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Harvest of Short-Rotation Woody Crops in Plantations with a Biobaler

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ABSTRACT

The biobaler is an alternative to the modified self-propelled forage harvester to cut and collect short rotation woody crops (SRWC). It is less capital intensive and more versatile, being able to harvest woody crops on plantations, on abandoned farmland, on brush land or within forest understory. The biobaler was evaluated specifically on five different plantations over 19 experimental units (546 bales harvested with an average mass of 427 kg and 49% moisture content). Average bale density was 266 kg wet mass (WM)/m^3 or 139 kg dry mass (DM)/m^3. Average harvest capacity was 35 bales/h (7.7 t dry matter/h), and ranged from 23 to 48 bales/h. Harvest in plantations with a 149 kW tractor cost on average CAN \$175/h, \$5/bale and \$22.84/t DM. Non recovered biomass (field loss) averaged 11% at random locations in the field and 8% at the point of bale ejection as a result of chip abrasion. While the biobaler remains a versatile harvester for SRWC, its preferred utilization will be in environments of diverse woody crops with final application as a rough mulch or for combustion in furnaces requiring minimal processing or size reduction.

Keywords: Biomass; Harvesting; Willow; Woody Crop; Feedstock

1. Introduction

Short rotation woody crops (SRWC), also known as short rotation coppice (SRC), are densely planted, high-yielding varieties of willow or poplar [1]. One year after planting, stems are usually cut back to encourage growth of multiple stems. The biomass is then harvested typically once every two to four years for a life cycle usually greater than 20 years.

The development of energy crops on farm land and in the forest zone depends on several factors such as land availability, expected markets, price of energy, alternate crops, cost of production, land owner expectations, policy and subsidies [2]. The growth of short rotation poplar has been suggested on riparian land (beach shore) in China to provide environmental improvement and a potentially important new source of biomass [3]. Willow plantations can also be established on underused low-to-medium quality agricultural land but harvest costs can be quite high, ranging between 39% and 60% of production

cost [4].

An Italian study indicated harvest costs of 15 €/green t when harvesting poplar SRC with a modified self-propelled forage harvester (SPFH) equipped with a specially-designed saw blade cutter-header [5]. These harvesters work well over large plantation areas in an industrial setting, with typical investment per unit between 340,000 and 440,000 €, depending on engine power in the range of 254 to 445 kW [5]. However, many future plantations are considered on small or segmented areas of marginal land, where smaller and relatively robust equipment would be preferable.

A novel harvester, called the biobaler, was developed to harvest woody biomass either in plantations or in natural stands in the form of round bales [6]. The biobaler represents a lower capital investment (\$150,000 or about 115,000 €) compared to the modified SPFH but it also requires an independent tractor. Although the original biobaler was also designed with a saw blade cutter [7], it has been commercialized with a more robust flail cutter [8]. The flail header was shown to be suitable to

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collect forest underbrush in Florida natural forest [9], to remove invasive brush in Saskatchewan prairie [10] and to harvest other native small woody crops in central Canada and Minnesota brushland [11].

Meanwhile, only limited data have been published on the biobaler's ability to harvest woody crops in plantations. The original experimental prototype with a flail cutter was used to harvest a limited quantity of willow from a plantation (52 bales) at an average rate of 11 t wet matter (WH)/h or 27 bales/h [6]. The commercial machine, known as the biobaler WB-55, is considerably more robust than the prototype. New machinery management data will be useful to assess capacity, operational requirements and limitations in cultivated SRWC. The objective of this study was to measure harvest capacity, fuel consumption and field losses in a wide range of SRWC plantations, and to estimate harvest cost in this context.

2. Materials and Methods

2.1. Description of Functional Principles of the Biobaler WB-55

A commercial version of the biobaler, manufactured by the Anderson Group [8] as model WB-55, was utilized for harvest. The main mechanisms of the biobaler are illustrated in **Figure 1**. A flail cutting and mulching roll is located in front of the machine to cut standing stems, partially shred them, move them through a feeding roll and push stems toward the compression chamber. Stems become more flexible as a result of partial shredding. When they reach the compression chamber, they are rolled into a spiral to form a round bale nominally of 1.22 m in diameter by 1.22 m in width. Compression rolls around the chamber perimeter exert pressure as the bale is formed. When the chamber is full, the baler stops in the field, twine is unrolled for attachment and, upon completion of tying, the tail gate opens, the bale is ejected and dropped onto the ground. Bale width and diameter can vary slightly depending on amount of bio-

mass and expansion after ejection from the chamber.

The original prototype cutting system was made of pivoting flail hammers [6]. The commercial model is composed of more aggressive interchangeable fixed cutting hammers (**Figure 2**). The total cutting roll width is 2.25 m. The machine can cut stems with diameters as large as 150 mm at the point of cut, but its capacity is higher when stems are smaller than 75 mm diameter. Proper operation of the commercial biobaler WB-55 requires a minimum tractor power of 134 kW (PTO 1000 RPM) and four hydraulic outputs. The tractor should be equipped with guards to protect vulnerable mechanical components such as the fuel reservoir, the radiator and hydraulic lines. For all experiments reported here, a Fendt 818 tractor was used to operate the biobaler in the field (**Figure 3**). The tractor had nominal power of 136 kW; its engine settings were adjusted to obtain a peak power of 149 kW.

2.2. Plantations

The research was conducted on five different SRWC plantations in Québec and Ontario (Canada) between August 2009 and November 2010. The plantations in Québec were single rows spaced 1.8 m apart in groups of six rows, with a larger 3.0 m spacing between groups of six rows. Cuttings were originally planted at a 0.3 m distance along the row (16,667 cuttings/ha). The plantations in Ontario were triple rows spaced 0.6 m apart, with a 2.0 m spacing between groups of three rows. Cuttings were originally planted at 0.6 m distance along the row (15,625 cuttings/ha).

Over time, each cutting becomes a stump with multiple stems. Just prior to harvest, plantations were characterized by stem density and stem diameter at breast height (DBH, *i.e.* 1.35 m above the ground). This was done by counting systematically all stems over random 5-m lengths and measuring stem DBH with a caliper (+/− 0.1 mm). Measurements on each 5-m length were replicated five times per plantation and scheduled harvest.
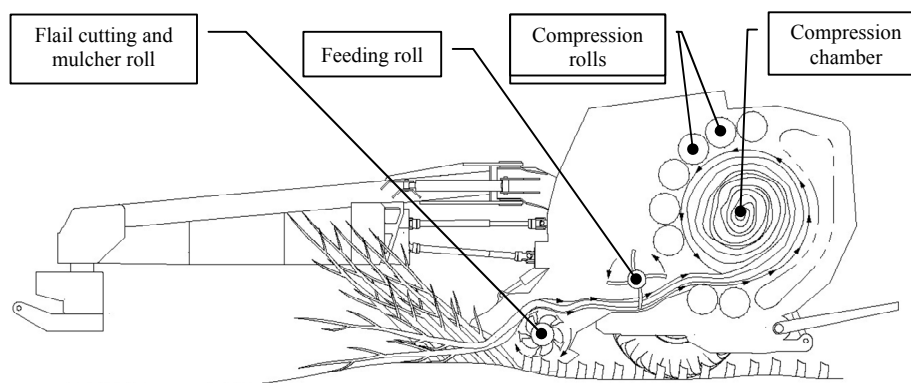

Figure 1. Schematic view of the biobaler WB-55.

Figure 2. Fixed hammer head.

Figure 3. Biobaler® WB-55 and Fendt™ 818 tractor.

The first harvest took place at the Willow Shade Farm in Godmanchester (Québec) on August 25-26th 2009 (willow only). The second harvest took place at the Agro Énergie farm in Saint-Roch-de-l'Achigan (Québec) on September 1st and 2nd 2009 (willow only). On November 30th 2009, willow and poplar were harvested in Kemptville (Ontario). On December 1st 2009, willow and poplar were harvested in Pickering (Ontario). On December 2nd and 3rd 2009, willow was harvested in Guelph (Ontario). Willow was harvested again at the Agro Énergie farm during the year 2010, on April 12th, June 29th and November 24-25th. Woody crops had leaves in August and September 2009, and in June 2010. At other times, leaves had fallen to the ground and only stems were collected.

2.3. Measurements during and after Harvest

Machine productivity was based on time measured within ±1 s at three steps: harvest, tying, and transition (time between bale ejection and start of a new bale). A typical experimental unit represented a continuous harvest se-

quence of 20 bales or more (about 400 kg per bale). For each experimental unit, total harvested area was measured. Each bale was measured for diameter and width with a measuring tape (±0.5 cm). It was also weighed with a platform type balance, Cardinal model 205 (0 to 2250 kg, ±0.5 kg). Bale moisture content was determined with wet material collected during harvest. A composite sample of about 1500 g was collected for every four consecutive bales. Samples were placed in paper bags, weighed (±0.1 g), and dried in an oven (Thermo Scientific OV128060, 4100 W) at 103˚C for 72 h. The dry samples were weighed again to estimate moisture content which is expressed on a wet basis (evaporated water mass × 100%/original wet mass of sample).

Diesel fuel consumption was measured after completing a harvest experimental unit (usually at least 20 bales). The fuel tank of the tractor was filled at the beginning of the harvest trial, and again at the end. The fuel mass was converted to volume by assuming a density of 0.8269 kg/liter [12].

After harvest, two types of loss were measured. The first type of loss was small particles (less than 20 cm) on the ground. These particles were picked up manually and placed in bags. Samples were taken over a length of 1.0 m along a row by the width of a group of rows (e.g. 3.2 m wide for a group of three rows 0.6 m apart plus the distance of 2.0 m from the next group of rows). The second type of loss was composed of long particles, often full length stems that were either cut and left on the ground or uncut and clinging to the stump after the passage of the baler. Over a distance of 40 m, all long particles were counted and the diameter of each stem was measured at the point of cut (or at 0.1 m from the ground for uncut stems). When long particles were not full length stems, a second diameter was measured near the small end of the stem. Empirical equations were used to estimate the mass of these long individual stems (m = $0.104\ D_c^{2.656}$, where m is wet stem mass in g, D_c is stem diameter at point of cut in mm; m = $0.364\ DBH^{2.514}$, where DBH is diameter at breast height, 1.35 m above the ground when stem is assumed to be cut at 0.1 m from ground; average ratio $D_c/DBH = 1.30$; parameters based on experimental data). The estimate of field loss was repeated three times per site and per day of harvest during the first six harvests.

2.4. Cost and Statistical Analyses

The cost analysis is based on a method used by the USDA Forest Service [13] and Auburn University [14] for estimating logging equipment cost. This method takes into account operating and ownership costs. The method is adapted to include some particularities of the biobaler. **Table 1** lists the major economic assumptions.

Table 1. Basic parameters and assumptions to estimate fixed and variable costs of the tractor and biobaler, with the base case scenario.

Parameter	Units[*]	Fendt 818 (134 kW)	Biobaler® WB55
Purchase price (P)	$ CAN	150,000	150,000
Salvage value (% of P)	%	20	10
Scheduled machine hours (SMH)	SMH/yr	800	800
Productive machine hours (PMH)	h/yr	560	560
Machine utilization rate (MUR)	%	70	70
Expected lifetime PMH	h	12,000	6000
Depreciation life	Yr	21	11
Average machine value (AMV)	$	90,000	82,500
Annual depreciation (AD)	$/yr	5,600	12,600
Interest rate (% applied to AMV)	%	8.0	8.0
Annual interest costs	$/yr	7200	6600
Insurance and tax rate (% applied to AMV)	%	3.5	2.0
Annual insurance and tax costs	$/yr	3150	1650
Total annual fixed costs	$/yr	15,950	20,850
Hourly fixed costs	$/h	28.48	37.23
Repair and maintenance (RM) costs (% of AD)	%	100	150
Annual R&M costs	$/yr	5600	18,900
Hourly R&M costs	$/h	10.00	33.75
Fuel cost	$/L	0.75	-
Average fuel consumption	L/h	30	-
Lube and oil, % of fuel cost	%	36.8	18.4
Average cost of fuel, lube and oil	$/h	30.77	4.14
Operator wage and benefit rate (WB)	$/SMH	15.60	-
Average WB considering MUR	$/h	22.29	
Twine cost	$/bale		0.25
Average baling capacity	bales/h		35
Average harvest capacity	t DM/h		7.68
Average twine cost	$/h		8.75
Total variable costs per PMH	$/h	63.06	46.64
Total fixed costs and variable costs	$/h	91.54	83.87
Total FC and VC per unit DM	$/t DM	11.92	10.92
Total costs	$/t DM	22.84	

[*]Hour unit (h) always refers to productive machine hour (PMH).

The experimental data were analyzed by linear regression. A total of 8 dependent variables were identified: Y1, wet bale mass (kg WM); Y2, wet bale density (kg WM/m³); Y3, dry bale mass (kg DM); Y4, dry bale density (kg DM/m³); Y5, harvest capacity (bales/h); Y6, harvest capacity (t DM/h); Y7, harvest capacity (t WM/h); and Y8, diesel fuel consumption (L/t DM). They were correlated with 8 independent variables: X1, woody crop species (1, willow; 2, poplar; 1.5, mix); X2, average DBH of large stems (DBH $\geq$ 10 mm), mm; X3, maximum DBH, mm; X4, number of small stems (DBH < 10 mm) per hectare; X5, number of large stems/ha; X6, moisture content (%); X7, presence or absence of leaves (0, absent; 1, present); X8, harvested yield (t DM/ha). The linear regressions were done by step-wise deletion, removing the least significant independent variables successively as long as they were not significant at the p = 0.05 level.

3. Results

3.1. Plantations Characteristics Prior to Harvest

Table 2 shows the main physical properties of woody crops measured just a few hours prior to harvest. Willow plantations had a greater total number of stems (135,000/ha) than poplar plantations (56,000/ha), but average diameter of the large stems (defined as having a DBH > 10 mm) was smaller for willow (17.4 mm) than for poplar (31.2 mm). The largest single diameter stems observed had a DBH of 56 mm in willow and 44 mm in

poplar. The variation between sites is explained partly by differences between clones, soil and climate. Some woody crops generate greater number of small stems while others produce a smaller number of bigger stems.

3.2. Bale Mass and Biobaler Harvest Rate in Plantations

Table 3 illustrates the average bale mass, bale density and moisture content. Out of 19 experimental units measured, only three contained poplar, two of which were

Table 2. Plantation characteristics just prior to harvest: number of years of growth (age), average stem diameter at breast height (DBH) of large stems, and number of stems per hectare [small stems are grouped by DBH < 10 mm; large stems, DBH ≥ 10 mm].

Site and species (W = willow; P = poplar)	Date	Age (yrs)	Average DBH (mm)	Maximum DBH (mm)	Small stems (#/ha)	Large stems (#/ha)	Total stems (#/ha)
Québec, Willow Shade Farm (W)	2009-08-25	3	21.0	55.0	51,000	52000	103,000
Québec, Agro Énergie (W)	2009-08-26	2	16.0	28.0	84,000	51000	135,000
Ontario, Kemptville (W)	2009-11-30	3	15.0	21.2	77,600	43200	120,800
Ontario, Kemptville (P)	2009-11-30	3	28.4	35.4	73,700	17300	91,000
Ontario, Pickering (W)	2009-12-01	3	19.1	33.8	26,600	45800	72,400
Ontario, Pickering (P)	2009-12-01	3	33.9	43.8	2500	19300	21,800
Ontario, Guelph (W)	2009-12-02	3	13.3	16.1	192,400	44100	236,500
Québec, Agro Énergie (W)	2010-04-12	2	18.6	36.1	59,000	98000	157,000
Québec, Agro Énergie (W)	2010-06-29	2	16.0	23.7	64,000	79000	143,000
Québec Agro Énergie (W)	2010-11-24	2	20.0	55.5	59,900	56100	116,000
Average (willow)		2.5	17.4	33.7	76,813	58650	135,463
Average (poplar)		3	31.2	39.6	38,100	18300	56,400

Table 3. Number of bales harvested in plantations per experimental unit, average bale mass on a wet matter (WM) basis, moisture content and bale density.

Site and species (W = willow; P = poplar)	Date	Nb. of bales	Ave. bale mass (kg·WM)	Moisture content (% w.b.)	Bale density (kg·WM·m^{-3})	Bale density (kg·DM·m^{-3})
Québec, Willow Shade #1 (W)	2009-08-25	23	439	42.6%	272	156
Québec, Willow Shade #2 (W)	2009-08-26	13	488	53.4%	297	139
Québec, Agro Énergie #1 (W)	2009-09-01	16	426	48.5%	252	130
Québec, Agro Énergie #2 (W)	2009-09-01	18	385	48.3%	239	124
Québec, Agro Énergie #3 (W)	2009-09-01	18	451	51.7%	293	142
Ontario, Kemptville #1 (W)	2009-11-30	23	463	50.8%	-	-
Ontario, Kemptville #2 (W)	2009-11-30	32	437	50.6%	-	-
Ontario, Kemptville #3 (P)	2009-11-30	35	512	56.0%	-	-
Ontario, Pickering #1 (W, P)	2009-12-01	43	470	50.6%	-	-
Ontario, Pickering #2 (W, P)	2009-12-01	52	454	50.6%	-	-
Ontario, Guelph (W)	2009-12-02	38	380	46.7%	-	-
Québec, Agro Énergie #4 (W)	2010-04-12	17	372	40.8%	242	143
Québec, Agro Énergie #5 (W)	2010-04-12	16	397	40.8%	241	143
Québec, Agro Énergie #6 (W)	2010-04-12	28	401	40.8%	245	145
Québec, Agro Énergie #7 (W)	2010-06-29	20	551	51.1%	355	174
Québec, Agro Énergie #8 (W)	2010-11-24	45	398	50.0%	269	135
Québec, Agro Énergie #9 (W)	2010-11-24	46	385	51.4%	264	128
Québec, Agro Énergie #10 (W)	2010-11-25	36	371	50.5%	259	128
Québec, Agro Énergie #11 (W)	2010-11-25	27	339	48.7%	228	117
Total		546				
Average		29	427	48.6%	266	139
Standard deviation		11.98	54.3	4.39%	33.9	14.8

mixed with willow. It is therefore difficult to distinguish the two species in terms of bale mass and density, even though the limited data indicated that polar produced heavier bales than willow (see the statistical analysis below). Overall average bale mass was 427 kg wet matter (WM), with an average moisture content of 48.6% (average DM of 219 kg/bale). Bale density averaged 266 kg WM/m^3 or 139 kg DM/m^3.

Harvest capacities are shown in **Table 4**. They ranged from 23 to 48 bales/h with an average of 35 bales/h. The total cycle time to harvest each bale averaged 1 min 47 s (01:47); it was divided on average as 0:59 for filling the bale chamber, 0:36 for tying and 0:12 for ejecting and starting a new cycle. Based on average bale mass and moisture content, the average harvest capacity with the biobaler was therefore 7.69 t DM/h or 15.0 t WM/h. The harvested yields ranged from 10 to 32 t DM/ha, with an average of 19.4 t DM/h (the actual total yield is estimated below by adding losses). Fuel consumption also varied considerably, from 2.1 to 7.0 L/t DM, with an average of 3.9 L/t DM.

Table 5 shows the results of the linear regressions between 8 dependent variables and 8 independent variables to explain variations notably in bales mass, bale

density, harvest rate and fuel consumption. According to models Y1 and Y3, bale mass was higher for poplar than for willow, and was also increased in the presence of leaves (62 kg more wet mass, 27 kg more dry mass per bale). Only wet density (Y2) increased as a function of moisture content while dry matter density (Y4) was not affected by any observed independent variables. All three harvest capacities (Y5, Y6, Y7) were affected positively by average stem DBH and harvested yield but negatively by maximum stem DBH. Mass capacity (Y6, Y7) was also affected positively by the presence of leaves, but not bale capacity (Y5). Increased moisture content affected negatively the dry matter harvest capacity (Y6). Finally, variations in fuel consumption were not explained by any of the eight observed independent variables. Other factors, such as soil conditions, wheel slip and operator experience are factors that would likely affect fuel consumption with a relatively novel harvest technology.

3.3. Dry Matter Losses

Table 6 presents estimates of dry matter loss as measured by random samples on six sites or dates. The average total loss observed was 2.33 t DM/ha, with a propor-

Table 4. Harvest capacity in bales per hour and mass of dry matter (DM) per hour, actual harvested yield and tractor fuel consumption during harvest.

Site and species (W = willow; P = poplar)	Date	Bales/h	Capacity (t DM/h)	Harvested yield (t DM/ha)	Fuel consumption (L/t DM)
Québec, Willow Shade #1 (W)	2009-08-25	33.75	8.51	31.84	2.74
Québec, Willow Shade #2 (W)	2009-08-26	23.48	5.34	19.55	4.36
Québec, Agro Énergie #1 (W)	2009-09-01	39.94	8.77	16.30	4.17
Québec, Agro Énergie #2 (W)	2009-09-01	43.14	8.58	24.14	3.23
Québec, Agro Énergie #3 (W)	2009-09-01	48.32	10.53	28.68	2.67
Ontario, Kemptville #1 (W)	2009-11-30	32.15	6.78	9.68	2.93
Ontario, Kemptville #2 (W)	2009-11-30	30.60	6.64	12.98	3.53
Ontario, Kemptville #3 (P)	2009-11-30	37.50	8.42	16.57	2.64
Ontario, Pickering #1 (W, P)	2009-12-01	39.51	9.24	14.69	2.12
Ontario, Pickering #2 (W, P)	2009-12-01	41.11	9.33	16.31	5.26
Ontario, Guelph (W)	2009-12-02	27.78	5.62	10.20	4.84
Québec, Agro Énergie #4 (W)	2010-04-12	33.37	7.35	22.77	6.96
Québec, Agro Énergie #5 (W)	2010-04-12	42.99	10.10	26.12	3.28
Québec, Agro Énergie #6 (W)	2010-04-12	37.33	8.86	21.47	2.76
Québec, Agro Énergie #7 (W)	2010-06-29	34.76	9.36	17.14	3.00
Québec, Agro Énergie #8 (W)	2010-11-24	37.52	7.46	23.14	3.03
Québec, Agro Énergie #9 (W)	2010-11-24	33.68	6.31	24.01	4.49
Québec, Agro Énergie #10 (W)	2010-11-25	26.02	4.77	18.64	5.49
Québec, Agro Énergie #11 (W)	2010-11-25	23.36	4.06	14.52	6.81
Total					
Average		35.07	7.69	19.41	3.91
Standard deviation		6.84	1.85	6.05	1.42

Table 5. Linear regressions to predict dependent variables as a function of independent variables observed during harvest in plantations with the biobaler.

Dependent variable	Model	R^2
Y1: wet bale mass (kg WM)	$271.80 + 122.97 * X1 + 61.83 * X7$	0.48
Y2: wet bale density (kg WM/m^3)	$58.25 + 436.16 * X6$	0.37
Y3: dry bale mass (kg DM)	$113.21 + 56.10 * X1 + 0.000616 * X5 + 27.001 * X7$	0.42
Y4: dry bale density (kg DM/m^3)	No significant variable	-
Y5: harvest capacity (bales/h)	$15.50 + 1.14 * X2 - 0.654 * X3 + 1.04 * X8$	0.69
Y6: harvest capacity (t DM/h)	$9.90 + 0.45001 * X2 - 0.172 * X3 - 17.15 * X6 + 2.05 * X7 + 0.143 * X8$	0.75
Y7: harvest capacity (t WM/h)	$2.75 + 0.899 * X2 - 0.354 * X3 + 3.88 * X7 + 0.3106 * X8$	0.78
Y8: diesel fuel consumption (L/t DM)	No significant variable	-

Independent variables: X1 = species (1, willow; 2, poplar; 1.5, mix); X2 = average DBH of large stems (DBH $\geq$ 10 mm), mm; X3 = maximum DBH, mm; X4 = nb. of small stems (DBH < 10 mm) per hectare; X5 = nb. of large stems/ha; X6 = moisture content (%); X7 = leaves (0, absent; 1, present); X8 = harvested yield (t DM/ha).

Table 6. Random samples of dry matter loss after passage of the biobaler.

Site and date	On the ground (t DM/ ha)	Standing stem (t DM/ha)	Total loss (t DM/ha)	Total Mean loss (t DM/ha)	Harvested yield (t DM/ha)	Relative loss (%)
	2.00	0.14	2.15			
	2.19	0.13	2.31			
Willow Shade Farm (2009-08-26)	1.56	0.60	2.16	2.75	25.69	9.7%
	1.78	0.20	1.98			
	4.99	0.17	5.17			
	2.73	0.05	2.77			
Agro Énergie (2009-08-31)	4.08	0.05	4.13	3.61	20.99	14.7%
	3.90	0.04	3.94			
	1.56	0.77	2.33			
Kemptville (2009-11-30)	2.45	2.93	5.38	2.97	11.79	20.1%
	1.10	0.09	1.19			
	1.04	0.49	1.53			
Guelph (2009-12-02)	2.17	0.26	2.43	1.95	10.32	15.9%
	1.64	0.26	1.90			
Agro Énergie (2010-04-12)	2.07	0.02	2.10	1.42	23.45	5.7%
	0.72	0.02	0.74			
	1.09	0.00	1.09			
Agro Énergie (2010-06-29)	1.63	0.00	1.63	1.28	17.14	6.9%
	1.11	0.00	1.11			
Average				2.33	18.23	11.3%

tion of 84% from particles on the ground and 16% of long stems (cut or uncut). When these absolute losses were compared to actual harvested yield (18.23 t DM/ha on average), total losses represented on average 11.3% of total yield (20.56 t DM/ha on average). Losses ranged from 5.7% to 20.1%. Some clones were stiffer and more breakable than others, explaining partly some differences in loss.

On the Agro Énergie site harvested on November 24-25, 2010, no loss estimate was made directly after har-

vest because of snow fall on the following day. However, in spring 2011, small heaps of wood chips were observed at the same location bales had been ejected. A set of 12 measurements of these heaps in May 2011 indicated that an average 1.97 t DM/ha of loss was due specifically to wood chips falling off the bales at the time of ejection. These small heaps had not been measured in the previous random samples reported in **Table 6**. At the Agro Énergie Farm on November 24-25, 2010, average harvested yield was 20.1 t DM/ha, so random losses estimated at an

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