ARF07 PROJECT

Optimization of Switchgrass Management for Commercial Fuel Pellet Production

Final Report

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Presented to

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Executive Summary

Ontario faces major challenges in securing its energy needs and in meeting its greenhouse gas commitments. Native warm season grasses like switchgrass hold significant promise as a means for the province to help provide a solution to these pressing problems. This project examined strategies to commercialize the development of switchgrass pellets as a new thermal energy fuel source for the province. The report identifies a number of new approaches to improve the economic viability of densified warm season grasses as biofuels. Historically, there have been several problems that have limited the development of grass pellet biofuels. These challenges include agronomic problems such as developing a reliable harvest strategy, large winter breakage losses associated with overwintering grasses and fuel quality problems associated with burning the grasses. This project identified that a late fall mowing of the grass prior to the onset of winter followed by spring baling increased field recovered yields by 23% compared to spring mowing and baling. Further logistics optimization through improved mowing and harvest techniques will improve field recovered yields.

Combustion trials indicated that both spring and fall harvested material were suitable fuel for commercial boilers with relatively low emissions similar to wood pellets. Fall harvested switchgrass had slightly higher emissions and fuel quality issues that make it a less versatile fuel for combustion applications. The main advantage of the overwintered grass is that it contains less aerosol forming compounds (such as K and Cl) as well as N, which enables it to be a clean combustion fuel source for use in smaller combustion appliances. Fall harvested grasses likely have more application for larger commercial and industrial boilers.

An economic assessment was made of projected costs for delivering switchgrass to pelleting and briquetting factories. A major cost problem identified was that rising land rents in Southern Ontario are causing land rental costs to be an important cost driver in grass pellet fuel production. Use of more marginal farmland, bulk harvesting methods, and production of fuel briquettes were promising means to reduce production costs appreciably. Harvesting costs could be reduced by $10.48/tonne. This could be done by switching from baling system which costs $20.32/tonne to a bulk harvesting system which costs $9.84/tonne. Briquetting had the potential to reduce densified fuel costs by $25.21--$28.01tonne through lower processing costs and reduced transport distance to plants. These integrated strategies reduce plant gate costs for densified overwintered switchgrass fuels from $146.75 to approximately $105.53/ODT or $5.61/GJ. The use of marginal farmland had the potential to further reduce delivered costs. The lowest cost option in Ontario to develop grasses into densified fuels appears to be to grow the crop on marginal land, bulk handle the material and deliver it to local briquetting plants. It is evident that densified switchgrass fuels is one of Ontario's most promising renewable energy opportunities as delivered fuel costs are highly competitive with other biofuels options. As well, it is highly competitive with natural gas prices. In March, 2008 natural gas costs were $10/GJ at the wellhead, or approximately $12.00-12.50/GJ, delivered to commercial users in Ontario. Long term research investments in breeding, crop management, supply logistics and processing technologies by the province are necessary to fully develop this promising biofuel option.

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1.0 Report Overview

The ***Optimization of Switchgrass Management for Commercial Fuel Pellet Production Project*** aims to evaluate and optimize switchgrass production to create a new biomass energy resource for the emerging agri-fibre pellet fuel heating industry in Ontario. This report provides details on the main project activities completed, organized according to the four main project objectives.

2.0 ARF07 Project Objectives and Outcomes

The project aimed to evaluate and optimize switchgrass production to create a new biomass energy resource for the emerging agri-fibre pellet fuel heating industry in Ontario through the following project activities:

A. **Assessment of the impacts of fall harvesting regime versus fall cutting and spring baling on yield and chemical composition of switchgrass.** This includes assessments in differences in harvested yield, field losses and biomass composition of conventional late-fall harvested switchgrass and fall-cut and swathed material left in windrows over the winter and spring harvested.

B. **Evaluation of strategies to reduce the harvest and delivery costs of switchgrass to pellet plants.** This includes a field performance assessment of baling and bulk harvesting of switchgrass.

C. **Assessing actual production costs and yields of switchgrass grown on two commercial farms in Ontario.** This includes costs associated with actual crop establishment, land rental, maintenance and harvest costs from switchgrass crops grown in two counties in Ontario.

D. **Combustion tests of switchgrass pellets in commercial boilers.** This includes a comparative assessment of fall vs. spring harvested switchgrass biomass and its fuel quality and combustion performance in a commercial boiler.

3.0 Principle Project Sites

Site A: A 6 hectare sandy loam field comprising a well established 10-year old stand of the variety of Cave-in-Rock switchgrass at the Richard Foley farm near Kinburn, Ontario was used to provide biomass quality data to support the assessment of impacts of fall harvesting regime.

Site B: Two mainly silt loam sites in Bruce (Site B1) and Huron (Site B2) county were used to provide data for the establishment study and examining harvest costs. Nott farms seeded 132 hectares to switchgrass in May 2006.

4.0 Impacts of harvesting regime on yield and chemical composition of switchgrass

4.1. Sampling methodology

To support the assessments of different harvest regimes, the effect of delayed harvest on yield was performed at the farm of Richard Foley (Site A) near Arnprior, Ontario. The site was a clay loam soil that had been planted to Cave-in-Rock switchgrass in 1999. The field was formerly an old hay field and was managed with relatively low inputs. No herbicides and fertilizer had been applied for 6 years after planting, however 50 kg N/ha as urea was applied in June in 2005 and 2006. The field is outside of the traditional corn belt in eastern Ontario which typically has a land rental value of about $150- 175/ha.

Two treatments were to be applied to the switchgrass crop produced during 2006/2007. The two treatments originally conceptualized for the study were: Treatment #1) a conventional fall mowing and baling; and Treatment #2) a fall cut and spring bale production system. Due to the extremely wet field conditions due to the record fall rainfall in eastern Ontario in 2006, it was evident that fall baling would not be possible at the site due to the wet nature of the material and inability to support balers and transport vehicles in the fields during the fall for bale removal. Treatment # 1 could remain as a fall mowing as before but would be spring baled. It was also decided to modify the study to assess Treatment #2 under a spring mowing (as opposed to fall mowing) and spring baling system. This was a viable option as the fields could support light farm equipment consisting of a modest sized tractor and mower conditioner.

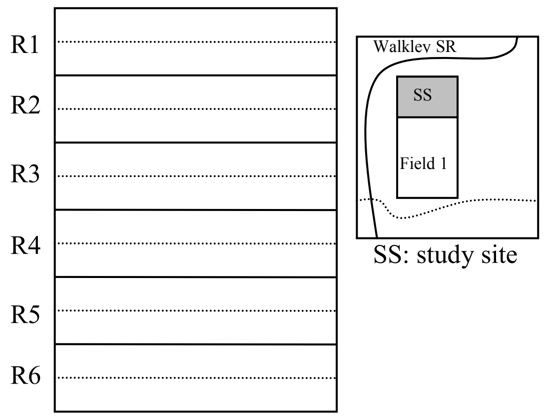

Figure 1: Foley field #1 study site: randomized plot design set up (L)

The study site was the western half of field #1 (7.3 ha) at the Foley Farm. A randomized plot design of 6 replicates with 2 treatments was used (Figure 1). Fall mown switchgrass for Treatment #1 was cut on November 25th, 2006 and left to overwinter in the field until baling in spring 2007 (soil was to wet in November to perform baling operations) (Figure 2). The plots were 6.6m x 150 m in length.

Figure 2: Study Site A replicates 4 and 5: November mowed switchgrass (L); Overwintered switchgrass in January 2007 (R). The snow appears to be preventing losses due to winter wind breakage. The somewhat “wavy” nature of the snow covered windrows can also be observed.

Baling of fall mowed material for Treatment #1 was completed on May 3rd, 2007. The spring mowed switchgrass in Treatment #2 was left standing in the field for overwintering, to be cut and baled in the spring of 2007. All spring mowed bales were harvested on May 4th, 2007. A gradient in the field was present in the field due to an uneven N fertilizer application in June 2006. The fertilizer was not evenly broadcast as 60 cm high patches of cool-season grasses were present at the time of fertilization and prevented even spreading in certain locations. The harvest experiment was therefore performed across the gradient which caused some difficulties with machine operations. Each treatment consisted of two passes on November 25, 2006 with the Hesston 12′ disc mower conditioner or approximately 7.3 meters (Figure 3). The harvest was performed against the furrows at a speed of 8 km/h (5 mph) at a mowing height of 10.1 cm. Subsequent field measurements indicated the effective operating width of the mower conditioner was determined to be 3.31m.

Figure 3: Hesston 1340 pull mower or disc bind

In the fall of 2006, the switchgrass averaged about 1.7 m in height (Figure 4) and had a fall yield of 10.9 tonnes/ha. As noted above, the soil was too wet to use the baling equipment, and therefore the cut switchgrass was left in windrows to overwinter.

Figure 4: Observed switchgrass height

For fall yield estimates, representative samples consisting of three 1 m^2 quadrates, were taken prior to the fall mowing from each replicate on November 24th, 2006. The quadrates were hand sheared to 10 cm, and the switchgrass was dried at 60°C for 48 hours. It was noted that the field had limited weed competition with an estimated 3% weed infestation observed consisting primarily of bromegrass, timothy, purple vetch, red clover, and goldenrod. A control of standing and residual biomass was determined using quadrate sampling (1 x 1 m) prior to harvesting in the fall of 2006. As with the fall sample, each quadrate was manually sheared to 10 cm to determine standing biomass followed by hand gleaning for residual biomass.

In the spring of 2007, background sampling was made prior to field harvesting operations. Standing biomass was measured on May 3rd in unmowed plots using the same methodology of three 1 m^2 quadrates as in the fall of fall 2006. Soil temperature was also measured on May 3rd, 2007. Temperatures were recorded both in the fall mowed areas (under and between windrows) and in the standing biomass plots prior to spring field operations. Samples were recorded 12 cm into the soil profile. Two temperature samples were taken in each plot and sample points were located at 30 m and 60m from the beginning of the plot. Soil moisture cores were also taken on May 3rd at 10 random locations per plot to determine differences in soil moisture between treatments. Samples were taken to a depth of 20 cm into the soil profile.

Machine activities commenced on May 3rd, 2007 for the fall mowed plots using a Hesston 4750 baler. Harvesting activities for the spring mowed plots were completed on May 4th, 2007. Machine test runs were made in areas adjacent to the plot area to evaluate the efficacy of harvesting prior to baling and to determine if raking was necessary. Eventually, it was decided to field rake all fall mowed plots prior to baling as the baler pickup was too narrow to effectively pickup the 2.13 m swaths. The fall swaths were observed also to be “wavy” and varied from approximately 1.8m to 2.58 m in width.

Both tramping of the tires while passing over the windrows and lack of effective recovery of the windrows with the baler pickup were considered problems. To correct for this, the material was subsequently raked with a side rake before baling. However, this raking process still caused some tramping of biomass when the tractor tires ran over some of the fall mown windrows (Figure 5). In the spring mowed plots, only a mowing operation was used as the windrows were sufficiently uniform to enable the baler to pass over them without the need for raking.

Figure 5: Raking operations on fall mown plots. Note trampling of windrows with tractor tires.

To measure the field harvest weights and the total yield/ha of each system, baling operations were initiated. Baling was done beginning from the south side of each field strip. Once a bale was formed and discharged the baler was stopped, then subsequently backed up a short distance to cause the discharge of the bale. The baler then proceeded to restart from the front of the plot. Two strips were machine harvested from each plot to determine the plots weight. The distance was then measured from the front of the plot to the end of the windrow area that had been harvested in each strip. During field operations, it was noted that the bale dropped at the end of each strip was actually the bale from the previous pass. The large square baler is designed to form a new bale while discharging the previously formed bale. To properly

Figure 6: Research team weighing individual bales on pickup truck-mounted digital platform scale

account for this, the research team tagged each bale from the production area from which it was actually produced. After all machine operations were completed, the bales were weighed using a pickup truck mounted flat bed scale (Figure 6). Individual bales were placed on the platform scale using a front end loader. Weights for each of the two bales produced per plot were recorded. The bales were then cored using a power drill with a 30 cm forage bit, with 4 cores taken per bale. The samples were then sealed in a plastic bag to be used to determine the biomass quality and moisture content of the harvested material.

For the estimates of harvest losses, 3 representative samples from each plot consisting of 2.83 m^2 quadrates each, were taken after the mowing and baling operations had been completed from each replicate in the spring across the harvested strip (Figure 7). These samples were taken on May 4th, 2007. The quadrate was first raked to collect the residual biomass below 10 cm and then hand gleaned. It should be noted that very fine material such as seeds and small pieces of broken panicles and leaves could not be recovered with this method. The samples were then soaked to remove any collected soil from switchgrass residues and then dried at 55 Degrees C before being weighed.

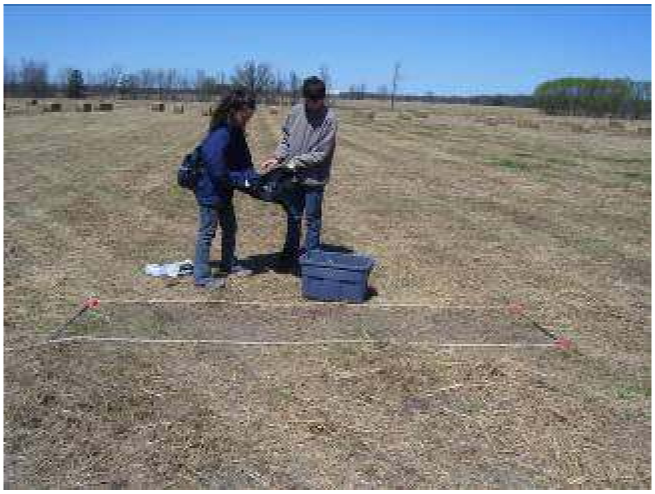
Figure 7: Quadrate sampling of residual biomass after spring field harvest operations.

4.2. Results and Discussion

4.2.1. Observations on fall vs. spring overwintering changes in dry matter and composition

Fall harvesting was found to be an unreliable option for switchgrass recovery on this clay loam farm site in eastern Ontario in 2006. There were two agronomic problems associated with fall harvesting. The first was that the material had a high moisture content at harvest, making it unsuitable for longer term storage. The second problem was that the field moisture content was excessive, making it impossible to engage in baling activities or bring in transport trucks for removal of the material. Sampling together with field observations indicated that the major problem with the fall field material was that the base of the stems remained green and wet late into the year. This portion of the plant appears to be protected from killing frosts, which usually browns-off the top of plants. As well, where there was some lodging of the switchgrass, this lodged material appeared to be consistently wetter than in the rest of the field where it remained upright. There were small sections found within the plots where material lodged early in the fall and was visually browner, indicating it was more vulnerable to decomposition.

Fall switchgrass subsamples indicated moisture contents ranging from 20% to 36%. The higher moisture contents appeared to be associated with lodged materials. The average moisture content of the Cave-in-Rock switchgrass at harvest in November, 2007 was 29%. It was observed that the lodged switchgrass stems were greener and the material was packed down, which prevented drying. In contrast, spring harvested material collected on May 2nd and 3rd, 2007 had an average moisture content of 7%. These results are similar to those reported by Adler *et al.,* (2006) who found fall harvested switchgrass in Pennsylvania had an average moisture content of 35%, while spring harvested switchgrass averaged 7% moisture. The low moisture content of the spring harvested grass is ideal for storage, grinding and pelleting. The optimal moisture content for fibrous material undergoing the pelleting process is 8-12% moisture (Colley *et al.,* 2006; Shaw and Tabil 2007). Considering that steam is generally added prior to processing to produce pellets with a high durability and low fines, harvested feedstock material having a 7% moisture content is desirable. As feedstock drying is a major cost in pellet production, sourcing a feedstock that requires no drying is highly advantageous. However fall harvested switchgrass still may be viable option as it has been performed successfully at the Foley farm in previous years. Switchgrass also appears somewhat more suitable to high moisture harvest than traditional forage grasses. In Wisconsin switchgrass was harvested at 24.7% moisture and was successfully stored indoors (Shinners *et al.,* 2006). Over a 10 month period, they observed the material dried to 14.1% moisture and experienced a 5% dry matter loss during storage. Likely if fall harvested switchgrass is to be successfully implemented on a reliable basis in Ontario it will require the use of both early maturing and lodging resistant cultivars. This will enable the material to have earlier fall senescence and good fall drydown as well as provide greater winterhardiness. Early maturing cultivars also will have improved biomass quality as the grasses have more time to leach K and Cl in the fall period prior to harvest (Elbersen *et al.,* 2002).

In the fall, switchgrass stems and leaves in the field were quite pliable with little to no breakage occurring during mowing operations. The seed heads were largely intact at the time of fall harvest, however some seeds had been lost. A botanical analysis from this 9-year old stand of Cave-in-Rock switchgrass in the fall determined that the head, leaf, leaf sheaths and stems comprised approximately 13%, 25% 15% and 48% of the plant, respectively (Table 4.1). Periodic visits were made to the plot area throughout the winter from late December, 2006 to the end of February, 2007. There were no visual signs of field breakage of leaves or seed heads observed with all visits made prior to the end February, 2007. However, by the end of the year, the seed heads were largely stripped of

Table 4.1: Switchgrass composition and moisture content

Botanical Component	Fall Moisture Content (%)	Fall 2006 Composition	Spring 2007 Composition
Head	4	12.5 %	5.2%
Leaf	15	25 %	13.2%
Sheath	13	14.8 %	17.9%
Stem	25	47.7 %	63.7%

seed (Figure 8). It is likely that the longer days in late winter caused the material to dry out. When late winter and early spring wind storms occurred, the most fragile portions of the plants, namely the seed heads and leaves were broken off. By spring, there were large losses of seed heads and leaves. Plant composition had changed to stems, leaf sheaths, leaves and seed heads comprising 63.7%, 17.9% 13.2% and 5.2% of the plant, respectively.

Figure 8: Standing overwintered Cave-in-Rock switchgrass at the time of spring mowing. Note that standing material is highly prone to breakage of seed heads and leaves.

A previous overwintering study conducted by Radiotis *et al.,* (1996) also determined similar composition during fall assessments of a 3 year old field of Cave-in-Rock switchgrass, finding that 14%, 30% 15% and 42% of the switchgrass biomass was in the head, leaves, sheath and stem, respectively. The higher stem and lower leaf content of the 9 year old stand at the Foley farm site is expected as stands tend to get taller and have fewer plants per square meter as they age. The spring composition changes in this experiment are also similar to that reported by Radiotis *et al.,* (1996) who found seed head and leaf content to decrease over the winter and the percentage of leaf sheath and stem to increase in the spring composition. They found whole plant spring composition for head, leaf, leaf sheath and stems of 4%, 27% 17% and 52% respectively.

The estimated losses for each component can be obtained by measuring changes in dry matter between the fall and spring period (Table 4.2). The average yield determined in the fall was 10.9 ODT/ha and the average spring yield was 7.0 ODT/ha. It was found that 73% of seed heads and 66% of leaves were lost over the winter. The seed head and leaf components together made up 2,800 kg/ha (72%) of the total biomass lost. Similarly Radiotis *et al.,* (1996) reported 80% dry matter loss of seed heads, 30% loss of leaves, 11% loss of leaf sheaths and 4% loss of stems over winter. The losses may have been larger in the current study as the test site was an open field while the Radiotis *et al.,* (1996) study was performed at sheltered field at the Lods Agronomy Research Farm at McGill University in Montreal.

Table 4.2: Switchgrass composition changes between the fall of 2006 and spring of 2007

Botanical component	Fall yield (kg/ha)	Spring yield (kg/ha)	Net loss (kg/ha)	Net loss (%)
Head	1,363	364	999	73%
Leaf	2,725	924	1,801	66%
Leaf sheath	1,613	1,253	360	22%
Stem	5,199	4,459	740	14%
Total	10,900	7,000	3,900	36%

It is evident that the fall mowing technique could be an important means to minimize the breakage losses of seed heads and leaves. Adler *et al.,* (2006) tried to also determine differences in chemical composition during fall and winter as a means to better understand dry matter losses. They found both soluble carbohydrates and storage polysaccharides, which represented about 2-7% of the total plant biomass at fall harvest, decreased by 80-85% over the winter period.

The large losses of dry matter (36%) and spring yield of 7.0 ODT/ha experienced with overwintering Cave-in-Rock switchgrass is consistent with other experiences in the region on less productive sites. However losses can vary year to year. Studies from 1995-1999 at two farm field sites in Ste Anne de Bellevue, Quebec, found average overwintering losses from cave-in-rock of 40% and an average spring yield of 7.2 ODT/ha (Jannasch *et al.,* 2001). The overwintering losses ranged over the 5 years from 33%-50% with Cave-in-Rock. On more productive sites with longer growing seasons, higher yields can be expected. Overwintered stands of mature Cave-in-Rock switchgrass plantings have averaged 9 ODT/ha at a productive farm site in Berwick, Ontario (Samson *et al.,* 1999b). As well mature stands of two unreleased cultivars of switchgrass have yielded more than 9 ODT/ha over 2 years in South-Western Quebec in overwintering trials (Jannasch *et al.,* 2001). Cave-in-Rock appears to be a particularly brittle cultivar. Other commercially released cultivars such as Pathfinder and Sunburst experienced losses of 32 and 33% respectively in the same field study where Cave-in-Rock experienced 40% losses. In the study, Pathfinder outyielded Cave-in-Rock producing average spring yields of 7.8 ODT/ha while fall yield assessments found Cave-in-Rock and Pathfinder to average 11.9 and 11.6 ODT/ha respectively (Jannasch *et al.,* 2001). Thus if breakage losses still proves to be important with fall mowing/spring baling, it may be important to select for cultivars that are less brittle to optimize field recovered yields. Ideally a cultivar should be selected that efficiently uses the solar energy and heat units available at the site. The Foley farm site has approximately 2650 CHU, Cave in rock is well suited to produce an effective fall yield at this site and has limited concern for winterhardiness problems if cut to 10 cm in the late fall.

In the experiment at the Foley farm, the amount of residual biomass that was collected below the biomass stubble hand sheared at 10cm from under the overwintered stand was determined to be 1308 kg/ha. The 1308 kg/ha was in the mid range between values previously recorded for unrecoverable spring material for cave-in rock switchgrass, which ranged from 711 kg/ha (Girouard and Samson 1996) to 2482 kg/ha (Girouard and Samson 1997). It should also be noted that hand gleaning assessment may under represent the actual losses as very fine materials such as seed and small pieces of plant materials were not able to be recovered with this method. Soluble carbohydrates and storage polysaccharides are also lost during the wintering period.

4.2.2. *Impact of fall mowing vs. spring mowing on yield and harvest losses*

In the fall of 2006, it was observed that very low amounts of residues appeared to be lost by the mowing process (Figure 9). The main source of unharvested residue left that was observed consisted of the standing 10 cm of switchgrass stems, some fine understory grasses in the switchgrass stand, and some residual field material from harvests in previous years. There was visually no appreciable material loss observed related to fall mowing operations.

Figure 9: Residue observed following fall mowing in November, 2006. Note that the material is weathered and shows residual from the previous spring harvest.

In the spring, assessments were made of the width of windrows with 30 width measurements made of the fall mown swaths. The fall swaths were observed to be "wavy" and varied in both height and width (Figure 10). Windrows were measured and found to be 1.8m to 2.58 m in width with an average of 2.13 m. This variable windrow width proved to be a problem as the pickup of the baler was only 1.83 m in width. In moving windrows with the rake, only a limited amount of switchgrass breakage was visually observed. The main problem observed was that the rake could not be set very low because the farmer operator was required to travel across the dead furrows because of the plot layout on the field. This caused some residual material to be left in the field, particularly in the dead furrow areas. As well, there were a few sections in the trial area where the fall mown windrows were quite thick and had larger accumulations of material. Tramping by tractor tires of the fall mown windrows also occurred because of the narrow distance between windrows (Figure 5; Figure 11). The rake did not fully relocate the mown windrow into the new windrow as can be observed in the photos. The raking operation also caused a limited amount of wet clay soil lumps to be picked up from the soil and harvested with the material. This was not considered an important problem but appeared to be a potential concern if raking is to be practiced with the switchgrass harvest on clay soils. A crop merger might prove to be a more effective device than a field rake if material needed to be turned or collected into a larger windrow. One additional advantage of not using the raking system with the fall mow was that there was no concern about the windrow height causing difficulty with catching underneath the tractor, which had been a concern in previous harvest experiments, especially where spring swathing was employed. In general, the farmer cooperator Richard Foley liked the fall mow–spring bale system. In previous years, he has had problems with excessive soil moisture during spring mowing. This resulted in field rutting, often delaying harvest considerably, which in turn caused delays in switchgrass regrowth. Overall, the most promising systems would produce a highly uniform (non-wavy) windrow that had a width such that the tractors tires could easily pass over it without tramping on the edges.


Figure 10: Windrows prior to raking on fall mown plots

Figure 11: Spring baling of fall mowed plots. Non-uniform losses are created by tramping of biomass during field operations and losses from deadfurrow areas. Unrecovered material is generally not of a fine nature and should be suitable for machine recovery. Also note greening in between rows during spring harvest.

Machine harvest yields from the plot area indicated that the fall mown and spring baled system achieved a 23% higher yield. Recovered field baled yields of 6.6 and 5.4 ODT/ha, for the fall versus spring mown systems, respectively, were found to be statistically significantly different (Table 4.3).

Table 4.3: Switchgrass yield and bale density comparisons between fall-mow and spring-mow systems baled in the spring of 2007

Treatment	Yield (ODT/ha)	Moisture content%	Bale density (kg/m3)
Fall mow-spring Bale (#1)	6.574	6.0	116.8
Spring mow and Bale (#2)	5.443	7.8	109.3

This increase in yield was attributed primarily to less loss during the winter as the material was protected in the windrow from breakage observed from windstorm events. The material was mowed in the fall at approximately 30% moisture, while in the spring it was mowed at approximately 10% moisture. Because of the dryness of the spring harvested material, significant shattering losses were observed during mowing operations (Figure 12). Previous research has similarly found that very large field losses can occur when very dry material is mowed with a mower conditioner in the spring, resulting in low yields (Adler *et al.,* 2006). Another factor enhancing losses of the spring mown material might be an increase in broken stem material from mechanical damage over winter, which is not recovered by the baler pickup as effectively as intact stems. The bulk density of the fall mown material was also found to be statistically higher than the spring harvested material. This may be related to the high stem content of the spring mown material (64%), which may have been more difficult for the bale chamber to compress than the fall mown material which likely contained more of the less fibrous plant components.

Figure 12: Baling of spring mowed materials. Note that windrows are uniform and contain most cut material. The residual material not recovered by baling is relatively fine and evenly distributed throughout the plot area indicating it is material shattered during mowing or winter breakage.

Overall, the field measurements of the residual material after field operations indicated serious losses on both the spring mowed and fall mowed plots. The total losses on the fall mowed and spring baled system were 1688 kg/ha while the spring mowed and baled system had total losses of 2072 kg/ha (which included unharvestable residual biomass losses of 1308kg/ha). It was observed that there were largely uniformly distributed small pieces of switchgrass fibre covering the spring mowed and harvested plots. In contrast, losses in the fall mowed and spring raked and baled areas tended to be longer material that was not uniformly distributed in the field. Losses that were important on the fall mown plots consisted primarily of areas not recovered in dead furrows, and tramped biomass in areas run over by tractor tires. Compression by winter snows may also have been factor but likely was much less important than the two aforementioned factors. In general however, the fall mown and spring harvested plots appeared to have somewhat lower levels of field residual biomass recovered. It was however quite non-uniformly distributed. This may have been the reason there were no statistical differences observed between treatments because of the high variability in the distribution of this biomass on the fall mown plots. If the residual biomass losses are included, previous research has shown even larger losses of 3648 kg/ha (Girouard and Samson 1996) and 3663 kg/ha (Girouard and Samson 1997) with the spring mown and baled system. Thus, the losses reported on the spring mowed and baled system in the current study were modest relative to other research findings. In the current study, the mower conditioner was set quite low in the spring (approximately 7cm) which may have helped recover material. In the fall mow system, a 10cm cutting height is required to prevent winter injury in eastern Ontario.

The yield comparisons between the two treatments indicated a significant difference of 1131 kg/ha between treatments. However, the comparison of recovered losses found a non-significant difference of 384 kg/ha. One explanation for this contradiction may be that the recovery method of garden raking surface residues within sampling quadrates and soaking to remove soil did not fully recover the fine residual biomass such as seed and broken awns and leaves.

The main source of losses from the fall mown and spring baled treatment can be attributed to the uneven nature of the field as a result of harvesting across the normal field working direction used by the farmer. Large losses were observed in dead furrow areas. As well, the wavy nature of the windrows led to losses as the raking operation missed some areas both due to heavier masses and wide windrow areas. Shattering losses caused by fall mowing and spring baling operations appeared minimal as the material was largely recovered intact as whole plants. In contrast, the spring mowed material appeared to leave short-length residual materials and much more subject to pickup and shattering losses.

Following these observations, a trial was conducted in the fall of 2007 at the farm of Normand Caron in Ste. Timothee, Quebec, with a major farm machinery manufacturing company to observe if more uniform windrows could be produced that were less wavy (i.e. had more uniformity in width and thickness). The main parameters assessed were the cutting angle of the cutter bar, travel speed, type of cutting blade and wing setting of the mower conditioner. These parameters affected the uniformity of the windrows that could be produced. The details of the trials could not be reported in this report as the work was considered confidential by the manufacturer. However, following these trials it is believed that uniform windrows can be produced by farmers that should allow material to be baled without the need for raking operations if mowing equipment is optimized. Properly mown windrows also need to include material laid down in such manner that it doesn't align with the baler pickup at a 90 degree angle to enable more efficient recovery with the baler pickup reel. Ideally, stems should be fed into the baler pickup at a 45 degree angle or less to ensure the pickup reel gathers in material into the bale chamber.

Through more efficient field operations it is evident that the losses experienced with the fall mown plots (1688kg/ha) at the Foley farm (Site A) in the spring of 2007 could be reduced considerably if tractor tires could be widened on equipment and windrows baled directly without raking. This would enable yield increases of about 1 t/ha. Yields of 7.6 ODT/ha could likely be achieved on this site with the fall mow and spring bale technique using Cave-in-Rock switchgrass. The use of more productive cultivars that are less brittle may also prove important in further increasing yields with the fall mow/spring bale technique. Cave-in-Rock is an unimproved variety of switchgrass that was collected from a native prairie in southern Illinois in 1958 and released in 1973 (USDA, 1986).

4.2.3. Effect of fall mowing on soil temperatures and moisture content

One of the hypotheses tested in this experiment was that fall mown material would have significantly warmer soil temperatures than spring harvested material. It was found that bare areas (areas between mown windrows) were significantly warmer than both areas under windrows and unmown areas in the spring when measured to a soil depth of 12 cm. On average, areas between windrows measured on May 4th were 10.6°C, while areas under windrows and in unmowed areas were 6.2°C and unmown areas were 5.6°C (Table 4.4). It was also observed that plot areas that were spring lodged were significantly cooler than areas where grass was standing upright. Two lodged areas measured 2 and 3.75°C, respectively. The fall mowing operation appears to have beneficial impacts on improving the logistics of spring harvest as it enables more rapid soil warming and requires less spring field activities. It was also noted that switchgrass regrowth was initiated on May 4th in mown areas (free of the swath) and the field was noticeably "greening up" (Figure 11). In contrast there was almost no growth initiated in the standing plots and in areas underneath windrows.

Table 4.4: Soil Temperature comparisons between fall-mow and spring-mow systems taken on May 3rd, 2007

Treatment	Fall Harvest (open soil)	Fall Harvest (under swath)	Spring Harvest (standing swath)
Average Soil Temperature (°C)	10.5	6.2	5.6

Soil moisture data that was recorded between treatments indicated non-significant soil moisture differences between treatments. However, it was visually observed at the time of measurements on May 4th that mown areas were visibly drying on the surface while unmown areas did not yet exhibit surface drying of soils. The average soil moisture contents sampled to 20 cm were 22.2 % and 23.1% for the fall and spring mowed plots respectively. Nonetheless, these differences may be important for field operations as on the mowed plots these moisture contents represented both areas between windrows and areas underneath windrow swaths. The dry soil at the surface in the open sections of fall mowed plots likely could better support field equipment earlier in the spring. This would be an advantage if the baler straddled windrows and was operating on warmer and potentially dryer soils. The farmer had several experiences in previous years where spring mowing was used and this significantly delayed harvesting because soils were slow drying under the heavy mulch. Overall the fall mowing technique appears to be highly advantageous for field operations relative to all activities being performed in the spring.

4.3. Yield Analysis Summary and Recommendations

It appears the fall mowing and spring baling system has considerable promise. Its main advantages are:

- allowance of efficient fall mowing operations;
- reduction in the breakage of material over winter by seasonal windstorms;
- promotion of earlier soil warming and more rapid early season regrowth;
- provision of better field support for farm machinery in the spring by promoting earlier drying of the field ;
- reduced spring labour demand and reduced risk associated with the harvest as mowing operations can be completed in the fall and a larger harvest window is created in the spring

- ensures harvesting of dry material which is suitable for pelleting without further energy required for drying;
- provides a higher overall recovery of biomass than spring mowing and harvesting systems;
- biomass combustion quality is improved compared to fall harvesting; and
- spring harvested material appears easier to pellet.

It is recommended that further field studies be completed under commercial conditions to optimize the fall mowing and spring baling operation. In future studies, the main improvements in the fall mow, spring bale system would be to optimize the mowing height, optimize the windrow width with the tractor tires/baling system, and to create uniform windrows that align with the baler at an appropriate angle for the baler pickup to function effectively. Crop mergers could also be tested to assess the ability to collect several windrows for more efficient harvesting with larger equipment including large bulk handling forage harvestors. Cultivar performance testing with switchgrass should be performed such that each cultivar is tested under the harvest management strategies identified in this report. It is apparent that brittle varieties like Cave-in-Rock are more conducive to field losses than other varieties. In southern zones of Ontario, cutting heights below 10 cm could be tested. However, previous field observations at the Foley farm indicated “shaving” fields during fall mowing operations led to stressed stands and delayed spring switchgrass regrowth, and maturity of the stand.

4.4. Impacts of harvesting regime on chemical composition of switchgrass

The laboratory test results for these tests were not available for inclusion in this report at the time of publication. However, they should be available by the end of March, 2008, at which time a revised copy of this study will be issued including these results.

5.0 Improving harvesting practices for pellet fuel production

5.1 *Overview of methodology*

Nott farms is Ontario's leader in the development of agro-pellets from crop milling residues and warm season grasses. Nott farms also has a large existing hay operation. The study assessed actual and projected costs that would be experienced by Nott farms in developing lower cost bulk biomass handling systems for warm season grasses like switchgrass. An important aspect of this study, a bulk harvest field analysis, could not be completed due inclement weather experienced in the fall of 2007. As such projections were made to the estimated costs of these operations and a more detailed analysis was made of bulk transport of biomass from the field to pellet and briquetting plants strategies to reduce delivered costs.

5.2 *Logistical challenges of the harvest and delivery of biomass to pellet plants*

A major problem of ligno-cellulosic biomass processing facilities is managing the logistics of the biomass supply to conversion plants. As an example, recent plans were announced to build cellulosic ethanol plants in the U.S.A using agricultural biomass resources in the order of 600,000 tonnes annually (1650 tonne/day) (GreenBiz.com, 2007). The biomass requirements of switchgrass pellet plants are in the order of 1/10 this size but nonetheless also represent a significant operational challenge. Pellet plants considered to be economically viable are those producing a minimum of 45,000-75,000 tonnes per year (Mani *et al.,* 2006). Mani *et al.,* (2006) found that in the case of wood pellet plants, a processing volume of 75,000 tonnes per year was required to achieve a relatively low cost for wood pelleting of $41/tonne (approximately $2/GJ). Plants processing pellets in the range of 45,000 tonnes of output annually were expected to experience pelleting costs of approximately $50/tonne. It is generally accepted from research and commercial production experience that pelleting costs are somewhat lower for densifying herbaceous biomass than wood pellets because of higher throughputs and lower drying costs. Switchgrass pelleting costs are estimated to be 20% below wood pelleting costs. The installation of briquetting facilities may be a potential solution to reduce densified fuel production costs by enabling lower capital investments, reduced grinding costs and lower feedstock delivery costs than pellet plants. Mechanical briquetting systems can have total (operational and capital) costs of less than $20/tonne or approximately $1/GJ with plants of 10,000 tonnes per year (Briquetting Systems 2008). The installation of briquetting facilitates may be a good solution for Ontario farmers to develop commercial fuel sales from biomass where local biomass supply can find local energy markets. The feedstock supply necessary to feed a briquetting plant would be approximately 1/70 that of a cellulosic ethanol plant which has obvious benefits in terms of cost, risk and scale impacts on existing farm activities in Ontario.

The main advantage of pellets is that they can meet a wider diversity of energy market applications and are also a well known product in rural communities. As well, pellet producers in Ontario can also produce other pellet products for other markets including livestock feed and animal bedding for horses and pets. Producing warm season grass pellets appears to be one of the most promising biomass conversion opportunities for Ontario farmers. If target plant sizes in the order of 50,000 tonne per year are required to be commercially viable, this will require efficient logistic systems. If overwintered switchgrass is assumed to yield 9 ODT/ha, a 50,000 tonne per year plant will require about 5,500 ha seeded to this feedstock annually. If it is assumed that 20% of the entire rural landscape is planted to switchgrass, this will require an area of 27,500 ha, this would be equivalent to an area whose radius would reach out approximately 95 km from a conversion plant. A rough assumption is that the average one way hauling distances in the order 70 km can be anticipated. Using the same assumptions as above, a briquetting plant requiring 10,000 tonnes per year would require 1,100 ha and be sourced from a surrounding land area of 5,500 ha. Assuming the plant is centrally located, this surrounding land area would have a radius of 42 km and the plant could be roughly estimated to have an average hauling distance of approximately 35km.

5.3 *Review of baling versus bulk handling*

Pellet plant project developers will want to develop a low cost, low risk logistics plan for the biomass supply for their conversion facility. An important requirement to meet this objective will be to ensure switchgrass field productivity is not impaired through the harvest management regime and that reliable weather conditions for harvest are present during the harvest period. As well, biomass quality has to be suitable for both pelleting and combustion applications. Agronomic research on warm season grasses like switchgrass has shown that the harvesting of switchgrass is best delayed not just until biomass growth has largely ceased, which may be in early September, but until shoots have essentially all senesced and died, which may not be till November or December (Parrish and Fike 2005). Previous studies (Sanderson *et al.,* 1999; Vogel *et al.,* 2002) reported yield declines of approximately 15% in the period from August to November, however this decline represents the transfer of nutrients from above ground to below storage (Parrish and Wolf 1992; Parrish and Wolf 1993). The transfer of nutrients below ground is vital for stand sustainability and therefore the best management strategy for switchgrass in northern latitudes is a single harvest taken after the tops have completely died back (Parrish and Fike 2005). Overwintering switchgrass, however, reduces the biomass yield obtained mainly due to breakage over winter. This has proven to be highly variety dependent as even cultivars with the same physiological maturity in the fall are experiencing different levels of dry matter loss overwinter (Jannasch *et al.,* 2001). Yield losses can be attributed to three factors:

1. Late season translocation of materials to the root system in winter (Parrish *et al.,* 2003);
2. Loss of soluble carbohydrates and storage polysaccharides during the late fall and winter period (Adler *et al.,* 2006); and
3. Physical loss mainly from leaves and seed heads during overwintering (Radiotis *et al.,* 1996).

In switchgrass overwintering studies in Quebec, the loss of dry matter was 4 percent from the stem component, 11 percent from leaf sheaths, 30 percent from leaves and 80 percent from seed heads compared to fall harvesting (Goel *et al.,* 2000). Other studies in

Quebec have found spring yields 15 percent below late October fall harvests where the crop is fully dormant at the time of fall sampling (Girouard *et al.,* 1998). However the loss of dry matter overwinter can vary with both switchgrass variety and year (Jannasch *et al.,* 2001). It is essential that integrated efforts to improve cultural management and to develop cultivars with less breakage are developed to minimize overwintering losses. Losses of biomass also occur during field operations (eg. cutting, baling, transport). Sanderson *et al.,* (1997) reported a 5 percent biomass loss from conventional fall harvesting of switchgrass (mower and baler) over a two-year study. A study conducted by REAP-Canada (Girouard and Samson 1996) found that conventional spring harvesting (mowing and baling) of switchgrass resulted in a 45% loss of biomass (32% as mowing losses and 13% as baling losses). The total spring residual material left in the field (included winter breakage that was deemed unrecoverable) from single windrow square baled switchgrass fields was assessed to be 3648 kg/ha. Losses specifically associated with the spring mowing operation were assessed at 2332 kg/ha. A recent switchgrass harvest study in Pennsylvania (Adler *et al.,* 2006) also found 45% of the biomass to be lost at spring harvest. Residual spring biomass losses in the field were assessed to be 3590 kg/ha when switchgrass was overwintered and a disc bine and round baler were used for harvest. Fall harvest losses by these scientists were assessed at 1910 kg/ha or 21% of the recovered biomass which was substantially higher than that reported by Sanderson *et al.,* (1997).

In an effort to reduce the shattering problem associated with use of a mower conditioner on dry material in the spring harvest a spring swathing operation was tested by REAP-Canada in 1997 in south western Quebec. In the first year of the overwintering harvest study, the total residual biomass that was left in the field was assessed to be 3966 kg/ha (Girouard and Samson 1997). The specific losses were assessed to be 1863, 1770 and 333 kg/ha for unharvestable residues (switchgrass residues found in stubble below 10cm cutting height), mowing and baling operations respectively. In the spring swathed plots, the total residual biomass left in the field was 2795 kg/ha consisting of 1863, 469 and 463 kg/ha for unharvestable residues, swathing and baling operations, respectively. Thus, spring swathing and baling operations reduced losses from mowing and baling from 2103 kg/ha to 932 kg/ha. However the system had several major gaps including: the unrecoverable residual biomass losses were excessive and were determined to be coming from winter breakage of seed heads and leaves; the spring swathing operation was slow and the cutter blade rode over winter lodged material; the heavy overwintering mulch delayed soil warming and switchgrass regrowth in the spring; and the swaths were very bulky causing problems with the tractor and baler ability to travel over the swaths. A similar assessment of the operation of a swather on commercial fields was made in 1998 and, which further clarified these limitations (Girouard et al. 1998). In 2006, Don Nott suggested to REAP-Canada staff that a reasonable option might be to fall mow the material and spring harvest. This approach was assessed in section 4.0 of this report and appears to have the potential to resolve many of the aforementioned problems.

Scientists have been investigating strategies to improve efficiencies of both baling and bulk handling systems as a means to reduce delivery costs to a processing facility. The logistics of the feedstock supply encompassing harvest, storage and delivery is an integral part of producing switchgrass as an energy fuel. Most collection options have included round or square baling (Cundiff, 1995, 1996; Bransby and Downing 1996; Cundiff *et al.,* 1997; Cundiff and Shapouri 1997; Venturi *et al.,* 2004). Typically, square baling operations are more expensive, however round bales are not suitable for large scale biomass handling because of their round shape and tendency to deform under heavy loads in a stack. Recent studies (Conrado *et al.,* 2005; Kumar and Sokhansanj 2007; Sokhansanj and Fenton 2006) have determined that the most economical harvest method is loafing. A loafer picks up the biomass from the windrow and creates large stacks on the side of the farm. Loafing is still in the developmental stages with regards to its use in biomass energy applications, (Kumar and Sokhansanj 2007) but appears to be economical in terms of on farm harvesting. However it is only viable for low hauling distances (under 50 km) if considering bulk transportation.

Biomass storage is another important component of biomass supply logistics as it is generally required to meet at least part of the pellet plant raw material supply. Storage of bales outside, unprotected, on the ground is the cheapest method. However, bales stored by this method have the greatest potential for dry matter and weather deterioration. Sanderson *et al.,* (1997) estimated that storage of switchgrass bales outside without protection resulted in dry matter losses of 13% compared to the original dry bale weight. Brummer *et al.,* (2002) compared storage of switchgrass under no coverage, coverage by tarpaulin, pole barns, metal buildings, fabric buildings and truss arches and found that storage in metal buildings required the highest initial investment but resulted in the lowest costs overall. The study also concluded that storage of small bales is more costly than large bales, and that uncovered storage is only justifiable for short storage periods. Permanent storage enclosures can lead to some loss of moisture from baled material which also helps reduce pellet fuel production costs.

In addition to harvest costs, transport costs play an important role in reducing the delivered cost of biomass to conversion facilities. Both Foley farms (Site A) and Nott farms (Site B) have considerable experience in hauling hay and straw. Foley Farms custom hauls switchgrass bales from 45 ha of switchgrass from their farm near Arnprior to a Metcalfe Ontario mushroom compost facility (approximately 160 km return trip). The switchgrass square bales are 34′ x 32′′ x 7½ foot in length and weigh 291 kg/bale (640 pounds/bale) at 12% moisture. This provides an estimated bale density of 160 kg/m3. It takes approximately 30 minutes to load and 15 minutes to unload the square bales off a transport vehicle. In 2006, Foley Farms custom hauled 20 tonne loads of switchgrass (12% m.c.) for $300 per trip or approximately $17.05 ODT. The breakdown for this cost was estimated by Foley farms to cost $66.66 for loading and $33.33 for unloading for each trip as well as $1.25 per km per round trip less than 200 km (both ways). Thus for a pellet plant with a 140 km haul, Foley farms would charge $275 or $15.63/ODT. For destinations of round-trip less than 100 km, Foley Farms would charge an estimated $2.00 per km. Thus if a briquetting plant required an estimated hauling distance of 70 km round trip, Foley farms would charge an estimated $100 for loading and $140 hauling or $240 per load or $13.64/ODT. Larger bales may help reduce the loading and unloading costs. Higher density bales could also likely reduce hauling and handling costs. Girouard and Samson (1996) found bale density of spring harvested switchgrass using a New Holland baler of 3′x4′ (0.85 x 1.2m x 1.5 metre in length) dimensions to be 136 Oven dry kg/m^3. Girouard *et al.,* (1998) found spring harvest of switchgrass using a New Holland 2000 large square baler producing 2.07m x 0.96 x 1.22 m bales to weigh 322 kg per bale at 13% moisture. Thus the bale density was 116 oven dry kg/m^3. Other studies have found very large switchgrass round bales (1.83m diameter x 1.52m width) to have similar densities of 135 kg/m^3 (Bransby *et al.,* 1996). Don Nott of Nott Farms typically produces 391 kg square bales of alfalfa hay which are .81m x 0.86m x 2.29m in length and 15% moisture content. The baling system has cutting knives as a pre-chop system before entry into the bale chamber which helps create a high bale density of 208 dry kg/m^3. Don Nott estimates bale weights of 346 kg when knives are not used on his baler. If there is no pre-chopping, bale density is reduced to 184 dry kg/m^3. In the case of switchgrass, Nott farms experienced bale weights of fall harvested switchgrass of 278.3 kg with an estimated bulk density of 153 dry kg/m^3 when no pre-chopping system was used on the baler. It is estimated a switchgrass bale density of 173 kg/m^3 could be achieved if a pre-chop system was used on the baler if the crops responds similar to alfalfa.

Both Nott farms and Foley farms believe it is easier to get a higher bale density using the 3′x3′ bales than the 3x 4′ bales. Krone Corporation has introduced a “Big Pack” 1290 High Density Press large scale press to the market which produces 90cm x120 bales using a pre-chopper device that pre-compresses material as well as a higher-than-normal compression bale chamber (Figure 13). These two features increase bale density by 20-25% compared to their standard large square baler. The company indicates that if material on an as-is basis is baled with their 1290 High Density Press baler they could increase bale density to 200-220 kg/m^3 (or 170-187 dry kg/m^3) versus the normal 160-180 kg/m^3 range achieved with their traditional large bale technology. This is within the range predicted by Nott farms for switchgrass harvest with a pre-chop system in their 32″ x 34″ baler.

Figure 13: Krone Corporation Big Pack 1290 High Density Press Baler

Foley Farms estimates their single drop step deck or “big belly” 53′ long hay trailers can hold 50 3′x 4′ x 8′ bales. Assuming a mean conventional bale density of 150 dry kg/m^3, or approximately 389 dry kg per .9m x 1.2m x 2.4m bale, the average load hauled to a pellet plant would be 21.8 tonne at 12% moisture or 19.2 ODT. Assuming a mean switchgrass high density bale system of 180 dry kg/m^3 could be obtained, the 1290 High Density Press bale technology the load would be increased for the 0.9m x 1.2m x 2.4m bales to 26.2 tonnes at 12% moisture or 23.1 ODT/load. This would decrease Foley farms cost of delivery to a pellet plant to $11.91/ODT and to a briquetting plant to $10.39/ODT. Foley farms “Big Belly” trailer combined with use of a high density baler appears to be a competitive means to haul bales to pellet plants but is more expensive than other options for short hauls (see Table 5.1).

5.4 Bulk harvesing

In the fall of 2007, a field assessment of a large Krone bulk forage harvestor developed for fine chopping corn silage for biogas applications in Europe (Figure 14) was scheduled to be tested at the farm of Don Nott in Clinton Ontario. The machine was delivered by Krone Corporation to the Nott Farm in Clinton and testing was scheduled for the month of November. A short trial run was made with the unit when it arrived on November 4th, 2007. However wet field conditions were present that day and the unit was pulled out of the field. During the remainder of the month an extended period with wet rainy/snow showers and cloudy cool days ensued. This prevented the planned field testing of the unit on the Nott switchgrass field to be completed.

The system that Nott farm aims to optimize in the future as a means to deliver low cost fibre to a pellet plant to mow the crop using their large 30′ Krone discbine in late fall (Figure 14), then to collect the windrows in the spring using a 30′ Miller pro crop merger (Figure 15). The material then would be fine chopped using the Krone BIG X 650 harvester (Figure 16) and be blown directly into a dump wagon and taken to a covered storage facility.

Figure 14: Krone Corporation BIG M 30 Mower Conditioner operating in alfalfa

Figure 15: Miller Pro Avalanche 310 Triple Head Power Merger merging hay windrows

Figure 16: Krone Corporation BIG X 650 Chop Forager harvesting perennial forages

Nott farms estimates the cost of the mowing and crop merging activities at $20/acre ($50/ha) for mowing and $7.50 per acre ($18.75/ha) for the crop merger. Nott farms has no experience with the large Krone BIG X 650 machine for bulk harvesting of forages. As the bulk harvesting study at the Nott farm could not be completed due to difficult field conditions, the estimates of the projected costs were made from consultations with experts and through a literature review. In the state of Wisconsin, Agrecol Corporation is examining bulk harvesting of switchgrass for commercial switchgrass pellet plants (Doudlah 2008). They estimate a cost of $5/tonne for bulk harvest of switchgrass. This is based on the facts that in the state of Wisconsin, custom operators charge $135-165/hr for forage harvesting. In the case of corn silage, these machines process 175 ton per hour of corn silage at 65% moisture content. This is equivalent to a cost of $3 ODT (metric) for processing 55 ODT/hr. Agrecol believes similar production levels can be achieved on a dry tonne basis with switchgrass but that more downtime will be experienced with equipment as the material is dry and will require more sharpening and repairs. As such they estimate $5/ODT to be a realistic cost if the material is gathered with a crop merger to reduce field passes and enable high throughput on the machine. Bransby *et al., (*2005) developed a switchgrass pellet production model that included costs of bulk harvesting and delivery to a processing facility. They projected costs for field chopping of switchgrass to be approximately $5/ODT based on field experiments in Alabama. For the purpose of the economic analysis (Section 6.0) we assume a bulk harvest cost of $5/ODT per ha (plus additional crop merger costs). It should be recognized that while some producers have experience bulk harvesting dry wheat straw as bedding, the technology for recovery of large volumes of dry biomass is not well established. Potential problems with the system that can be anticipated are significant losses of dry matter during transfer operations to the dump wagon and the potential for fire to occur. This bulk harvest system will require optimization to ensure it is a robust and safe operation.

For the bulk harvesting analysis, an assessment was also made to estimate the cost of delivery of the fibre to a processing facility versus bales. Nott farms fine chopped switchgrass using a hammermill with 1/8″ screens (3mm). They found a bulk density of their fall harvested switchgrass to be 6.33kg/cu′ or approximately 197 dry kg /m^3. This assessment is similar to other reported literature on bulk density for ground switchgrass with 3.0 mm screens of 181 kg/m^3 (Kaliyan and Morey 2006). In contrast, ground oat hulls (the main agro-pellet fuel material processed by Nott farms) had a measured bulk density of 9.87 kg/cu′ or approximately 317dry kg/m^3. Nott farms presently has several large biomass and pellet transport vans with walking floors (Figure 17). These are used for hauling 71/2′ hay bales, pellets and crop milling residues. The estimated biomass volumes the transport van can hold is presented in Table 5.1. The inside dimensions of the trailer are 47′ 10″ long, 8′10″ high and 8′ wide for a total volume of 3450 sq feet or 97.7 m^3. The trailer can hold 51 bales of 7½ feet in length. In hauling hay bales the trailer space is not fully utilized as there are significant spaces not filled by bales. Experience has shown that Nott farms can actually carry 36 tonnes of ground oat hulls at 9% moisture content in their van or 32.8 ODT or 5.8% higher than that predicted from the bulk density test in the 1′ sq grain density chamber at Nott farm. Don Nott attributes this additional load weight to a compaction effect created by filling the oat hulls 8′ deep into his trailer. Thus the actual transport weight for the switchgrass could be 20.3 ODT per trailer load. As such ground switchgrass could have a major transport advantage over conventional or high density switchgrass bales in a transport (Table 5.1).

Conventional wisdom amongst biomass scientists was that bulk biomass handling was inefficient compared to baled biomass. However this assessment indicates up to 62% higher loads could be carried with switchgrass in a fine ground state suitable for densification applications compared to transport of conventional switchgrass bales in a large transport van. The advantage will be highly dependent on the chop size that is transported as research has shown that chop size has a major influence on chop bulk density (Kaliyan and Morey 2006; Mani *et al.,* 2004). If the BIG X 650 does not adequately reduce the chop to the equivalent of a 3mm screen size hammermill grind it may require a second fine grind to provide a high transport load as found in Table 5.1. Otherwise lower load weights similar to bales may be realized. Future studies are required that measure actual loads carried in transport vans with switchgrass of various grinds. The data sourced from this analysis are further developed into an economic analysis in section 6 to identify efficient strategies to reduce biomass delivery costs to densification plants.

Figure 17: The 97.9 m^3 Titan van used by Nott Farms for bulk biomass hauling

Table 5.1: Total transport capacity for various biomass options

Cargo	**Bulk density (dry kg/m^3)**	**Maximum Van Load**	**Briquetting transport cost per ODT (70km return delivery)**	**Pelleting transport cost per ODT (140km return delivery**
Conventional SG bales	153	12.5 ODT	\$8.01	\$16.02
High density SG bales	173	14.1ODT	\$7.10	\$14.20
Ground switchgrass	197	19.2 ODT	\$5.21	\$10.42
Gound oat hulls	317	31.0 ODT	\$3.23	\$6.46

**van load assumes 51 bales weighing 278 kg at 12% moisture content for conventional bales and 314.5 kg bales at 12% moisture for the high density SG bales.*

Nott farm estimates a cost per running km of 1.43/km for their 97.9 m^3 Titan van (Nott 2008)

6.0 Commercial field production costs of switchgrass

6.1 Overview of methodology

A major need for successfully developing a commercial switchgrass production industry in Ontario is to improve understanding of strategies to reduce overall production and delivery costs for biomass to conversion facilities. This includes improved understanding of yields, establishment and annual maintenance costs as well as harvest, storage and delivery costs.

Establishment and production cost data for switchgrass and biomass handling costs were collected from sites Nott Farms (Sites B1 & B2). As well an analysis of agronomic challenges experienced at the two sites over the two project years was overviewed. Economic projections were made for strategies to reduce delivered production costs using Nott farms as the basis for the analysis. Comparisons were made between the conventional option, bale delivery to a pellet plant to a potentially lower cost scenario consisting of bulk delivery to briquetting plant with a reduced distance for biomass transport delivery.

6.2. Assessing actual production costs and yields of switchgrass grown on commercial farms in Ontario

Nott farms of Clinton Ontario has been Ontario's leader in the emerging agro-pellet and grass pellet fuel industry in Ontario. In 2006 they sowed 132 ha of cave in rock switchgrass in Huron county and Bruce county. The Bruce and Huron sites differed in soil type and had crop heat unit ratings of 2750 and 2900, respectively. Typical land rents that could be obtained on Bruce and Huron county sites were stated by Don Nott to be approximately $125 and $155/acre/yr in 2007, respectively. In 2007, Nott farms seed an additional 57 ha of coastal panic grass (*Panicum amarum*). Nott Farms also is a major alfalfa producer in Huron and Bruce county and have many years of practical experience in optimizing logistic systems for biomass handling. In this report an economic analysis of delivered switchgrass production costs was developed using producer input from Nott farms and estimates based on present state of understanding of commercial forage production and handling systems. Due to the short-term nature of the Alternative Renewable Fuels funding for this project, fully established yields were not able to be sourced and estimates were made based on yield experiences in eastern Ontario and southwestern Quebec.

6.2.1 Establishment costs of switchgrass at the Nott farm sites in Bruce and Huron county

In the seeding year of 2006, the site in Bruce county (Site B1), a 74 ha Listowel silt loam soil site had a superior establishment with switchgrass reaching an average height of approximately 60 cm (Figure 18). This soil had better natural drainage than site B2 although both sites were systematically tile drained. At the site in Huron county (siteB2), a 58 ha Huron clay loam site with gravel loam sections, experienced significantly more foxtail pressure and the switchgrass establishment was much less uniform. At the Huron site, switchgrass reached a height of approximately 30 cm in the heavily infested areas and was above the height of foxtail at fall dormancy in areas where less competition was experienced. No weeds other than foxtail provided any appreciable interference with establishment. Even though weed competition was quite high at the Huron county site, the stand successfully established a crop. Previous experience by REAP-Canada has demonstrated that if switchgrass seedlings are present in the understory and approximately 15 cm in height by fall freeze-up, the field will be successful in establishment. The biomass present on both sites was insufficient in the spring of 2007 to warrant a harvest and was left in place. The subsequent crop was allowed to regrow through the residue in the spring of 2007.

In the spring and summer of 2007, the stands progressed remarkably well given that a summer drought was experienced in Bruce and Huron counties and the seedlings had major weed pressure at the Huron county site in 2006. Don Nott of Nott Farms decided that due to rising demand in interest for switchgrass seed, they would proceed to harvest seed from the 132 ha as a means to improve the economic return on their investment. In the spring of 2007, seed of Cave-in-Rock switchgrass was selling for approximately $22/kg of pure live seed. Approximately 100 ha were harvested for seed in October 2007. At the Huron county site the crop was swathed at 13 cm and then combined after field drying. At the Bruce county farm the crop was direct harvested. Approximately 200 kg/ha of seed was harvested from the two sites with a total seed production of approximately 20,000 kg of rough seed harvested prior to processing. Wet field conditions prevailed after the seed harvest and no baling of residual switchgrass straw was possible at the Bruce county farm. At the Huron county clay loam farm site a total of 292 bales of switchgrass were recovered from 18.2 ha. This production level represented a yield of 4.0 ODT/ha. Previous experience on clay loam sites has shown these sites can be slower to enable the crop to produce maximum yields. In eastern Ontario, clay loam sites in Berwick Ontario and Alfred Ontario had 1st production year yields of 4.5 and 6.1 ODT while fully established crops on these sites in subsequent years yielded 12.8 and 10.8 ODT/ha (Jannasch *et al.*, 2001 and Samson *et al.*, 1999b). The overall experience to date in eastern Canada is that switchgrass establishment is more reliable on lighter soils and 1st year production yields higher than on clay loam soils.

Figure 18: First year switchgrass on Site B1 in Bruce County (L) and B2 in Huron County (R)

Establishment and production cost data for switchgrass was collected from 132 ha of the fields seeded in May 2006 by Nott farms (Sites B1 & B2). The direct establishment costs (Year 1) at the sites were estimated at approximately $857.36/ha or $346.96/acre. An assumed 12-month operating loan at 6.0% incurred an additional cost of $51.44 per hectare for an overall establishment cost of $908.80/ha (Table 6.1). The amortization of establishment costs over 10 years results in a yearly cost of $90.88/ha. From the analysis in Table 6.1 it is evident that land rental costs are an important cost driver representing over 42% of the total establishment cost. We estimated presently a yearly rental cost of $383.01 per hectare at the two sites. At the outset of the study the two sites were estimated by Nott farms to rent for $125 and $155/acre. The rising value of wheat, corn and soybeans commodity prices in 2008 are further increasing land rents in Huron and Bruce county. Thus we used $155/acre or $383/ha for the average land rent for the area under switchgrass cultivation. The economic situation for using these lands for switchgrass has become less favourable due to a dramatic turnaround in grain commodity prices in the last two years because of large government incentives for biofuel production from corn and oilseed commodities. Switchgrass currently has no biofuel incentives in Ontario. Nott farms seeded the switchgrass fields in the spring of 2006 as they believed it could become a competitive fuel with rising delivered natural gas costs in commercial heating applications such as greenhouses in the future. It is evident that land rental costs are much lower in other regions of Ontario outside of the main corn and soybean cash cropping belt. For example the Foley farm near Arnprior Ontario had typical land rents in the $150-$175 range at the outset of this study. Likely the main production belt for switchgrass that will evolve will be the 2300-2700 Crop Heat Unit (CHU) area, which encompasses the Foley farm in Arnprior (approximately 2650 CHU). The Nott farm in Huron County has approximately 2900 CHU due to its proximity to Lake Huron. For corn and soybean production it has a longer growing season and is less prone to killing frosts during the early spring and late summer period. It is likely that the Bruce county Nott farm site (2750 CHU) and the Foley farm site near Arnprior (2650 CHU) are strong candidate locations for production. In longer growing season areas (i.e. greater than 2700 CHU) the main production from switchgrass can be expected to be developed on less productive farmlands.

If the establishment costs experienced by Nott farms occurred on sites with land rental costs of $150.00/ha, establishment costs would be decreased by 30% to $639.50/ha. The second most important expense during the establishment year was weed control (herbicides and mowing) at 22% of total establishments (Table 6.1). A review of recent establishment budgets for switchgrass (Bransby *et al.*, 2005; Duffy 2008; University of Tennessee 2007) demonstrate a range in establishment costs from US$406.71/ha to US$607.90/ha excluding land rental costs, which is comparable to the estimated establishment costs of CAN$528.80/ha (excluding land) in this report. There are several potential ways that the economics of switchgrass crop production in the first year could be improved. Establishment could be improved if switchgrass varieties with improved seedling vigor and affordable effective herbicides were available in the seeding year. This might provide a modest yield similar to that experienced by direct seeded alfalfa in the seeding year. Nott farms utilized both herbicides and mowing for weed control and yet still experienced heavy foxtail weed competition at the Huron county farm site. Previous research has shown that some unreleased cultivars of switchgrass have improved seedling vigor and reach a more advanced development in the seeding year (Samson *et al.*, 1999a). New herbicides are also being tested to improve grass weed control in switchgrass in the seeding year. Drive (Quinclorac) herbicide is now registered in the United States for weed control in some states. Mike Cowbrough at the University of Guelph performed some herbicide selection trials on switchgrass in 2007 and identified several herbicides that appeared promising (Cowbrough 2007) for annual grass control in switchgrass. Perhaps the most cost effective means to improve switchgrass establishment for use on more productive farmland would be to establish the crop under wide-row corn. Normand Caron of Ste Timothee Quebec, the leading Quebec farmer growing switchgrass, successfully established switchgrass as an intercrop in corn planted at high density in 1.52 metres rows. This practice provides significant income in the establishment year as wide row corn yields about 80-85% of a normal crop if corn rows are seeded at higher than normal density.

Table 6.1: Year one establishment costs determined from Site B

Establishment Year 1	**$/hectare**	**$/acre**	**% of Costs**
Land Rental	383.01	155.06	42.1%
Direct Seeding Establishment			
Cultivation	74.10	30.00	8.2%
Stone picking	7.41	3.00	0.8%
Seed – 10 kg/ha	132.20	53.52	14.5%
Seeding	29.64	12.00	3.3%
Packing	29.64	12.00	3.3%
Herbicide - burndown & broadleaf control	132.20	53.52	14.5%
Herbicide – application (2x)	34.58	14.00	3.8%
Clipping (2x)	34.58	14.00	3.8%
1st year operating loan @ 6.0% interest	51.44	20.82	5.7%
Total Establishment Year Expenses	**$ 908.80**	**$ 367.93**	
Annualized Establishment Cost (over 10 years)	**$ 90.88**	**$ 36.79**	

Annual production costs for years 2 to year 10 in the production cycle were estimated from Site B based on second year inputs and production levels once the crop is fully established. A harvest was performed on both sites B1 and B2 in the spring of 2007 resulting in 200kg/ha of rough seed, prior to processing, as well as a switchgrass pug (straw residues after seed combining) yield of 4.0 ODT/ha for Site B1. As the switchgrass was not fully productive in the second year and poor weather prevented a biomass harvest late in the fall, yield estimates based on mature stands were made from other production data in eastern Canada. For the heat units and soils present at the Huron and Bruce county sites it was estimated that 9 ODT/ha of biomass could be realized at these sites in the future.

Overwintered stand yields of fully established switchgrass on productive have measured 9 ODT/ha with cave in rock switchgrass at the farm of Rick Rutley in Berwick Ontario (Samson *et al.,* 1999b). Later maturing upland switchgrass ecotypes such as Carthage and the experimental line NU 94-2 also appear to have potential to further increase yields in longer season areas. The ecotypes Carthage and NU 94-2 when fully established, yielded 9.3 ODT/ha over two years when spring harvested on a productive Ste Bernard silt loam site in Ste Anne de Bellevue Quebec (2900 CHU). These late maturing cultivars utilize more effectively the available solar radiation in a longer season growing area than early maturing plant materials. Of these ecotypes, NU- 942 on average headed 14 days later than cave in rock when tested at 2 sites at the Alfred Campus of Guelph University (Samson *et al.,* 1999a). Carthage (NJ-50) was found to be 20 days later in maturity than cave-in-rock with a relative maturity of 155 and 135 days respectively for the two ecotypes (Jannasch *et al.,* 2001). The fall yield potential of cave-in-rock is commonly about 12 ODT/ha once fully established (Jannasch *et al.,* 2001). Nott farms has a diverse and extensive management experience having cropped up to 5000 ha in previous years, they have a very strong production background to optimize the yield potential of switchgrass for their region.

Production costs can be divided into two categories, crop maintenance, accounting for 56% of the cost and, harvest and delivery representing 44% of the cost (Table 6.3). As can be seen from the analysis, once established annual input costs are extremely modest with only $66/ha used for fertilizer applications. No potassium or phosphorus fertilizer is generally applied to overwintered switchgrass as the export of these elements in pellets is very low (Samson *et al.,* 2005). For a yield of 9 ODT/ha, field export is estimated to be in the order of 2 and 5 kg/ha per year for phosphorus and potassium respectively. These minerals could also periodically be recycled from ash from combustion boilers.

Table 6.2: Estimated annual production and baled harvest costs from Nott Farms

Production Years (2-10)	**$/hectare**	**$/tonne**	**% of Costs**
Crop Maintenance			
Fertilizer - 50 kg N/ha 46-0-0[1]	60.00	6.67	6.2%
Custom Work (fertilizer application)	6.00	0.67	0.6%
Land Rental	383.01	42.56	39.9%
Annualized Establishment Cost	90.88	10.10	9.5%
Total Crop Maintenance	**$ 539.89**	**$ 59.99**	**56.2%**
Harvest & Delivery (9ODT/ha)[2]			

Mowing	48.80	5.42	5.1%
Baling	153.85	17.09	16.0%
Stacking	29.04	3.23	3.0%
Storing	45.00	5.00	4.7%
Hauling- to Pellet Plant 140 Km round trip	144.18	16.02	15.0%
Total Harvest & Delivery Expenses	**$ 420.87**	**$ 46.76**	**43.8%**
Total Production Costs (ODT)	**$ 960.76**	**$ 106.75**	
Total Production Costs (12% m.c.)		**$ 94.00**	

[1] Molenhuis, 2008; [2](Nott 2008)

Nott Farms operates 1000 acres (400ha) of alfalfa hay production on a 3 cut system using two Hesston balers producing 3′x3′x7.5 bales. Nott farms determined their current cost per acre for both variable and fixed costs to harvest and handle each cut of alfalfa to be $139.80/ha (these figures include equipment depreciation). The addition of approximately 190 ha of warm season grasses to the existing farming operations provides Nott farms with an opportunity to use their existing farm machinery during a larger part of the growing season. As such the anticipated cost per hectare to harvest the switchgrass will be quite modest as they expect to bale the material in late April or early May. Foley farms has approximately 45 ha of switchgrass and they typically can mow the crop in one day and bale the harvest in two days using the equipment described in the harvest study (Section 4.0) With two Hesston balers, Nott farms should be able to bale 190 ha in 4 working days. Using their 30′ Krone mower, the crop can be mowed in 1.5-2 days. It is evident that forage producers with existing equipment have a tremendous advantage in adding switchgrass as a new crop production activity that can more fully utilize their existing investments. With the assumed switchgrass yields of 9 ODT/ha (as opposed to approximately 3 ODT/ha per cut for alfalfa) a somewhat slower baling operation is anticipated than experienced in alfalfa production. Nott farms estimates baling and handling costs per hectare for the annual switchgrass cut to be 10% higher than baling a hay cut or approximately $153.78/ha (Table 6.2). Assuming a recovered yield of 9 ODT/ha this provides an estimated cost at $17.08/ODT for baling and handling switchgrass.

6.2.2. Storage Costs

In 2006, Nott farms completed construction of a large (300′x160′) metal storage shed for storing biomass. It is estimated to hold 13,000 bales of dimensions of 3x3x7.5′. The switchgrass bale weight from the fall harvest of 2007 was determined to be 278.3 kg or approximately 245 ODkg. Thus this storage facility is estimated to hold approximately 3618 ODT of switchgrass. The construction cost of this building was $264,000 and the building is expected to last at least 30 years. The annual interest on this capital investment is $15840 using a 6% interest rate. The building will also be used for storage of alfalfa and cereal straw as the building will begin emptying of switchgrass in the summer and fall period. The building will require some periodic maintenance investment and annual allocation to pay off the principle. For the purposes of this analysis we assume that for a switchgrass pellet producer, 100% of a switchgrass crop will need to be stored and that $18,000 in annual costs is associated with the buildings primary use (switchgrass storage). Thus a value of $5/ODT is assumed for storage of the 3600 tonne of switchgrass.

6.2.3. *Hauling Costs*

The hauling costs are reviewed in detail in Section 5.4 and summarized in Table 5.1. Nott Farms custom hauls in a 97.9 m^3 (3450 ft^3) walking floor trailer which has an actual cost of $1.43 per km. This unit allows efficient transport of bulk commodities and rapid loading and unloading of feedstocks which is ideally suited to short haul applications of bales or bulk biomass such as a 35 km trip to a briquetting plant. For longer distances such as a 70 km trip to a pellet plant, bales would like be more efficiently transported through the use of high density bales on a big belly flatbed such as that owned by Foley Farms. For the purposes of this analysis, bale hauling costs are assumed to be $8.01 and $16.02/ODT for hauling to a briquetting and pelleting plant respectively. An assessment was also made for bulk hauling and found to be significantly lower at $5.21 and $10.42 for hauling to the briquetting and pelleting plants, respectively.

Bulk harvesting and transportation costs are estimated in Table 6.3. The crop maintenance costs are the same as stated in Table 6.2 at $539.89/ha or $59.99/tonne and in the bulk harvest scenario represents approximately 66.1%. Don Nott plans to use dump wagons in conjunction with the forage harvester and use a permanent storage site in close proximity to the field. He estimates costs to run the dump wagons to the storage depot at $25/ha.

Table 6.3: Estimated bulk harvest and transportation costs from Site B

Production Years (2-10)	**$/hectare**	**$/tonne**	**% of Costs**
Total Crop Maintenance	**$ 539.89**	**$ 59.99**	**66.1%**
Harvest & Delivery (9ODT/ha)[1]			
Mowing[1]	49.40	5.49	6.0%
Merging[1]	18.53	2.06	2.2%
Bulk harvesting[2]	45.00	5.00	5.5%
Transport to storage	25.00	2.78	3.1%
Storage	45.00	5.00	5.5%
Hauling- to Pellet Plant 140 Km round trip	93.78	10.42	11,5%
Total Harvest & Delivery Expenses	**$ 276.71**	**$ 30.75**	**33.8%**
Total Production Costs (ODT)	**$ 816.60**	**$ 90.74**	
444Total Production Costs (12% m.c.)		**$ 79.85**	

[1] Nott 2008; Mowing and merging estimates were $20/acre and $7.50/acre respectively

[2] Bransby *et al.,* 2005; Doudlah 2008.

3 Assumption made is that bulk storage is similar to bale storage, the bulk density of the biomass will be higher but it will likely require more investment in the pad of the storage structure

6.2.4. Summary of processing costs for pellets and briquettes

A final comparison is made below which analyzes the potential to further reduce densified fuel costs by establishing local briquetting plants of 10,000 tonnes of annual production as an alternative to 50,000 tonne per year pellet plants. The main financial advantages of briquetting are that the system has both lower capital investment costs and operating costs. As well the briquetting plants should experience lower biomass delivery costs as feedstock sourcing can be made closer to biomass conversion facilities. The main cost savings that are projected are reduced processing costs ($20/tonne) and reduced transport costs of $5.21 for bulk delivery and $8.01 for bale delivery for a total projected savings of $25.21-28.21. The bulk harvest system also is a significant cost reduction strategy that can reduce cost for baling and bale collection from $20.32 to $9.84/tonne. As well bulk delivery can save $2.80 per tonne for delivery to a briquetting plant and $5.60/tonne in delivery cost to a pelleting plant. In total, the use of a conventional management strategy of baling and trucking to a pellet plant can be reduced by up to $41.22/ODT. The low-cost bulk handled switchgrass briquette plant system could have an FOB price for switchgrass briquettes of $105.53 or $5.61/GJ. Given that current delivered natural gas prices in Ontario are approximately $12/GJ in March, 2008 this could be a highly competitive fuel in the future. Furthermore a recent report identified that a $2-$4/GJ incentive for densified biomass fuels in Ontario would be the lowest possible GHG offset strategy the province could implement in the renewable energy sector (Samson *et al.*, 2008). The only other potential major cost reduction strategy that could be identified in this report would be to source farmland with lower land rents. If this were the case even if yields were lower, the net cost per tonne would still be reduced appreciably. The use of farmland in the 2300-2700 CHU combined with the use of bulk handling and processing into briquettes appears to be the lowest cost strategy for producing densified grass fuels in Ontario.

Table 6.4: Estimated pellet and briquetting cost of switchgrass using baled and bulk delivered fibre

	Pelleting Plant[1]		Briquetting Plant[2]	
Production Years (2-10)	Baled $/tonne	Bulk $/tonne	Baled $/tonne	Bulk $/tonne
Total crop maintenance	59.99	59.99	59.99	59.99
Total harvest & delivery expenses	46.76	30.75	38.75	25.54
Subtotal Total Production costs (ODT)	106.75	90.74	98.74	85.53
Densification costs	40.00	40.00	20.00[3]	20.00
Total FOB (ODT)	**$ 146.75**	**$ 130.74**	**$ 118.74**	**$ 105.53**
Total FOB (7.7% m.c)	**$ 135.45**	**$ 120.67**	**$ 109.60**	**$ 97.40**

[1]Travel distance of 140km round trip;[2]Travel distance of 70km round trip;[3]Briquetting Systems 2008.

7.0 Combustion tests of BioHeat pellets in commercial boilers

7.1 Overview of methodology and pelletization process

A total of five (5) tonnes of fall harvested and 2.5 tonnes of spring harvested switchgrass pellets were used for assessments in the CANMET combustion laboratory trials. The unusually wet field conditions in the fall at the Foley Farm (Site A) did not allow baling operations for the cut material. To provide a sample for the combustion trials of fall harvested material, early November harvested switchgrass bales were sourced from the farm of Normand Caron of Valleyfield Quebec and sent to Les Luzerniers Belcan du Lac St-Jean Inc. of Hebertville-Station, Quebec.

For pelletization, the material was ground with a tub grinder and then passed through a 150 HP champion hammermill with a 7/64" screen. The material was then pelleted with a 200 HP Sprout-Waldrin pelleter using a ¼ inch die with a 2 ¼ inch thickness to provide a 9:1 L/D (length/diameter) which has proven suitable for switchgrass pellet production. The pellets produced from the fall harvested switchgrass were slightly inferior to the spring harvested pellets which were largely without fines and had a shiny gloss.

Comparative combustion tests of the switchgrass pellets were completed by NRCAN in a commercial boiler at the CETC-O facility in Bells Corners, Ontario. The combustion tests completed included CO, CO_2, SO_2, NO_x emissions, PAH/VOC emissions, unburned carbon in ash, particulate matter and overall efficiency. As well a test was made in a Blue Flame stoker installed in a greenhouse in eastern Ontario.

7.2 Results of combustion tests

For testing, the pellets were delivered to the CANMET Energy Technology Centre in Ottawa (CETC-O) as well as to Burt's Greenhouse in Odessa, Ontario. In mid January 2007, a week long testing of various feedstocks was conducted by NRCAN at Burt's Greenhouses. These assessments included emission studies with wood residues, wood pellets and switchgrass pellets in a Blue Flame Stoker boiler (Figure 19) equipped with emission testing apparatus.

The main combustion tests were conducted at the CETC-O combustion facilities in a 1 MW (thermal) KMW moving grate furnace (Figure 20). This unit is typically for wood chips and hog fuel in the sawmill and pulp and paper industries.

The results found that the fall harvested switchgrass pellets have a calorific value of 18.95 MJ/kg on a dry basis and can be combusted in a grate furnace. The fuel was handled and conveyed into the chamber without major problems. The steady state conditions were 9.6% O_2 and approximately 1000ºC. The total particulate emissions were normalized to 7% O_2 and were found to be 117 mg/m^3, without having gone through any particulate control devices. The majority of volatile organic compounds were not detected. Benzene and cholorobenzene were measured in the largest concentrations at 30.8 and 7.28 ug/m^3. The total VOCs measured was 55.8 ug/m^3. The fuel size was consistent and the bulk density was 721 kg/m^3 which is a desirable fuel property. Switchgrass pellets are an ideal biomass fuel because they could be transported economically, they had good combustion characteristics and low emissions. It should be noted that this fuel is highly volatile at 80wt% and therefore the combustor used should have sufficient volume and over-fire air capacity to complete the combustion of the fuel. Otherwise, much higher emissions from incomplete combustion, such as, volatile organic compounds, and carbon monoxide would be expected.


Figure 19: Blue Flame Stoker Combustion Unit


Figure 20: Combustion of pellets in the 1MW grate furnace

Initial results are presented below for the differences between spring and fall harvested switchgrass (Table 7.1). Some advantages appear to be present with regard to ppm emissions of NO_x, S and CO emissions with the spring harvested grass. Further analytical data is forthcoming from the CANMET Combustion lab which will enable a more complete comparison of the pellets produced from the two harvest periods and their impact on combustion efficiency and ambient air quality. Details of the findings to date are provided in Appendix I in this report.

Table 7.1: Combustion test results comparing spring harvested to fall harvested switchgrass pellets

Combustion Parameter*	Unit	Spring harvested Average	Fall harvested Average
SO2	ppm	47.39	117.52
SO2 Norm		73.09	132.19
Stack O2	%	11.89	8.48

Stack CO	ppm	39.34	49.85
Norm CO		60.68	46.20
Stack CO2	%	8.73	11.83
Norm CO2		13.47	13.25
Stack NOx	ppm	107.39	245.14
Norm NOx		165.62	280.99

** note: all emissions are normalized to 7% oxygen*

8.0 Literature Cited

Adler, P. A., Sanderson, M. A., Boateng, A. A., Weimer, P. J., & Jung, H. G. (2006). Biomass yield and biofuel quality of switchgrass harvested in fall and spring. Agron. J., 98, 1518-1525

Bransby, D., Smith, H., Taylor, R. and Duffy, P. 2005. Switchgrass budget model: An interactive budget model for producing and delivery switchgrass to a bioprocessing plant. Industrial Biotechnology. Summer 2005, 122-125

Bransby, D.I., Downing, M. 1996. Yield effects on bale density and time required for commercial harvesting and baling of switchgrass. Proc., BIOENERGY "96-The Seventh National Bioenergy Conference: Partnerships to Develop and Apply Biomass Technologies, September 15-20, 1996, Nashville, Tennessee.

Briquetting Systems. 2008. Retrieved in Feb, 2008. <www.briquettingsystems.com/lease/costs.htm#pucksvspellets; www.briquettingsystems.com/lease/costs.htm>

Brummer, E., C. Burras, M. Duffy and K. Moore. 2002. Switchgrass production in Iowa: Economic analysis, soil suitability and varietal performance. Final report to Bioenergy Feedstock Development Program. Oak Ridge National Laboratory Oak Ridge, Tennessee 37831-6422. 80pg.

Colley, Z., Fasina, O., Bransby, D., Lee, Y. 2006. Moisture effect on the physical characteristics of switchgrass pellets. ASABE. 46 (6): 1845-1851.

Conrado, R., Linden, K., Martin R., Pinge, A. 2005. Switchgrass feedstock logistics systems. ENGS 190/290 Final Report, Winter 2005, Report number-27, Thayer School of Engineering at Dartmouth College, 8000 Cummings Hall, Hanover, NH 03755-8000.

Cowbrough, Mike. 2007. University of Guelph Staff, *personal communication*.

Cundiff, J.S. 1995. Delayed harvest of switchgrass. 1994-1995 Annual Report. Biological Systems Engineering Department. Virginia Tech. Blacksbourg, VA 24061-0303. 16 pg.

Cundiff, J.S. 1996. Simulation of five large round bale harvesting systems for biomass. Bioresource Technology 56, 77-82.

Cundiff, J.S., Dias, N., Sherali, H. 1997. A linear programming approach for designing an herbaceous biomass delivery system. Bioresource Technology 59, 47-55.

Cundiff, J.S., Shapouri, H. 1997. Cost and direct energy input to produce fuel cubes from switchgrass. An ASAE Meeting Presentation paper 976078. St. Joseph, MI 49085-9659: ASAE, 32 pg.

Doudlah, Mark. 2008. Agrecol Corporation, *personal communication*.

Duffy, M., 2008. Estimated cost for production, storage and transportation of switchgrass. Ag Decision Maker-File A1-22. Iowa State University. Retrieved in Feb, 2008 <www.extension.iastate.edu/agdm/crops/pdf/a1-22.pdf>

Elbersen, H. W., Christian, D. G., Bacher, W., Alexopoulou, E., Pignatelli, V., & van den Berg, D. 2002. Switchgrass Variety Choice in Europe. (Final Report FAIR 5-CT97-3701 "Switchgrass")

Girouard, P. and R. Samson. 1996. Evaluation of conventional haymaking equipment for spring harvesting switchgrass. REAP-Canada report prepared for Domtar Inc., Noranda Inc. and Natural Resources Canada. Ottawa, Ontario. 12 pp.

Girouard, P. and R. Samson. 1997. Evaluation of haymaking equipment to harvest switchgrass/Part II. REAP-Canada internal report. Ste-Anne-de-Bellevue, QC. 12 pp.

Girouard, P., R. Samson, B.B. Mehdi. 1998. Harvest and Delivered Costs of Spring Harvested Switchgrass: Final Report. REAP-Canada final report to Natural Resources Canada. Ottawa Ontario. 12 pp.

Girouard, P., Samson, R., Zan, C. and B. Mehdi. 1999. Economics and carbon offset potential of biomass fuels. REAP-Canada final report to the Federal Panel on Energy Research and Development (PERD) Contract 23341-6-2010/00 1/SQ. 120 pp.

Goel, K., R. Eisner, G. Sherson, T. Radiotis and J. Li. 2000. Switchgrass: A potential pulp fibre source. Pulp & Paper-Canada 101(6):51-45.

Green, J. and Benson, G. 2006. Switchgrass for biomass energy production: Estimated revenue, operation cost, fixed cost, and net returns per acre in the establishment year. North Carolina State University. Retrieved in Feb, 2008 <www.ag-econ.ncsu.edu/extension/budgets/switchgrass_energy_87-11.pdf>

GreenBiz.com 2007, "Energy Dept. Invests $385M in Cellulosic Ethanol." Published online 8 March 2007 < http://www.greenbiz.com/news/news_third.cfm?NewsID=34699>

Hemmings, M.S. 1995. Spring Harvest of Reed Canary Grass (Phalaris arundinacea). In: Proc. Biomass for Energy, Environment, Agriculture and Industry. 8th E.C. conference. October 3-5, 1994. Vienna, Austria. 708-711.

Jannasch, R. Duxbury, P. and R. Samson. 2001. Development of bioenergy feedstocks: Agronomy data from Eastern Canada. REAP-Canada final report to Natural Resources Canada, Ottawa, Ontario. Contract # 23384-005068/001/SQ. 28pp.

Kaliyan, N., and Morey, V. 2006. Densification characteristics of corn stover and switchgrass. ASABE paper No. 066174. St. Joseph, Mich.: ASABE.

Kumar, A., Sokhansanj, S. 2007. Switchgrass (Panicum virgatum, L.) delivery to a biorefinery using integrated biomass supply analysis and logistics model (IBSAL). Bioresource Technology 98 1033-1044.

Mani, S., Sokhansanj, S., Bi, X., and Turhollow, A. 2006. Economics of producing fuel pellets from biomass. App Eng Agri. 22(3): 421-426.

Mani, S., Tabil, L., Sokhansanj, S. 2004. Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass. Biomass & Bioenergy. 27: 339-352.

Molenhuis, J. 2008. 2008 Field crop budgets, publication 60. Ontario Ministry of Agriculture, Food and Rural Affairs. Retrieved in Feb, 2008. www.omafra.gov.on.ca/ english/busdev/facts/pub60.htm#2005

Nott, Don. 2008. Switch Energy Corporation, *personal communication*.

Parrish, D.J and J.H. Fike. 2005. The biology and Agronomy of Switchgrass for Biofuels. Critical Reviews of Plant Sciences. 24:423-459.

Parrish, D.J. and D.D. Wolf. 1992. Managing switchgrass for sustainable biomass production. In: Proc. Symp. Liquid Fuels from Renewable Resources. Pp 34-39. Nashville, TN, 13-14 December 1992. ASAE, St. Joseph, MI.

Parrish D.J. and D.D. Wolf. 1993. Switchgrass as a biofuels crop for the upper Southeast. In: Proc First Biomass Conference of the Americas, Burlington, VT. 1:248-253. National Renewable Energy Lab, Golden CO.

Parrish D.J., D.D. Wolf, J.H. Fike and W.L. Daniels. 2003. Switchgrass as a biofuels crop for the upper southeast: Variety trials and cultural improvements. Final Report for 1997 to 2001, ORNL.SUB-03-19SY163C/01. Oak ridge National Laboratory, Oak Ridge, TN.

Radiotis, T. ', J.Li, K. Goel and R. Eisner. (1996). Fibre characteristics, pulpability and bleachability studies of switchgrass. Proc. Of the 1996 Tappi pulping conference p. 371.-376.,

Samson, R. A., Blais, P-A., Mehdi, B., & Girouard, P. 1999a Switchgrass Plant Improvement Program for Paper and Agri-Fibre Production in Eastern Canada. (Final report prepared by REAP-Canada for the Agricultural Adaptation Council of Ontario)

Samson, R., Girouard, P., & Mehdi, B. 1999b. Establishment of commercial switchgrass plantations. (Final report prepared by REAP-Canada for Natural Resources Canada)

Samson, R., S. Bailey Stamler, J. Dooper, S. Mulder, T. Ingram, K. Clark, and C. Ho Lem. 2008. Analysing Ontario Biofuel Options: Greenhouse Gas Mitigation Efficiency and Costs. Final Report with Biocap-Canada. 42 pp.

Samson, R., Mani, S., Boddey, R., Sokhansanj, S., Quesada, D., Urquiaga, S., Reis, V., & Ho Lem, C. 2005. The potential of C4 perennial grasses for developing a global BIO HEAT industry. Critical Reviews in Plant Science, 24, 461-495.

Sanderson, M.A., R.P. Egg and A.E. Wiselogel. 1997. Biomass losses during harvest and storage of switchgrass. Biomass & Bioenergy. 12(2):107-114.

Sanderson, M.A., J.C. Read and R.L. Read. 1999. Harvest management of switchgrass for biomass feedstock and forage production. Agron.J. 91:5-10.

Shaw, M., and Tabil, L. 2007. Compression and relaxation characteristics of selected biomass grinds. ASABR Paper No. 076183. St. Joseph, Mich.:ASABE.

Shinners, K., G. Boettcher, R. Muck, P. Weimer and M. Casler. 2006. Drying, harvesting and storage characteristics of perennial grasses as biomass feedstocks. ASAE paper # 061012, 19 pp.

Sokhansanj, S. and J. Fenton. 2006. Cost benefit of biomass supply and pre-processing. Biocap research integration program synthesis paper. Biocap Canada. 32 pages.

United States Department of Agriculture (USDA). 1986. Fact sheet: 'cave-in-rock' switchgrass. USDA Natural resources conservation service, Columbia, M.I., U.S.A. Retrieved Feb, 2008 <http://plant-materials.nrcs.usda.gov/pubs/mopmcfscavinroc.pdf>

University of Tennessee. 2007. Switchgrass production budget estimated expenses per acre-2007. Retrieved in Feb, 2008 <http://economics.ag.utk.edu/text/switch3.html>

Venturi, P., Monti, A., Piani, Il., Venturi G. 2004. Evaluation of harvesting and post harvesting techniques for energy destination of switchgrass. In: W.P.M. Van Swaiij et al. (Ed.) Proceedings of the 2nd Conference on Biomass for Energy, Industry and Climate Protection, 10-14 May 2004, Rome, pp. 234-236.

Vogel, K.P., J.J. Brejda, D.T. Walters and D.R. Buxton. 2002. Switchgrass biomass production in the Midwest USA: Harvest and nitrogen management. Agron. J.94:413-420.

APPENDIX I

DRAFT REPORT: **Combustion Testing of Switchgrass Pellets on a 1 MWth KMW Industrial Grate Furnace**

CANMET Energy Technology Centre – Ottawa
Industrial Innovation Group

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