Biogas and combustion potential of fresh reed canary grass grown on cutover peatland

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SUMMARY

(1) In Finland, in recent years, the combustion of *dry* reed canary grass (RCG, *Phalaris arundinacea*) grown intensively on cutover peatlands, has decreased markedly. We therefore made experiments in two areas to assess the alternative of using *freshly* harvested RCG grown for biogas production on cutover peatland. We measured both biogas production and combustion energy release.

(2) The experiments show that the RCG biomass yields in total solids (TS) in both areas, with two cuts a year, were surprisingly small (yields of 2.7 and 4.2 Mg ha^{-1} [1 Mg ha^{-1} = 100 g m^{-2}]); having biogas and combustion potentials, on the two areas, of 277–348 dm^3 kg^{-1} VS (volatile solids) and 14.8–16.3 MJ kg^{-1} TS, and 11.8–21.9 MWh ha^{-1} in combustion.

(3) Fresh RCG may produce larger biomass yields if cut several times a year, together with lower lignin proportion, and better suitability for biogas production compared with spring harvested dry RCG.

(4) For cutover peatlands there are several after-use possibilities, however, with different benefits and challenges. For example, peat soil emissions may be affected during the after-use period, and this should be considered when planning the use of cutover peatlands.

KEY WORDS: bioenergy, biomass, energy crop, marginal land, *Phalaris arundinacea*

ABBREVIATIONS:

BMP	Biological Methane Potential	**TS**	Total Solids
CHN	Carbon, Hydrogen, and Nitrogen analysis	**VFA**	Volatile Fatty Acids
HHV	Higher Heating Value	**VS**	Volatile Solids
RCG	Reed canary grass	**FW**	Fresh weight
TKN	Total Kjeldahl Nitrogen		

Editor's note. *Mires and Peat* usually requires that only SI approved symbols and pre-multipliers appear in 'units' expressions, all other qualifiers to be included in the name of the variable and symbol (if used). In this article non-standard expressions appear because they are the currency in the field of the article, and effectiveness in communicating with the target community over-rides standard rules.

INTRODUCTION

Currently, bioenergy is promoted globally as it is renewable. Most bioenergy is produced from e.g. wood or agricultural residues (Landolina & Maltsoglou 2017). The sustainability of bioenergy is under debate however owing to, for example, competition with food production (Popp *et al.* 2014, Tomei & Helliwell 2016). The use of marginal land such as cutover former peatlands, with a thin layer of peat over mineral soil, and of no routine agricultural value (Picken 2006, Salo & Savolainen 2008)) is therefore attractive (e.g. Parviainen 2007, Pahkala *et al.* 2008, Hytönen *et al.* 2018). Such cutover former peatlands are common in Finland.

Reed canary grass (RCG, *Phalaris arundinacea*) is a commonly studied perennial energy crop. In Finland, for example, thousands of hectares of cutover peatlands have been brought under RCG cultivation since the 1990s (Pahkala *et al.* 2008). It became clear, however, that dry RCG is far from being a good feedstock for combustion in a power station: its dry bulk density is low, it produces a lot of slag, and it needs to be co-fired with a primary fuel and in a critical ratio (M. Kautto, VAPO Production Engineer, personal communication 12 May 2014). Consequently, large investments for new equipment were necessary. In Finland, the RCG cultivated area decreased rapidly to as little as 6000 ha by the end of 2015 (Farm business register 2015). There were thus large areas of unused cutover peatlands and different after-use methods were sought. One of these was RCG as feedstock for biogas production (Lehtomäki 2006, Laasasenaho *et al.* 2016).

RCG is a potential energy crop on cutover peatlands because the plant has adapted to peat soils and wet conditions (Parviainen 2007, Reinikainen *et al.* 2008, Kukk *et al.* 2011, Järveoja *et al.* 2013). Its low yield on cutover peatland is a drawback, however. In these conditions it yields total solids (organic plus inorganic TS) of about 1–6 Mg ha^{-1} yr^{-1}, compared with 8–12 Mg ha^{-1} yr^{-1} (Heinsoo *et al.* 2011)) for RCG cultivated on mineral soil. This difference contributed to the economic failure of RCG on cutover peatland.

RCG has potential environmental benefits such as nutrient removal (Picard *et al.* 2005) and working as a carbon sink (Järveoja *et al.* 2013). A recommendation is that a 10–20 cm thick layer of peat is left on the surface soil to improve soil fertility, if cutover peatlands are used for growing RGC or for forestry (Pahkala *et al*. 2005, Salo & Savolainen 2008). However, greenhouse gas (GHG) emissions from peatland soil can be significant, if there is a thick layer of peat and low water table on peatland and the peat is starting to mineralise. In that case, peatlands can be net GHG sources instead of carbon sinks (e.g. Kandel *et al*. 2013a, Karki *et al.* 2014). However, cutover peatlands are not ideal for traditional agriculture due to the occurrence of frost damage, repeated temporary flooding, and low soil pH. From the environmental point of view, RCG growing may be a good thing, even if not economic for fuel. In this situation, we consider that RCG as a feedstock for biogas production might be a sustainable solution for cutover peatlands.

The main difference in cultivation of RCG as feedstock for biogas production (rather than combustion) is the harvesting time. For combustion, RCG is generally harvested as naturally dried grass in the spring, whereas for biogas production RCG is harvested twice during the growing season and used in the undried (fresh) state. For example, yields per total solids (TS) in a year in two differently fertilised experiments were 11 ± 0.8 and 16 ± 1 Mg ha^{-1} [1100 and 1600 g m^{-2}]. The first experiment was fertilised (N, P, K) before growth began; the second was fertilised before growth and a second time after the first harvest (Kandel *et al.* 2013b).

In a Finnish study, in boreal conditions, the highest methane yield per hectare (approximately 20 MWh a^{-1}) was achieved when RCG was harvested twice per year (Seppälä *et al*. 2009). The calorific value of the energy crop varies with the stage of the crop. For RCG harvested in spring or late autumn, a higher heating value (HHV) of 16.6−19.3 MJ kg^{-1} TS (Burvall 1997) with an average value of 17−18 MJ kg^{-1} TS has been reported (Strašil 2012, Fournel 2015, Alakangas *et al*. 2016) while HHV as low as 15.2−16.1 MJ kg^{-1} TS has been reported for freshly harvested RCG grown on a Polish landfill (Kołodziej *et al*. 2016). Furthermore, the stage and the cultivation conditions of the crop also affect the methane yields of the energy crop: methane yields of 253–430 dm^3 kg^{-1} VS (volatile solids) have been reported for RCG in different studies (Lehtomäki *et al*. 2008, Seppälä *et al*. 2009, Kandel 2013, Kandel *et al*. 2013b, Nekrošius *et al*. 2014, Butkute *et al*. 2014).

The objective of our study was to evaluate the use of cutover peatlands for fresh RCG production for biogas production and combustion. The purpose was to calculate bioenergy potential and offer knowledge to policymakers and energy business stakeholders to develop bioenergy-based commercial activity on cutover peatlands. The biomass yield and biogas and combustion energy potential of RCG grown on cutover peatland was assessed experimentally, for two sites and for two harvests, to screen the potential of present cutover peatlands. Two study areas were used because every peatland has unique geography (Picken 2006) and environment, and both areas were considered to represent typical cutover peatlands with no optimised fertilisation for biomass cultivation.

METHODS

Reed canary grass experiments: cultivation and sampling

Two cutover peatlands with different local environments in Ilomantsi and Alajärvi, Finland, were chosen for this study (Table 1). Both areas have been drained and the water table is managed by ditches. At each area, four sampling points with adequate RCG growth were visually selected (without deliberate bias by other characteristics) by using a square collection frame (of side 50 cm, total area 0.25 m^2, one sample at each). The RCG was approximately 50 cm tall and the distance between the four sampling points was 10–40 m (cultivation size of 10–50 ha). Samples for yield measurements and laboratory analyses were collected from the same points for both first and second harvest, by cutting the plants at a height of 3 cm above ground level.

The harvested samples were packed in cooled rubber bags and plastic buckets (30 dm^3) and transported to the laboratory within 24 hours. Upon arrival at the laboratory, the samples were stored at 4 °C and flushed with nitrogen gas (99 % pure) until further use. For the biochemical methane potential (BMP) assays, fresh RCG samples were cut with scissors and then milled in the laboratory to 2 cm particle size (Kenwood electronic blender). The rest of the samples were dried and stored at room temperature until used for other analyses.

Laboratory analyses

We measured TS, VS, ash, Klason lignin, Total Kjeldahl nitrogen (TKN), the composition of hydrocarbons and volatile fatty acids (VFAs), calorific value, and methane proportion of biogas produced in BMP assays. We had separate replicates (n = 3) from the field samples in each analysis. Methods and equipment are detailed in Table 2. Short descriptions follow.

The BMP of RCG from both areas and from both harvests were determined in batch assays in triplicate glass bottles with 1 dm^3 liquid volume. The inoculum originated from a farm-scale mesophilic biogas plant (Metener Oy biogas plant Laukaa, Finland) treating cattle manure, fodder and industrial sewage. Substrate and inocula were added to reach inoculum: substrate VS ratio of 1:1 for the first RCG harvest and 2:1 for the second harvest (Table 3). In addition, 2.25 g of $NaHCO_3$ was added to each bottle as a pH buffer. Final volume (0.75 dm^3) was reached by adding tap water (normal electrical conductivity 110–212 µS cm^{-1} in Jyväskylä, Finland (Alva 2018)). Additional assays in which substrate was replaced with water were prepared to extract the methane potential of the inoculum from those of the substrates. The bottle headspaces were flushed with N_2 (99 % purity) for 3 minutes. The bottles were then sealed with rubber stoppers and held statically at 35 ± 1 °C. The biogas evolved was collected in aluminum bags and measured by water displacement in a column.

Experimental HHV of RCG was determined with a bomb calorimeter (University of Jyväskylä 2014). In addition to iron wire, paraffin and cotton string were used to prevent the loss of dusty and dry RCG samples in the bomb calorimeter. These were weighed before combustion. The heating value of 45.1 kJ g^{-1} for paraffin, 5.9 kJ g^{-1} for iron wire, and 17.5 kJ g^{-1} for the cotton string were used in corrections to the final values using Equation 1:

Table 1. Relevant characteristics of the two sampled sites.

	Ilomantsi	Alajärvi
Location	N 62° 54.36', E 31° 18.22'	N 62° 59.41', E 24° 18.05'
Nearest weather station	Mekrijärvi (N 62.77°, E 30.98°)	Möksy (N 63.09°, E 24.26°)
Weather station mean temperature (°C): 2014, and 30-yr mean (1981–2010; Finnish Meteorological Institute 2016)	4.1, 2.1	4.5, 3.0
Weather station precipitation (mm): 2014, and 30-yr mean (1981–2010; Finnish Meteorological Institute 2016)	560, 685	565, 616
RCG var. Palaton planted	2002	2004
Harvest schedule 2011–2013 before experiment began	As dry grass in Spring	
Fertiliser (single application in 2011 before experiment began)	N, P, and K (at respective rates of 60, 50, and 30 kg ha^{-1})	
First harvest in our experiment	18 June 2014	16 June 2014
Second harvest in our experiment	7 August 2014	5 August 2014

$$HHV = (C\,\Delta T - Q_h) / m_S \qquad [1]$$

where, C is the heat capacity of the calorimeter (8773.4) J K^{-1}, ΔT is the temperature difference (K) reading on the thermometer, m_S is the mass of the dry sample (g) and Q_h is the energy released from the combustion of the paraffin layer, the iron wire, and the cotton string (J).

Table 2. List of analyses, methods and equipment used in the laboratory studies.

Analysis	Method and equipment
Heating value	A bomb calorimeter (IKA-Kalorimeter C400 Adiabatisch) equipped with a thermostat (Julabo F20 HC, 17.2 °C) and a thermometer (IKA-TRON DKT400) was used. Air dried RCG was milled to 2 mm size particles. The sample was then further dried at 100 °C for less than 30 minutes on a hot plate. When pressurising the bomb, the dried sample was covered with paraffin to prevent loss of fuel. Cotton string was attached to the iron wire to ensure ignition of the paraffin (applied method, University of Jyväskylä 2014).
Methane content	A gas chromatograph fitted with flame ionisation detector (STP, T = 293 K, pressure = 1 bar, Perkin-Elmer Clarus 500, Perkin Elmer Elite Alumina 30 m × 0.53 mm) was used (Lehtomäki 2006). Operation conditions were as follows: oven 100 ºC, detector 225 ºC, injection port 250 ºC; and argon was used as the carrier gas (Bayr 2014).
Biogas volume	A water displacement column with 0.05 dm^3 accuracy was used.
Ash, TS, VS	The APHA 1998 standard was used.
pH	A pH meter (Phenomenal VWR) was used.
C, H, N Proportion	Vario EL III (2005)
Klason-lignin	Two-step strong acid hydrolysis was used (Sluiter *et al*. 2008). Dried samples (0.3 g) were placed in a 100 mL bottle and sulfuric acid was added (3 mL with concentration of 72 %), then the bottle was placed in a water bath for 1 h at 30 °C. The second stage was carried out as follows: 84 mL of deionised water was added to dilute sulfuric acid concentration to 4 %. Then, after autoclaving for 1 h (1.4 bar, 121 °C), the samples were vacuum filtered (glass filter funnel crucibles). The residues (acid insoluble lignin) were dried in an oven at 105 °C for 16 h. The final Klason-lignin was determined after subtracting the ash mass after incineration (at 550 °C for 3 h).
TKN	Performed according to Tecator application note (Perstorp Analytical Tecator 1995), using Kjeltec system (Tecator Kjeltec System 1002 distilling unit).
VFAs	A gas chromatograph (GC-2010 PLUS Shimadzu) fitted with FID and Perkin Elmer Elite FFAP column (30 m, 0.32 mm, 0.25 µm) (Bayr 2014) was used. The analysis included the following acids: acetic, iso-butyric, butyric, propionic, iso-pentanoic (iso-valeric), pentanoic (valeric) and hexanoic (caproic).
Hydrocarbons	The samples were dried at 40 °C for 1–2 days and homogenised to <1 mm particle size. Dry matter (DM) was analysed using a Sartorius MA 30 moisture analyser at 105 °C. Aigh-performance liquid chromatography (HPLC) system equipped with a Shimadzu RI-detector was used to determine monosaccharides (d-glucose, d-xylose, and l-arabinose) on a Dionex Summit (Sluiter *et al*. 2008).

Table 3. Actual values (nominal 1:1 and 2:1 by VS content mL g^{-1}) in incubation experiments.

Area	Ilomantsi		Alajärvi	
Harvest	First	Second	First	Second
Inoculum (ml)	9.27	9.01	9.27	9.01
RCG substrate (g)	9.81	4.80	9.92	4.84

RESULTS

Biomass yield and composition of RCG

The biomass yield and composition of the two harvests determined experimentally for RCG cultivated on two cutover peatlands (in Ilomantsi and Alajärvi municipalities) are presented in Table 4. For both locations, harvesting RCG in June (first harvest) resulted in approximately 70 % higher biomass yield (1.88 and 3.05 Mg ha^{-1} TS) than the second harvest (August, 0.77 and 1.07 Mg ha^{-}1 TS) while the total biomass yields were 4.1 and 2.7 Mg ha^{-1} TS in Ilomantsi and Alajärvi respectively.

The chemical analysis showed that harvest time influenced the biomass composition too (Table 4). For both areas, second harvest RCG had higher TS, VS, ash proportion and Klason lignin proportion than did the first harvest. The Klason lignin proportion ranged from 14.7 % to 17.8 % per TS with higher values in the second harvest than in the first harvest. With respect to carbohydrates, glucan proportion increased (with harvest sequence) while the proportion of pentose sugars, i.e. xylan and arabinan, decreased with harvest sequence.

For both areas, the first harvest RCG had higher BMP (338 and 347 dm^{3} kg^{-1} VS) than did the second harvest (276 and 324 dm^{3} kg^{-1} VS). Moreover, RCG grown at Ilomantsi resulted in 2.8 % and 17 % more BMP than at Alajärvi. The second harvest RCG had slightly higher HHV (10 % and 20 %) than the first harvest for both areas. The HHV ranged from 14.8 to 16.3 MJ kg^{-1} TS and the BMP was from 58 % to 81 % of the energy achieved by combustion (Table 4). The range of total gross energy yield was 8.1–16.9 MWh ha^{-1} a^{-1} with biogas production and 11.8–21.9 MWh ha^{-1} a^{-1} with combustion on both areas.

DISCUSSION

Biomass yield and composition

The results of the experiments suggest that the use of fresh RCG, with two cuts per growing season, can be a suitable after-use method for cutover peatlands to produce biomass for biogas production and combustion. This fresh RCG is an alternative to the dry, spring harvested, RCG which has proved uneconomic and technically unsuccessful. However, the RCG biomass yields in both of the studied areas appeared to be relatively small (total annual yield of 4.2 and 2.7 Mg ha^{-1} TS in Ilomantsi and Alajärvi, respectively), compared with RCG cultivated (first and second harvest) in two fertilised (N, P, K) Finnish test fields (total annual yield of 6.8 and 8.1 Mg ha^{-1} TS (Seppälä *et al.* 2009)). Thus, RCG cultivation must be optimised with sufficient fertilisation to achieve higher biomass yields on cutover peatlands. The difference in biomass yield per hectare between the two study areas suggests an effect of the local conditions that give every peatland unique natural conditions (such as soil properties and weather conditions) which may make the RCG cultivation unfavourable for bioenergy production if cultivation conditions are not optimised. For example, the second cut yields, with and without fertilisation, in Danish drained peatlands, were 3.5 and 8 Mg ha^{-1} TS respectively (Kandel *et al*. 2013b).

The chemical properties of RCG differed among the sample locations and harvesting times (Table 4). This affects biomass and bioenergy yields on cutover peatlands and makes bioenergy utilisation of fresh RCG different from that of spring harvested dry RCG. In both places, the TS, VS, ash, HHV, Klason lignin and glucan proportions were greater in the second cut, whereas biomass yield, BMP, nitrogen, xylan and arabinan proportions were greater in the first cut. The high carbohydrate proportion in RCG in the present study was in accord with the literature values for general non-wood feedstock: cellulose 30–45 %, hemicellulose 20–35 %, and lignin 10–25 % (Alén 2011). Previously in a three-harvest study, a decrease in lignin proportion without any increase in cellulose was reported in RCG after the second harvest (Tilvikiene *et al*. 2016). However, in that work an increase in lignin and cellulose was noticed only after the third harvest. The reason for this discrepancy with an increase in lignin and carbohydrate proportions between the two harvests

Table 4. The composition of freshly harvested RCG (two cuts) for biogas production and combustion. Standard deviation (±, of 3 separate replicates from the field samples) is not marked if it is less than 10 % of the mean value.

Property	Units	Alajärvi		Ilomantsi	
		First harvest	Second harvest	First harvest	Second harvest
Biomass yield	Mg ha^{-1} TS	1.9	0.77	3.5	1.7
TS	% (FW)	23.6	28.5	21.8	33.5
VS	% (FW)	22	26.5	20.6	31.4
Ash	% (FW)	1.5	2	1.2 ± 0.1	2.1
Experimental HHV	MJ kg^{-1} TS	15.8	16.3	14.8	16.0 ± 1.7
Methane yield	dm^3 kg^{-1} VS	338.3	276.9 ± 46	347.8 ± 35	324.2 ± 53
Methane yield HHV	MJ kg^{-1} TS	11.5	9.4	12	11.1
Total N	mg g^{-1} TS	14.9	15.0	17.8	14.3
C	% TS	45.5	45.0	45.5	45.2
H	% TS	6.3	6.1	6.2	6.2
N	% TS	1.6	1.4	1.5	1.3
Klason Lignin	% TS	15.1 ± 1.6	16.7	14.7	17.8
Glucan	% TS	35.9	39.6 ± 4.0	36.7	38.9 ± 4.2
Xylan	% TS	17.5	10.8 ± 2.5	17.8	15.3
Arabinan	% TS	13.4 ± 2.7	4.0 ± 0.8	13.1 ± 2.2	9.3 ± 4.5

was attributed to fertilisation of the crop between the harvests. However, harvesting a crop before flowering may result in low lignin proportion and improve the biodigestibility of the crop (Kandel *et al.* 2013b). The ash proportion of the freshly harvested RCG samples in the present study is similar to spring or late autumn harvested RCG (Alakangas *et al*. 2016). The traditional spring harvest of RCG has proved best for combustion purposes in several studies (e.g. Burvall 1997, Pahkala *et al*. 2005). In combustion, the use of freshly harvested RCG is meaningful only if the mixing ratio in the main fuel is regulated to avoid technical issues, such as slagging and corrosion in the furnace due to the high ash and chlorine content (Raiko *et al*. 2002).

The results of our experiments suggest that fresh RCG can be used for energy production although the high moisture content can lower the energy value of the grass as received in the combustion plant, compared to combustion of spring harvested dry RCG. For combustion, the fresh RCG has to be dried before use. In biogas production, the high moisture content reduces the BMP per unit of fresh matter but does not affect the energy value of the produced biogas. The BMP values in the present study were between 348 and 277 dm^3 kg^{-1} VS and were slightly lower than the values of 368 and 323 dm^3 kg^{-1} VS reported for the first and second harvests of RCG respectively (gas volume corrected to NTP conditions, Kandel *et al.* 2013b). For instance, BMP values of 390 and 367 dm^3 kg^{-1} VS were reported for RCG after first and second harvests respectively (Nekrošius *et al.* 2014). However, the BMP of 400 dm^3 kg^{-1} VS was reported for RCG in long-term (over 100 days) batch experiments (Lehtomäki *et al.* 2008). Also, Kandel *et al.* (2013b) reported that fertilisation of RCG between first and second harvest improved the BMP by approximately 20 dm^3 kg^{-1} VS compared to the unfertilised RCG. The HHV of 14.8–16.3 MJ kg^{-1} TS obtained in the present work is close to the values of 15.2–16.1 MJ kg^{-1} TS reported for freshly harvested RCG in Poland (Kołodziej *et al.* 2016). These results indicate that with increase in maturity, lignin proportion increases and thereby increases the HHV of the biomass. When compared with the traditional RCG harvesting (dry grass after winter), freshly harvested grass has significantly lower HHV. For comparison, the highest HHV of 17.6–17.9 MJ kg^{-1} TS was reported for dry and spring harvested RCG (Alakangas *et al*. 2016). In this study, the biogas energy content of RCG per TS is from 58 % to 81 % compared to HHV per TS. For instance, the energy yield (per TS) via methane production is only 60 % of the energy yield achieved by combustion reported for Estonian semi-natural grasslands (Melts *et al.* 2013).

General discussion

Fresh RCG is harvested during summer, which may result in higher biomass yields with several cuts, lower lignin proportion, and better digestibility for biogas production compared with traditional dry-harvested RCG. Cultivation of RCG on these peatlands should follow the traditional agronomic practices and subsidies with proper water table adjustment and fertilisation in order to improve biomass and energy yields over those obtained in the former RGC cultivation for spring harvesting. However, there are several after-use alternatives for cutover peatlands - such as afforestation, agriculture, restoration and bird reserves - which compete with energy crop cultivation (Salo & Savolainen 2008). Currently, landowners see energy crop cultivation as the second most popular after-use (afforestation is the first). This could limit the cultivation of RCG in practice (Laasasenaho *et al*. 2017).

On cutover peatlands, the combustion of RCG may have higher energy potential per unit area than has biogas production, but both energy conversion technologies deserve study. Combustion may have higher needs for inorganic fertiliser, and for feedstock drying and handling, than biogas production. The economic profitability of both energy production technologies depends on energy prices and agriculture subsidies as well as energy input costs, which should be calculated separately.

Currently, the climate impact on, and CO_2 emissions from, peatlands used for agricultural cultivation is under discussion (e.g. Kandel *et al.* 2013a, Kekkonen *et al*. 2019). It is possible that CO_2 emissions from peat soil mineralisation during the after-use period may be sufficiently high to be important. The peat soil CO_2-equivalent emission values presented by Grønlund *et al*. (2008) are 29–32 Mg ha^{-1} a^{-1}. However, if the CO_2 fixation by RCG growing on cutover peatland is taken into account, the net CO_2 emissions would be smaller. For example, the net CO_2 emissions of RCG cultivation as C-equivalent values have been reported to be 8.1 ± 0.2 Mg ha^{-1} a^{-1} in cultivated drained peatland in Denmark (Karki *et al*. 2015). In general, we need to know more about soil-originated CO_2 emissions from cutover peatlands especially in boreal conditions. Suitable hydrological conditions, such as those created by adjustment of the water table or rewetting, are required to make cutover peatlands into net carbon sinks (Kekkonen *et al*. 2019). Further research is also needed to make a more detailed analysis of the variation of biomass yields in different growing areas, as well as of energy inputs and costs for RCG cultivation on cutover peatlands for biogas production. Practical issues such as the landowner's willingness, the effect of peat soil emissions, and locations and sizes of suitable areas should also be considered.

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AUTHOR CONTRIBUTIONS

KL wrote the first draft of the manuscript and participated in the laboratory experiment as a corresponding author. FR and HK contributed to the laboratory analyses and commented on the manuscript. PK supervised the laboratory experiment and contributed to writing the manuscript. JK took part in writing and commenting on the manuscript. JR commented on the final manuscript and finalised the manuscript together with KL.

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