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A Modified Round Baler to Harvest Small-Diameter Woody Biomass

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Abstract: A round baler was modified to harvest woody crops with a basal stem diameter up to 75 mm at the point of cut. Two innovative headers were designed to cut, shred and feed the woody biomass into the round bale chamber. In 2006, a first header was designed and constructed, specifically for row-planted willow. It included a 1.97-m wide four-saw-blade horizontal cutter, a 1.55-m wide horizontal rotor shredder and a 1.2-m wide baler. The machine could harvest one or two willow rows at a time with continuous cutting and baling rates between 8 and 12 t wet matter/h. In 2006, more than 90 bales were harvested. Bale diameter ranged between 1.0 and 1.5 m; density between 220 and 300 kg wet/m³. The rotary saw blades used in the first header left a neat and clean cut stubble which favours rapid regrowth of plantations. However, the saw blades are expected to be less efficient in uneven land with natural shrubs and scattered rocks. In 2007, a second header was designed without saw blades; it used a more aggressive and wider rotary shredder (2.30 m) including 20 flail hammers or 60 flail knives able to simultaneously cut and shred the woody crop. This second header was used to harvest natural brushes on abandoned agricultural land, natural pasture with sporadic shrubs and forest understory vegetation. In the western Canadian prairie, the prototype harvested natural willow rings around marshes at rates from 5 to 7 t wet crop/h. This innovative "bio-baler" could therefore be used to harvest fast growing willow plantations or naturally growing woody brushes as new sources of biomass, in addition to rejuvenating the land from sometimes undesirable shrubs.
Key words: Woody crop, willow, brush, cutting, shredding, baling, harvesting.

INTRODUCTION

In several regions of the world, woody biomass is becoming scarcer because of its increased use for bio-products (panel boards, animal bedding) and bio-energy (wood pellets, direct combustion, cellulosic conversion). New sources of woody crops are needed to complement traditional forest products. For example, rapid growing woody biomass, also know as short rotation intensive culture (SRIC), may be cultivated and harvested regularly, typically in 3-year cycles. One of the most widely used species for SRIC is willow (Labrecque and Teodorescu, 2002; Stolarski, 2008). Other woody biomass can come from natural brushes growing on abandoned agricultural land, along river banks and on natural pastures (Fitch et al., 2001). Another important source of woody biomass is within natural and planted forests where the understory vegetation needs to be removed regularly to reduce the risk of high-intensity forest fires and to favour the growth of trees (Busse et al., 2000).

A major challenge with small woody biomass is its collection and transportation. This type of biomass has a relatively low value and a low mass density. Currently, commercial harvesters available for SRIC are modified self-propelled forage harvesters with a wide saw blade header (Lechasseur and Savoie, 2005). However, these machines can be quite expensive (> $500k) and are not suitable to harvest non-planted woody biomass such as shrubs or forest understory vegetation on rough and rocky terrain.

The objective of this project was to develop and test an experimental harvester able to collect woody stems either from row plantations or from natural fields and semi-wooded areas.

PROTOTYPE DEVELOPMENT

The harvest platform chosen was a round baler for several reasons. A round baler is a relatively low cost machine; it produces a package that is easy to handle and transport. The round baler does not have as high a throughput as the self-propelled harvester but it provides an intermediate and low-cost alternative.

The original concept proposed by Savoie et al. (2006) for plantations included a new header made of four horizontal saw blades (total width of 1.97 m) and a shredder with 12 hammers or 24 flail knives (1.55 m wide rotor). The header was integrated in front of a round baler; it ejected the processed stems into the bale chamber (Fig. 1). The round baler was a modified New Holland BR 740. The original flat narrow belts of the compression chamber were replaced by a single full-width belt to better contain the woody residues inside the chamber. A 3.66-m long swing-pivot tongue was designed to offset the baler up to 2.35 m on each side of the tractor's line of travel (Fig. 2). The frame was reinforced to support the extra weight (800 kg) of the cutter head.

A double push bar system in front of the baler header was designed with a dual purpose: to force the upper part of the stems forward in front of the saw blades and to protect the power transmission components from the flow of freshly cut material. The pull type harvester required a 100 kW tractor with four hydraulic circuits to be operated efficiently. The original cutter head and modified baler are described in detail by Lavoie et al. (2007).

A second cutter head was designed to harvest brushes on fallow land and on rough terrain. The header was composed of a full-width (2.30 m) shredder which combined cutting, shredding and ejection into the bale chamber (Fig. 3). Flail cutting is known to leave a rough edge on the stumps, thereby allowing water to stagnate and slowly penetrate into the root system after harvest. This can be detrimental to stump and root health. However, slow regrowth of the woody crop after harvest can actually be an advantage in some cases such as abandoned fallow land, river bank brush and understory vegetation in forests. The flail cutter was expected to be more robust than saw blades when hitting earth mounds or rocks, and capable of gathering stems of various shapes and standing angles.

The rotor diameter of the second shredder cutter head was 200 mm. Its length of 2.30 m was practically equal to the length of the baler axle. Either 20 hammers or 60 knives (in groups of three) were placed helicoidally along the rotor at a distance of 115 mm center to center and at an offset angle of 90°. Each hammer weighed 1.7 kg, had a cutting width of 145 mm and was hinged to the rotor on a 20 mm diameter bolt which allowed partial rotation like a flail. The cutting width of the hammers had an overlap of 15 mm on each side. The length of each hammer was 125 mm from the hinge to the cutting edge; the distance between the rotor surface and the hinge was 25 mm. Therefore, the cutting edge rotated along a radius of 250 mm from the rotor's centre.

Figure 1. Original (2006) four-saw cutter head concept developed to harvest willow plantations.

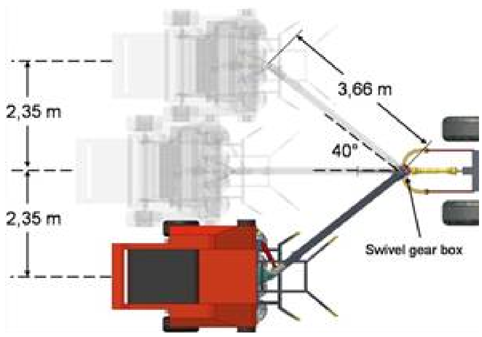

Figure 2. Aerial view of baler offset.

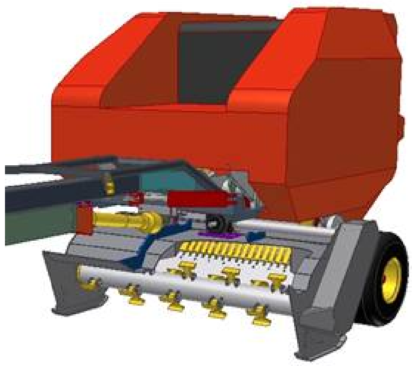

Figure 3. Second (2007) shredder cutter head concept developed to harvest natural vegetation on fallow land and over rough terrain.

Alternately, hammers could be replaced by knives placed in groups of three. Each knife weighed 0.29 kg, was 125 mm long and had a 50 mm hitting width parallel to the rotor's axis. The total cutting width of each group of three knives was 150 mm which provided an overlap of 18 mm between each group. Overlap of hammers or knives ensured every brush was cut and shredded. The cutting edge of knives also rotated at a radius of 250 mm from the rotor's center. At a rotor speed of 2200 RPM, the peripheral speed of the cutting edge of hammers or knives was 58 m/s. This second header and other modifications are described in detail by Lavoie et al. (2008).

MARERIALS and METHODS

The prototype was evaluated in 2006 with the first header composed of four saws for cutting. It was operated at five different periods in three different willow plantations in Quebec and New York state during the first year. In 2007, the prototype was equipped with the second header, without saws but using the shredder to simultaneously cut and process stems. The second header and baler were evaluated in Quebec, in western Canada and in southern USA. Various vegetation types and working conditions were tested during the second year.

The prototype was operated by a tractor with a minimum of 100 kW power. Another tractor equipped with front end forks was used to handle bales. Each bale was weighed on a platform scale (1000-kg full range; precision ± 0.2 kg) generally within two days of harvest. Each bale was measured for three circumferences (±10 mm). The wet density was calculated as the ratio of wet mass to bale volume. Each bale was harvested by moving at a normal speed chosen by the tractor operator. The forward speed ranged between 1 and 4 km/h; it was adjusted according to crop yield. Time to harvest each bale was clocked (± 1 s). Any delay (e.g. turning to another row, stopping for any reason) was noted, and subtracted from the total time to estimate the actual harvest rate to form each bale. The travel length to fill the baler and form each bale was measured to estimate the area covered and the biomass yield. To measure moisture content, three stem samples were collected randomly in the field at different times during the day. The method was similar to the one used to measure moisture in forages (ASABE Standards, 2006a). The samples were dried in the oven at 103°C but the time was extended beyond 24 h, typically up to 72 h or until such a time that the sample mass ceased to change and no more water evaporated. Field loss was estimated by manually collecting residues remaining in the field from five random specific areas after baling.

RESEARCH RESULTS

During the five trials in 2006, 92 bales were collected. Plantations in Cazaville and Huntingdon were composed of single rows spaced 1.5 m between rows and with stumps planted every 0.3 m along the row. The plantation in Syracuse NY plantation was a double row system: 0.75 m between rows in pair and 1.5 m between pairs of row. Table 1 presents the average baling capacity of the harvester equipped with the four-saw header for each trial in 2006. The overall average baling capacity was 7.9 t/h (wet matter) and the average area capacity is 0.25 ha/h. These capacities do not take into account the idle time for wrapping and unloading bales in the field, the turning time and other inefficiencies.

Field loss was evaluated during the fifth trial in 2006. An average of 28 % of total yield was left behind the harvester. Losses came mainly from the compression chamber and in front of the header. Figure 4 shows the prototype working in a willow plantation in November 2006.

The diameter of the 92 bales collected in 2006 ranged between 0.99 to 1.54 m. The wet matter density of these bales varied from 222 to 300 kg/m³ during the five trials. On a dry matter (DM) basis, the range was from 111 to 167 kg DM/m³. An increased of the bale chamber belt tension significantly increased bale density by up to 10%. Moisture content of willow at harvest ranged from 44 to 51%.

During the 2007 harvest trials with the srhedder header, five sets of bales were monitored (Table 2).

The first trial was carried out on a 15-year-old abandoned agricultural land where brushes had lasr been cut in 2002. The second trial was carried out in a willow plantation of parallel single rows spaced 1.5 m between each other. A total of 26 bales were harvested with the shredder header using flail hammers and 26 other bales were harvested with flail knives. The third trial was performed in Saskatchewan on natural willow vegetation that surrounds marshes (sloughs) in prairies referred to as willow rings (Fig. 5).

Table 1. Results of willow harvesting with 2006 four-saw header-baler.

Trial	Date (2006)	Place	Bales Harvested	Average Yield[a] (t/ha)	Area Capacity (ha/h)	Baling Capacity (wet mass) Average (t/h)	Baling Capacity (wet mass) Maximum (t/h)
1	19-20 June	Cazaville, QC	8	74.1	0.14	6.1	NA
2	24 July	Cazaville, QC	11	47.8	0.26	9.22	13.1
3	30 Aug.-1 Sept.	Huntingdon, QC	29	NA	0.28	7.1[b]	11.8
4	8-9 Nov.	Syracuse, NY	25	76.5	0.28	9.72	14.3
5	27 and 29 Nov.	Cazaville, QC	19	NA	0.30	7.52	11.1
		Total	92	Average	0.25	7.9	12.6

[a] Yields were not estimated during third and fifth harvest trial because of excessive variation in the field.
[b] Bale mass was measured two weeks after harvest.

Figure 4. Harvest of willow in plantation with four-saw header in Cazaville (Quebec), November 2006.

In the second trial, the baling capacity was highest (up to 16.8 t/h) because of the good harvesting conditions in a willow plantation. Field loss was evaluated at Indian Head, SK; it averaged 35% of total yield.

Trials performed in the Osceola Natural indicated that small brushes such as palmetto, gall berry and wax myrtle could also be harvested with the bio-baler. On site 1 of the natural forest, the area capacity for mechanical harvest was higher than on site 2 due to tree density (50 trees/ha on site 1 vs. 200 trees/ha). It was easier to manoeuvre around trees in a less dense forest area.

The baler was also operated in a commercial pine forest in southern Georgia (USA) where trees were aligned and rows were spaced 3 m between each other. Operating the harvester under such conditions was much easier than in a natural forest because the harvester was able to run in a straight line. However, part of the vegetation was not harvested (about 0.7 m wide for each 2.3 m of cut width) because it was not worth passing a second time between the same trees to harvest less than a third the yield compared to the first passage.

DISCUSSION

When harvesting in plantations, the field efficiency of such a woody crop harvester is expected to be similar to the efficiency of an agricultural round baler harvesting forage, e.g. typically 65% (ASABE Standards, 2006b). The average field harvest capacity would be about 5 t/h with the four-saw header in willow plantations, but this could be improved to at least 9 t/h with minor improvements because baling capacities above 14 t/h were observed in good working conditions in 2006 (i.e. with high yields and in relatively uniform plantations).

Table 2. Summary of natural brush and willow harvesting capacity with 2007 header.

Trial	Date (2007)	Place	Bales Harvested	Average Yield (t/ha)	Area Capacity (ha/h)	Baling Capacity (wet mass) Average (t/h)	Baling Capacity (wet mass) Maximum (t/h)
1	13 June	Cap St-Ignace, QC (fallow land)	7	NA	NA	4.6	5.2
2	30 July- 2nd Aug.	Cazaville, QC (willow plantation)	52	NA	0.29[a]	11.1	16.8
3	23-24 October	Indian Head, SK (pasture brushes)	15	23	NA	5.4	6.6
4a	10 December	Lake City, FL Site 1 (forest understory)	4	16.6	0.42	2.0[b]	NA
4b	11-13 December	Lake City, FL Site 2 (forest understory)	14	18.7	0.3	2.4 [b]	NA

[a] Average calculated with 10 bales
[b] Continuous harvest capacity

harvesting woody crops either in plantations or on fallow land. The more robust shredder header operated continuously either on a level plantation or on rough terrain whereas the four-saw cutter head worked well on a level plantation. Light flail knives provided sufficient cutting and processing to bale the woody stems. Heavy flail hammers also provided good cutting and processing, but the harvest rate was 15% less with hammers than with knives (Lavoie et al. 2008). The relative breakage of particles by knives or hammers was not quantified but it is hypothesized that hammers provided excess shredding that was unnecessary to form bales.

A future versatile woody crop baler could be designed with interchangeable headers. One header would use the shredder as the cutting mechanism; the other header would use saw blades for cutting. Saw blades are considered preferable in plantations for a neat cut, stump health and rapid regrowth. The shredder header is versatile in itself because it can operate on fallow land, on various natural sites invaded by brushes, and also in plantations. The disadvantage of the shredder header in plantations is the risk of disease as a result of stump shredding and water stagnation along the cut stems. This disadvantage has yet to be demonstrated economically and over the long term in plantations. Therefore, a shredder header might actually be a good compromise when both natural brushes and planted trees have to be harvested.

The total material and manufacturing cost of the harvester was initially about $42,800 CAN. The main purchased components were a three-year old baler ($23,000), a modular cutterbar ($5,100), a shredder ($2,600), a swivel gear box ($3,200) and a full-width rubber compression belt ($900). Other parts included pulleys, transmission belts, bearings, hydraulic cylinders and various attachments (total of $4,900). More than a hundred steel parts were laser cut or formed at a cost of $5,800. After each of the five field trials in 2006, several modifications were made with purchased material and metal work at a extra cost of $6,500. The total material and manufacturing cost for the 2006 prototype was $52,000 by the end of the year. Labour and design costs were not included.

The second header built in 2007 that incorporated the 2.30-m wide shredder cost about $10,000 in parts and material. This cost would be added to the baler and modifications for proper integration. With the current experience, a new cutter-baler-shredder with either a saw-blade header or a flail shredder header would cost about $45,000 to build, and twice this price when labour, design and engineering costs are accounted for.

Following the two-year experience, several recommendations to improve the next prototype were made. The compression chamber of the baler should be better sealed to reduce particle loss and to minimize clogging problems. The cutter heads have to be improved to reduce energy requirement and shredding aggressiveness while maintaining good crop flow throughout the harvester.

CONCLUSION

The results showed the feasibility of harvesting woody biomass using a conventional round baler. The baling capacity of the prototype ranged from 2 to 17 wet t/h. Several modifications have already been done the harvester to improve the concept and the flow of woody crop from cutting, to shredding and forming round bales. The next woody crop baler should improve crop recovery and reduce field loss which was about 30% with the current prototype.

The project showed the feasibility of harvesting woody biomass both on fallow land and in willow plantations. Two original headers were developed, using either saw blades to cut stems on plantations or using a robust flail shredder to cut stems of natural brushes. The flail shredder was able to cut and process brushes on fallow land at a harvest rate of about 4 t of wet matter (WM)/h at 50% moisture content. The same shredder header harvested woody branches at a rate of 10 to 12 t WM/h in a level willow plantation.

Future work should focus on improving the robustness, reliability and self-cleaning capability of the harvester when working in wet and potentially sticky conditions. Such future work will provide valuable technology to improve the management of natural brushes on fallow land and other areas that need to be cleared regularly of undesirable woody vegetation. This harvest technology should also provide a valuable tool for short-rotation woody crops.

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