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Comparing energy crops for biogas production – Yields, energy input and costs in cultivation using digestate and mineral fertilisation

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ABSTRACT

Analyses of six crops grown in southern Sweden for biogas production (hemp, sugar beet, maize, triticale, grass/clover ley, winter wheat) showed varying performance regarding methane yield per hectare and energy input and costs in the production and supply of crops as biogas feedstock. The highest biomass and biogas yield was observed for sugar beet. Crops with lower risk of negative environmental impact in cultivation, such as ley and hemp, produced less than half the methane energy yield per hectare. Triticale, also having less risk of negative environmental impact, gave an energy yield similar to that of winter wheat grain and maize.

Replacing most of the mineral fertiliser with biogas digestate did not, with the exception for hemp, influence crop yields per hectare, but energy input in cultivation decreased by on average 34% for the six crops tested. For hemp and sugar beet the biogas feedstock costs for the freshly harvested crop per GJ methane were close to that of the economic reference crop, winter wheat grain. For maize, beet tops and first and second year ley, the feedstock costs were lower, and for triticale much lower. When ensiled crops were used for biogas the feedstock costs increased and only those of triticale silage remained slightly lower than the cost of dried wheat grain. However, all feedstock costs were so high that profitable biogas production based solely on ensiled crops would be difficult to achieve at present Swedish biogas sales prices.

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1. Introduction

In Europe today, biomass contributes 4% of the total energy supply. According to the European Commission Renewable Energy Directive [1], the use of renewable energy should contribute 20% by 2020, while the share of renewable fuels in the transportation sector should be 10%. The majority of this increase in renewables is expected to originate from biomass from agriculture, but also forestry. This in turn has been estimated to require 15% of the arable land in Europe [2]. In Germany, an estimated 16% of agricultural land was used for energy crops in 2011, whereof 40% was energy crops for biogas production [3]. An increased supply of agriculture-based biofuel feedstock will include various crops and residues, which all give different energy yields per hectare, but also have different environmental and economic performance. In an effort to reduce potential land use conflicts between food and energy production, new policy regulations within EU may limit the amount of agricultural land to be used for biofuels production based on food crops in the future. This complicates the issue of which crops are preferable for sustainable renewable fuel production.

To enable sustainability assessments, there is a need for updated and developed life cycle assessments that also include effects on potential land use changes, in order to identify the aspects of the bioenergy production chain that have the main impact on environmental performance. Since arable land is limited, minimisation of land use is also important, which makes fuel output and climate benefits per unit of land important parameters. High land use efficiency will minimise the risk of future negative indirect land use changes resulting from expanded cultivation of energy crops (see e.g. Refs. [4,5]). Life cycle assessments today are often made based on general data or statistics, and the quality of the input data can vary depending on the technical status of the bioenergy production chain. For new and less studied production chains, the input data might be less reliable [6]. One example of a less studied production chain is energy crops for production of biogas as a fuel in the transport sector, which is the focus of this study. In order to make more reliable environmental assessments of biogas systems from crops, specific local and regional conditions have to be included [7]. This in turn requires new and accurate life cycle inventory data taking into account the specific design of the crop-based biogas systems studied. Thus, there is a great need for updated data, especially regarding crop yields per unit of land and subsequent methane yields, since these parameters are crucial for the life cycle performance and greenhouse gas balances of the various biogas systems [6].

The project ‘Crops 4 Biogas’ is an interdisciplinary research collaboration, where the overall aim is to establish and compare land use, energy, greenhouse gas and economic efficiency for biogas as vehicle fuel derived from six potential energy crops, including wheat grain as a reference crop. The aim of the present paper is to present new and dedicated life cycle inventory data for the production and supply of crops as feedstock for a crop-based biogas system in southern Sweden. Experimental data on crop and methane yields and crop mineral content from cultivation trials where mineral fertiliser or digestate from a biogas plant was applied are presented. Crop yields were normalised to eliminate annual variations and to allow comparison on a basis more generally valid for the region, and land use efficiency as methane energy yield per hectare and primary energy input in crop production was analysed. This paper also compares the economic efficiency, e.g. the costs for production and supply of the selected energy crops as feedstock for biogas production. Data on production and supply of crops as biogas feedstock presented in the present paper will be used as input in assessment of greenhouse gas efficiency, economic efficiency and energy efficiency of the whole production chain from field to vehicle fuel in forthcoming papers from the same research project.

2. Experimental methods

2.1. Cultivation trials

In cultivation trials, the effect of applying mineral and biofertiliser was evaluated regarding the effect on biomass yield and on mineral uptake in the crop. The cultivation trial was started in 2006 at the experimental farm Lönnstorp of the Swedish University of Agricultural Sciences in southern Sweden (~55°N, ~13°E, 10 m above sea level). The soil is a fertile, loamy clay with 15% clay content and 3% organic matter. The experimental design was a criss-cross design, with blocks replicated three times. Five annual crops were grown: hemp, sugar beet, maize, triticale (a crossing of wheat and rye, *Triticum* x *Secale*) with undersown ley, followed by two years of ley and finally winter wheat (Table 1). Market-available cultivars were chosen for most of the crops, the main focus being high biomass yields rather than food or feed quality. For the sugar beet, a cultivar low in sugar content and high in biomass production was provided by a plant breeding company and tested for biogas production from the whole plant (beet and tops). The ley was a mix developed at the

Table 1 – Energy crops, cultivar, type and harvest stage and time, 2007–2010.

Crop	Cultivar	Type	Harvest (harvest time)
Hemp	Futura 75	Late flowering type	Biogas optimum (late September)
Sugar beet	Test type	Leafy type	Beets and tops, (late October)
Maize	Arabica	Stay green type	Late fodder stage (late September)
Triticale	Tulus	Fodder type	Whole green plant, early dough stage (mid July)
Ley year I	Mixing	High biomass yield	Biomass optimum, 2 yields (June and August)
Ley year II	Mixing	High biomass yield	Biomass optimum, 2 yields (June and August)
Winter wheat	Opus	Starch rich type	Full maturation, grain and straw (late August)

experimental farm, consisting of 25% white and red clover, 50% hybrid ryegrass and the rest a mix of two ryegrasses.

The choices of harvest times for the crops were based on recommendations given in the literature. Hemp was harvested in the beginning of September [8]. Sugar beets and tops were harvested at the conventional harvest time in October. Maize was harvested at full ripeness [9]. Triticale, sown in the autumn before the harvest year, was harvested at early dough stage (stage 80 of the cereal decimal code [10,11]), as recommended by Amon et al. [12]. Ley was harvested two times, in mid-June (cut 1) and in late August (cut 2) and kept in the crop rotation for 2 years (years I and II). Winter wheat was harvested at full maturation in 2007–2008 and from 2009 on as a whole green crop. Winter wheat grain of fodder quality, which is a very common crop in the region for the study, was used as the reference crop for comparison of energy balances and economic production costs.

The crops studied were chosen with the aim of achieving sustainable cultivation for energy purposes through a well-planned crop rotation that can potentially decrease energy inputs in the form of mineral fertiliser, pesticides, diesel and use of machinery. The multifunctionality of each crop was important, i.e. not only its potential for high biomass yield, but also its competitive ability against weeds or pathogens, its effect on soil structure, its growth period, its growth pattern/physiology and the amount of nutrient residues left for the next crop. All these aspects were taken into consideration to minimise the use of herbicides or other pesticides, to decrease the need for tillage and to minimise nutrient leakage by keeping the soil covered during the winter. However, the crops also had to be traditional crops, well-known to farmers and requiring only commercially available sowing and harvest machinery.

Mineral fertiliser and bio-fertiliser were applied in the spring. The bio-fertiliser used was the digestate (effluent) from a biogas plant treating mainly municipal and industrial food waste (NSR, Helsingborg, Sweden). For all the crops in the crop rotation, a standard application of mineral fertiliser was used as the control (referred to as NPK), consisting of 140 kg ha^{-1} nitrogen (N), 22 kg ha^{-1} phosphorus (P) and 50 kg ha^{-1} potassium (K). Digestate fertilisation was limited in order to comply with Swedish legislation on P application by organic fertilisers, i.e. a maximum application of 22 kg ha^{-1} P per year (5-year average) on phosphorus rich soils such as that on the experimental farm [13]. The ammonium nitrogen (NH_4-N) content of the digestate was on average 8.2% of dry matter, resulting in 88 kg ha^{-1} of NH_4-N. Similarly, the digestate added 40 kg ha^{-1} K on average. In one additional part of the field experiment, mineral fertiliser was used to complement the digestate in order to obtain the same level of N, P and K as in the control with the mineral fertiliser. This complementary application of 52 kg ha^{-1} N and 10 kg ha^{-1} K on average across all trial years (referred to as digestate + NK) was made at the same time as the digestate application.

A restricted set of pesticide treatments for weeds, fungi and insects was applied within the cropping system, when motivated by threshold values. No irrigation was used. The experiment started in 2006 but data for biomass yield and biogas potential refer to 2007 onwards, leaving the first year as an establishment year. The weather conditions varied greatly during these field trial years. 2007 was a very good year, with a warm and wet spring and a normal amount of rain during the growing season. During the following three years the winters were long and cold, damaging some of the winter crops and delaying spring sowing. In addition, the summers were drier than normal, followed by rainy periods during early autumn, i.e. the harvest period. This affected crop establishment and crop development during the summer.

2.2. *Sampling*

The crop cultivation trials provided data on dry matter (DM) yields and also provided the biomass samples that were used for analysis of crop mineral content and biogas yields. Samples from each crop were taken from a harvested area, with border rows discarded, and immediately stored in a freezer (−18 °C). For DM content, additional samples were taken, weighed and dried at 60 °C for 48 h. For crop mineral content, separate samples from triplicate cultivation plots fertilised with digestate or NPK from one growing season were analysed ($n = 3$ for each fertiliser treatment). For ley, the samples from triplicate cultivation plots were pooled, and the two cuts (mid-June and late August) and two years of ley (I and II) fertilised with digestate or NPK from one growing season were analysed separately ($n = 4$ for each fertiliser treatment). For methane yield determinations, samples from triplicate cultivation plots were pooled and analysed as one sample.

2.3. *Crop analyses*

2.3.1. *Mineral content*

After acid digestion of the whole sample (Swedish standard SS028311), the minerals were analysed by elementary analysis (N), ICP-OES (K, P, S, Ca, Mg, Fe) or ICP-MS (Co, Mo, W, Se, Cu, Ni) by LMI AB (Helsingborg, Sweden). Analyses of DM and volatile solids (VS) were performed according to standard methods on fresh crops frozen within 5 h of harvest [14].

2.3.2. *Biochemical methane potential*

The biochemical methane potential (BMP) of selected crop samples was determined in triplicate as described elsewhere [15]. The temperature in the BMP tests was set to 310 K. Two sets of controls were included: one set with only the digestate and a second with microcrystalline cellulose (Avicel PH-101, Sigma–Aldrich, St. Louis, MO, USA). Gas yields (dry gas) were normalised by correcting to a temperature of 273 K and assuming a pressure of 101.3 kPa, and the lower heating value of methane (35.7 MJ m^{-3}) was used for conversion to energy units. For hemp and maize, samples from parallel energy crop cultivation trials in the same region were included for comparison [8,16]. All crops were milled to a particle size of between 2 and 4 mm. In all BMP tests, inocula from the same source was used (digestate from Söderåsens Bioenergi, Bjuv, Sweden, a biogas process treating mainly municipal and industrial food waste). The digestate was sampled three times during a period of 9 months and analysed for minerals in the same way as the crops. This digestate was also used for calculation of the effect of digestate fertilisation on energy input in crop cultivation,

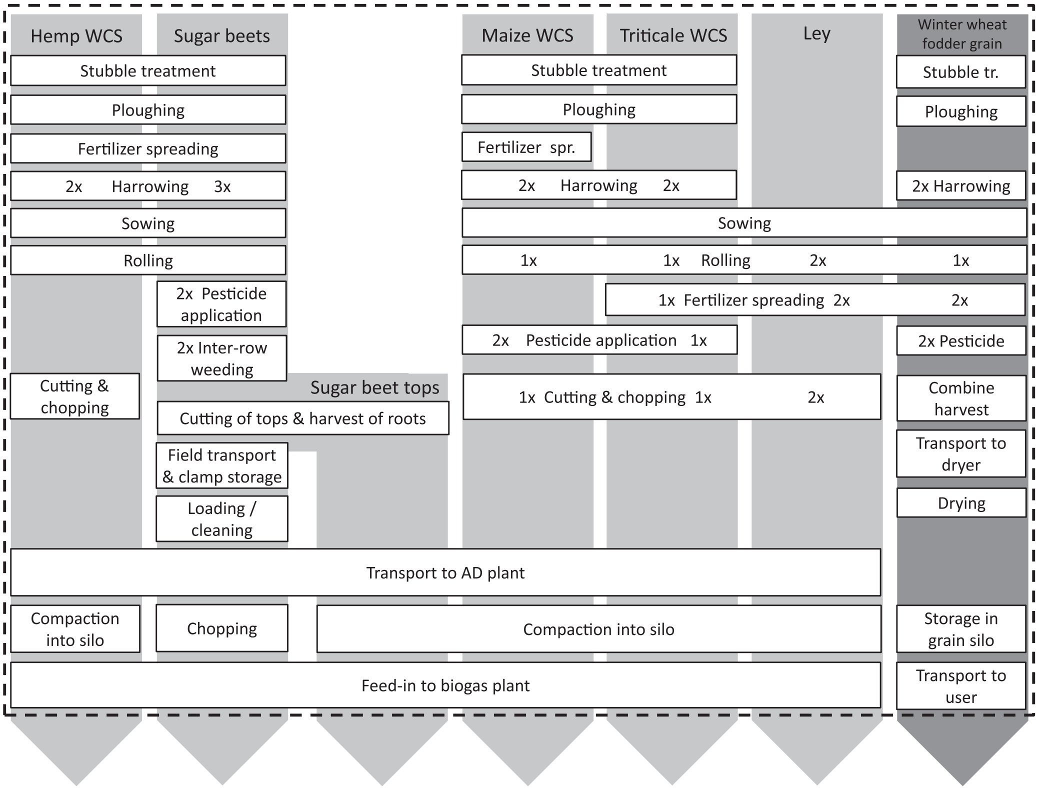

Fig. 1 – Schematic overview of the field, transport, storage and feed-in operations accounted for in the energy input calculations for the crops supplied as biogas feedstock. Wheat grain cultivated for fodder purposes was used as the reference crop. WCS = whole-crop silage.

since a thorough environmental and energy systems analysis has been performed on that biogas system [17], supplying reliable input data on these aspects. The average mineral content of this digestate is shown in Tables A.1 and A.2. The digestate contained the macro- and micro-minerals essential for successful anaerobic microbial degradation, ensuring a well-functioning BMP trial.

2.4. *Statistical analyses of experimental data*

For crop yields, statistical analyses were performed using the statistical software SAS (SAS 9.2 TS Level 2M2 for Windows version 6.1.7601, by SAS Institute Inc., Cary, NC, USA). All the groupings of the crop yields from the different fertiliser treatments were made using the GLM procedure and Fisher's LSD as post hoctest at 5% significance level. The GLM procedure also gives the root mean square error, RSME, denoting the standard deviation of the residuals in the model.

Statistical analyses on methane yields were performed using one-way ANOVA and Tukey's multiple comparison tests using the statistical software Prism (Prism 5 for Mac OS X, version 5.0b, GraphPad Software Inc., La Jolla, CA, USA). Crop mineral content was analysed by paired sample t-test ($P \leq 0.05$), using statistical package SPSS, version 16 software. The term 'significant' is only used when statistical analysis of significance was performed. A significance level of 95% was used throughout all statistical analyses. Methane yields from multiple trials were combined according to standard statistical rules to provide a standard deviation (sd) of the final result.

3. Calculations and assumptions

3.1. *Normalisation of biomass yields*

Biomass yield data from small cultivation trial plots apply to experimental conditions. Therefore, normalisation of the available biomass DM yield data was necessary, i.e. literature data were adjusted to represent whole-crop yields from average quality soils, average farmer cultivation skills and normal cultivation intensity in the coastal agricultural area *Götalands södra slättbygder* (Gss) situated in Scania and Halland county, southern Sweden. Note, that normal cultivation intensity means crop-adjusted conditions, e.g. crop-specific fertilisation levels. Normalisation was carried out as described by Prade et al. [18]. For the normalisation the DM yields of the biogas crops were adjusted from published yield data for the energy crop relative to the yield of spring barley cultivated in the same trial or on the same farm. Spring barley was chosen as the basis for comparison because it is a common crop in the region of this study and in the rest of the country. The value of grain yield for spring barley from each field trial was related to the 5-year average

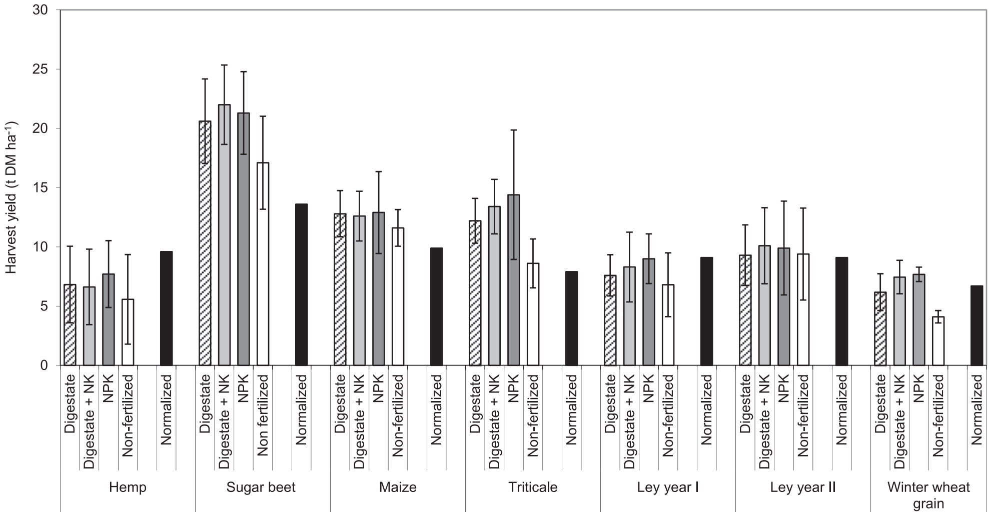

Fig. 2 – Crop yields when digestate was used as the sole fertiliser (striped bars) compared with a combination of digestate and mineral N + K (light grey bars) or mineral fertiliser (NPK) (dark grey bars). Error bars show standard deviation. The white bars show the non-fertilised control. The black bars are not based on experimentally derived data, but show the corresponding normalised crop yield, which was the basis for further calculations of energy input and crop production costs.

yield statistics in *Gss* [19]. The yield of the energy crop from the same field trial was then adjusted by the same relative difference. For example, when the 5-year average yield in the *Gss* region was 20% lower than the spring barley yield in the field trial, the corresponding yield of the energy crop was accordingly reduced by 20%.

Table A.3 shows the assumptions used in calculation of the normalised yields for the energy crops investigated in this study and for the reference crop, i.e. fodder quality wheat grain. The normalised crop yields are also shown in Fig. 2 in comparison with experimentally determined crop yields from the cultivation trials. Winter wheat fodder grain yield was calculated using the same method of normalisation, based on 5-year average standard yield data [19]. However, the published average yield is based on both bread and fodder wheat. A proportion of 60/40 for bread/fodder wheat and a 10% higher yield for fodder than bread wheat yield were assumed in order to calculate the average fodder wheat grain yield, which is in line with earlier findings [20]. In the case of triticale, wheat and sugar beet, other plant parts not included in the available standard yield data were accounted for, e.g. with corresponding straw yields [21] and yield data for sugar beet tops, respectively [22]. For hemp and maize, where only data from cultivation trials were available, harvest losses for mechanical harvest processes were estimated [23,24]. For ley crops, standard whole crop yields were available [19]. However, these data were not applicable, as ley crop yields registered in the standard yield statistics include extensively cultivated ley crops from conventional but also organic cultivation systems. Furthermore, ley crops are predominantly grown on less fertile soils. Therefore, the ley crop yield was increased by 51% according to trials which included both barley (comparison crop) and intensively grown ley crops [25,26]. Furthermore, studies have shown that a 10% higher dry matter yield can be achieved if the harvest date is delayed to prioritise energy rather than protein yield [27]. For ley, results from the field trials are presented separately for years I and II, but only an average normalised biomass yield for both years was calculated.

3.2. *Primary energy input for production of crops as biogas feedstock*

Production of biomass requires multiple operational steps, e.g. tillage, sowing, fertilisation, harvest, transport and storage. The individual field, transport, storage and feed-in operations for the crops investigated in this study supplied as biogas feedstock are shown in Fig. 1. Each operation requires an energy input. The analyses of energy input were made on the basis of normalised biomass yields and general crop-specific cultivation recommendations (e.g. N-fertilisation level, use of pesticides, etc.). All energy inputs were calculated as primary energy inputs. Energy inputs can be divided into two types, direct and indirect energy inputs. Direct energy inputs refer to energy carriers utilised directly within the production flow, e.g. vehicle fuel or electric power. The primary energy factor for diesel was assumed to be 1.19 (15% for diesel production and 4% for lubricants used during machinery operation), resulting in 44.5 MJ primary energy per litre diesel used. Data for consumption of diesel were taken from a database [28] as consumption per hour typical for each field operation and the associated effective capacity and frequency. The primary energy factor for electricity was assumed to be 2.1 [17]. Indirect energy refers to the energy utilised e.g. for production of fertilisers, fuels, building materials and manufacture of machinery. For fertilisation, N was accounted for with 48.0 MJ kg^{-1}, P with 18.7 MJ kg^{-1} and K with 10.6 MJ kg^{-1}. Indirect energy consumption for use of materials in production of buildings and machinery was assumed to be 17.5 MJ kg^{-1} for iron, 10.0 MJ kg^{-1} for cast iron, 85 MJ kg^{-1} for tyres and 0.83 MJ kg^{-1} for concrete. Plastics for covering biomass silage were assumed to use 86 MJ kg^{-1} in production. Embodied energy of machinery was calculated according to the assumption of 45% iron, 45% cast iron and 10% tyres. For machinery without tyres, an even blend of iron and cast iron was assumed. Indirect energy consumption was then calculated from the annual use, the machinery's nominal lifetime and the weight of the machinery [24]. Energy for the production of seed material was calculated from the accumulated energy inputs for each crop in this paper (excluding the energy for seeds), typical seed yields, and assumed energy inputs for drying and transport of the seeds. For reasons of simplicity, it was further assumed that the seed production process was identical to the biomass production process. Energy inputs in the form of pesticides were calculated from amounts of pesticides as suggested by the Swedish Rural Economy and Agricultural Societies [25] and associated indirect energy inputs [29]. Energy inputs that were not accounted for are human labour, solar energy, transportation of building materials for storage areas and machinery, demolition of buildings and machinery and material recycling.

The energy input of production and supply of crops as biogas feedstock was calculated for each crop based on normalised yields (Table A.3). For each crop, two different fertilisation strategies were investigated (Table A.4): According to the first strategy, the crops were fertilised with 100% mineral fertiliser at P and K levels reflecting the amount of nutrients removed from the field with the biomass, while N fertilisation was assumed to follow general crop-specific recommendations [25,30–32]. In the second strategy, digestate from the Söderåsens Bioenergi biogas plant, as described under Section 2.3.2, was used as the basis for calculating the effect of digestate fertilisation. The content of ammonia-nitrogen (NH_4-N), P and K was analysed in the digestate on three occasions. During storage in covered storage tanks, 1% of the nitrogen was assumed to be lost [17], giving an N concentration after storage of 4.51 g L^{-1}, whereof 3.33 g L^{-1} was in the form of NH_4-N. This was the value used in calculating the effect of digestate fertilisation on energy input for normalised crop yields. To enable comparisons, digestate was added until either N, P or K requirements were fulfilled or a maximum of 22 kg P ha^{-1} was reached. Nutrient requirements not fulfilled at the individual crop level were complemented with mineral fertiliser to reach the same fertilisation level as in NPK-fertilisation. Production of winter wheat grains was assumed to follow guidelines for fodder production to allow direct economic comparison on the basis of an existing market [25]. Based on an environmental and energy systems analysis performed for Söderåsens biogas plant, the energy input in biogas production was all allocated to the biogas produced [17]. The energy input for digestate use included loading, transport to the field (distance 8 km) and spreading.

3.3. *Methane energy output*

The energy output as methane per ha was calculated based on the normalised biomass yields and the experimentally determined methane yields. The normalised biomass DM yields included DM losses during harvest. For losses during ensiling and handling of the crops at the biogas plant, an additional DM loss of 5% was subtracted in the energy output calculations. Furthermore, the experimental methane yields determined at laboratory scale were decreased by 10% to account for the lower methane yield that is likely to be achieved in a full-scale continuous biogas process. The methane yield of wheat grain was not determined in the present study, but a value of 369 m^3 t^{-1} DM was used, i.e. 90% of 410 m^3 t^{-1} DM [33].

3.4. *Costs for production and supply of crops as biogas feedstock*

For production costs, winter wheat grain was used as the economic reference crop, being the standard most profitable alternative crop for the farmers. Production and supply costs were calculated for this reference crop as biogas feedstock, as well as for the five other crops, both fresh and ensiled. The production costs of winter wheat grain are presented both as a biogas feedstock (including costs for crushing and feeding into the biogas plant) and as a reference fodder crop. The costs were calculated using total step calculations [30]. All calculations included direct costs in the form of seed, fertiliser, etc., all transport, the costs of the grower's own work and a real interest rate on capital of 6%. The costs of chopping the biogas crops (or crushing in the case of cereals), transport from the field to the biogas plant (using an average distance of 8 km for all crops) and feeding the crops into the reception tank at the biogas plant were included in the calculations. Costs for stored crops also included storage in bunker silos and storage losses of 5% of crop DM. Overhead costs on the farm, for example bookkeeping, road maintenance, etc., were included in the production costs as: Cereals €89, sugar beet €111, sugar beet tops €11 and other biogas crops €78 per ha and year. The calculations refer to biogas crops fertilised with mineral fertiliser according to the recommendations for the normalised yield levels used here (Appendix Tables A.3 and A.4) and the operations outlined in Fig. 1. Costs for land and EU subsidies (single farm payments, inventory grants or environmental grants) were not included in the production costs. Costs were calculated in Swedish kronor (SEK) and converted to Euro (€) with an exchange rate of 9 SEK/€ and are presented per unit crop DM.

For the calculation of energy-specific production costs, the production costs per DM were combined with experimentally determined methane yields based on the same assumptions of decreased methane yields and ensiling/handling losses as described in Section 3.3. For the cost of fresh crops, no ensiling losses were taken into account, assuming feed-in of fresh crops directly from harvest with no further losses.

4. Results and discussion

4.1. *Cultivation trials*

The average biomass yields for all the energy crops from the different fertilisation treatments and the non-fertilised reference are shown in Fig. 2. As a comparison, the normalised yields given in Table A.3 are shown. For hemp, sugar beet and maize, the results shown are the results after 4 years

(2007–2010), while those shown for ley, triticale and wheat grain are the results for 2 years (2009–2010 for ley and triticale, 2007–2008 for wheat). Background data are given in Tables A.5a and A.5b. All of the energy crops tested except hemp gave good or very good biomass yield when fertilised with only the digestate (striped bars, Fig. 2). The yields of sugar beet, maize, triticale, ley and the reference crop winter wheat grain were at the same level as when fertilised with digestate with addition of mineral NK (light grey bars) or mineral fertiliser (dark grey bars), i.e. with no significant difference in yields (Tables A.5a and A.5b). This implies a higher efficiency of the nitrogen applied (in the form of ammonium nitrogen) in producing biomass yields. For all crops except hemp there was no significant difference in biomass yield when using digestate with a complementary mineral fertiliser of nitrogen and potassium compared to using standard mineral fertilisation.

The resulting biomass yields reflect the fact that the crop rotation was designed for lower input requirements in the form of diesel, mineral fertiliser and pesticides. Furthermore, the crops were all grown at the same level of fertilisation and with the same fertiliser application date. For instance, under standard conditions the ley crop would be fertilised after the first cut to support the second cut, but this was not done in the trials. Considering this, the yields of biomass for biogas production were generally higher than expected.

Hemp, normally regarded as a reliable producer of biomass, did not perform as expected in the field trials, mainly due to growing conditions. While the average yields for all the fertilised treatments during the period 2007–2010 were between 6.6 and 7.7 t DM ha^{-1}, the yields from the hemp plots during 2007 were on average between 11 and 13 t DM ha^{-1}, hinting at what the potential capacity of the crop. Apart from rather demanding requirements concerning weather conditions, the hemp in the present study also showed a need for very good conditions during early establishment.

Energy beet, i.e. a sugar beet cultivar more suitable for high biomass production, was the highest yielding crop in the crop rotation, especially since both the beet and the tops were harvested. The yield of the whole beet ranged from 14.8 to 27.8 t DM ha^{-1} in the fertilised treatments during 2007–2010. This great biomass potential is remarkable, although the need for herbicide and fungicide treatment might be greater than for other crops. The same goes for maize, which has a higher need for weed treatments, but these are two of the most widespread biogas crops in Europe today and their acreage is increasing, for instance in Germany [34]. However, in the present study maize did not give quite the yields expected compared to normal yields in the region, with average yields of the different treatments the different years between 9 and 15 t DM ha^{-1}.

Triticale was harvested as a whole green plant, at early dough stage, from 2009 onwards. The biomass yield when it was harvested as a whole crop ranged from 9.4 to 22.0 t DM ha^{-1} in all fertilised plots during 2009 and 2010. This is substantially more than the yield of both “high input” and “low input” triticale (8.2–5.9 t DM ha^{-1} respectively; similar fertilisation levels as in the present study) in a field trial in north-eastern Germany [35]. Triticale, together with cereals such as barley, oats and rye, also has the advantage of being ranked “high yielding” and of obtaining a high agri- environmental ranking when the European environment agency estimated the environmentally compatible potential of energy crops [36]. Thus, the relatively high biomass yields of triticale, as in this study, and relatively lower environmental effects make it a potentially interesting crop for biogas production.

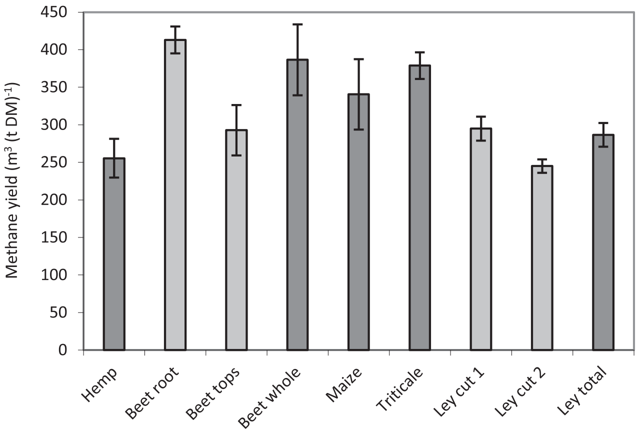

Fig. 3 – Methane yields for the test crops (dark bars) or parts of crops (light bars). The value for whole sugar beet (beet + tops) was calculated based on the harvested proportion of beet (10.6 t DM ha^{-1}) and tops (3 t DM ha^{-1}) under normalised conditions (Table A.3). The value for ley total was calculated based on methane yields for cut 1 and 2 and the harvested proportion from the fertilised plots in the cultivation trials, where cut 1 on average contributed 83% of the total DM at harvest. Error bars indicate standard deviation (sd).

The ley crop harvested over two years also gave promising biomass yields. The yields obtained, varying between 6 and 11 t DM ha^{-1} for first year ley and between 6 and 13 t DM ha^{-1} for second year ley, are normal to high yields for southern Sweden.

The reference crop, winter wheat grain, harvested as fully matured grain, yielded 6.2 t DM ha^{-1} on average when only fertilised with digestate, 7.4 t DM ha^{-1} on average when fertilised with digestate plus complementary mineral NK and 7.7 t DM ha^{-1} when fertilised with mineral fertiliser. This is in line with ordinary winter wheat yields in this region, and also with the normalised yield used for further calculations of energy input and production costs.

4.2. *Crop analysis*

4.2.1. *Crop mineral content*

The mineral content in crops for biogas production, or actually the lack of certain essential elements, is important in assessment of the suitability of a crop for biogas production. Thus, the mineral concentrations in the test crops were analysed. A range of micro-minerals is essential for anaerobic degradation to proceed, but some macro-minerals serve the same purpose and are also important for determining the value of the digestate (the effluent from the biogas plant) as a bio-fertiliser. The mineral concentrations in the crop were compared for crops fertilised with mineral fertiliser (NPK) and

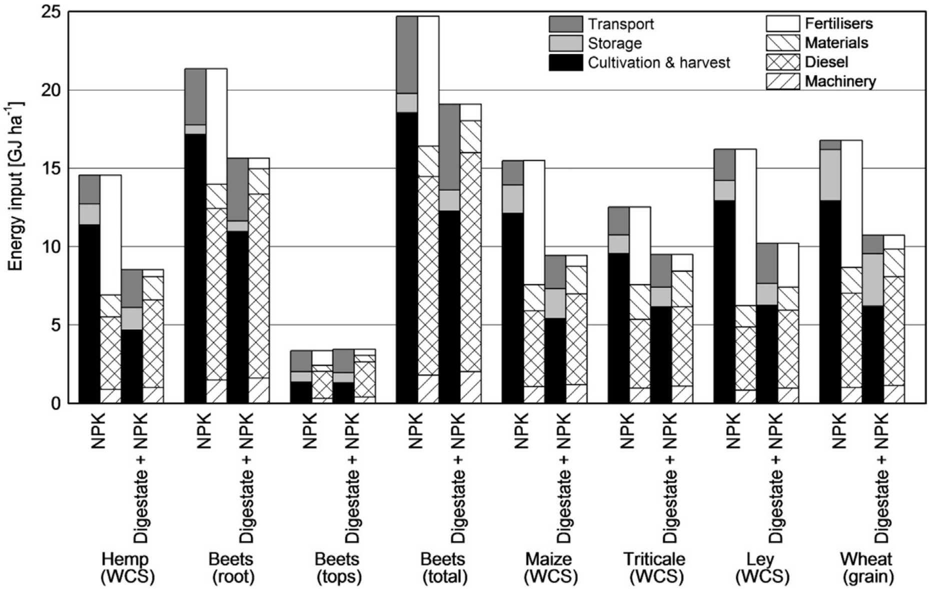

Fig. 4 – Energy inputs in biogas feedstock production from the test crops as outlined in Fig. 1 and attributed to operation (cultivation, storage and transport) and production means (machinery, diesel, materials and fertilisers) for crops fertilised with 100% mineral fertiliser (NPK) and crops fertilised with digestate complemented with mineral fertilisers (digestate + NPK). WCS = whole crop silage.

digestate (Tables A.1 and A.2). In over 80% of the pairs analysed, no significant difference in mineral content was observed. The cases where a significant difference was observed (marked in Tables A.1 and A.2) were quite random, with no general correlation between fertiliser treatments or between crops. The general conclusion is that under the conditions investigated, varying the fertilisation treatment did not influence mineral uptake and concentrations in the crops. Note, however, that this analysis was only carried out for samples from one year (2007) of cultivation.

4.2.2. *Methane yields*

The methane yields for different samples of the same crop were compared (Table A.6). The only significant difference observed was in the comparison between methane yields for ley from cut 1 (June) and cut 2 (August). For the other samples investigated, fertiliser treatment, location and cultivation year gave no significant differences in DM-based methane yield. Thus, the individual results were combined to produce the data on methane yields shown in Fig. 3. Methane yields are here given and evaluated on DM-basis, but in the following text presented and discussed on VS-basis, since this is more commonly seen in the scientific literature.

Studies on hemp as a biogas crop are few, but the average methane yield of hemp presented in this study (276 m^3 t^{-1} VS) is within the range previously reported for hemp harvested in September–October [8,15]. The average methane yield achieved in this study for sugar beet (419 m^3 t^{-1} VS) is what can be expected based on theoretical calculations for a sugar-dominated substrate. For the beet tops, the VS-based methane yield was 361 m^3 t^{-1} VS, while for beet and tops combined based on the normalised proportion at harvest, the methane yield was 408 m^3 t^{-1} VS. The average methane yield for finely ground maize, 360 m^3 t^{-1} VS, was similar to that achieved in Austrian and German studies, where maize harvested at wax ripeness gave 326 m^3 t^{-1} VS [9], or the average for all harvesting times for 5 cultivars, which gave a methane yield of 334 m^3 t^{-1} VS [37]. For methane yields from maize, existing information in the literature varies widely, possibly due to the fact that DM and VS determinations for ensiled material without correction for the loss of volatile compounds during DM determination result in overestimation of the methane yield [15,38]. This potential error is worthy of note since it has a high impact on assessment of land use efficiency, costs and energy balance. Published studies on ensiled maize presented without VS-correction report values of e.g. 398 or 418 m^3 t^{-1} VS [12,39]. Herrmann et al. [40] report methane yields for maize silage without additives of 342–378 m^3 t^{-1} VS, in one of the few studies where VS has been corrected for the loss of volatiles. Very low methane yields for maize are also presented in the literature, and it has been shown that this can be an effect of digestion under nutrient-limited conditions [41]. Such values are not representative of what can be achieved in well-balanced digestion. The methane yield presented in the present study is considered a good representation for both fresh and ensiled maize. For triticale, unfortunately samples from only one year of cultivation trials were taken due to miscommunication. The methane yield for whole crop triticale harvested in early dough stage was 397 m^3 t^{-1} VS. Triticale harvested as a whole crop in the soft dough stage has been reported to yield 342–354 m^3 t^{-1} VS (after ensiling without additives and with VS corrected for volatiles) [40]. However, Amon et al. [12] presented significantly lower yields (236–265 m^3 t^{-1} VS) for ensiled whole crop triticale harvested at the milk stage of grain. The difference in these results could be due to differences in sample pre-treatment, since whole grains are poorly degraded. The sample in this study was finely milled, ensuring that all grains were disintegrated, while in the study by Amon et al. [12], no further disintegration of the sample after harvest is described. The methane yield achieved here for triticale can thus be considered a good representation for a sample which is thoroughly disintegrated, and energy input and production costs for cereals in the present study included crushing. For ley, the two cuts investigated gave significantly different methane yields, 327 $m^3\ t^{-1}$ VS (cut 1, June) and 271 $m^3\ t^{-1}$ VS (cut 2, August). The methane yield probably depends on the grass/clover cultivars included, and time of cut has also previously been shown to influence methane yields. In grass cultivation with 3 cuts, the average methane yield has been reported to be 338, 232 and 216 $m^3\ t^{-1}$ VS for cut 1, 2 and 3, respectively [12]. As discussed for maize, studies on ensiled ley presented without VS-correction report higher methane yields of 361–420 $m^3\ t^{-1}$ VS [42–44]. The results achieved in the present study, when combined based on the proportion at harvest in the cultivation trials, gave an average ley methane yield of 317 $m^3\ t^{-1}$ VS. This is considered a good representation of the average annual methane yields for ley with two cuts per growing season in both the first and second year after sowing.

4.3. *Energy input in cultivation*

Energy input per ha in production and supply of crops as biogas feedstock was similar for maize, hemp, triticale, ley and wheat grain. These crops required 12.5–16.8 GJ ha^{-1} when fertilised with mineral fertiliser (NPK, Fig. 4). As the reference scenario, the energy input for fodder wheat was calculated. If the fodder wheat grain were to be used for biogas production instead under the same conditions as for the other crops (8 km transport distance, grains crushed and fed into reception tank at biogas plant), the energy input would increase from 16.8 to 17.6 GJ ha^{-1}. The required energy input for these crops decreased by 24–41%, to 8.5–10.7 GJ ha^{-1}, when mineral fertiliser was partly replaced by digestate (digestate + NPK, Fig. 4). The reduction for sugar beet (incl. tops) was 23%, but its production was 47–124% more energy-demanding than that of the other crops. When digestate partly replaced mineral fertiliser, the energy inputs for machinery and diesel increased by 12–16%, while those for mineral fertiliser use decreased by 72–94%. The digestate itself in this case was not attributed an energy input, since primary energy input in production was allocated by economic allocation and the digestate did not generate an income at the biogas plant [17]. Detailed data are presented in Appendix Tables A.7 and A.8.

Digestate use in Sweden is limited to 22 kg P per hectare and year for the type of soils as used in these field trials [13]. This limit only applies to organic fertilisers and is accounted for as an average annual P supply for a period of 5 years. This means that more digestate could be applied in one year, e.g. to fully satisfy the nutrient requirements of N and K, as is likely to be the case in practice. However, this would decrease the amount of P from organic fertilisers such as digestate that could be spread in the following four years. The cultivation trials in this study showed that even crops fertilised with digestate solely (not complemented with NPK) yielded as much as those fertilised with mineral fertiliser.

Values for energy input for mineral-fertilised crops calculated in the present study are similar to those found in the literature. The energy input in biomass production from triticale, maize and hemp in this study of 12.5, 15.5 and 14.6 GJ ha^{-1}, respectively, can be compared to the 11.2, 12.5 and 11.8 GJ ha^{-1} reported by Plöchl [35]. For maize, whole-crop sugar beet and ley crops, energy input in biomass production was reported to be 15.6, 22.5 and 10.7 GJ ha^{-1}, respectively, in another study [45]. However, while biomass yields in this study were similar to those reported previously [35], important parameters, e.g. the energy costs of fertiliser production, are not available for evaluation of differences from the latter. Replacement of NPK with digestate + NK has been reported to decrease energy input in hemp biomass production by approximately 40% [24], which was confirmed in the present study.

4.4. *Methane energy output*

The land use efficiency given as gross methane energy output per land unit varied greatly for the test crops (Fig. 5). Whole sugar beet (including both beet and tops) gave more than 80% higher energy output per hectare (160 GJ ha^{-1}) than the reference crop wheat grain (88 GJ ha^{-1}), while the other crops were within a range of +17% (maize) to −15% (hemp) of the energy output of wheat grain. Ley and hemp are both considered to give a low risk of negative environmental impact in cultivation [46], but only gave half the energy yield per hectare of whole sugar beet. Whole crop triticale gave an energy yield similar to that of maize, and is considered to have lower risk of negative environmental impact in cultivation than winter wheat, maize and sugar beet [46]. The energy input in cultivation, transport, crop storage and feed-in at the biogas plant as outlined in Fig. 4 can be compared to the potential energy output per hectare in the form of methane (Fig. 5). Note, however, that the energy input related to the output shown in Fig. 5 only includes the feedstock production and supply (as outlined in Fig. 1) for the crop based biogas system. When mineral fertiliser was applied, triticale (14%) and beet tops (13%) had the lowest relative

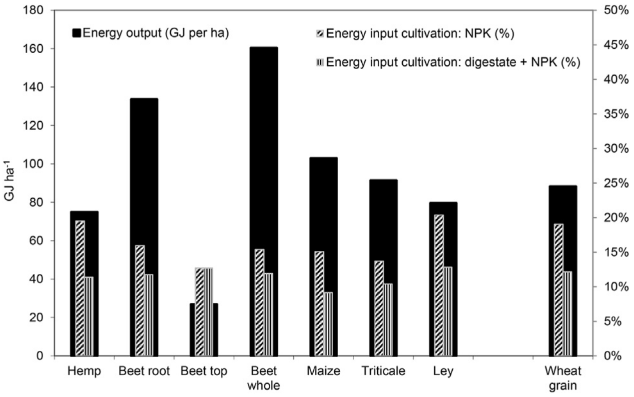

Fig. 5 – Energy output expressed as methane (LHV) yield per hectare for the respective crops (black bars, left axis). Energy input data from Fig. 4 were recalculated to show primary energy input as a percentage of methane energy output for the respective crops with NPK and digestate + NPK fertilisation (striped bars, right axis).

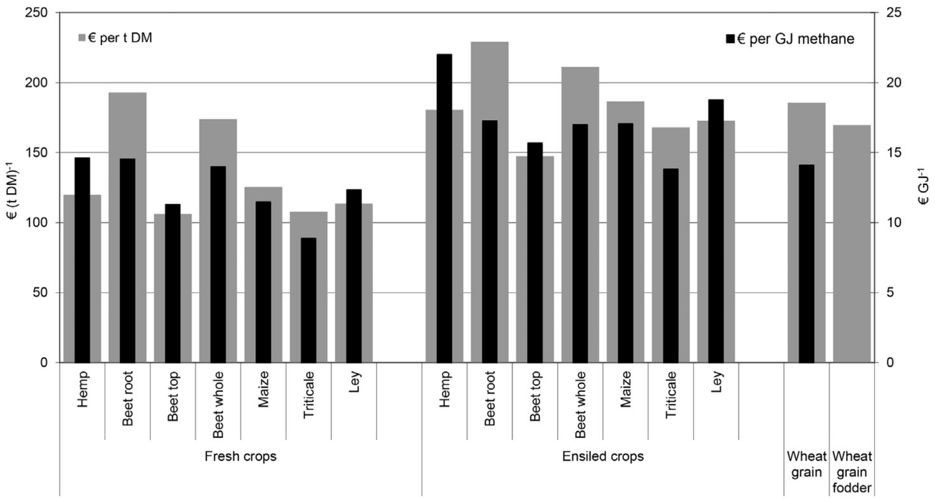

Fig. 6 – Costs of crop production and handling per ton DM (left axis, grey bars) and per GJ methane (LHV) (right axis, black bars). Note that only the costs of biomass production and handling are included, and not the costs of the biogas production process. Wheat grain produced for biogas production and fodder wheat are included for reference.

energy input, while wheat grain and hemp (both 19%), and ley (20%) had the highest. When part of the mineral fertiliser was replaced with digestate, the mean primary energy input decreased from 17 ± 3% to 11 ± 1% of the methane energy output for the crops investigated, with small differences between crops.

4.5. *Production costs*

Fig. 6 shows the costs of production and supply for crops as biogas feedstock, both per t DM and per GJ methane produced. Under the conditions specified, whole crop triticale gave the lowest feedstock costs, both as fresh crop and when ensiled. Sugar beet had very high feedstock costs based on DM, but due to the high methane yield of the crop the differences in cost per GJ methane were smaller. However, fresh beet roots and hemp both had slightly higher costs (14.5 € GJ^{-1}) than the reference crop wheat grain (14 € GJ^{-1}). Ensiling and storage of the biomass represented a large proportion of the feedstock costs, corresponding to an increase of approximately 20% for sugar beet and 49–56% for hemp, maize, triticale and ley compared with feeding fresh crops directly into the biogas plant. Taking ensiling costs and losses into account, triticale was the only crop with slightly lower feedstock costs (13.7 € GJ^{-1}) than the reference wheat grain. Hemp had the highest feedstock costs per GJ methane (21.9 € GJ^{-1}), while beet roots or whole beet and maize had similar costs (17.2, 16.9 and 17.0 € GJ^{-1}, respectively) and ley had slightly higher (18.7 € GJ^{-1}). The feedstock costs for beet tops when related to the methane produced were 78% (fresh) and 91% (ensiled) of the feedstock costs of the root. The tops can be regarded as a by-product of sugar beet cultivation, giving them a competitive advantage at high alternative values of land. Among the crops mentioned above, sugar beet had the highest energy production per hectare, giving decreased sensitivity to high land costs. If the alternative value of land decreases (e.g. at low wheat prices), cultivation of hemp, maize, triticale and ley would become relatively more economically favourable.

These crop feedstock costs can be compared to biogas feedstock prices presented in German guidelines from 2010 [47]. Feedstock prices recalculated per methane energy expected (using LHV for methane) are there given as 7.6, 10.6 and 14.2 € GJ^{-1} respectively for maize silage, ground cereal grains and grass silage. Crop feedstock costs can also be compared to the Swedish sales price of upgraded biogas as vehicle fuel, which in 2011 was 18.7–20.2 € GJ^{-1} [48].

5. Conclusions

This study compared aspects of crops as feedstock for biogas production under well-defined conditions. Comparing the land use efficiency expressed as biogas energy yield per hectare, the best crop was sugar beet with tops (160 GJ ha^{-1}). Ley and hemp, which are both considered to give a lower risk of negative environmental impact in cultivation, only gave half the energy yield per hectare of sugar beet with tops. Whole crop triticale gave an energy yield similar to that of winter wheat grain and maize, which is interesting since triticale is considered to have a lower risk of negative environmental impacts in cultivation than winter wheat, maize or sugar beet.

The primary energy input represented by mineral fertiliser in cultivation accounted for on average 48% of the total energy input in crop production and supply as biogas feedstock. When the majority of the mineral fertiliser was replaced by digestate, the decrease in primary input was significant, on average 34%. The primary energy input was then on average 11% of the energy output as methane, with small differences between the six crops studied. Since a shift from mineral fertiliser to digestate, complemented with mineral fertiliser, in the cultivation trials, was shown to have no significant effect on crop yields, except for hemp, per hectare or methane yields per crop DM, this is a promising strategy for improving the energy balance in energy crop cultivation.

When feedstock production costs were compared on the basis of the methane energy yielded by each crop, those of hemp and beet as fresh crops were almost as high as those of the economic reference crop, winter wheat grain. The other crops, including the by-product beet tops, had lower or much lower feedstock costs, with triticale having the lowest costs. For ensiled crops the feedstock costs increased significantly, and only those for triticale remained on a level slightly below those of the reference crop. However, all feedstock costs were so high that profitability is unlikely at present biogas prices for a crop-based biogas plant using only ensiled crops.

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Appendix A. Supplementary data

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.biombioe.2014.03.061.

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