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IMPACT OF HARVESTING TIME ON ULTIMATE METHANE YIELD OF SWITCHGRASS GROWN IN EASTERN CANADA

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ABSTRACT Green energy production from crops has been under investigation for the last two decades. In Europe, this led to the development of energy crops-fed full scale bioreactors. Switchgrass was recognized as one of the most promising crops for energy production among several perennial grass species grown under moderate to hot climates. However, few studies were initiated under colder climate conditions. The aim of this study was to determine the mesophilic methane yield of switchgrass grown under the cooler growing conditions of the north-eastern area of North America. Switchgrass was harvested at three different times (late July, late August, and late September) in 2007 and conserved as silage. The regrowth of plots harvested in late July was also harvested in late September as a two-cut strategy. The switchgrass silage samples were anaerobically digested using small-scale (30 L) laboratory digesters. Specific methane yield decreased significantly with advancing plant development (from 0.289 to 0.207 L_N CH_4 g^{-1} VS), but was similar between the first harvest in late July and the regrowth in late September. Approximately 25% more methane could be produced by hectare for the two-cut strategy compared to harvesting once in late August. Further studies are required to determine the effect of cutting times and strategies on the long term yield of switchgrass in order to adequately establish the production cost of this green energy.

Keywords: Switchgrass, anaerobic digestion, methane production, energy crops, green energy

INTRODUCTION

Cleaner and more renewable energy sources than petroleum-based energy are required. Methane produced from anaerobic digestion is a significant energy source for the generation of heat and power from the organic fraction of municipal solid wastes (Bolzonella et al. 2006), animal and agricultural wastes (Wohlt et al. 1990; Massé 1995; Sakar et al. 2009), sewage (Lettinga 1995), animal carcasses (Chen and Shyu 1998; Massé et al. 2008) and energy crops (Amon et al. 2007a; Demirel 2009). Many perennial grasses were identified as promising energy crops, such as Miscanthus (*Miscanthus* × *giganteus*), sorghums (*Sorghum*), reed canarygrass (*Phalaris arundinacea* L.) and switchgrass (*Panicum virgatum* L.). The C4 grasses were recognized as more promising energy crops than C3 grasses because of a more efficient photosynthetic pathway (Lewandowski et al. 2003). Perennial grasses require less nutrient (McLaughlin and Walsh 1998) and pesticide (Börjesson 1999; Lewandowski et al. 2003) inputs than annual crops. Switchgrass has been recognized as one of the most promising energy crops because of its superior aerial biomass yield across a wide geographical range, its adaptability to marginal quality land, and its low water and nutrient requirements (McLaughlin and Kszos 2005; Heaton et al. 2008). Moreover, switchgrass roots enhance soil structural stability and requires relatively low inputs of energy, water and agrochemicals per unit of energy produced (McLaughlin and Walsh 1998).

Methane yield of various energy crops anaerobically digested was assessed (Chynoweth et al. 1993; Mähnert et al. 2005; Lehtomäki 2006; Amon et al. 2007a; Amon et al. 2007b). Some studies focused on methane yield per surface area since crop yield varies among plant species and varieties in the US and Europe (Weiland 2003; Amon et al. 2007a). Switchgrass yield usually decline in late summer, as explained by the translocation of aboveground biomass to underground parts (Sanderson et al. 1996). Fewer investigations focused on crops produced in colder climates, such as in Finland (Lehtomäki et al. 2008; Seppälä et al. 2009) or in the northern part of North America (Madakadze et al. 1999b).

The harvest period influences methane yields of anaerobically digested crops since plants chemical composition varies with stages of development (Cherney et al. 1986; Gunaseelan 1997; Lehtomäki et al. 2008; Heiermann et al. 2009). Lehtomäki and colleagues (2008) established that for most grasses, methane yield per unit of volatile solids (VS) content increased with delayed harvests, as opposed to a reduced methane yield for some grasses and clover (Kaparaju et al. 2002; Prochnow et al. 2005).

No information is available regarding the effect of harvest time and strategy on potential methane yields per gram of VS of switchgrass under north-eastern cool climate conditions of America. This information is required to determine the potential methane yields per surface area of switchgrass. The objectives of this project were to determine methane yields of anaerobically digested switchgrass harvested at different times and under different harvesting strategies.

MATERIALS AND METHODS

Switchgrass production and harvest

Two experimental sites were located in St-Lambert (46° 48' N; 71° 23' W), Quebec (Canada). Sites were seeded with *Panicum virgatum* L. (Cave-in-rock) in 2002 and 2006. In 2007, 12 plots of 2 × 5 m in size were set in each of the two fields. Three harvesting treatments were used, each replicated four times. The first harvesting treatment consisted of a two-harvesting strategy with the first harvest in late July and the regrowth harvest in late September. The second and third harvesting treatments consisted of a one-harvest strategy with the harvest in late August and late September, respectively. Switchgrass was harvested at a 5-cm height using a flail-type self-propeled Carter^{TM} forage harvester (Carter MGF Co., Inc., Brookston, IN, USA).

Silage procedure

After the determination of the switchgrass yield, approximately 10 kg (humid basis) of each replicate sample were air-dried into a greenhouse until it reached a dry matter (DM) content of 35%. Dried samples were doubled-chopped (25-50 mm) using a stationary straw chopper prior to ensiling. Switchgrass samples (5 kg at 35% DM) were bagged in 6-mil plastic bags enclosed in plastic buckets. Buckets were hermetically sealed using appropriate plastic lids with a rubber grommet for airlock as a backup. Silage buckets were left at room temperature for six weeks prior to characterization. Samples for methane production assays were thereafter kept frozen at -20 ºC.

Laboratory assay description

Sludge from a mesophilic (35^{o}C) anaerobic SBR (sequential batch reactor) fed with swine manure was collected at the end of an anaerobic digestion cycle and used to inoculate switchgrass. Prior to each assay, physico-chemical characteristics of the inoculum were determined. Each bioreactor (30-L barrels) was filled with 20 L of the inoculating sludge and 500 g of unfrozen switchgrass silage (wet basis). Methane yield of each sample was assessed in duplicate using a pair of bioreactors. Silage samples were digested anaerobically under mesophilic conditions (35^{o}C) in a temperature controlled room. Sludge and silage samples were mixed three times a day during assays. The digestion assay was considered over when the cumulative biogas production reached a plateau and the concentration of volatile fatty acids (VFAs) decreased to negligible levels. The plateau value of the plotted cumulative methane production of each reactor was considered as the methane yield. Specific methane yields were calculated based on the mass of volatile solids (VS) added in the reactor.

Bioreactors monitoring

Wet tip gas meters were used to monitor daily biogas production. Biogas components (CH_4, H_2S, CO_2) were determined weekly. Methane production is reported in norm litre per gram of volatile solids of energy crop (L_N CH_4 $(g\ VS)^{-1}$), i.e. the volume of methane production is based on norm conditions (273^{o}K; 1 atm). Methane production from the inoculum alone was measured (varying from 2.4 to 19.4% of total methane production, data not shown) and subtracted from the methane production as a background noise in digested switchgrass bioreactors. Liquid samples were collected in each bioreactor and analyzed weekly for pH and volatile fatty acids (VFAs). Alkalinity, total and soluble chemical oxygen demand (TCOD and SCOD), solid content, total Kjeldahl nitrogen (TKN), and ammonia nitrogen were determined before and after each batch treatment.

RESULTS

Chemical composition of inocula and switchgrass silages

Inoculum batches significantly ($P < 0.05$) differed for the measured parameters, but the values were within the same range (data not shown). Inocula contained negligible concentrations of VFAs and their pH was around 8.0. The VFAs found in switchgrass silage samples were acetic (600 to 4419 mg L^{-1}), propionic (0 to 637 mg L^{-1}) and butyric acids (0 to 680 mg L^{-1}). The pH of almost all silage samples was around 4.0, except for one silage sample showing a value of 8.5 with low concentrations of VFAs, suggesting a low quality silage sample. Nonetheless, this sample was processed in the anaerobic methane yield assays. Silage total solids (TS) content was mostly composed of VS, with proportions ranging from 90 to 95% of TS.

Cumulative methane production

Specific methane yields from both sites were pooled together (Fig. 1) because no significant ($P > 0.05$) difference between sites was observed. Specific methane yields significantly ($P < 0.001$) decreased with plant maturity from 0.289 ± 0.035 L_N CH_4 g^{-1} VS in late July to 0.207 ± 0.034 L_N CH_4 g^{-1} VS in late September (Fig. 2). However, specific methane yields were similar ($P=0.26$) for both the first cut of late July and the second cut of late September (0.272 ± 0.044 L_N CH_4 g^{-1} VS).

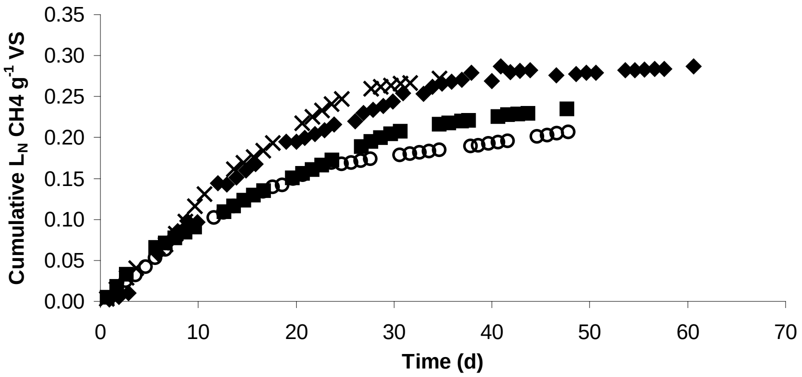

Figure 1. Cumulative specific methane yields of anaerobically digested switchgrass harvested at different times. Late July (♦); late August (■); late September (○); late September, 2nd cut (×).

Switchgrass yield and area specific methane yield

The two sites did not differ significantly ($P = 0.08$) in switchgrass yield. The switchgrass yield with the single harvest in late August was significantly ($P < 0.05$) greater than that with a single harvest in late July or late September, and similar to that with a two-cut strategy (Fig. 2). These data as well as results from the methane yield assays were used to calculate the area specific methane yields (Fig. 2), i.e. the volume of methane produced per hectare. The yield of the regrowth harvested in late September was very low and, consequently, its area specific methane yield was lower than for switchgrass harvested only once. The highest area specific methane yields were reached (3.13 ± 0.47 L_N CH_4

ha^{-1}) with the 2-cut strategy (Fig. 2). However, even though these values were numerically higher than those obtained for the one-cut strategy, they did not significantly ($P > 0.05$) differ.

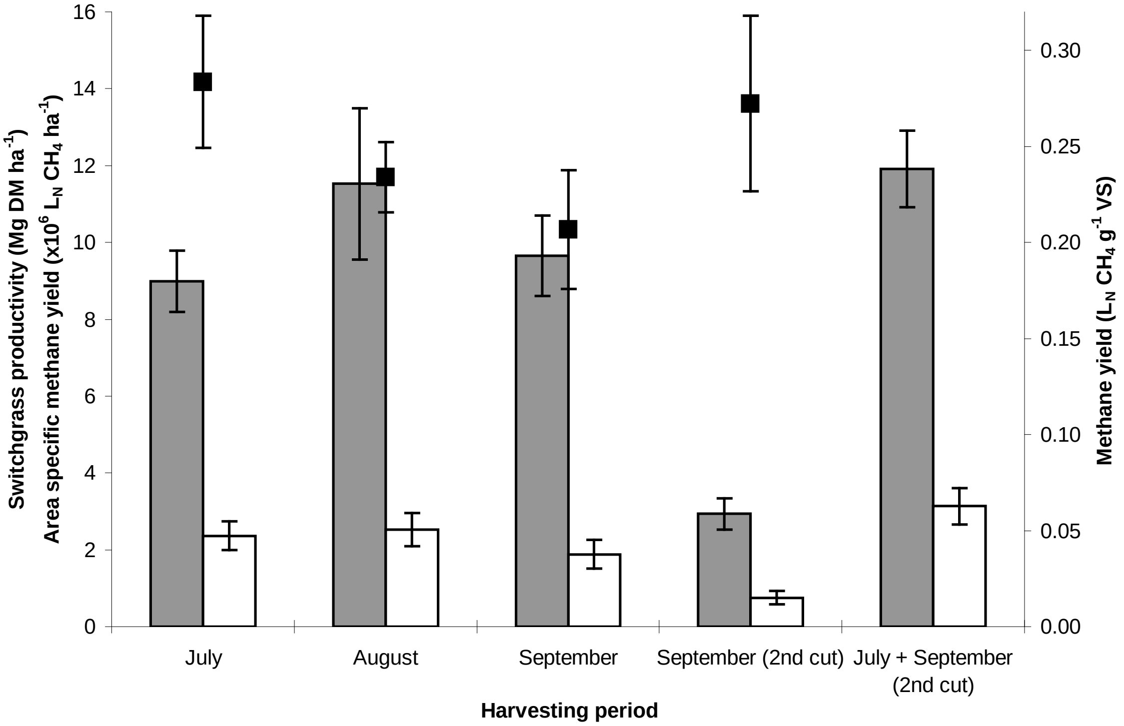

Figure 2. Effect of harvest times and strategies on switchgrass yield (▨), methane yields per hectare (☐) and specific methane yields (■).

DISCUSSION

Chynoweth and colleagues (1993) found specific methane yields ranging from 0.16 to 0.39 L CH_4 g^{-1} VS for various grasses grown under different conditions. Others reported values ranging from 0.25 to 0.39 L_N CH_4 g^{-1} VS for anaerobically digested field-dried cocksfoot (*Dactylis glomerata* L.), tall fescue (*Festuca arundinaceae* Schreb.), reed canary grass (*Phalaris arundinaceae* L.) and timothy (*Phleum pratense* L.) grown in Finland and harvested at various stages of development (Seppälä et al. 2009). Some studies showed higher methane yields for grass silage, with values ranging from 0.26 to 0.50 L_N CH_4 g^{-1} VS (Chynoweth et al. 1993; Seppala et al. 2008; Koch et al. 2009), due to the biological transformation of slowly digestible matter such as fibre into VFAs. Amon and colleagues (2007a) reported specific methane yields of 0.398 ± 0.023 L_N CH_4 g^{-1} VS for different maize varieties, from 0.140 to 0.343 L_N CH_4 g^{-1} VS for wheat, and from 0.190 to 0.454 L_N CH_4 g^{-1} VS for two varieties of sunflower. Our values of specific methane yield obtained from switchgrass silage were slightly less than those observed from other grass species and annual field crops but they were slightly greater than those obtained with switchgrass.

Specific methane yields decreased with plant development, with higher values observed for the earliest harvest time (late July). Similar results were observed for meadow foxtail (*Alopecurus pratensis* L.) grassland where substrate-specific biogas yields decreased linearly throughout the season from 0.547 L_N g^{-1} VS in June to 0.299 L_N g^{-1} VS in February (Prochnow et al. 2005). Kaparaju and colleagues (2002) also reported that the production of methane from clover harvested at the vegetative stage was 33% higher than for clover harvested at the flowering stage. As for several grasses, non-digestible lignin content of switchgrass increases with plant development (Madakadze et al. 1999a; Dien et al. 2006). Moreover, the proportion of stems increases while that of leaves decreases with switchgrass development (Sanderson 1992). Dien and colleagues (2006) found that the stage of development did not significantly influence the gross energy content of crops determined by calorimetry. This suggest that the specific energy content of switchgrass does not vary during growth and development, but it becomes less available for biological degradation as the plant matures, due to a shift toward non-digestible matter in plant components.

Many studies have attempted to determine the best harvesting management strategy to optimize energy crops yields. Parrish and Fike (2005) reported that highest crop yields were observed with switchgrass harvested once or at most twice a year. Our results show that specific methane yields on the regrowth (late September) was comparable to those measured with switchgrass harvested the first time in late July. Similar results were reported with napiergrass (*Pennisetum purpureum*) and energycane (*Saccharum* sp.) (Chynoweth et al. 1993). However, some studies showed that harvesting switchgrass more than once a year could significantly decrease yields (Parrish and Fike 2005). Even though specific methane yields were higher for switchgrass harvested in late July and for the regrowth harvested in late September, the knowledge of switchgrass yields over a number of years is necessary to determine the best harvesting strategy regarding potential energy production per surface area. Switchgrass yields obtained in this study for the one-cut strategy in late July, late August and late September (8.87 to 12.61 Mg DM ha^{-1}) were in the same range than previously published results (Heaton et al. 2004; Adler et al. 2006; Fike et al. 2006). Heaton and colleagues (2004) reviewed the scientific literature prior 2004 regarding switchgrass yields of various cultivars and calculated an average productivity of 10.3 Mg DM ha^{-1}. Adler and colleagues (2006) found a productivity of 8.57 Mg DM ha^{-1} for *P. virgatum* (Cave-in-Rock) grown in Hagerstown silt loam, when harvested in fall (late October to early November). In another study, the Cave-in-Rock cultivar yield was assessed throughout eight sites across five states in the upper Southeastern USA (Fike et al. 2006). They found switchgrass production ranging from 8.7 to 16.4 Mg DM ha^{-1} for the one-cut strategy (early November) and from 12.9 to 21.3 Mg DM ha^{-1} for the two-cut management (late June and early November). The latter values are significantly higher than those obtained in our study (11.84 to 12.00 Mg DM ha^{-1}) for the two-cut management strategy. This could be explained by a longer and warmer growing season compared to Eastern Canada. Madakadze and colleagues (1999a; 1999b) evaluated the productivity of various switchgrass cultivars grown in a free draining sandy clay loam, in Eastern Canada (Montreal), for different harvesting strategies. They reported seasonal yields of 11, 10 and 8 Mg DM ha^{-1} when harvesting Cave-in-Rock in late September or at 6- (July and September) and 4-weeks intervals (July, August and September), respectively.

Few studies have evaluated the area specific methane yield of switchgrass. Preliminary results obtained by Katsvairo and colleagues (2007) showed that 2.3×10^6 to 5.4×10^6 L_N CH_4 ha^{-1} could be obtained for different varieties of switchgrass (Alamo, DeFuniak, Miami, Stuart and Wabasso) grown in Florida. These values are slightly higher than those obtained in our study for ensiled switchgrass (1.8×10^6 to 3.4×10^6 L_N CH_4 ha^{-1}). In a study designed to optimize biogas production from energy crops grown in Austria, Amon and colleagues (2007a) reported area specific methane yields ranging from 3.2×10^6 to 4.5×10^6 L_N CH_4 ha^{-1} for cereals, from 2.6×10^6 to 4.6×10^6 L_N CH_4 ha^{-1} for sunflowers, and from 2.7×10^6 to 3.5×10^6 L_N CH_4 ha^{-1} for an alpine grassland; the highest area specific methane yields of 7.5×10^6 to 10.2×10^6 L_N CH_4 ha^{-1} were achieved from maize varieties. Weiland (2003) reported methane yields per hectare for various crops grown in Germany ranging from 2.3×10^6 to 5.8×10^6 L_N CH_4 ha^{-1} for root crops (potato; forage beet and leaves), 1.2×10^6 to 5.8×10^6 L_N CH_4 ha^{-1} for grain crops (rape; barley; wheat; maize), and 1.7×10^6 to 4.1×10^6 L_N CH_4 ha^{-1} for green forage plants (marrowstem kale; clover; alfalfa; ryegrass). The latter values are comparable to those obtained for ensiled switchgrass.

CONCLUSION

Maximum cumulative specific methane production from anaerobically digested switchgrass decreased with advancing plant development. Specific methane yields were highest for switchgrass harvested at either the end of July or in late September on a regrowth. Area specific methane yields obtained for ensiled switchgrass grown in eastern Canada were lower than other energy crops grown in warmer areas, but were still within the range of various forage species; this suggests that switchgrass remains an interesting renewable alternative energy source for this part of the world. Our results also indicate that approximately 25% more methane could be produced by hectare for the two-cut strategy compared to harvesting once in late August. However, it is necessary to determine the energetic and financial costs associated with a second harvest to ensure that obtaining this extra yield is worthwhile. Further studies are also required to determine the effect of this cutting strategy on the productivity and persistence of switchgrass under the cool and humid climate of Eastern Canada.

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