Impact of Harvest Date and Cutting Length of Grass Ley and Whole-Crop Cereals on Methane Yield and Economic Viability as Feedstock for Biogas Vehicle Fuel Production

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Abstract

Grass ley and whole-crop cereals used for biogas production are often finely chopped for subsequent ensiling and anaerobic digestion. Chopping can impact not only ensiling stability, digestibility and risk of process hick-ups in the digester but also harvesting capacity and fuel consumption. Based on field experiment data, the aim of this study was to investigate how three different nominal cutting lengths in the range of 3.5 mm to 12.5 mm impact methane yield and economic viability of grass ley and whole-crop cereals used as biogas substrate. A shorter cutting length affected the specific methane potential differently for the different crops, + 14 to − 25%. In biogas vehicle fuel production, balancing the additional energy and economic costs for shorter cutting length required an increased methane potential of less than 1% and 3%, respectively. As long as a decrease in cutting length increased the methane potential, the energy balance and economic result improved, despite higher energy inputs. However, mechanisms behind the impact on methane potential deserve further attention. In conclusion, we have shown that it is economically viable to produce methane gas, as a vehicle fuel, from several agricultural crops grown in the south of Sweden, i.e. grass ley and whole-crop rye and wheat, when they are harvested/chopped with a forager, ensiled as biogas feedstocks and processed to methane gas in a large-scale biogas plant.

Keywords Methane potential · Energy yield · Anaerobic digestion · Biofuel · Energy crops · Techno-economic assessment

Introduction

Crops such as grass ley (a grass and legume mixture) and whole-crop cereals (maize, wheat rye, triticale, etc.) are often

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used as substrate/feedstock for biogas production in Sweden and other parts of Europe. These biogas crops are mainly ensiled to provide year-round substrate supply to the biogas plant. Particle size reduction by chopping such crops finely facilitates a quick start of the microbial ensiling process [1]. But, also feed-in and transport through the anaerobic digestion process can be facilitated by reduced particle size through a reduced risk of problems such as blockages, floating and formation of crusts which can lead to process interruptions in the anaerobic digester.

Besides improving the ensiling process and facilitate handling, decreasing particle size may result in higher specific methane yields by increasing the reaction surface [2]. In practice, the trend has gone to the use of forage harvesters with specific biogas chopping drums with increased cutting frequency, e.g. by an increased number of knives or increased chopping drum speed, resulting in minimum nominal cutting lengths of 2–4 mm.

However, a finer cutting length generally increases fuel consumption and decreases capacity of the harvesting chain and therefore adds to the costs of substrate supply [3]. There is likely a lower limit under which additional particle size

reduction of grass will increase cost without leading further improvements of the ensiling process, methane yield or handling properties. A too short cutting length can therefore become uneconomic [4]. An economically optimal cutting length of in between some millimetres and some centimetres, dependent on substrate and its properties, has been suggested [5].

Besides cutting length, crop maturity can influence the specific methane potential. The proportion of cellulose, hemicellulose, protein and lignin can change over crop maturation. Of the content of these macromolecules, lignin content was found to correlate strongest to the methane potential of grasses and grass-clover mixtures [6]. Plant morphology also changes during maturation, e.g. by increased thickness of secondary cell walls, and negatively influences the accessibility of plant components to degradation [7]. For perennial grasses, a higher number of cuts per year have been shown to lead not only to a higher specific methane yield [8, 9] but also lower biomass yield per cut.

To our knowledge, there is no study that has investigated the combined effect of cutting length and crop maturity on the specific methane potential of grass ley, wheat and rye harvested as whole-crop cereals and the impact on production economics of methane gas vehicle fuel.

The aim of this study was to investigate how cutting length and harvest date influence the potential methane yield from grass ley and whole-crop cereals and their overall economic viability as biogas substrates.

Materials and Methods

Field Experiments

Grass Ley

In 2012, a randomised block field experiment with grass ley was established on a production field of a farm in Southern Sweden, Vrams Gunnarstorp (56° 05' N, 12° 57' E), on heavy clay soil (> 40% clay) and a soil organic matter content of 4%. The grass ley was sown in a growing cereal crop (triticale) as a grass legume mixture including timothy (27 wt%), tall fescue (24 wt%), alfalfa (24 wt%), red clover (18 wt%) and chicory (8 wt%) in June 2011, using a grass seeder mounted on a weed harrow. The whole experimental field was fertilised with 35 m³/ha of digestate from the biogas plant (Söderåsens Bioenergi AB). This resulted in fertilisation of 105 kg/ha, 21 kg/ha and 39 kg/ha for ammonium-N, phosphorous and potassium, respectively. Five days after the first cut, additional 60 kg/ha mineral N (ammonium nitrate, 27% N) was applied. There was no additional nitrogen application after the second cut, which would have been a normal procedure.

For grass ley harvest, two harvest systems, i.e. two and three cuts per year, each with three nominal cutting lengths, were investigated (Table 1). At each harvest occasion, biomass yield was determined in hand-harvested 0.5 m × 0.5 m squares in 45 replicates (3 × 3 = 9 per block and harvest system). Dry matter (DM) content was determined from fresh and oven-dried (48 h at 65 °C) samples. After hand harvest of biomass in the small squares, bigger plots (10.5 m × 15.0 m) were mowed in three 3.5 m × 15.0 m lanes and mowed biomass was laid into one windrow per lane by a tractor-mounted rotary disc mower to allow for a split-plot design for the different cutting lengths using a forage harvester. After field-drying to approx. 35% DM content, the windrows were chopped using a self-propelled forager equipped with a pick-up. The three lanes per block and harvest system were chopped at the three different cutting lengths: (1) to estimate technical biomass recovery in comparisons with biomass yields derived from hand-harvested samples and (2) to provide material for ensiling and subsequent methane potential assays.

Whole-Crop Cereals

In 2013, randomised block field experiments were carried out on production fields in Southern Sweden for whole-crop cereals: (a) rye, variety *Visello*, sown on 1 October 2012 and fertilised on 1 October 2012 (14 kg/ha N and 15 kg/ha P), 5 April 2013 (82 kg/ha N) and 28 April 2013 (35 kg/ha N) on a 25-ha field (55° 31' N, 13° 08' E), and (b) wheat, variety *Cubus*, sown on 16 October 2012 and fertilised on 16 October 2012 (14 kg/ha N and 15 kg/ha P), 6 April 2013 (81 kg/ha N) and 2 May 2013 (64 kg/ha N) on a 91-ha field (55° 28' N, 13° 26' E). By mistake, the rye field experiment was treated with straw-shortening treatments. Biomass yield and DM content were determined from 15 plots (0.5 m × 0.5 m) for each field for three different nominal cutting lengths and three harvest dates (Table 1). Hand-harvested samples for different harvest dates were chopped manually at 12.5 mm cutting length. At the medium harvest date, different cutting lengths were produced by harvesting with a self-propelled forage harvester equipped with a direct cut header for whole-crop cereals.

Ensiling of Samples

Biomass samples were pooled for each cutting length/harvest occasion and were subsampled into triplicates. These were ensiled for subsequent assessment of biochemical methane potential by adding 4 g Lactisil Stabil per Mg of sample (Medipharma AB, Sweden). Ensiling was carried out in gas-tight buckets (4.8 L total volume) each with an attached gas collection bag [10].

Table 1 Treatments and harvest dates for grass ley and whole-crop rye and wheat investigate in this study

Crop	Field/study	Study	1st cut	2nd cut	3rd cut
Grass	Wrams/3 cuts/year	Harvest date	4 June 2012	31 July 2012	20 September 2012
		Cutting length	Mechanical (4 mm, 8 mm and 12 mm; all cuts)		
Grass	Wrams/2 cuts/year	Harvest date	25 June 2012	20 September 2012	
		Cutting length	Mechanical (4 mm, 8 mm and 12 mm; all cuts)		
Rye	Skabersjö		<i>Early</i> harvest	<i>Medium</i> harvest	<i>Late</i> harvest
		Harvest date	8 July 2013	15 July 2013	22 July 2013
		Crop stage	<i>Late milk</i>	<i>Early dough</i>	<i>Late dough</i>
		Harvest type (cutting length)	Manual (12.5 mm)	Manual (12.5 mm) Mechanical (3.5 mm, 5.5 mm and 12.5 mm)	Manual (12.5 mm)
Wheat	Näsbyholm	Harvest date	17 July 2013	22 July 2013	29 July 2013
		Crop stage	<i>Early dough</i>	<i>Late dough</i>	<i>Mature</i>
		Harvest type (cutting length)	Manual (12.5 mm)	Manual (12.5 mm) Mechanical (3.5 mm, 5.5 mm and 12.5 mm)	Manual (12.5 mm)

Cutting length categories: *fine* = 3.5–4 mm, *moderate* = 5.5–8 mm and *coarse* = 12–12.5 mm

Biochemical Methane Potential Assays

Biochemical methane potential (BMP) assays were carried out on ensiled samples using the Automatic Methane Potential Test System (AMPTS) II (Bioprocess Control AB, Lund, Sweden). Gas volumes were corrected as dry gas at 0 °C and 101,325 Pa. Inoculum was collected from the Källby wastewater treatment plant (VA Syd) in Lund, Sweden, and incubated in aliquots of 4 L for 5 days in water baths set at 37.5 °C (the same as that for BMP tests), prior to BMP tests. Total solids (TS) and volatile solids (VS) were determined with standard methods with a drying temperature of 105 °C for TS determination on fresh, frozen crop samples based on Kreuger et al. [10]. A total of 300 mL of the inoculum was added to each BMP test flask. The inoculum-to-sample ratio was 2:1 in terms of VS. Stirring was set at 160 rpm (80% of maximum setting) and was on for 5 min and off for 25 min, every 30 min. The experiments were terminated after 33–35 days, and the results were reported for 30 days of digestion.

Two BMP test rounds were performed: one for grass ley samples and another for whole-crop cereal samples. Two sets of controls were included in each round: one set in which only the inoculum was used and a second with microcrystalline cellulose (Avicel PH-101, Sigma-Aldrich, St. Louis, MO, USA) to test the activity of the inoculum. In the first BMP test round, ensiled grass samples were digested (Table 1). The number of replicates was three for samples and controls. In the second BMP test round, ensiled wheat and rye samples were digested (Table 1). Four replicates were used for each sample, three for cellulose control and five for inoculum control.

One bucket of ensiled sample was opened at a time, mixed and sampled for BMP and pH determination. Samples were

added to the BMP test flasks, prefilled with the inoculum, within 2–10 min after exposing the silage to air.

Potential methane production per unit VS was calculated using the amount of methane produced in the test flask minus the average amount of methane produced from the inoculum (controls). The difference was then related to the amount of VS added to the flask. In the data analysis, standard deviations given include only a variation among test flask replicates, not including a variation in the controls or the DM and VS content used to calculate the amount of VS added to the BMP test flasks.

Statistical Analyses

Statistical analyses were carried out using the software package R [11]. Significant differences were analysed using ANOVA general linear models and Tukey's post hoc test for $p < 0.05$. Two-way ANOVA models were used to analyse the factors cutting length and harvest date and their interaction for grass ley data. Models for analysis of field experiment data included also block as random factor. Influence of cutting length and harvest date in whole-crop cereals on methane potential was tested in separate models.

Systems Analysis Methodology

Effects of cutting length and harvest system (grass ley) and those of cutting length and harvest date (cereals) on the energy balance and substrate cost for use as biogas substrate were assessed using life cycle assessment methodology following the ISO standard 14044 [12]. For that purpose, data from the field and lab experiments were complemented with literature

data for crop cultivation and processing costs (anaerobic digestion, upgrading, etc.).

Biogas Production System

We have simulated the whole production system for renewable vehicle fuel (methane) in order to estimate energy and economic costs for each operation. The production steps included cultivation and harvest of the biogas crops, transport and storage of the biogas feedstock, feed-in to a large-scale biogas plant with biogas production and upgrading of the raw biogas to pure methane gas according to biogas vehicle fuel standard. Furthermore, the vehicle fuel was stored, distributed on-road and refuelled at filling stations. Energy and economic costs for storage of biogas vehicle fuel were included in the upgrading costs.

For the energy balance, we accounted for direct and indirect energy inputs and weighted that against the potential energy production in the form of biogas vehicle fuel. For the economic balance, we accounted for costs of biogas crop cultivation and harvest, in transport and at the biogas plant, and weighted the costs against the potential revenue from biogas vehicle fuel sales.

Assumptions made for the crop cultivation are listed in [Appendix B1](#). The indirect energy inputs based on material utilisation, manufacturing processes and repairs were calculated based on the model presented by Börjesson [13].

Technical Biomass Yields

Dry matter yield data from the hand-sampled field experiments were further adjusted for yield losses and full fertilisation in order to represent realistic technical harvest potentials ([Appendix B2](#)).

Harvest Capacity and Diesel Consumption

Whole-crop cereals were assumed to be harvested with a direct cut header on the forager, while grass ley was cut and windrowed with a rotary disc mower first. Windrows of grass ley were assumed to be field-dried to a DM content of 35% before they were chopped, assuming the use of a forage harvester with a windrow pick-up header. A combined chopping and transport model was used to calculate diesel and time consumption of whole-crop cereals and grass ley ([Appendix B3](#)).

Other Production Steps

Data used for modelling the diesel and time consumption for other cultivation-related machinery operations and biomass transport are listed in [Appendices B4 and B5](#). Furthermore, the [Appendix](#) lists data regarding the storage of biomass (B6),

the biogas plant and upgrading unit (B7), production means (B8) and energy input assessment (B9).

Methane Potential

The technical-specific methane potentials for ensiled crops were estimated from the results of the BMP tests and their statistical analysis by using the mean for each harvest system and adjusting with the relative differences between harvest dates and between cutting lengths ([Table 2](#)). Furthermore, methane potentials were decreased by 10% in order to reflect a scaled-up production process as well as rounded to the nearest 10.

Net Energy Yield

The net energy yield was calculated based on potential energy yield (PEY) and energy costs for feedstock production (ECF), for biogas production (BPC), for biogas upgrading (BUC) and for digestate storage (DSC) (Eq. 1).

$$NEY \left[\frac{GJ}{ha} \right] = PEY \left[\frac{GJ}{ha} \right] - ECF \left[\frac{GJ}{ha} \right] - BPC \left[\frac{GJ}{ha} \right] - BUC \left[\frac{GJ}{ha} \right] - DSC \left[\frac{GJ}{ha} \right] \quad (1)$$

Substrate Costs

Cost for production and handling of substrate was calculated using a total step model [14]. The model used the same working steps as for the calculation of energy inputs. Costs for fertiliser, machinery, seed material, pesticide use, substrate storage, biogas production and upgrading (removal of CO₂, H₂S and compression to 200 bar) and storage of digestate were calculated using literature data (A10). The impact of land rent costs on the substrate costs was tested using a typical value in the south of Sweden of 400 €/ha [15].

Biogas Production Costs and Ability to Pay

The biogas production costs varied between 6.4 and 12.1 €/GJ for the different crops and treatments, reflecting higher and lower volumetric productivity in the reactor relative to a maize reference crop ([Appendix B11.1](#)).

The ability of a large-scale biogas plant to pay for substrates was calculated as a range from the difference between an assumed market price of biogas vehicle fuel excluding taxes and the costs for biogas production, upgrading, digestate storage, distribution and refuelling of the biogas vehicle fuel (Eq. 2; [Appendix B11.4](#)). In the years 2016–2018, the market price of biogas vehicle fuel at the gas station varied between 1.56 and 1.90 €/kg, excluding taxes [16].

Table 2 Methane potential and content of volatile solids (VS) for grass ley and whole-crop cereals with different numbers of cuts and different harvest dates, respectively, as used in the energy and economic assessment

	Harvest	VS content (% of DM)	Methane potential (Nm ³ /Mg VS; coarse/moderate/fine)
Grass ley			
2-cut system	1st of 2	91.8	290/290/230
	2nd of 2	92.5	270/270/220
3-cut system	1st of 3	90.7	320/320/320
	2nd of 3	91.0	310/310/310
	3rd of 3	90.6	290/290/290
Whole-crop cereals			
Rye	Early	95.0	280/290/300
	Medium	95.0	330/340/350
	Late	95.0	280/290/300
Wheat	Early	95.0	340/290/290
	Medium	95.0	340/290/290
	Late	95.0	340/290/290

$$\text{Ability to pay}_{\text{substrate}} \left[\frac{\text{€}}{\text{MWh}} \right] = \text{Market price}_{\text{excl.taxes}} - \text{Costs}_{\text{biogas production}} - \text{Costs}_{\text{upgrading}} - \text{Costs}_{\text{digestate storage}} - \text{Costs}_{\text{distribution}} - \text{Costs}_{\text{refuelling}} \quad (2)$$

Results and Discussion

Biomass Yields

Grass Ley

The field experiment with grass ley showed significant differences ($p = 0.001$) in biomass yield between harvest systems with two and three cuts per year, respectively. The highest biomass yield with, on average, 16.6 Mg/ha DM was achieved in the two-cut system, which was 9% higher than the yield in the three-cut system (15.2 Mg/ha DM). These levels were well above the average yields in the region (approx. 7.0 Mg/ha DM); however, statistical yield data includes both extensive and organically cultivated grass ley with generally lower yields [17]. Amon et al. [8] found a similar relationship between two- and three-cut systems for alpine grasslands, but at generally lower yields.

Whole-Crop Rye

The biomass yield of rye increased significantly ($p = 0.005$) from 8.5 Mg/ha DM on 8 July to 10.0 Mg/ha DM 1 week later (15 July). No significant change in biomass yield (9.7 Mg/ha DM) was observed another week later (22 July). These yields were in line with regional yield statistics, when recalculated with a straw/grain ratio of 0.78 [18] and a 10% decrease adjusting for harvest losses [19], resulting in 9.8 Mg/ha DM of whole-crop rye biomass. However, since straw-shortening treatments were applied

by mistake, total biomass yields without these treatments would probably have been higher compared with regional statistical yield levels.

Whole-Crop Wheat

The biomass yield of wheat did not vary significantly between 17 July (*early dough*) and 29 July (*mature*) and was, on average, 13.5 Mg/ha DM. These yields were considerably higher in comparison with regional yield statistics, when recalculated with a straw/grain ratio of 0.60 [18] and a 10% decrease adjusting for harvest losses [19], resulting in 9.5 Mg/ha DM of whole-crop biomass. Similarly, Nadeau [20] found whole-crop silage yields between 8.4 and 10.8 Mg/ha DM for spring wheat and between 9.6 and 9.8 Mg/ha DM for triticale, both harvested in Southern Sweden at early dough stage.

Methane Potential

Grass Ley: Influence of the Number of Cuts

Comparing the average methane potential of the two-cut and three-cut systems, grass ley harvested in the three-cut system had an average specific methane potential of 340 ± 4 Nm³/Mg VS, which was 18% higher ($p = 0.000$) than the average for the two-cut system (290 ± 7 Nm³/Mg VS). In both the two- and three-cut systems, methane potential decreased significantly ($p = 0.003$ and $p = 0.000$, respectively) per Mg VS from one harvest to the next. The methane potential of the first cut

in the three-cut system was 21% higher than the first cut in the two-cut system ($p = 0.000$). The decrease of the specific methane potential from the first to the second cut in the two-cut system, from the first to the second cut in the three-cut system and from the second to the third cut in the three-cut system was 6%, 5% and 6%, respectively.

Assuming the 15 April as starting date for plant growth, the number of growing days was calculated for each harvest occasion. Figure 1 shows how the specific methane potential of grass ley decreases with an increasing number of growing days. This is in line with Wilson and Hatfield [7], who suggested that a decreasing digestibility of grasses (in rumen) with increasing maturation can be explained by morphological changes (e.g. the presence of different cell types) rather than by changes in chemical composition.

The specific methane potential in the two-cut system was on the same level as earlier studies reported for grass ley, where the first and second cuts resulted in methane potentials of 290–300 $\text{Nm}^3/\text{Mg VS}$ and 245–270 $\text{Nm}^3/\text{Mg VS}$, respectively [19, 21]. Grass ley on permanent grasslands resulted in methane potentials of 320–360 $\text{Nm}^3/\text{Mg VS}$, 190–270 $\text{Nm}^3/\text{Mg VS}$ and 190–240 $\text{Nm}^3/\text{Mg VS}$ for cuts 1, 2 and 3, respectively [9]. Grass ley cut four times per year had a specific methane potential of 340 $\text{Nm}^3/\text{Mg VS}$ on average, which did further increase the overall methane potential [9]. However, the fourth cut contributed with only less than 3% of the total methane yield per hectare, which implies that the changed harvest dates of the first three cuts and the resulting increase in specific methane potential are more important for the methane yield than what the fourth cut contributed. Similarly, Dickeduisberg et al. [22] showed a decrease of total methane yield for tall wheatgrass harvested in a four-cut system compared to a two-cut system. It should be borne in mind that the ley used in the current study contained mainly grasses and little clover at harvest. Since grasses and legumes differ in composition and morphology and mature differently [7], the results might differ for a ley with a higher share of legume.

Grass Ley: Influence of Cutting Length

In the two-cut system, the specific methane potential of grass ley chopped at 8 mm and 12 mm cutting lengths was $310 \pm 4 \text{ Nm}^3/\text{Mg VS}$, which was 24% higher ($p = 0.021$) than grass ley chopped at 4 mm cutting length ($250 \pm 10 \text{ Nm}^3/\text{Mg VS}$). Error intervals are given as standard error. In the three-cut system, cutting length had no significant impact on methane potential ($340 \pm 4 \text{ Nm}^3/\text{Mg VS}$).

A higher methane potential at longer cutting lengths was presented earlier by a Finnish study that reported methane potentials of 320 $\text{Nm}^3/\text{Mg VS}$ and 350 $\text{Nm}^3/\text{Mg VS}$ at cutting lengths of 5 mm and 10 mm, respectively [23]. An additional increase of cutting length in the same study to 20 mm, however, did decrease methane potential to 270 $\text{Nm}^3/\text{Mg VS}$, with no explanation offered on potential causes.

Comparing the two-cut and the three-cut systems, only in the two-cut system cutting length had an impact on methane potential. A possible explanation is that cutting the more mature grass in the two-cut system more finely exposed the cell content so that easily degradable compounds (soluble sugars and other metabolites) were respired aerobically between chopping and the time when oxygen becomes depleted in the ensiling process and therefore were lost in the harvesting process. However, two findings partly contradict this explanation: (a) more mature grass plants exhibit lower contents of soluble carbohydrates [1] which would lead to the conclusion that respiration of storage molecules such as starch would account for the larger part of the effect, and (b) although mechanical treatment of e.g. wheat leaves leads to a strong increase in respiration [24], this would likely apply to all finely chopped grass, not just in the two-cut system. Still, while the latter effect is the one recognised in living cells, a fine cut likely opens a higher number of cells and leads to enzymatic degradation even of otherwise inaccessible metabolites such as starch, which is more abundant in more mature plants [1]. Since secondary walls mainly contain polymers that are degradable under anaerobic conditions, Wilson and Hatfield [7]

Fig. 1 Effect of the number of growing days of grass ley on specific methane potential for the two-cut system and the three-cut system

hypothesised that the degradation likely occurs mostly from the inside of cells, where increased chopping could open up structures and facilitate increased degradation of degradable components.

This indicates that the specific methane potential as determined in the BMP test could be lower after fine chopping if the losses from aerobic degradation are larger than the gains from increased anaerobic digestibility and vice versa. However, these explanations are hypothetical and need to be tested in future studies.

The current study focused on the influence of chopping on the methane yield after 30 days of BMP test. A longer digestion time than 30 days is generally applied for crop digestion, mainly due to limitations of the dry matter content in reactors and the high dry matter content of crops [25]. Chopping might influence the rate of degradation and methane production during initial days of fermentation. An analysis of the influence of initial degradation rate on reactor performance and economy was considered irrelevant for commercial reactor settings fermenting crop biomass with a much longer retention time.

Whole-Crop Rye: Influence of Cutting Length

Rye which was harvested on 15 July and chopped at 3.5 mm cutting length had a specific methane potential of $360 \pm 9 \text{ Nm}^3/\text{Mg VS}$, which was 12% higher ($p = 0.011$) than that chopped at 12.5 mm cutting length ($320 \pm 7 \text{ Nm}^3/\text{Mg VS}$).

An increase of the specific methane potential for rye at shorter cutting lengths is confirmed by a German study that reported methane potentials of $320 \text{ Nm}^3/\text{Mg VS}$ and $360 \text{ Nm}^3/\text{Mg VS}$ at cutting lengths of 16 mm and 4 mm, respectively [26], using a self-propelled forage harvester. The same study reported a significantly higher methane potential at a cutting length of 6.8 mm ($336 \text{ Nm}^3/\text{Mg VS}$) compared to a cutting length of 11 mm ($308 \text{ Nm}^3/\text{Mg VS}$). These differences were reported for a rye variety harvested at the beginning of flowering while, for two other varieties and other growth stages, no significant differences in methane potential between cutting lengths were reported. However, the reported growth stages at harvest were approx. 4–5 weeks earlier than those in the present study.

A reason for increased methane potential at shorter cutting length of rye could be due to increased accessibility to degradable components, as suggested in the explanation for higher methane yield at three cuts than at two cuts for ley in the section “[Grass Ley: Influence of the Number of Cuts](#)”.

Whole-Crop Rye: Influence of Harvest Date

In the present study, the methane potential of whole-crop rye was significantly higher ($p = 0.005$) at harvest on 15 July, $380 \pm 12 \text{ Nm}^3/\text{Mg VS}$ (early *dough* stage), at a DM content of 46%, compared to harvest on 8 and 22 July (late

milk and late *dough* stage, respectively), when it was $330 \pm 8 \text{ Nm}^3/\text{Mg VS}$. An earlier study reported the methane potential of rye increasing between milk growth stages ($243 \text{ Nm}^3/\text{Mg VS}$) until full maturity ($275 \text{ Nm}^3/\text{Mg VS}$) [9]. However, Heiermann et al. [27] reported an optimum of methane potential at the milk growth stage for rye chopped at 10–15 mm nominal length.

Whole-Crop Wheat: Influence of Cutting Length

Whole-crop wheat chopped at a nominal cutting length of 12.5 mm had a specific methane potential of $370 \pm 8 \text{ Nm}^3/\text{Mg VS}$, which was 16% higher ($p = 0.001$) than that of wheat chopped at 3.5 mm and 5.5 mm cutting lengths ($320 \pm 5 \text{ Nm}^3/\text{Mg VS}$). It is unknown what caused the lower methane potential of wheat at *moderate* and *fine* cutting length. However, the high methane potential for *coarsely* chopped wheat was confirmed in this study by the results of the methane potential analyses of wheat harvested earlier and later, which had a high methane potential of $350 \pm 9 \text{ Nm}^3/\text{Mg VS}$ on average.

A study by Herrmann et al. [26] reported a methane potential of triticale (a hybrid of wheat and rye) which increased significantly from 300 to $330 \text{ Nm}^3/\text{Mg VS}$ when the cutting length of manually cut biomass decreased from 16 to 4 mm. The same study reported also a significant increase in methane potential of triticale (variety *Grenado*; dough stage) from 335 to $351 \text{ Nm}^3/\text{Mg VS}$ when the cutting length was reduced from 8 till 4 mm and using a self-propelled forage harvester for chopping [26]. For the variety *Talentro* (milk stage), no significant difference was found. Similarly, Kaparaju et al. [23] found no effect of cutting length (5–20 mm) on the specific methane potential of whole-crop oat at full maturity.

Whole-Crop Wheat: Influence of Harvest Date

The methane potential of wheat harvested as whole crop was $350 \pm 9 \text{ Nm}^3/\text{Mg VS}$ on average with no significant differences between harvest dates. Similarly, an earlier study reported no significant difference in the methane potential between harvest dates corresponding to milk growth stages, dough and full maturity, and the methane potential was much lower (228 – $251 \text{ Nm}^3/\text{Mg VS}$) for two different varieties [9]. Rincón et al. [28] reported methane potentials for whole-crop wheat at milk stage ($360 \text{ Nm}^3/\text{Mg VS}$) and dough stage ($346 \text{ Nm}^3/\text{Mg VS}$), which were not significantly different and similar to the results presented here. The study used a single (and unspecified) variety, milled to 5–15 mm length. Also, Pouech et al. [29] found no decrease of the specific methane potential of wheat at maturity.

Energy Analysis

Energy Inputs in Biomass Production

With 12.5–12.9 GJ/ha, crop cultivation represents the highest fraction of the energy inputs (69–82%) in biomass production (Fig. 2a). Harvest and transport account for 1.2–3.3 GJ/ha (8–18%) and 1.1–1.9 GJ/ha (7–10%), respectively. The fraction of storage is only 0.4–0.5 GJ/ha (2–3%) of the total energy input.

Energy input in grass ley production in the two-cut system (17.4–18.0 GJ/ha) was approx. 10% higher compared with that (16.2 GJ/ha) reported in an earlier study [19], which was based on 25–28% lower biomass yields per hectare. The same study reported an energy input of 12.5 GJ/ha for triticale harvested as whole crop, which is 19–25% lower than the that of 15.4–16.6 GJ/ha for whole-crop rye and wheat presented here. Biomass yields per hectare for triticale in that study were 25–35% lower compared to the yields of whole-crop rye and wheat in the present study, while the specific methane potential was 8–35% higher in the same comparison.

An explanation to the almost equally high energy inputs in cultivation for grass ley and whole-crop cereals in the present study is that the indirect energy inputs for fertilisation are higher for grass ley than for cereals, while the direct energy inputs for field work are higher for the cereals.

Energy Balance

The net energy yield varied within the range of 66–130 GJ/ha (Fig. 2b). Rye harvested at *medium* harvest date as well as

coarsely chopped wheat (at all harvest dates) had a substantially higher net energy yield per hectare compared to grass ley, whole-crop rye at other harvest dates and whole-crop wheat at other cutting lengths.

The additional direct energy in the form of diesel and indirect energy in the form of machinery hours needed in feedstock production when choosing a shorter cutting length was at maximum corresponding to 0.7% of the energy yield in the form of biogas vehicle fuel. In comparison, the effects of decreasing cutting length on the BMP affected the net energy yield much stronger, i.e. in the range of –30 to +10%.

Energy Yield Sensitivity

Rye, *finely* chopped at medium harvest date, resulted in the highest net energy yield (130 GJ/ha) (Fig. 3a). For the other crops to result in equally high energy yields, wheat, coarsely chopped, at early harvest date, would have to yield 13.1 Mg/ha DM, grass ley in the three-cut system 15.7 Mg/ha DM and grass ley in the two-cut system 17.5 Mg/ha DM. This would mean an increase in biomass yield by 8%, 29% and 38% for wheat in the three-cut system, grass ley in the three-cut system and grass ley in the two-cut system, respectively. The grass ley in the three-cut system produced a 10% higher energy yield per hectare than that in the two-cut system, despite a 4% lower biomass yield. For whole-crop cereals, the biomass yield was a determining factor because of the very similar specific methane potentials for rye and wheat.

Fig. 2 Energy inputs (a) and energy yield (b) for production of biogas substrate for different crops, harvest dates and cutting lengths divided into production steps (left: *coarse*; middle: *moderate*; right: *fine*). The energy potential was based on machinery harvests (losses subtracted) and technical methane potential (90% of methane potential results of the field study)

Fig. 3 Sensitivity analysis for net energy yield (a) and production costs (b) in relation to biomass yield with a variation of $\pm 40\%$ for the best harvest alternatives

Economic Analysis

Substrate Costs

Substrate costs per GJ methane vehicle gas produced was lowest for rye, harvested at medium harvest date, and for wheat, coarsely chopped at all three harvest dates, 9.1–9.5 €/GJ (Fig. 4), including 400 €/ha land rent cost. Grass ley in the three-cut system as well as coarsely and moderately

chopped grass ley in the two-cut system had costs of between 10.2 and 10.6 €/GJ.

An earlier study reported substrate costs for grass ley yielding 7.7 Mg/ha DM in a two-cut system to be 730 €/ha, excluding land rent cost [30]. A more recent study calculated substrate costs for grass ley cut three times per year to be between 815 and 955 €/ha, excluding land rent cost [31]. Costs for grass ley as biogas substrate at a biomass yield of 7.5 Mg/ha DM were calculated earlier to be much higher, approx. 1300 €/ha, excluding land rent cost, based on a two-cut system, but with a much more expensive transport solution as silage bales [32].

Substrate costs excluding land rent cost were estimated earlier to be much higher, i.e. 17.1 €/GJ and 18.0 €/GJ for grass ley and whole-crop triticale, respectively, which was based on lower biomass yields of 9.1 Mg/ha DM and 7.9 Mg/ha DM, respectively, compared to the yields presented here [19, 33].

Production Costs

The total vehicle fuel (methane gas) production costs, excluding land rent cost, varied between 23.4 and 31.0 €/GJ (Fig. 5). Rye harvested at medium harvest date and coarsely chopped wheat had the lowest overall costs, 23.4–24.1 €/GJ.

For raw biogas based on grass ley with a biomass yield of 9 Mg/ha DM and 7.7 Mg/ha DM in the three-cut and two-cut systems, respectively, lower costs of between 13.0 and 13.6 €/GJ were presented in studies investigating much smaller-sized biogas plants [30, 34]. An earlier study presented total costs for vehicle fuel from grass ley with a biomass yield of 10 Mg/ha DM in a two-cut system to be 18%, 20%, 33% and 32% higher compared to that based on maize, sugar beet, whole-crop triticale and wheat grain, respectively [25]. The same study presented costs for biogas vehicle fuel from whole-crop triticale of 26 €/GJ at a biomass DM yield of 7.5 Mg/ha DM, while in the present study, costs for whole-

Fig. 4 Substrate costs (€/GJ) for different crops, harvest dates and cutting lengths divided into production steps (left: coarse; middle: moderate; right: fine)

Fig. 5 Production costs (€/GJ) for upgraded vehicle fuel for different crops, harvest dates and cutting lengths divided into production steps (left: *coarse*; middle: *moderate*; right: *fine*). On the right side, literature data adjusted from Lantz et al. [25] is given for comparison

crop cereals at equal biomass yield would be 24.5–28.4 €/GJ. Although presenting similar total costs, the other study demonstrated considerably higher feedstock cost but lower process costs compared to the present study.

The additional costs for diesel and increased machinery use needed in feedstock production when choosing a shorter cutting length were at maximum corresponding to 2.7% of the value of the produced biogas vehicle fuel. In comparison, the effects of decreasing cutting length on the BMP affected the revenue much stronger, i.e. in the range of –39% to +11%.

Production Cost Sensitivity

Changes in biomass yield per hectare affected substrate costs, measured per unit vehicle fuel produced, relatively little at biomass yields in excess of 10 Mg/ha DM (Fig. 3b).

A decrease in biomass yield with 40% led to higher substrate costs (15% for grass ley in a two-cut system, 18% for grass ley in a three-cut system, 16% for rye chopped finely at medium harvest date and 16% for coarsely chopped wheat). An increase of biomass yield by 40% resulted in substrate cost reductions of 6%, 7%, 7% and 7%, respectively, for the crops mentioned above.

Ability to Pay

The ability of a potential biogas plant to pay the substrate costs excluding the land rent costs was good for all crops independent of cutting length and harvest dates (cereals)/number of cuts per year (grass ley) investigated in this study, except finely chopped grass in the two-cut system (Fig. 6). When the assumed land rent cost of 400 €/ha was included, only few combinations of cutting length and harvest dates/number of cuts per year were found to be well within the economic viable range, e.g. grass in the three-cut system, rye harvested at medium harvest date and coarsely chopped wheat.

Suitability as Biogas Substrate

This study has shown that grass ley and whole-crop cereals can give high net energy yields per hectare. The recoverable biomass DM yields for whole-crop cereals were assumed to be around 12 Mg/ha DM; however, 25–50% higher biomass yields have been demonstrated for wheat, rye and triticale under similar conditions [35, 36]. This indicates that whole-crop cereals have a large potential as biogas crops for vehicle fuel production.

In regard to the ongoing discussion about utilisation of *food crops* as transportation fuel feedstock, this potential of wheat and rye will likely not be exploited to a large extent. According to the latest reading of rules proposed by the European Commission for the production of renewable vehicle fuel, tax exemptions or reductions will only be available for the approved, so-called advanced crops that are characterised as non-food crops with a high content of lignocellulose [37]. Currently, biogas vehicle fuel production is often dependent on tax reductions or other subsidies for economic viability in Sweden and other European countries.

Even the grass ley has resulted in high net energy yields, if somewhat lower than from whole-crop cereals. The biomass yields assumed in this study were on a relatively high level already compared with what has been reported earlier. The potential to further increase biomass yields per hectare is therefore rather limited compared to whole-crop cereals. Also, other studies have shown that second-year biomass yields of grass ley can be up to 30% lower compared to first-year yields [38]. Such biomass yield decrease of grass ley would result in a decrease of net energy yield and an increase of substrate costs in a three-cut system by 32% and 6%, respectively.

However, other aspects of grass ley such as the function as break crop in the crop rotation or its contribution in increasing soil organic carbon pools are important arguments for the overall sustainability of crop production systems [39]. An

Fig. 6 Substrate costs (€/GJ) including and excluding land rent cost in relation to the ability to pay of potential biogas plants (grey bars) for different crops, harvest dates and cutting lengths (left: *coarse*; middle: *moderate*; right: *fine*)

increase in soil carbon content during growth of the biogas crop contributes to sequestration of carbon as well as potentially improving soil fertility. Belonging to the group of potentially approved feedstock crops in the European Union, grass crop-based vehicle fuels may receive tax reductions and may furthermore be counted double in national statistics for renewable energy production [37].

In the economic comparison with whole-crop cereals, grass ley was somewhat more expensive per energy unit of produced vehicle fuel in this study. This difference is not likely to increase drastically even if second-year biomass yields may drop by 30% per hectare, as discussed above. With this and the fact that the EU Renewable Energy Directive continues to disfavour food crops such as rye and wheat as feedstock in the production of transportation fuels [40], grass leys remain to be a highly interesting feedstock for transportation fuel production, nonetheless for farmers with need to improve the fertility of their soils.

The investigated biogas crops had lower production costs than the ability to pay of a potential large-scale biogas plant. Under optimal harvest conditions (harvest date and cutting length), even costs for potential land rent under Swedish conditions can be covered. A lower specific methane potential burdens the ability to pay twofold, since this increases both substrate production costs and costs for processing calculated per unit energy produced. A lower specific methane potential also means a lower degree of degradation in the biogas reactor, which, for biogas crops with a DM content of approx. 35%, may require a higher amount of water added and higher heating costs for this additional water in the biogas plant.

Harvest Conditions

Cutting length at harvest affected the methane potential significantly for all investigated crops. While coarse chopping was the optimal condition for a high methane potential for

grass ley and wheat, fine chopping resulted in a higher methane potential for rye.

It is unclear what causes these differences, but earlier studies confirm this finding [26]. Rye was harvested somewhat later than usual, resulting in rather high DM content values already at *early* harvest. A possible explanation of these opposite effects of cutting length could be that the specific methane potential of a more mature cereal crop is affected positively, while it affected negatively for a less mature crop, e.g. because of easily degradable substances that are more abundant before maturity, which get lost during the harvesting and ensiling processes. The specific methane potential of a more mature crop may potentially be improved; e.g. by chopping the grains, the likelihood of which is increased at shorter cutting lengths. Crop maturity may therefore be an important factor for the methane potential of a crop. This is a hypothesis that is supported by other studies as discussed above. Resolution of harvesting intervals and cutting lengths has been limited in this study due to economic constraints mainly in the methane potential assessment. Another limitation of this study was that the harvest dates were not synchronised for rye and wheat according to crop maturity. The hypothesis of maturity-affected methane potential should therefore be investigated in future studies in order to optimise methane yield of biogas crops chopped with a forage harvester.

Cutting length settings affected the specific methane potential, diesel consumption and harvest capacity, which caused differences in substrate costs. The effect of increased diesel consumption for finer chopping of rye was, however, outweighed by the effect of increased specific methane potential, with regard to both net energy yield and economic result.

For grass ley, a three-cut system resulted in higher methane potentials and lower substrate costs per energy unit of methane gas compared to a two-cut system, even though biomass yield per hectare was slightly lower in the three-

cut system. A fourth cut per year is, however, not regarded as relevant for grass crop cultivation in Northern Europe, since there are no indications that methane energy potential per hectare would increase further [8], even if four and sometimes five cuts per year are used in the south of Sweden in grass ley in milk production.

Conclusions

In this study, we have shown that it is economically viable to produce methane gas, as a vehicle fuel, from grass ley and whole-crop rye and wheat grown in the south of Sweden, when they are ensiled as biogas feedstock and processed to methane gas in a large-scale biogas plant.

Whole-crop rye and wheat as well as grass leys in a three-cut system provide high net energy yields per hectare when used as ensiled feedstock for biogas vehicle fuel production in Southern Sweden.

For grass leys, three instead of two cuts per year increased the specific methane potential and energy yield per hectare most, while cutting length had a minor impact. A short cutting length affected the specific methane potential of grass leys negatively for more mature crops, i.e. at two cuts per year, which strongly impacted economic viability as feedstock for biogas vehicle fuel production.

For whole-crop rye at early dough stage, 3.5 mm cutting length led to a higher specific methane potential compared with a cutting length of 12.5 mm and compared with harvest 1 week sooner or later, leaving a very short window for optimal harvest.

For whole-crop wheat, harvest date corresponding to between early dough stage and maturity had no impact on specific methane content, indicating a long harvest. A cutting length of 12.5 mm at the *late dough* stage led to the highest specific methane potential for whole-crop wheat, indicating a possibility to save diesel fuel, time and cost in feedstock harvest.

For all feedstocks, the additional energy and economic cost when choosing a shorter cutting length were negligible in comparison to the effect of a shorter cutting length on the specific methane potential. Specific methane potential was affected differently for the investigated crops and at different harvest dates, indicating that crop maturity, as influenced by harvest date of whole-crop cereals and number of cuts, two or three per year, in grass crops strongly impacted the economic viability of biogas vehicle fuel production.

Mechanisms explaining the contrasting results of the effect of cutting length and harvest date on specific methane potential in this study need to be explored further, e.g. by studying the impact of DM content and crop maturity on methane potential.

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Authors' Contribution Thomas Prade designed the study, carried out the biomass sampling, performed the energy and economic assessments and wrote the first version of the manuscript. Sven-Erik Svensson designed the machinery studies and, together with Torsten Hörndahl, carried out the machinery studies. Emma Kreuger designed and carried out the methane potential assays. All authors contributed to the reading, commenting and writing of the manuscript.

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