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Evaluating intermediate crops for biogas production – Effects of nitrogen fertilization and harvest timing on biomass yield, methane output and economic viability

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ABSTRACT

Intermediate crops (ICs) are grown on large areas in Sweden and elsewhere for their function as cover or catch crops and to increase soil fertility, and they are usually soil-incorporated. The aim of this study was to investigate if aboveground biomass from ICs can be a sustainable source of biofuel feedstock. For that, the biomass yield of fertilized and unfertilized ICs was studied in field experiments and their energy potential determined using methane potential assays. Furthermore, we estimated the economic viability of biogas vehicle fuel production using the IC biomass. Our results indicated that it is economically viable to produce biomethane gas for vehicle fuel quality, from several intermediate crops grown in Northwest Europe, when the intermediate crop biomass was harvested with a self-loading forage wagon, used fresh or as silage as biogas feedstock and processed to methane gas in a large scale biogas plant. Nitrogen fertilization of intermediate crops was useful only when the intermediate crop is established early enough for the plant to make use of the nitrogen and 3 of the 9 investigated IC species could be grown economically feasible even without nitrogen fertilization and covering the full feedstock production costs. Other factors important for economic viability were a high gross methane yield per hectare combined with a high dry matter content in the IC biomass, with high dry matter yields to be prioritized over a higher specific methane yield. Further research is needed on the impact of IC maturity on methane production and suitable harvest technology.

1. Introduction

Green biomass is considered to be an important feedstock as substrate in production of biogas, which can be used to replace fossil energy carriers, e.g. upgraded as vehicle fuel, or as feedstock in the chemical industry as part of the circular bioeconomy [1–3]. In the recent decade, the cultivation and use of arable crops for that purpose has been limited due to the competition with food and feed production for the growing world population [4]. In this context, intermediate crops (i.e. a crop grown in the intermediate period between two main crops) may be a feedstock that can be used for biofuel generation. The main crops in such a cultivation system may be crops such as cereals, rapeseed, sugar beet, potatoes, field vegetables, etc. with the emphasis of producing food, while the intermediate crop is either a cover crop or a catch crop [5], possibly used for energy generation and recycling of plant nutrients. Such a use of intermediate crop biomass would not compete with food and feed production [6–10].

The use of intermediate crops, primarily as under-sown grasses in the main crop, is a common practice in cereals in Sweden [11–13]. Such under-sowing of grasses has been promoted through subsidies since the grass is acting as a catch crop, i.e. decreasing nitrogen leakage from the soil during the winter period [14,15]. Due to changes in subsidiaries, the interest in intermediate crops among farmers in Sweden has increased a lot. In 2023, farmers in Sweden applied for support for approximately 86,000 and 77,000 ha (ha; 1 ha = 10,000 m^2) to be grown with catch crops and intermediate crops, respectively [16], corresponding to a total of 6.5 % of the total arable land area. In terms of intermediate crop type, some reports have indicated that the interest for under-sown grasses,

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used as catch crops, has declined [14], while cover crops, such as oil seed radish, phacelia and buck wheat, are receiving increased attention [12,17]. In 2016, around 75 % of the 65,000 ha with intermediate crops were grasses and approx. 20 % were radish or oil seed radish in Sweden [18]. According to new rules in Sweden, intermediate crops can be mulched or harvested as feed or as a biogas feedstock, after the 20th of October.

Several studies have indicated a positive effect from the use of intermediate crops on soil nitrogen leakage, organic matter, structure and erosion [5,19–22]. Also, other multifunctional advantages such as reduction of plant diseases and weed control have been demonstrated from the use of intermediate crops [23–25]. Besides having the function of reducing nitrogen leaching from the soil, further multifunctionality of intermediate crops has been reported: as feedstock for production of biofuels [26], such as biogas. Biomass from several intermediate crops, also called energy cover crops [9], harvested in late autumn are suitable for use as feedstock in biogas production [27] without any competition with food production [6,7], potentially reducing nutrient losses to the environment [28].

The introduction of intermediate crops in an agricultural cultivation system can provide a sustainable intensification of the system, with a potential reduction of the ecological footprint, especially if the intermediate crops are used as biogas feedstock and the produced biogas and digestate substitute natural gas and mineral fertilizer, respectively [6,8,9]. Biogas can also be injected and stored in gas grids, mixed with natural gas [29–31].

In the south of Sweden, with a temperate climate and productive soils, several intermediate crops, e.g. buckwheat, hairy vetch, industrial hemp, oil seed radish, phacelia, Sudan grass, white mustard, can produce 3–7 metric Mg of dry matter (DM) per hectare (ha), when harvested in the end of October. However, in order to achieve such high biomass yields, the intermediate crops have to be seeded between mid-July to the beginning of August [32–34]. The intermediate crop biomass can be used fresh or as silage [31], to provide year-round feedstock supply, for biogas production [35]. However, despite their climate change mitigation potential [9,10], high costs have earlier been pointed out as barriers for cultivating intermediate crops [36]. It further remains unclear if use as biogas feedstock could improve their economic viability sufficiently [37], especially under Northern European conditions.

To our knowledge, there is no study that has investigated the combined effect of fertilization and harvest date on the specific methane potential of intermediate crops, established in mid-July to the beginning of August, after harvest of conventional main food crops. Also, studies evaluating the impact of such intermediate crops on economic feasibility of methane gas as vehicle fuel are lacking.

The aim of this study was to investigate how nitrogen fertilization and harvest date influence the biomass yield and the potential methane yield ha^{-1} from intermediate crops, under south Swedish conditions, and their overall economic viability as biogas feedstock in production of methane gas as vehicle fuel.

2. Materials and methods

2.1. Field experiments

2.1.1. Experimental sites

Two separate field cultivation experiments were carried out in southern Sweden during 2013 and 2014, with intermediate summer crops, grown after harvest of the main crops being green peas and whole crop wheat, respectively. In 2013, Stora Markie Farm, Anderslöv, Skåne, (55°26′4.32"N, 13°17′49.80"E) was used as experimental site, while in 2014 the experimental site was Kronoslätt Farm, Trelleborg, Skåne (55°22′3.61"N, 13°22′17.74"E). The accumulated growing degree days and precipitation (Table 1) were calculated from data from the nearest Lantmet weather station (Anderslöv, #40000).

Table 1
Growing degree days and precipitation accumulated over the growth period of the intermediate crops.

Year	Sep	Oct	Nov
Accumulated growing degree days [GDD]			
2013	304	309	310
2014	528	588	615
Accumulated precipitation [mm]			
2013	112	139	230
2014	196	236	336

2.1.2. Soil properties

The soil was at both sites a clay loam with pH 7.3 and 7.8 in Stora Markie and Kronoslätt, respectively. P-AL was determined as being between Classes III and IVA for Stora Markie and IVA for Kronoslätt, while P-HCL corresponded to Class 4 for both sites. The K-AL was Class III and K-HCL was Class 4 for both sites, as determined using the Swedish Standard SS28310T1 [38].

2.1.3. Soil preparation, drilling and fertilization

At both experimental sites, the fields were cultivated to a depth of 15 cm using a Väderstad TopDown multipurpose cultivator after the harvest of the pre-crop, to loosen the topsoil layer, and to incorporate the green pea residues (in Stora Markie) and straw stubble (in Kronoslätt), on 10 and 11 July, in 2013 and 2014, respectively. Directly thereafter, the intermediate crops were drilled in 30 m long and 8 m wide strips using a Väderstad Rapid 800 seed drill in Stora Markie and in 40 m long and 6 m wide strips using a Väderstad Rapid 300 seed drill in Kronoslätt.

In order to investigate if biomass and biogas yields could be improved, a nitrogen fertilizer was applied. Since intermediate crops grown as catch crops are intended to take up residual soil nitrogen, only a low dose of 40 kg ha^{-1} nitrogen fertilizer seemed applicable. To also test the limit of the potential fertilization effect, a doubled dose (80 kg ha^{-1} nitrogen) was included in 2014. In 2013, part of the intermediate crops area was fertilized with 40 kg nitrogen (N) ha^{-1} in the form ammonium nitrate (N27) in an 8 m broad band across all strips using a boom mineral fertilizer spreader, so that each 8 m pass with the seed drill comprised two fertilization treatments: unfertilized (0 kg N ha^{-1} = ‘0’) and fertilized (40 kg N ha^{-1} = ‘40’). Similarly, in 2014, part of the intermediate crop area was fertilized with 40 respectively 80 kg N ha^{-1}, in the form of ammonium nitrate (N27). The nitrogen fertilization was done in two passages, across all seeded strips, using a boom mineral fertilizer spreader 12 m wide, so that each 6 m perpendicular pass with the seed drill, now comprised of tree fertilization treatments: unfertilized (0 kg N ha^{-1} = ‘0’), fertilized with 40 kg N ha^{-1} (=‘40’) or fertilized with 80 kg N ha^{-1} (=‘80’). This gave a regular lattice design to the experiment plots, where one factor (intermediate crop treatments) was arranged as strips in one direction and the other factor (0 or 40 kg N ha^{-1} in 2013 and 0, 40 or 80 kg N ha^{-1}) was applied perpendicular to these strips as split plot. The control plots without any intermediate crop vegetation (treatments E and L) were tilled one more time at the end of September to keep them free from weeds (Table 2).

2.1.4. Intermediate crops

The following intermediate crops were included in the experiment in 2013 at Stora Markie: oilseed radish, white mustard, buckwheat, phacelia, hairy vetch and winter rye (Table 2). In 2014, the following intermediate crops were used in the experiment at Kronoslätt: industrial hemp, oilseed radish, phacelia, Sudan grass, vetch and white mustard (Table 2). All seed material was obtained from Olssons Frö AB, Helsingborg, Sweden. When combining several intermediate crops, the seed rate was calculated according to the formula: Proportion of the species in the treatment multiplied with the normal recommended total seed rate in kg ha^{-1} (Table 2).

Table 2
Intermediated crops with corresponding seeding rates as tested in the field experiments in 2013 and 2014.

Treatment	Intermediate crop, 'cultivar' (Latin name)	Seed rate (% of recommended)[a]
Stora Markie. 2013		
A.	1) Oilseed radish, 'Colonel' (*Raphanus sativus* L. *var. oleiformis* Pers.)	100
B.	1) White mustard, 'Accent' class I (*Sinapsis alba* L.)	60
	2) Oilseed radish, Colonel' (*Raphanus sativus* L. *var. oleiformis* Pers.)	40
C.	1) Buckwheat, 'Hajnalka' (*Fagopyrum esculentum* Moench)	60
	2) Phacelia, 'Stala' (*Phacelia tanacetifolia* Benth.)	40
D.	1) Rye, 'Palazzo' (*Secale cereale* L.)	40
	2) Hairy vetch, 'Dr. Baumann's' (*Vicia villosa* ssp. *villosa* Roth)	20
	3) Buckwheat, 'Hajnalka' (*Fagopyrum esculentum* Moench)	20
	4) Phacelia, 'Stala' (*Phacelia tanacetifolia* Benth.)	20
E. (Control)	No intermediate crop, bare soil after harvest of the main crop - green peas	–
Kronoslätt, 2014		
F.	Oilseed radish, 'Colonel' (*Raphanus sativus* L. *var. oleiformis* Pers.)	100
G.	White mustard, 'Accent' class I (*Sinapsis alba* L.)	100
H.	Hemp, 'Futura 75' (*Cannabis sativa*)	100
I.	Sudan grass, 'Piper' (*Sorghum sudanese*)	100
J.	Hairy vetch, 'Dr. Baumann's' (*Vicia villosa* ssp. *villosa* Roth)	100
K.	Phacelia, 'Stala' (*Phacelia tanacetifolia* Benth.)	100
L. (Control)	No intermediate crop, bare soil after harvest of the main crop - whole-crop wheat	–

[a] Recommended seeding rates were oilseed radish 15 kg ha^{-1}, white mustard 12 kg ha^{-1}, buckwheat 60 kg ha^{-1}, phacelia 12 kg ha^{-1}, winter rye 180 kg ha^{-1}, hairy vetch 50 kg ha^{-1}.

2.1.5. Sampling

In 2013, intermediate crop biomass yield was determined by hand-harvesting three randomly selected sub-areas (0.25 m^2) in all intermediate crop plots (A-D). The sampling was done on three different occasions during autumn, on 13 September, 7 October and 6 November. Intermediate crop biomass was cut to approximately 2 cm above the soil surface and the samples from the three sub-areas in the crop plot were pooled to one sample per plot.

For determination of specific methane gas production and methane yield ha^{-1}, another separate sample (0.25 m^2) was taken in every intermediate crop treatment on the three measuring occasions, giving a total of eight samples per sampling occasion (A0, A40, B0, B40, C0, C40, D0 and D40). These samples were chopped in a compost shredder (Cotech) at 2850 rpm to approx. 2–3 cm length. In 2014, fresh hand-harvested samples of the intermediate crop were taken at Kronoslätt in 24 September, 15 October and 4 November, in the same way as in 2013, at Stora Markie.

Subsamples of the fresh samples, hand-harvested in 2013 and 2014, were used to determine DM content based on weight before and after drying at 105 °C for 48 h. Volatile solids (VS) content was determined based on weight of dried samples before and after incineration at 550 °C for 2 h. The remaining part of the fresh biomass samples were frozen at −18 °C for later analysis. Before further analysis of the frozen samples, these were thawed at room temperature.

2.2. Biochemical methane potential assay

Biochemical methane potential (BMP) assays of the intermediate crop samples were performed using an Automatic Methane Potential Test System II (AMPTS II, by Bioprocess Control, Lund, Sweden). The incubation temperature was 37 °C and time 30 days. The methane contents of the head spaces of the test flasks were determined in the end of the assay using a gas chromatograph fitted with a thermal conductivity detector. The intermediate crop samples were kept frozen for maximum 7 months prior BMP assays. Multiple AMPTS II units were used to fit all samples. Samples and controls were tested in quadruplicates, except the cellulose control in harvest 2013, which was tested in triplicates. Two controls were included: one with only the inoculum and a second with inoculum and microcrystalline cellulose (Avicel 179 PH-101, Sigma-Aldrich, St. Louis, MO, USA and cellulose powder microcrystalline, MP Biomedicals, USA, for BMP of crops harvested in 2013 and 2014, respectively). For controls as well as samples, 300 g inoculum per replicate and an inoculum to substrate ratio of 2:1, based on VS, was used. Methane yields (dry gas) were normalized by correcting to a temperature of 0 °C and a pressure of 101.3 kPa. The lower heating value of methane (35.8 MJ m^{-3}) was used for conversion to energy units. Inoculum was taken from an anaerobic digestion reactor at Källby municipal wastewater treatment plant, Lund, Sweden (VA SYD, Sweden). The inoculum was pre-incubated (anaerobically) for 5 days at 37 °C, in aliquots of 4 L. The methane potential of samples was evaluated based on their specific methane yield (SMY) in cubic meters of methane per Mg of volatile solids (m^3 CH_4 Mg^{-1} VS) added, defined as the total volume of methane produced during the digestion period per amount of sample initially added.

2.3. Statistical analyses

Biomass yield, DM content and methane potential data were tested statistically using SAS software (SAS Institute Inc, Cary, USA), Version 9.4, in order to find statistically significant differences between treatments. Fertilization level and harvest date were used as factors for an ANOVA analysis using a general linear model. Where factors did not result in statistical differences, the impact of fertilization level were tested using the post-hoc Tukey's test for each harvest date and for each crop individually in order to investigate if there are any harvest date-related significant differences in the responses ($p < 0.05$).

2.4. Economic assessment

Effects of nitrogen fertilization level and harvest date on methane potential per hectare and cost for the intermediate crops as biogas feedstock were assessed using life cycle assessment methodology following ISO standard 14044 [39]. For that purpose, data from the field and lab experiments were complemented with literature data for crop cultivation and processing costs for anaerobic digestion and upgrading of biogas to vehicle fuel standard.

To assess the value of intermediate crops harvested as biogas feedstock, cost and revenue were estimated using a step-by-step calculation. This calculation included all necessary machinery operation in the field, transport, storage and processing (anaerobic digestion and upgrading the biogas to vehicle fuel standard) in a simulated biogas plant.

Results of the field and lab experiments used as data for the assessment, were modified to reflect the technical potential of the crops, i.e. (1) biomass yields were assumed to be 90 % of the hand-harvested yields and (2) the specific methane potential of the intermediate crops was assumed to be 90 % of the SMY as determined in the BMP assays [40].

The specific methane potential for intermediate crops fertilized with 0 or 80 kg N ha^{-1} was assumed to be the same as for the same intermediate crop fertilized with 40 kg N ha^{-1}. Phacelia was already withering in the field experiment, which resulted in a very low SMY. Therefore, a higher earlier value of 275 m^3 CH_4 Mg^{-1} VS was assumed for the harvest in September [41]. Additional data used in the assessment of the intermediate crop cultivation is presented in Table 3.

2.4.1. Machinery operations

All field operations assumed the use of a 200 kW tractor. A false seedbed was assumed to be prepared using a harrow with a field capacity of 4.8 ha h^{-1}, followed by the seedbed preparation for the intermediate crop by using a one-pass multipurpose cultivator (Väderstad TopDown) with an effective field capacity of 2.9 ha h^{-1}. The intermediate crop was then assumed to be sown and fertilized with mineral nitrogen in one pass by using a combi seed drill (Väderstad Rapid 400 C, 4 m working width) with an effective field capacity of 2.0 ha h^{-1}.

Harvest of the intermediate crop was assumed to be carried out according to the harvest date in the field experiments, in one pass, by using a tractor-drawn mowing and self-loading forage container wagon (zero grazing harvester as described in Holohan, Russell, Mulligan, Pierce and Lynch [42]) with a maximum capacity of 13 Mg biomass or 40 m^3. A maximum harvesting speed of 15 km h^{-1} was assumed for biomass yields per hectare lower than approx. 15 Mg wet weight ha^{-1}, or approx. 2.25 Mg ha^{-1} DM. The harvested biomass was assumed to be transported by the tractor on field roads (1.0 km away at an average speed of 25 km h^{-1}) to a place where the forage container was switched to an empty one. The harvest capacity was between 1.0 and 1.5 ha h^{-1}, depending on the level of biomass yield per hectare. Three full containers, at a time, approx. 40 Mg of biomass where transported by a container trailer truck to the biogas plant (30 km away at an average speed of 60 km h^{-1}). Costs for machinery operations are given in Table 4.

At the biogas plant, the biomass was assumed to be unloaded in a concrete bunker silo, and then compacted as silage using a 12 Mg front loader. The bunker silo was assumed to be covered with silage plastic covers. The removal of biomass and feed-in into the reception tank of the biogas plant assumed the use of the same front loader as used for compaction of the biomass to silage. Transport density was estimated based on a DM density of 85 kg DM m^{-3} [43] and the corresponding DM content. The costs of machinery operation were estimated according to cost per hour and the amount of time used for the different field operations using standard cost recommendations [44].

Table 4
Machinery costs according to branch recommendations [44].

Machinery	Specifications	Capacity	Costs[a] [€ h^{-1}]
Tractor	200 kW		114
Harrow	8 m	4.8 ha h^{-1}	127
Multicultivator	4 m (disc, tine roller)	2.9 ha h^{-1}	150
Combi seed drill	4 m, 3300 L	2.0 ha h^{-1}	182
Self-loading forage wagon	56 m^3	118 t h^{-1}	230
Truck with 2 containers	2 × 36 m^3, max 60 t		126
Front loader	12 t, 110 kW	Compaction: 0.4 min Mg^{-1} Feed-in: 104 t h^{-1}[b]	77

[a] Including costs for driver and fuel.
[b] Assuming an effective bucket volume of 4.5 m^3, 300m transport distance, 20 km h^{-1} transport speed and a filling and unloading time of each 10 s per bucket load.

2.4.2. Feedstock storage

Costs for storage in bunker silos were assumed to be 2.68 and 5.59 EUR m^{-3} a^{-1} for the silo and covering the silo with a plastic cover, respectively [45]. Storage density was estimated according to Hjelm and

Table 3
Data used for the economic assessment of the intermediate crop production and transport logistics.

Year	Crop	Harvest	Fertilization[a]	Seeding material		DM content	VS content	Transport density	Storage density
			[kg N ha^{-1}]	[kg ha^{-1}]	[€ kg^{-1}]	[%]	[% of DM]	[kg m^{-3}]	[kg m^{-3}]
2013	Oilseed radish	Oct	0	15	3.9	12.6	87.7	676	1000
2013	Oilseed radish	Oct	40	15	3.9	11.1	86.4	766	1000
2013	Oilseed radish	Nov	0	15	3.9	9.5	85.2	897	1000
2013	Oilseed radish	Nov	40	15	3.9	12.0	86.1	711	1000
2014	Oilseed radish	Oct	0	15	3.9	11.2	90.5	758	1000
2014	Oilseed radish	Oct	80	15	3.9	11.9	90.5	715	1000
2014	Oilseed radish	Nov	40	15	3.9	18.0	90.5	473	851
2013	White mustard + oilseed radish	Oct	0	12	3.4	19.2	88.4	443	820
2013	White mustard + oilseed radish	Oct	40	12	3.4	18.0	90.3	473	851
2013	White mustard + oilseed radish	Nov	0	12	3.4	19.2	87.9	443	819
2013	White mustard + oilseed radish	Nov	40	12	3.4	24.3	87.9	350	721
2014	White mustard	Sep	0	12	3.4	25.4	92.2	334	704
2014	White mustard	Oct	80	12	3.4	19.4	92.2	437	813
2014	White mustard	Nov	40	12	3.4	39.5	92.2	215	578
2013	Buckwheat + phacelia	Oct	0	41	1.8	15.9	85.9	536	917
2013	Buckwheat + phacelia	Nov	0	41	1.8	22.2	81.5	384	756
2013	Rye + hairy vetch + buckwheat + phacelia	Oct	0	96	1.4	13.6	85.6	626	1000
2013	Rye + hairy vetch + buckwheat + phacelia	Nov	0	96	1.4	28.3	81.1	300	668
2013	Rye + hairy vetch + buckwheat + phacelia	Nov	40	96	1.4	13.1	78.6	649	1000
2014	Hemp	Sep	0	30	5.9	29.5	89.3	288	655
2014	Hemp	Sep	80	30	5.9	29.0	89.3	293	660
2014	Hemp	Nov	40	30	5.9	30.0	89.3	283	650
2014	Sudan grass	Sep	0	25	2.3	19.0	90.6	448	824
2014	Sudan grass	Oct	80	25	2.3	19.8	90.6	430	805
2014	Sudan grass	Nov	40	25	2.3	21.7	90.6	392	765
2014	Hairy vetch	Sep	0	50	2.9	11.1	86.2	768	1000
2014	Hairy vetch	Nov	40	50	2.9	15.8	86.2	538	920
2014	Phacelia	Sep	0	12	1.2	16.4	84.6	518	899
2014	Phacelia	Sep	80	12	1.2	14.2	84.6	597	983
2014	Phacelia	Nov	40	12	1.2	28.6	84.6	297	665

[a] Mineral nitrogen fertilizer was assumed to cost 1.0 € kg^{-1} [69].

Spörndly [46], but was limited to a maximum of 1000 kg m^{-3}, Eq. (1):

$$Required\ storage\ density\left[\frac{kg}{m^3}\right]=DM\ content\ [\%]\bullet 3.5\left[\frac{kg}{\%\bullet m^3}\right]+90\left[\frac{kg}{m^3}\right] \quad (1)$$

2.4.3. Biogas process

The whole system for production of biogas vehicle fuel was modelled in order to estimate costs for each operation. The production steps included cultivation and harvest of the intermediate crops, transport and storage of the biogas feedstock, feed-in to a large-scale biogas plant and upgrading of the raw biogas to pure methane gas, according to vehicle fuel standards (95–99 % CH_4).

Cost for production of biogas were estimated for a biogas plant with a production capacity of 110 GWh of methane per year. It was assumed that the digestion process at a medium and large scale biogas plant varied between 0.315 and 0.431 € m^{-3} methane, respectively [47]. As these data were originally calculated for the digestion of starch-containing energy crops such as maize, a correction factor was calculated for each of the feedstock options. This correction factor was based on the substrates' methane production in m^3 m^{-3} reactor volume, Eq. (2):

$$\boldsymbol{Correction\ factor}=\frac{\boldsymbol{Volumetric\ productivity}_{maize}\left[\frac{Nm_{methane}^3}{m^3_{reactor\ volume}}\right]}{\boldsymbol{Volumetric\ productivity}_{substrate}\left[\frac{Nm_{methane}^3}{m^3_{reactor\ volume}}\right]} \quad (2)$$

2.4.4. Biogas upgrading

Costs for upgrading the raw biogas to vehicle fuel quality (pure methane) were estimated to be between 6.9 and 13.7 € MWh^{-1} methane [47].

2.4.5. Digestate handling

The total volume of required digestate storage was assumed to cover 50 % of all annually produced digestate, because the digestate was assumed to be used both in spring and in autumn sown crops. Costs for using a liquid storage pit with gastight roof were assumed to be between 1.4 and 2.8 € m^{-3} a^{-1} [44]. The economic role of digestate for the biogas plant was not accounted for, since local conditions will steer if digestate is an income or a cost. In that respect we assumed that removal of intermediate crop biomass also would have resulted in removal of plant nutrients. Of the removed nitrogen, only a limited fraction would have been made available to the next crop, due to mineralization and nutrient leakage, if the biomass is left on field. When removed and processed in the biogas plant, nitrogen would have been preserved to a high degree (usually assumed around 90–95 %) which could have been made available through spreading of the digestate to a crop in need of fertilization. Together with costs for spreading the digestate, we assumed that economic gains and cost for digestate utilization would balance each other.

2.4.6. Ability to pay

The ability of the biogas plant to pay for feedstock was calculated as the difference between an assumed market price for biogas vehicle fuel and the plant's costs for biogas production and upgrading to vehicle fuel quality (Table 5), Eq. (3):

$$\boldsymbol{Ability\ to\ pay}_{substrate}\left[\frac{€}{\boldsymbol{MWh}}\right]=\boldsymbol{Market\ price}_{vehicle\ fuel}-\boldsymbol{Costs}_{biogas\ production}-\boldsymbol{Costs}_{upgrading}-\boldsymbol{Costs}_{digestate\ storage} \quad (3)$$

Table 5
Parameters concerning the market price of biogas vehicle fuel used to calculate the ability to pay in Equation (3).

Parameter	Unit	Range	Reference
Market price[a]	[€ kg^{-1}]	1.63–2.39	[48]
Upgrading costs	[€ MWh^{-1}]	342–469[b]	[47]
Distribution costs	[€ MWh^{-1}]	24.2[c]	[70]
Refueling costs	[€ MWh^{-1}]	11.3[c]	[70]

[a] Range given for prices between 2018 and 2022, excluding taxes.
[b] Used as low and high case, respectively, to produce a range of ability-to-pay calculations.
[c] Adjusted by an increase of 50 % as indicated by the price development of biogas vehicle fuel between 2014 and 2022.

In the years 2018–2022, the market price of biogas vehicle fuel at the gas station varied between 1.59 and 3.92 € kg^{-1} excluding taxes [48]. For the assessment the market price of biomethane fuel at the gas station was assumed to be between 1.63 and 2.39 € kg^{-1} corresponding to the 15 and 85 % percentile.

3. Results and discussion

3.1. Biomass yields

3.1.1. Impact of nitrogen fertilization on intermediate crop biomass yield

Intermediate crops yielded on average 4060 and 3470 kg DM ha^{-1} in November in 2013 and 2014, respectively (Table 6). Nitrogen fertilization of 40 kg N ha^{-1} did not contribute to any significant biomass yield increase, when cultivated after incorporation of nitrogen-rich green pea residues into the soil at Stora Markie in 2013 and harvested in October, for any of the investigated crops. For oilseed radish harvested in November 2013, fertilization with 40 kg N ha^{-1} increased the biomass yield with 40 %, indicating that nitrogen fertilization can increase biomass yields when there is enough growing time to take up the nitrogen. Oilseed radish is known to be insensitive to light frost and to have a continuous growth even in November [33], an effect also appearing for oilseed radish in 2014 of the present study.

Despite this, the biomass yield did not increase in November 2014 at the high fertilization level (80 kg N ha^{-1}) compared to when the medium fertilization level (40 kg N ha^{-1}) was used at Kronoslätt, with whole-crop wheat harvested in July as a pre-crop. Similar fertilization effects (no impact of the high fertilization level in November) were seen for the other intermediate crops in 2014, except for the hairy vetch. The latter is a legume, a likely reason for not showing the same response to nitrogen fertilization as the other not nitrogen-fixating intermediate crops, with the exception of when it was harvested in November. Biomass yields of hairy vetch were lower in October and November compared with September.

The biomass yield of the investigated crops did not differ significantly due to differences in crops or fertilization levels in 2013 (Table 6a). Oppositely, significant differences were seen both for N fertilization level (both comparing 0 and 40 kg N ha^{-1} and comparing 0 and 80 kg N ha^{-1}) and for the different intermediate crops, when cultivated after the whole-crop wheat at Kronoslätt in 2014. The different responses to nitrogen fertilization can be explained by the residual nitrogen left in the soil profile after the main crops. Green pea is

Table 6
Biomass yield of summer intermediate crops (LS-mean, kg dry matter per hectare) grown at various nitrogen fertilization levels and harvest dates, at a) Stora Markie in 2013, after the main crop green pea, and at b) Kronoslätt in 2014, after the main crop whole-crop wheat. The number of replicates for the crops were n = 4 in 2013 and n = 3 or 4 (as given) in 2014. Means with the same capital letter (horisontal comparison) or lower case letter (vertical comparison) are not significantly different (Tukey method $p < 0.05$). Numbers in brackets indicate standard deviation).

Parameter	Biomass yield per intermediate crop (kg dry matter per hectare)					
A) Stora Markie 2013	Oilseed radish	White mustard, oilseed radish	Buckwheat, phacelia	Rye, hairy vetch, buckwheat, phacelia		
N fertilization (kg ha^{-1})						
0	2821 (±1270) Aa	3303 (±1162) Aa	2862 (±1036) Aa	2530 (±1340) Aa		
40	3647 (±1605) Aa	3835 (±1098) Aa	2951 (±827) Aa	2977 (±986) Aa		
Harvest time						
Sept	1807 (±1176) Ac	2234 (±533) Ab	2044 (±384) Ab	1588 (±603) Ac		
Oct	3390 (±1200) ABb	3988 (±450) Aa	3255 (±715) ABa	2823 (±703) Bb		
Nov	4504 (±1090) Aa	4486 (±757) Aa	3420 (±904) Aa	3849 (±856) Aa		
B) Kronoslätt 2014	Hemp n = 3	Oilseed radish n = 4	Phacelia n = 3	Sudan grass n = 3	Hairy vetch n = 3	White mustard n = 4
N fertilization (kg ha^{-1})						
0	1976 (±335) *Cc*	2705 (±286) ABc	3124 (±420) Ab	1944 (±34) *Cc*	2829 (±623) Aa	2258 (±39) BCc
40	4144 (±506) BCb	4498 (±224) Bb	5553 (±597) Aa	3436 (±155) Cb	2487 (±567) Da	3497 (±279) Cb
80	5629 (±719) ABa	5400 (±416) ABCa	6169 (±573) Aa	4456 (±316) Ca	2402 (±557) Da	4895 (±83) BCa
Harvest date						
Sept	4376 (±1968) ABa	3968 (±1450) ABb	5078 (±1545) Aa	3087 (±1104) Ba	3178 (±333) Ba	3493 (±1293) ABa
Oct	4007 (±1931) ABCa	4511 (±1465) ABa	5389 (±1761) Aa	3369 (±1333) BCa	2451 (±49) Cb	3677 (±1334) ABCa
Nov	3367 (±1622) ABb	4123 (±1212) Aab	4380 (±1532) Aa	3380 (±1354) ABa	2089 (±371) Bb	3480 (±1349) ABa

known for leaving large amounts of nitrogen in the soil profile, which likely would reduce or mask the effect of nitrogen fertilization [49]. In comparison, the effect would be stronger in a N-emptied soil profile found after a cereal crop [49]. Given a low mineral nitrogen level in the soil, responses are likely more pronounced than when high mineral nitrogen levels in the soil add to the fertilization effect. In general, increased amount of N fertilizer contributed to an increase in yield in 2014 for the intermediate crops seeded after harvest of whole-crop wheat, except for hairy vetch, where no significant variation in yield was found for the different N fertilization levels. Furthermore, phacelia showed no yield increase from 40 to 80 kg N ha^{-1}. Among the unfertilized intermediate crops from 2014, phacelia, hairy vetch and oilseed radish resulted in high biomass yield of 2700–3100 kg DM ha^{-1} (Table 6b).

3.1.2. *Effect of harvest date on intermediate crop biomass yield*

In 2013, when the pre-crop was green pea, the harvest in October or November gave higher biomass yields (2800–4500 kg DM ha^{-1}) than harvest in September (1600–2200 kg DM ha^{-1}) for all crops (Table 6). For oilseed radish and the mixture of winter rye, phacelia, buckwheat and hairy vetch, the biomass yield increased when harvested in November compared to October. When the intermediate crops were harvested in October in 2013, the mix of white mustard and oilseed radish resulted in a higher biomass yield per hectare than the mixture of winter rye, phacelia, buckwheat and hairy vetch (Table 6a), differently to the harvest in September and November that resulted in no differences in yield among the different crops.

In 2014, when the pre-crop was whole-crop wheat, no positive yield effect of a late harvest of the intermediate crops was found in contrast to 2013, with green pea as pre-crop (Table 6b). In fact, higher biomass yields in October and November were only found for oilseed radish. For hairy vetch, the highest yield was found in September and for industrial hemp when harvested in September or October. No significant difference in biomass yield was found among any of the harvest occasions for phacelia, Sudan grass or white mustard in 2014 (Table 6b).

Even without fertilization, the biomass yields shown in the current study were on average considerably higher than reported earlier for white mustard and oilseed radish cultivated in the same climate zone, in Denmark, and harvested in October and November [27]. The reasons are unknown since many factors differ between field experiments such as soil type, soil preparation, pre-crop, sowing date, precipitation and year of cultivation. Biomass growth is usually positively correlated to the number of growing days and ambient temperature. Therefore, an earlier sowing date during the summer will likely mean considerable higher biomass yield, given that temperature and growth time are the growth-limiting factors. A recent study found a considerable higher biomass production the earlier the intermediate crops were established [33]. However, plant access to sufficient water resources may hinder establishment of intermediate crops during dry and hot summers. Future studies aiming to find which species-specific factors promote a high

Table 7
Biochemical methane potential (BMP) of intermediate crops in m^3 Mg^{-1} VS (volatile solids) grown during 2013 and 2014, in 2013 with different levels of fertilization and harvested at different occasions. The SMY of the crops cultivated at Kronoslätt in 2014 was only determined for crop samples after fertilization with 40 kg N and harvest in November. Means with the same capital letter (horisontal comparison) or lower case letter (vertical comparison) are not significantly different (Tukey method $p < 0.05$). Numbers in brackets indicate standard deviation).

2013	BMP	2014	BMP
Crop		Crop	
Oilseed radish	325 (±26) a	Hairy vetch	343 (±20) a
White mustard + oilseed radish	266 (±31) b	Sudan grass	319 (±18) ab
Buckwheat + phacelia	264 (±21) b	Oilseed radish	297 (±10) bc
Rye + hairy vetch + buckwheat + phacelia	258 (±12) b	White mustard	279 (±7) c
		Hemp	246 (±16) d
Fertilization		Phacelia	178 (±9) e
0	289 (±35) a		
40	270 (±46) a		
Harvest			
Oct	291 (±42) a		
Nov	272 (±36) a		

biomass yield, and low variation thereof, are motivated since the biomass yield has a strong influence on the economic output of biogas and digestate production from intermediate crops.

3.2. Methane yield

The specific methane yield (SMY) of intermediate crops varied considerably between approx. 180–340 m^3 Mg^{-1} VS (Table 7). For crops grown in 2013 the highest SMY was found for oilseed radish with approx. 325 m^3 Mg^{-1} VS. The SMY of the three intermediate crop mixtures were significantly lower, in average 20 % lower. For crops grown in 2014 the highest SMY were obtained for hairy vetch with approx. 343 m^3 Mg^{-1} VS (Table 7). Oilseed radish and white mustard had a SMY significantly lower, in average 24 % lower, than the SMY of hairy vetch. The SMY of hemp and phacelia were 29 % and 48 % lower than the SMY of hairy vetch, respectively, and significantly lower than all other crops cultivated in 2014. The SMY of the cellulose controls and the relative standard deviations of them were in all BMP tests within the reference values used for BMP assays [50].

Fertilization and month of harvest had no significant effect on the SMY when all intermediate crops and crop mixtures were compared together. However, for some of the individual crops and crop mixtures, differences were found between harvest in October and November and for fertilization level, as presented in Table 8. For fertilized oilseed radish harvested in November, a significantly lower SMY was found compared to unfertilized oilseed radish harvested in October and November and fertilized oilseed radish harvested in October. For the co-cultivation of oilseed radish and white mustard the SMY of unfertilized crop harvested in October was higher than fertilized crop harvested in October and November.

The SMY of unfertilized oilseed radish was found to be independent of harvest time from September to November, in agreement with results presented by Belle, Lansing, Mulbry and Weil [51]. They reported a lack of influence of harvest time on the SMY of unfertilized oilseed radish when comparing harvest after two and four months of cultivation in Maryland, USA, and pointed out that it provides an opportunity for farmers to have flexible harvest over two months. Compared to the present study, Molinuevo-Salces, Larsen, Ahring and Uellendahl [52] reported similar or higher SMY of oilseed radish (368–474 m^3 Mg^{-1} VS) cultivated as intermediate crop.

The high SMY from hairy vetch is in agreement with a study by Molinuevo-Salces, Larsen, Ahring and Uellendahl [27] where three co-cultivations with hairy vetch as intermediate crop all gave high SMY of 340–415 m^3 Mg^{-1} VS. In accordance with the present study, Herrmann, Idler and Heiermann [41] reported SMY of silages of a Sudan grass hybrid (*Sorghum bicolor x sudanese*) and of forage Sorghum (*Sorghum bicolor*) to be around 340 m^3 Mg^{-1} VS.

The SMY of white mustard was similar to SMYs earlier reported by Molinuevo-Salces, Larsen, Ahring and Uellendahl [27]. Wójcik Oliveira and Słomka [53] reported an influence of harvest time on the SMY for white mustard, cultivated in pure stand, with a lower SMY when cultivated for three months (July to October) than when cultivated for two months (August to October), in Poland. In the current study, no significant difference was shown in the SMY of co-cultivated oilseed radish and white mustard with varying harvest time from September to November in 2013 (Table 8). A difference could be expected based on the results by Wójcik Oliveira and Słomka [53]. However, the difference in growing days were only 6 days between September and November and small differences are difficult to prove.

The SMYs of hemp was similar to, and in the higher range, of yields previously reported [27,54]. The lowest SMY was found in phacelia with only 178 m^3 Mg^{-1} VS. According to Ahlberg and Silva Nilsson [55], phacelia had the highest lignin content of all the crops investigated in 2014 and lignin is known to restrict the extent of anaerobic digestion of plants [41]. Herrmann, Idler and Heiermann [41] reported a SMY of around 300 m^3 Mg^{-1} VS for phacelia, which is considerably higher compared to the present study. Maxin, Graulet, Le Morvan, Picard, Portelli and Andueza [56] measured the *in vitro* true organic matter digestibility, as an indication of ruminal digestibility, of phacelia and found a statistically significantly higher digestibility and crude protein content of phacelia harvested at vegetative stage than at flowering stage. Based on these studies, the harvest time of phacelia in the present study was likely later than optimal for the highest SMY and possibly also for highest methane yield per hectare. Herrmann, Idler and Heiermann [41] determined the SMY of co-cultivated and ensiled buckwheat and phacelia to be around 250 m^3 Mg^{-1} VS, in likeness with the current study. Maxin, Graulet, Le Morvan, Picard, Portelli and Andueza [56] reported a high content of phenolic compounds in buckwheat, especially in the flowering stage, in relation to for instance phacelia, and refer to studies showing inhibiting effects of phenolic compounds on methanogenesis.

The DM content of the intermediate crops biomass varied considerably, between 9.5 and 39 % (Table 8). In a maturing crop, the DM content increases, and the chemical composition changes [57], which may have a negative impact on the SMY, as pointed out above.

Table 8

Dry matter (DM) content, specific methane yield (SMY) and gross methane yield of summer intermediate crops grown during 2013 and 2014 with different levels of fertilization and harvest month. Means with the same letter are not significantly different (Tukey method $p < 0.05$). The gross methane yield per hectar is based on the average biomass yield of the treatments, their volatile solids content and their SMY. Numbers in brackets indicate standard deviation).

Year	Intermediate crop	Fertilization	Harvest month	DM content [%]	SMY [m^3 Mg^{-1} VS]	Gross methane yield [m^3 ha^{-1}]
2013	Oilseed radish	0	Oct	12.6	329 (±19) ab	859
2013	Oilseed radish	0	Nov	9.5	339 (±19) ab	1080
2013	Oilseed radish	40	Oct	11.1	341 (±24) ab	1121
2013	Oilseed radish	40	Nov	12.0	259 (±48) defg	1175
2013	White mustard + oilseed radish	0	Oct	19.2	310 (±12) abcd	1063
2013	White mustard + oilseed radish	0	Nov	19.2	271 (±6) defg	988
2013	White mustard + oilseed radish	40	Oct	18.0	230 (±13) g	851
2013	White mustard + oilseed radish	40	Nov	24.3	253 (±10) fg	1073
2013	Buckwheat + phacelia	0	Oct	15.9	276 (±15) cdef	755
2013	Buckwheat + phacelia	0	Nov	22.2	253 (±22) fg	704
2013	Rye + hairy vetch + buckwheat + phacelia	0	Oct	13.6	260 (±15) efg	527
2013	Rye + hairy vetch + buckwheat + phacelia	0	Nov	28.3	256 (±11) defg	840
2013	Rye + hairy vetch + buckwheat + phacelia	40	Oct	13.1	257 (±13) efg	738
2014	Hemp	40	Nov	30.0	246 (±16) fg	807
2014	Oilseed radish	40	Nov	18.0	297 (±10) bcde	1218
2014	White mustard	40	Nov	39.5	279 (±7) cdef	833
2014	Phacelia	40	Nov	28.6	178 (±9) h	749
2014	Sudan grass	40	Nov	21.7	319 (±18) abc	1009
2014	Hairy vetch	40	Nov	15.8	343 (±20) a	580

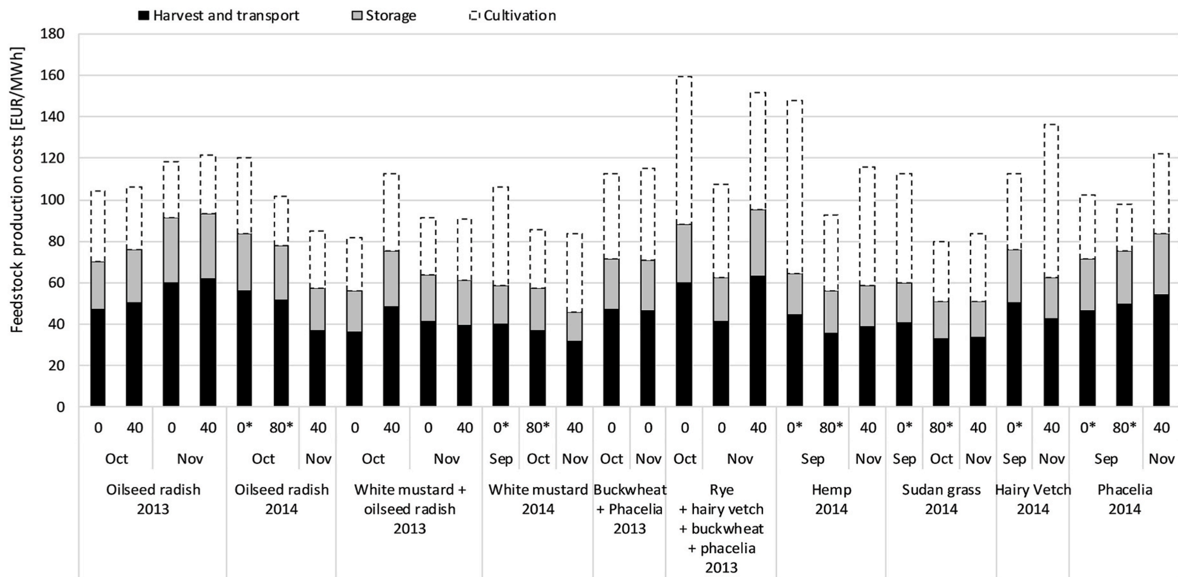

Fig. 1. Feedstock production costs, EUR MWh^{-1}, for the different intermediate crops as related to harvest and transport (black), storage (grey) and cultivation (white, dashed). Numbers above harvest dates indicate the amount of nitrogen fertilizer applied. A star marks intermediate crops unfertilized or fertilized with 80 kg N ha^{-1}, where the methane potential was assumed to be the same as for the same intermediate crop fertilized with 40 kg N ha^{-1}. For 0 and 80 kg N ha^{-1}, the harvest dates with the highest corresponding biomass yields are presented.

3.3. Economic viability

The feedstock production cost, varied between 80 and 160 EUR MWh^{-1} of produced vehicle gas for the various intermediate crops, grown during the summer and autumn of 2013 and 2014 (Fig. 1). This corresponds to a cost of 180–395 € Mg^{-1} DM (data not shown). The total feedstock production cost was divided into costs related to a) cultivation, b) harvest and transportation from field to the biogas plant, and c) ensiling and storage of the intermediate crops in the biogas plant. These costs amounted to between 23 and 56 %, 30–51 % and 13–27 %, respectively, of the total cost (Fig. 1). In comparison, Niemetz, Kettl, Szerencsits and Narodoslawsky [58] assumed a considerably lower cost range for intermediate crops as biogas feedstock of 50–80 € Mg^{-1} DM, at yields of 3–5 t DM ha^{-1}. Similarly, Igos, Golkowska, Koster, Vervisch and Benetto [37] presented costs for winter rye as a cover crop to be around 100 € Mg^{-1} DM. On the other hand, Molinuevo-Salces, Larsen, Biswas, Ahring and Uellendahl [59] indicated low breakeven yields of 1.2–2.8 Mg DM ha^{-1}, but at relatively high BMPs of 375–400 m^3 CH_4 kg^{-1} VS. Their corresponding typical harvest costs were 134–201 € ha^{-1} and very similar to the ones found in the present recalculated with machinery costs corresponding to the 2012 price level [60]. Costs for machinery and production means and specifically for fuel have increased considerably in recent years. Similar to earlier findings of Holman, Arnet, Dille, Maxwell, Obour, Roberts, Roozeboom and Schlegel [61], hairy vetch had considerable higher cultivation cost compared to other intermediate crops due to high costs for seeding material (141 € ha^{-1}). The present study found the same to be true for hemp that had even higher seeding material costs as compared to hairy vetch, 169 € ha^{-1}.

The lowest feedstock production cost, approx. 80 EUR MWh^{-1}, was found in Sudan grass, fertilized with 80 kg N ha^{-1} and harvested in October 2014. During 2013, the lowest production cost, approx. 82 EUR MWh^{-1}, was found in the white mustard and oilseed radish mix, unfertilized and harvested in October (Fig. 1).

Additional five intermediate crops also resulted in relatively low feedstock production cost, of up to 91 EUR MWh^{-1} (max 15 % higher than the intermediate crop with the lowest cost): white mustard, Sudan grass and oilseed radish, fertilized with 40 kg N ha^{-1} and harvested in November 2014, white mustard, fertilized with 80 kg N ha^{-1} and harvested in October 2014, as well as the white mustard and oilseed radish mix, fertilized with 40 kg N ha^{-1} and harvested in November (Fig. 1).

In the feedstock production cost range up to 103 EUR MWh^{-1} (max 30 % higher than the intermediate crop with the lowest cost), 12 out of the 30 evaluated intermediate crops were found, with no clear pattern as to fertilization level, harvest date or growing year. The highest feedstock production cost, approx. 160 EUR MWh^{-1}, was found in the unfertilized mix of winter rye, hairy vetch, buckwheat and phacelia, harvested in October 2013.

Only 37 % of the intermediate crops had such a low feedstock production cost, that a biogas plant had the ability to pay the full feedstock cost (cultivation, harvest, transportation and storage of the crops) with no subsidy applied in relation to the value of the produced methane gas from the feedstock (Fig. 2, crosses).

Since 2023, a subsidy is in place in Sweden (corresponding to approx. 128 EUR ha^{-1} in 2023 and possibly varying between 113 and 141 EUR ha^{-1} in coming years) for cultivation of unfertilized intermediate crops, grown as cover crops, i.e. with the purpose of carbon sequestration and improving soil structure [62]. To qualify for this new type of subsidy, harvest may not occur before the 20 October in the southernmost cultivation areas in Sweden (10 October in the remaining subsidy-qualifying cultivation areas further north in Sweden). Such a subsidy would push the economic balance of two more intermediate crops to become feasible (Fig. 2, triangles). Even though this seems to be a small economic effect, this subsidy could lower the threshold of perceived risk for farmers considerably and therefore contribute to a much larger implementation of intermediate crop cultivation, independent of if the crop is harvested or not.

Assuming that farmers have an interest in cultivation of intermediate crops to retain nitrogen in the soil, increase soil organic matter, control weeds and promoting biodiversity, etc., farmers may be interested in growing these crops anyway, and may therefore be willing to cover the cultivation costs. With these cost covered, utilization of intermediate crop biomass in a biogas plant became economically viable, for 25 of the 30 intermediate crops with no subsidy applied (Fig. 2, circles). Of these, white mustard, Sudan grass and hemp, all grown in 2014, showed the best economic outcome. A later harvest date improved the economic outcome for Sudan grass and fertilized white mustard.

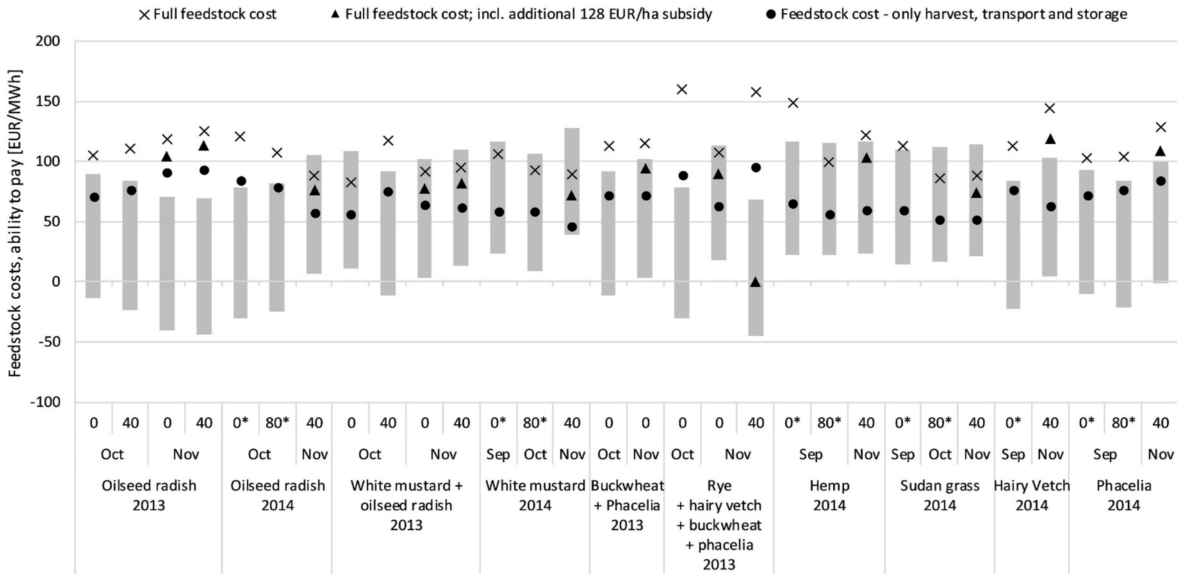

Fig. 2. Ability to pay (grey range) and corresponding feedstock costs shown as full costs (cross), full costs including the current 128 EUR ha^{-1} subsidy for intermediate crops (triangle) and costs limited to those for harvest, transport and storage (circle). Economic viability requires the cost to be within the grey range or below. Numbers above harvest dates indicate the amount of nitrogen fertilizer [kg ha^{-1}] applied. A star marks intermediate crops unfertilized or fertilized with 80 kg N ha^{-1}, where the methane potential was assumed to be the same as for the same intermediate crop fertilized with 40 kg N ha^{-1}. For 0 and 80 kg N ha^{-1}, the harvest dates with the highest corresponding biomass yields are presented.

Eleven out of those with economic viability, were unfertilized intermediate crops. Here, oilseed radish, the white mustard and oilseed radish mix, the rye mix, and phacelia showed an economic result in the same range as or better than fertilized crops. Despite assumption of a higher SMY for phacelia fertilized with 80 kg N ha^{-1} than found in the present study, phacelia did not perform better than the unfertilized crop. Early maturing and corresponding withering of the biomass early in the autumn as has been observed in the field experiment, may further limit the feasibility of phacelia as crop harvested for biogas production.

A high biomass yield in combination with a high SMY resulted in high gross methane yields per hectare, over 1000 m^3 ha^{-1} for seven of the intermediate crops. Still, of those treatments not all were economically feasible. Beside a high gross methane yield, high DM content of the harvested biomass was an important factor, resulting in low process costs per unit of energy and low transportation cost per unit of energy, respectively (not shown). For instance, oilseed radish harvested in November 2014 showed both a relative high gross methane yield and a relative high DM content in the biomass (Table 8) and resulted in a high ability to pay, covering even full feedstock costs (Fig. 2). In comparison, oilseed radish grown in 2013 still showed relative high gross methane yields, but had rather low DM content in the biomass and therefore had a considerably lower economic performance. Measures for increasing the DM content of the harvested biomass such as field-drying and their impact on SMY and economic feasibility should therefore be investigated further in future studies. Another way to further improve feasibility is to feed the intermediate crops fresh, not as silage, into a biogas plant, thereby avoiding the ensiling and storage costs. In the present study, total feedstock costs could thereby be lowered by 13–27 %. This is somewhat higher than what was reported in a case study, where addition of crops directly fed to the biogas plant instead prior ensiling in storage reduced annual feedstock costs with 10 % [35].

The role of digestate for economic viability was not evaluated in this study, since local conditions such as demand for digestate, its DM content, nutrient content and transportation distance determined if the digestate is a net income or a cost. Its value as fertilizer is also strongly influence by the mix of substrates added to the biogas process. In order to investigate the potential contribution of digestate to the overall economic outcome, we suggest that future works include case studies that can define these conditions in sufficient detail to enable a further economic assessment.

This innovative application of intermediate crops, grown as energy cover crops, offers therefore new economic incentives to the agricultural sector. At the same time, this intermediate crop cultivation increases ecosystems services such as weed control, soil organic carbon contribution and when flowering even nectar production for pollinators.

3.3.1. Feasibility of intermediate crop harvest

Based on the results in this study and published studies in the same context, harvest of intermediate crops has the potential to contribute with a considerable amount of biomass to be used as biogas feedstock. Intermediate crop biomass may also be used for other biomass-based processes, such as plant protein extraction [2], that could easily be combined with anaerobic digestion of the fibre and brown juice fraction occurring as by-products after the protein extraction. In both cases, a major part of plant nutrients and carbon could be returned to agricultural land for fertilization and contribution to the soil organic carbon pool [9,10]. In the ongoing debate about nitrous oxide (N_2O) emissions from the topsoil there seems to be agreement that N_2O is released, i.e. after immature green biomass has been subjected to freeze and thaw cycles [10,63]. However, the extent of the emissions seems to vary considerably [64], with a recent study implying that emission factors may be strongly underestimating N_2O emission from green crop residues [65], which is another argument for harvest and removal of green biomass from the field before the winter [66]. In this way the potentially large emissions of GHGs from the soil top layer, after decomposition of intermediate crops with low carbon to nitrogen ratios will be avoided [65].

Removal of intermediate crop biomass may however be limited by wet field conditions typical for the autumn season in the countries in Northwest Europe. Timing of the harvest would need to avoid use of machinery with heavy wheel loads, on water-logged soft soils, which leads to soil compaction and subsequent decrease in crop yields in the following years. It may be of interest to develop or modify light machinery that could be used for harvest with a lower risk for causing soil compaction, such as equipment used for zero grazing or cut and carry [42,67]. In conditions with a frozen topsoil, harvest could occur, if the intermediate crops are still standing and haven't withered too much.

4. Conclusions

In this study, we have shown that it is economic viable to produce biomethane gas in vehicle fuel quality from several intermediate crops grown in Northwest Europe, harvesting intermediate crop biomass with a a self-loading forage wagon and processing it, fresh or as silage, in a large scale biogas plant.

Specifically, results of this study show that nitrogen fertilization of intermediate crops is useful only when the intermediate crop is established early enough for the plant to make use of the nitrogen. Furthermore, dependent on the pre-crop and the amount of residual nitrogen in the soil, even unfertilized crops can produce high biomass yields. Of the intermediate crops investigated in this study, 3 of out of 9 species could be grown economically feasible even without nitrogen fertilization and covering the full feedstock production costs. On the other hand, fertilization improved the economic feasibility for several intermediate crops, but not for all. If fertilization can be applied, and provides an economic improvement, needs therefore to be investigated for the actual intermediate crop, the crop rotation and against local regulations.

A high gross methane yield per hectare alone was found not to be sufficient for economic feasibility for the investigated intermediate crops. A high dry matter content was also needed for low costs in transport and in the anaerobic digestion process. As there was no clear trend for the impact of harvest date on biomass yield, SMY or economic feasibility, an individual assessment of the intermediate crop maturity would therefore be interesting to investigate as a determining factor for a high SMY and economic feasibility in a future study. Crop-specific maturity, e.g. as determined as different growth stages, could then be used as an indicator for harvest date optimization. Still, biomass yield was one of the major factors for the economic results of intermediate crop utilization in biogas production. Consequently, the results of this study are deemed applicable to other cold climate regions, to which Scandinavia, Eastern Europe, Canada and the north-eastern quarter of the USA belong [68], indicating the importance of our findings.

CRediT authorship contribution statement

Sven-Erik Svensson: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Eva Johansson:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Emma Kreuger:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Data curation, Conceptualization. **Thomas Prade:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization.

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Data availability

Data will be made available on request.

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