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CUTTING, BUNDLING AND CHIPPING SHORT-ROTATION WILLOW

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Abstract

Willow is a fast-growing plant with large potential to produce biomass and reduce greenhouse gas emissions. It can yield between 10 and 20 tonnes of dry matter per year, per hectare, depending on soil, fertilization and climate in several cultivated areas of Canada. It can provide an alternate cropping system with minimal maintenance to marginal land that has been left fallow or has been underutilized for traditional agricultural crops. It is estimated that out of a total of 65 million ha of agricultural land in Canada, 1 to 2% of the land could be used over the next 20 years to produce dedicated biomass crops such as willow to complement traditional wood feedstock for pulp and paper and particle board or oriented strand board. Moreover, willow could also become a significant source of energy either by combustion or by chemical conversion. The technology to cut and harvest short-rotation willow is still in development, with most previous work coming from Europe. The paper reviews current technology to cut, bundle and chip short-rotation woody crops such as willow. It presents current knowledge and areas that require innovative work, notably in willow mechanical properties, cutting mechanisms and bundling systems for long stems. The paper proposes future research directions that are needed to develop appropriate technology as this potential market develops.

INTRODUCTION

Short rotation intensive culture (SRIC) of willow has been suggested as a means of maintaining or enhancing crop production on marginal and abandoned agricultural land (Labrecque and Teodorescu, 2003). SRIC may also provide considerable environmental benefits as a sink for excess greenhouse gas, industrial waste and municipal sludge (Perttu and Kovalik, 1997) and as a source of biomass for energy and the chemical industry (Morris and Ahmed, 1992).

Canada has a large agricultural land base of about 67 Mha (Statistics Canada, 2005; Table 1). An estimated 36 Mha is covered by agricultural crops. Eight major crops represent more than 90% of the cultivated area: wheat (10.6 Mha), tame hay (7.5 Mha), barley (5.0 Mha), canola (4.7 Mha), oats (2.2 Mha), peas (1.3 Mha), corn (1.2 Mha) and soyabean (1.1 Mha). There has been an increase in agricultural crop area of more than 5 Mha between 1981 and 2001, or an average increase of 270,000 ha/year.

There is still 31 Mha of farmland that is not in agricultural (or cultivated) crops: about 4.8 Mha in seeded pasture, 15.4 Mha in natural pasture, 6.2 Mha in woodland and 4.7 Mha in summer fallow (Statistics Canada, 2005). This remaining non cultivated farmland has probably less potential for conversion into annual crops than the previous 5 Mha that were converted between 1981 and 2001. However, large areas may still hold good potential for additional cultivated perennial crops such as SRIC of willow and poplar. Over the next twenty years, a projection of 1 Mha of new plantations in SRIC to provide new crops for energy and bioproducts would not appear unreasonable.

Table 1. Farmland area use between 1981 and 2001 (Reference: Statistics Canada, 2005).

Area use	Year of Agricultural Census				
	1981	1986	1991	1996	2001
Total farmland (ha)	65,888,916	67,825,757	67,753,700	68,054,956	67,502,447
Total area owned (ha)	45,554,298	43,218,905	42,961,352	43,060,963	42,265,707
Total area leased (ha)	20,334,618	24,606,852	24,792,348	24,993,993	25,236,740
Land in crops (ha)	30,965,812	33,181,235	33,507,780	34,918,733	36,395,151
Land not in crops (ha)	34,923,104	34,644,522	34,245,920	33,136,223	31,107,296

Over the last thirty years, considerable work has been done to understand and promote the use of SRIC for energy and environmental benefits. A handbook was developed on short rotation forestry, based largely on the European experience (IEAB, 1995) but also on some limited Canadian experience (Tardif, 1994). Over twenty years ago, a Canadian company, Hyd-Mech, and the National Research Council of Canada developed a harvester prototype, the FB7, to cut and bundle fast-growing hybrid poplar and sycamore (Curtin et al., 1985; Golob et al., 1986). More recently, experiments in southern Quebec have shown an excellent potential in terms of yields of SRIC of willows (more than 10 t dry matter/ha/yr according to Labrecque and Teodorescu, 2003).

The options to harvest SRIC in Canada were described by IEAB (1995) as: (1) labour intensive harvest with chainsaw; (2) skidding cut trees with a farm tractor; (3) highly mechanized harvest with feller-bunchers. However, the current feller-bunchers are designed for large diameter trees (usually up to 200-300 mm in diameter) spaced typically in a 3 m by 3 m grid and to work relatively slowly cutting about 1000 trees/ha. The feller-bunchers are not designed to collect a large number of small size willow stems (between 20 and 75 mm diameter). Typical willow density is 20,000 plants/ha and each plant may sprout 4 to 8 stems. Some European machines may be applicable, but differences in plantation patterns, planted areas and crop characteristics may justify some independent research and development. The purpose of this paper is to review the current technology to harvest SRIC of willows and identify future directions to respond to this potentially high-growth market. The paper is subdivided in the following sections: crop characteristics, cutting mechanisms, collecting mechanisms and an assessment of previous SRIC harvesters.

CROP CHARACTERISTICS

Willow plantations were established in eastern Canada in 1995 by Labrecque and Teodorescu (2003). They consisted of two species, *Salix Viminalis L.* and *Salix Discolor Mühl*. The pattern of plantation developed in eastern Canada was however different from the one typically used in Europe (pairs of rows 0.75 m apart and spaced 1.5 m between pairs). The seedlings in eastern Canada were planted in six rows 1.5 m apart and spaced 3.0 m between groups of six rows. The interval between plants along a row was 0.3 m (Figure 1). This Canadian spacing was developed to facilitate mechanical weeding during the plantation's establishment whereas the European spacing was developed on the assumption that chemical weeding would be favoured.

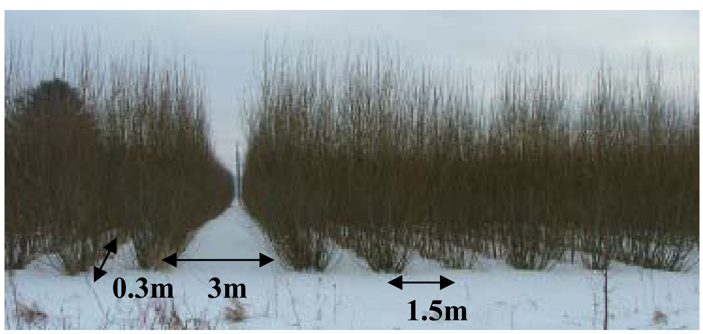

Figure 1. Disposition of the cultures

The dry matter yield of willow varied considerably between species, soil type, and growth cycle (Labrecque and Teodorescu, 2003). In the first three-year cycle after plantation, yields varied from 15 to 45 t DM/ha. In the second three-year cycle, yields varied from 22 to 70 t DM/ha. *S. Viminalis* on clay soil with a fertilizer treatment produced the highest yield in both cycles (45 and 70 t DM/ha, respectively). The average stem diameters in the second cycle ranged from 24 to 39 mm, and stem height from 2.2 to 5.4 m. The average number of stems per plant ranged from 6 to 11, with an average of 8 stems per plant in the higher yield conditions (*S. viminalis* on clay soil). Actual variation of individual stem diameter was much broader, from 20 to 80 mm and some plants included a multitude of smaller branches.

Cutting height recommended is between 100 and 150 mm from the ground in order to minimize damage to the stump. Harvest must be done ideally at the end of third or fourth year of growth. Beyond this period, the density of stems and leaves becomes too large, reduces light to lower branches and decreases subsequent growth potential. Harvest must also be done when the plant is dormant, ideally after frost in late fall.

CUTTING MECHANISMS

The choice of the cutting tool is a critical stage in the design of a willow harvester. The cutting system will encounter simultaneously several stems of various diameters. All stems tend to shoot up vertically from the stump. However, some stems form an elbow between the stump and their vertical projection. Cutting in an elbow will require more energy than cutting a vertical stem because of a larger horizontal cutting area.

The cross-over of branches from different trees within a row or between rows also complicates harvest. The small branches are easy to cut but are likely to roll up on mobile mechanical components. A stripping at the level of the stump is therefore recommended. The cut must be done between 100 and 150 mm from the ground in order to cut above the separation of the stems and to minimize the impact on the seedling. The damage to the stump should be minimized to avoid propagation of disease (Stuart 1994).

Circular Saw. The circular saw is commonly used in the field of wood cutting, whether for log or timber. It has the advantage of offering a very clean cut. On the other hand, if the saw is a full disc, it tends to accumulate snow and to transport it with the biomass, which is critical during harvest and transformation into chips (Boyd et al. 2000). The blade notches undergo wear during their use. A hardening as well as a surface treatment will minimize considerably this wear (Nieuwenhof 2003).

Disc. This approach is less widespread than blades with teeth. Coppice Resources LTD (2000) designed a header with sharpened discs. These discs are meant for easy maintenance, allowing fast sharpening in the field. There may be however a crushing of the stem at the intersection of the two discs. The cut is of inferior quality than the cut of a circular saw with teeth.

Chain Saw. The chain saw is very widespread in the forestry industry and may be found in various forestry cutting heads. This principle is economical but requires more maintenance that the circular saw or the disc (Pellerin et al. 1999). It is also slower. In winter conditions, the chain saw minimizes the inclusion of snow compared to other cutting mechanisms. Avoiding the presence of undesired moisture is important for good conservation of wood chips (Boyd et al. 2000).

Inertial blade. This principle is found in mowers, especially for ground preparation. Maintenance is easy and economical because it is possible to change a single damaged blade. On the other hand, the stems are fractured rather than cut, which is to be avoided in order to allow a good regeneration of the seedling (United States Department of Agriculture, 2000).

Flail. The flail consists in a cylinder with teeth laid out in a spiral pattern. The cylinder rotates at high speed parallel to the ground. The stems are fractured rather than cut. This method can be used only for harvest in chips (Felker et al. 1999). After the passage of a flail harvester, the rate of survival of the plantation is generally null (Stuart 1994).

Cutting speed. A minimal cutting speed of 10 m/s was suggested by Persson (1987) for impact cutting. Dalois (1990) suggested that cutting speed with circular saws could range between 5 and 50 m/s, but higher speeds (40 to 50 m/s) were more reliable for a clean cut of logs along the longitudinal axis. He even indicated speeds of 70 m/s when the saw was designed with a smaller number of teeth. Quelch (1971) suggested a standard peripheral saw speed of 45.7 m/s (9000 ft/min). Field prototypes using circular saws have tended to operate at higher peripheral speeds, in the range of 63 to 118 m/s (Table 2).

Table 2. Peripheral speeds of circular saws used to cut short rotation plantations.

Harvester	Saw diameter (mm)	Rotary speed (rpm)	Peripheral speed (m/s)	Reference
Lydum	450	5000	118	Sweden (IEAB, 1995)
Hvisted	500	3200	84	Sweden (IEAB, 1995)
VPI/DOE	610	3000	96	U.S.A. (IEAB, 1995)
Hyd-Mech	600	2000	63	Canada (Curtin et al., 1985)

COLLECTING MECHANISMS

There are two major methods to collect willow and other long-stem fibrous crops: either as full length stems or by chipping. Full length stems may be handled in a bulk stack or may be tied and bundled.

Full length stems. Stems collected in full length are sometimes used to stabilize river banks, decontaminate soiled ground or fabricate live acoustic walls. To ensure a good regeneration of full-length stems, the time between harvest and plantation must be less than three weeks.

Full length stems may also be used for energy or various bioproduct applications. A storage period is therefore required. The conservation of stems in full length is very simple and risks of degradation are practically non-existent (Boyd et al. 2000). According to Culshaw and Stokes (1995), no infrastructure is necessary for storage and losses are minimal. Storage of full length stems provides an additional benefit of natural air drying. At harvest, Europeans willows have a typical moisture content of 53 to 55%. The moisture content decreased to 19% after seven months of storage (Hilton 2000). At this moisture content, wood is ready to be transformed into energy without further drying. The stems only need to be chipped prior to this transformation. In Canada, the moisture content of willow at harvest was found to be in the range of 45 to 47% (Labrecque et al. 1997).

The transport of full length stems is more complicated than the transport of chips, even when the stems are tied in bundles (Boyd 2000). Culshaw and Stokes (1995) indicated lower harvest and transport capacities with long stems compared to chips because of a considerably lower density. If full length stems are used as a feedstock for energy or forestry products, they will have to be converted into chips in any case. Producing chips directly at harvest facilitates transport.

Chips. The harvest of biomass transformed into chips in the field is the most widespread method in Europe, mainly for energy production by gasification or combustion. However, it is necessary to reduce the moisture content under 30% for energy production (Hilton 2000). The chips of willow can also be integrated in the paper industry or for particle boards without any modification of equipment (Sirois 2000).

The transformation into chips at harvest implies the use of a trailed wagon or a truck for immediate transport of the willow particles. Wagons or trucks should be equipped with wide tires to reduce wheel pressure and minimize damage to the ground (Boyd et al. 2000). The storage of fresh wood chips requires an infrastructure to dry mechanically (ventilation, heating, mixing machinery) and to avoid biomass decomposition (Culshaw and Stokes 1995). Enormous costs may be generated by these post-harvest operations. Moisture in the chips is to be minimized during harvest. During a winter harvest, equipment should be operated in such a way as to minimize the introduction of snow in the chips. Harvest too early in the fall should also be avoided because a large number of leaves are still attached to the stems and bring undesired organic matter and moisture in the chips (Hilton 2000).

Energy to cut and collect willow. Table 3 indicates the engine power, fuel consumption, and harvest capacity of a number of machines previously used to cut and chip or cut and bundle short rotation plantations. The specific energy to cut and chip ranged between 0.95 and 1.20 L of fuel/t of fresh wood. The specific energy to cut and bundle was generally less, in the range of 0.50 to 1.00 L of fuel/t of fresh wood.

Table 3. Specific energy to cut and chip or cut and bundle short rotation plantations.

Harvester	Engine power (kW)	Fuel consumption (L/h)	Harvest capacity (t fresh/h)	Specific energy (L/t fresh)	Reference
Cutter-chippers					
Austoft 7700	175	30	25	1.20	Sweden (IEAB, 1995)
Bender	125	25	20	1.25	Sweden (IEAB, 1995)
Claas Jaguar 695	257	40	40	0.95	Sweden (IEAB, 1995)
Cutter-bundlers					
Empire 2000	140	30	50	0.60	Sweden (IEAB, 1995)
Fröbbesta	80	20	20	1.00	Sweden (IEAB, 1995)
Hyd-Mech	45	10	20	0.50	Canada (Curtin et al., 1985)

PREVIOUS SRIC HARVESTERS

Spinelli (1996) described several SRIC harvesters that have been tested and used in Europe (Table 4). Some of these machines are further illustrated and discussed below.

Claas Jaguar. The first version of Claas's header, the HS1, was very heavy and wide. The feeding system, made up of two horizontal rolls, sometimes became clogged. The mechanical drive was very complex and fragile according to Spinelli (2001, 2000). The Claas HS2 header was a largely improved version. Two 700 mm circular saws with 60 teeth were used for cutting. Fingers turning in opposite direction guided the stems towards the chipping cylinders (Pellerin et al. 1999). The cutting cylinders were modified from the standard forage harvester by removing half the knives to produce chips of longer length than forage particles. A push bar guided the fall of stems after the cut. Skid-shoes maintained a constant ground clearance. The harvester could move up a single or a double row of willows (spaced by 0.75 m according to European standards). This machine offered an optimal cut for stem diameters between 35 and 55 mm and could handle trees up to 8 m high (Spinelli and Hartsough 2001). The large fingers of the feeding cylinders caused snow to fall off and therefore minimized the undesired moisture added to the chips. Other evaluations carried out by Pellerin et al.(1999) indicated an output of 8.1 t DM/h for forward speeds between 3 and 8 km/h. Blades with a carbide tip provided a very clean cut. However the carbide blades were vulnerable to rocks and had to be replaced after approximately 10 ha.

Figure 2. Claas HS2

Table 4. List of European SRIC harvesters and some characteristics (Spinelli, 1996).

Model	Functions	Origin	Attachment	Power (kW)	Mass (kg)	Country
Fröbbesta	cut-only	mower	towed	70	3000	Sweden
Loughry	cut-and-bundle	prototype	towed	70	3000	N. Ireland
Nicholson	cut-and-bundle	mower	towed	65	3000	Britain
Dansalix	cut-and-pull	mower	towed	65	2000	Denmark
Berni	cut-and-pull	mower	towed	80	2000	Italy
Hvidsted	cut-and-pull	mower	self-propelled	80	6000	Denmark
Segerslätt	cut-and-pull	prototype	self-propelled	130	12000	Sweden
ESM 901	cut-and-pull	prototype	self-propelled	74	7000	Sweden
Gandini	cut-and-chip	prototype	hitched	50	850	Italy
Diemelstadt	cut-and-chip	prototype	hitched	90	800	Germany
MBB Biber	cut-and-chip	prototype	self-propelled	52	4300	Germany
Bender I	cut-and-chip	prototype	hitched	85	950	Sweden
Bender II	cut-and-chip	prototype	hitched	120	1250	Sweden
Austoft 7700	cut-and-chip	sugar cane harvester	self-propelled	179	12500	Sweden
Claas Jaguar	cut-and-chip	forage harvester	self-propelled	230	9400	Germany
JD/Kemper	cut-and-chip	forage harvester	self-propelled	301	11700	Britain

Segerslätt Empire 2000. This harvester was designed to collect full length stems. Its cutting head was equipped with two 700 mm circular saws. A hydraulic pump powered the head. The hydraulic transmission was used because it is generally more permissive to impacts and blocking than a mechanical drive. The machine could harvest trees up to 9 m high and a maximum diameter of 80 mm. The machine was heavy and could not be used on non frozen ground (Spinelli and Hartsough 2001). The output was approximately 6.7 t DM/h (Hartsough and Yomogida 1996). The cut trees were accumulated in a V-shaped bin, then dropped out at the end of the row.

Figure 3. Segerslätt Empire 2000

Austoft 7700. This machine was adapted from a sugar cane harvester to collect short rotation coppices. It was operated hydraulically and used a crawler traction, thus reducing soil compaction. Its cutting system consisted of two 600 mm saws overlapping by 50 mm, allowing the cut of two simultaneous rows (spacing of 0.75 m). The height of cut could be adjusted by the operator. Two pairs of hydraulic rolls guided the stems through the chopping cylinders to transform stems into chips. The output was similar to the Claas header (Pellerin et al. 1999). During various tests, Spinelli (1996) noticed certain clogging problems, uneven heights of cuts, damage to the stumps and chips of poor quality.

Figure 4. Austoft

Salix Maskiner Bender Mark V. This machine was attached to the three-point hitch of an agricultural tractor and was intended to cut and chip. The original characteristic of this harvester was its cutting mechanism which used a free chain saw on the entire frontal width. The machine could cross a field even where rows were non-existent. This free chain was relatively inexpensive and evacuated snow. However, maintenance was complicated and frequent (after every 4 h of operation). The machine required a 150-220 kW tractor for sufficient hydraulic power. After the cut, two large chains guided the stems towards the chopping cylinders to produce chips. The ground clearance was adjustable with skid-shoes (Pellerin et al. 1999). The machine could cut trees smaller than 150 mm of diameter but the forward speed then had to slowed to avoid clogging.

Figure 5. Salix Maskiner

CRL. The header of Coppice Resources LTD was carried in front of a forage harvester. It consisted of two sharpened discs of 1 m in diameter rotating at 411 rpm. The cutting discs were fabricated with a laser and could be sharpened in the field with an angle grinder. As the cutting discs overlapped, alignment with the row was less critical but there was a risk of clogging between the blades. During tests carried out by Coppice Resources LTD (2000), problems of lack of power, clogging, mechanical failures and tractor unsteadiness were observed. It should be noted that the CRL cutter could be adapted to machines that chip or bundle with appropriate modifications.

Figure 6. CRL header adapted to a self-propelled forage harvester.

Nicholson. This harvester was effective only for trees of small diameter. The cutting mechanism could be adapted to a two-row corn forage harvester. The cutting system consisted of two circular saws. The whole machine included a stem gathering component to form bundles. A sensor automatically launched a fastening procedure and discharge of the package at the end of the tying cycle. Misalignment with the row could generate blocking of the system (Hartsough and Yomigida 1996).

Fröbbesta. This harvester was also towed. It cut the stems and accumulated them on a platform. When the stand was full, the batch was ejected. This machine could cut only small diameter stems and a single row at a time (Hartsough and Yomigida 1996).

Loughry. Of a towed type, this machine cut trees of small diameter and fastened stems in a bundle. The package was ejected behind the machine. Some clogging was observed. (Hartsough and Yomigida 1996).

Figure 7. Loughry

Figure 8. Frobbesta

A recent report by Hilton et al. (2005) and the British Department of Trade and Industry (DTI 2005) indicated that harvesting must be considered at the plantation stage. Specifically, they suggested to provide headlands of at least 8 m for vehicle turning, an access road parallel to long fields for trucks and other hauling vehicles, storage areas close to the plantation fields and row spacing adapted to the machinery being used. Curently in the United Kingdom, two harvested are being used to harvest SRIC of willow. The first harvester is an unmodified sugar cane harvester that produced billets of 150 to 200 mm length. The second harvester includes a twin saw header adapted in front of a self-propelled forage harvester to produce chips. Compared to Swedish conditions, the UK researchers considered that harvest machinery had to be more robust than Swedish machinery because of a longer growth season in the UK, larger diameter stems and more heterogeneity of stands. In a perspective of maintaining long-lasting plantations, up to 25 years in UK conditions, the harvester should provide a clean, low cut, ideally below 100 mm from the ground. All stems should be cut and no cut material should be left in the field. Clearly, the development of future harvesters has to take into account plantation characteristics, type of storage desired and form of end product.

CONCLUSIONS

Since the Canadian market for short rotation intensive culture is not yet developed, a versatile machine where the cutting head may be adapted to a chipper or a bundler would appear as a useful compromise. Currently, the principal uses of willows in eastern Canada require full length stems. These are niche markets with harvested areas of less than 10 ha/year in the province of Quebec. Long-term future markets for energy and bioproducts could represent several hundred thousands of hectares per year.

A harvester prototype with integrated tying using net wrap rather than twine would meet several short-term research objectives: collecting all biomass material including small branches, allowing natural drying of biomass and providing long-stem material for some of the niche applications described. In the medium-term, a high performance cutting head could be paired with a forage harvester to carry out chipping in the field and to provide feedstock for energy and forest industry applications.

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