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FRESH AND ENSILED CROPS – A NEW WAY TO ORGANIZE YEAR-ROUND SUBSTRATE SUPPLY FOR A BIOGAS PLANT

Report from a project within the collaborative research program *Renewable transportation fuels and systems*

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THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This project has been carried out within the collaborative research program Renewable transportation fuels and systems *(Förnybara drivmedel och system)*, Project no. 39122-1. The project has been financed by the Swedish Energy Agency and f3 – Swedish Knowledge Centre for Renewable Transportation Fuels.

f3 Swedish Knowledge Centre for Renewable Transportation Fuels is a networking organization which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

- Provides a broad, scientifically based and trustworthy source of knowledge for industry, governments and public authorities
- Carries through system oriented research related to the entire renewable fuels value chain
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The f3 centre is financed jointly by the centre partners and the region of Västra Götaland. f3 also receives funding from Vinnova (Sweden's innovation agency) as a Swedish advocacy platform towards Horizon 2020. Chalmers Industriteknik (CIT) functions as the host of the f3 organization (see www.f3centre.se).

The project was carried out as case studies for the biogas plants in Jordberga and Örebro owned by Swedish Biogas International (SBI) that in January 2017 was acquired by the energy company Gasum AB and was renamed Gasum AB. The work was divided between the partners as follows:

Thomas Prade and Sven-Erik Svensson, SLU, Dept. of Biosystems and Technology, were responsible for choosing the energy crops (substrates) for the biogas plants Jordberga and Örebro as well as deciding the crop performance such as crop yield, harvest time and biogas yield. Anneli Ahlström (Gasum AB) was responsible for describing the biogas plants. Håkan Rosenqvist did the calculations of cultivation costs and Carina Gunnarsson (RISE, former JTI) calculated costs for harvest, transport and storage of the biogas substrates. The calculated costs were validated with help of Christer Lingman (Gasum AB). Developing of the optimization model and modelling of the costs to supply the biogas plants with substrates all year round was done by David Ljungberg, SLU, Dept. of Energy and Technology. The project group together discussed and analysed the results of the calculations and optimizations.

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EXECUTIVE SUMMARY

For crop-based biogas plants, the cost for buying the crops is a predominant production cost and efficient systems for production, harvesting, transportation and storage are therefore of major importance. Furthermore, there is a discussion going on about competition on land between food and energy production. EU has decided to strongly limit the production of transportation fuel based on crops grown on arable land. For crop-based biogas production it is therefore very interesting to examine ways to reduce substrate costs for crops as well as to find alternative crops that are not competing with food production.

This project was carried out as a case study for two crop based biogas plants in Jordberga and Örebro, both of them owned by Gasum AB, former Swedish Biogas International (SBI). The overall aim of the project was to reduce substrate costs by at least 10%, by organizing the supply of crops in a new way, combining fresh and ensiled crops. The underlying assumption was that substrate costs could be reduced by feeding fresh crops into the biogas digester during the harvest period and thereby reduce costs for storage and avoid losses of dry matter during storage.

The goal of this project was to improve cost calculations and develop an optimization model for substrate supply to analyze how different fresh and ensiled substrates should be best combined to minimize substrate costs during various times of the year. In the previous f3 financed project ”Optimized logistics for biogas production” a model based on linear programming was developed for optimization and strategic planning of the logistics for biogas plants. In the present project, the model was further developed to optimize the supply for the year divided into different periods, instead of on annual basis as in the previous project.

In the first part of the project, an inventory of crops to include in the case studies and crop properties such as harvest times, dry matter yield and biomethane yield was carried out. Using GIS a geographical inventory for the case study sites was carried out based on the national database of agricultural land receiving subsidies from the EU. The agricultural fields were classified as small fields (1-5 ha) and large fields (>5 ha). For each field the real-world transport distance to the biogas plant was calculated. The fields were then divided into 7 zones with different transport distance from 0-100 km and for each zone the field area for small and large fields were summarized. The average transport distance for all fields in each zone was calculated.

Based on the inventory cultivation costs were calculated. Reflecting the production potential of crops otherwise grown on the field, a land use cost was also calculated. The harvest systems were adapted for small and large fields. Costs for transport with tractor or truck were calculated and the cheapest alternative for each crop and zone was used in the optimization model. For crops harvested with a precision chop forage wagon an additional pre-treatment cost (bio-extrusion) was added to sufficiently reduce particle size. For the ensiled crops, a storage cost was added based on storage in bunker silos. Dry matter losses during storage were accounted for.

An optimization model was developed to minimize the cost of substrate supply with fresh and stored crops during different periods of the year when producing 80% of the annual biomethane production of the biogas plants. The period from May to November, when fresh crops were available, was divided into one-week periods, while the rest of the year was divided in two periods when only ensiled crops were available, reflecting different storage need of different crops. Based on the selected crops, a list of substrates was prepared, where the properties for every harvest opportunity

for a fresh crop, and every period when an ensiled crop was available, was represented by unique list entries. It was assumed that the ensiled crops were harvested at the time resulting in the lowest cost per biomethane production. For the Jordberga case, 19 crops were selected, and since many were available during several periods, this resulted in a list of 255 potential substrates. For the Örebro case, 15 crops were selected, resulting in 237 potential substrates. Transport costs were calculated for 14 zones, where zones A1-A7 represented agricultural land in large fields and B1-B7 represented agricultural land in small fields.

Scenarios with different land use and crop combination constraints were tested and compared with a reference scenario (1) without optimization including the crops used currently which is ensiled whole-crop cereal and maize in Jordberga and ensiled whole-crop cereal and grass-clover in Örebro. In scenario 2 an optimization was done using only ensiled crops enabling comparison of optimized results with and without fresh crops. In scenario 3 both fresh and ensiled crops were included with (3a) and without (3b) the restriction that maximum 1/3 of the crops supplied could be fresh to avoid any negative effects on the biogas process of supplying only fresh crops. In scenario 4a the effect of using only so called 2nd generation biofuel crops was studied. Scenario 4b analysed if grass-clover is more competitive as a biogas substrate if its positive effect on other crops in a cereal based crop rotation was considered. The results of the optimizations are summarized in the table below.

Scenarios	1, reference	2, ensiled	3a, mixed	3b, mixed unrestricte d	4a, advanced biofuel	4b, advanced biofuel with crop rotation values
Jordberga						
Total annual cost, MSEK	46.9	46.1	44.3	42.0	59.2	56.5
Average cost, SEK/Nm3	4.94	4.86	4.67	4.43	6.24	5.95
Average cost, SEK/t DM	1 349	1 287	1 274	1 256	1 594	1 475
Savings, % (reference)	-	2	5	10	-26	-20
Örebro						
Total annual cost (MSEK)	14.7	12.3	12.2	12.1	17.2	15.7
Average cost (SEK/Nm3)	4.38	3.67	3.64	3.61	5.11	4.67
Average cost (SEK/t DM)	1 101	974	969	965	1 225	1 119
Savings, % (reference)	-	16	17	17	-17	-7

For Jordberga the optimized solution allowing only ensiled crops (Scenario 2) included whole-crop cereal as the only crop grown on 2754 ha. This can be compared with 1000 ha maize and 1500 ha whole-crop cereal in the reference scenario. If both fresh and ensiled substrates were included in the optimization without restrictions (Scenario 3b), fresh whole-crop cereal and sugarbeet tops were added to the solution. Annual costs were reduced to 10% lower than the reference scenario. This means that the goal of the project to decrease cost costs with 10% was reached with this scenario. When restricting the amount of fresh crops to maximum 1/3 of the crops used each week

(Scenario 3a), annual substrate costs were 5.5% lower compared with the reference scenario. Maximum transport distance was 15 km.

Örebro biogas plant today uses ensiled whole-crop cereal and grass-clover (Scenario 1). The optimized solution based on only ensiled substrates (Scenario 2) included only whole-crop cereal grown on 1219 ha in zone 1-3 up to 15 km transport distance. When allowing fresh substrates in the optimization (Scenario 3a), whole-crop cereal was complemented by fresh whole-crop cereal in the optimal solution and the costs were reduced by 17% compared to the reference scenario (1).

The suggested update of the EU renewable energy directive (RED) will require biogas plants producing vehicle fuel from crops to find alternative crops suitable as advanced biofuel crops. Scenario 4a and 4b therefore only included grass-clover, landscape conservation grass, green rye, cover crops and sugarbeet tops (only in Jordberga) following the definition of food-based biofuel from the Swedish Energy Agency (maize, whole-crop cereal and sugarbeets excluded). For Jordberga the optimization resulted in ensiled green rye being the main crop followed by grass-clover from large fields. Also fresh sugarbeet tops, landscape conservation grass and green rye (as a winter cover crop) were included in the solution. To supply Jordberga biogas plant with crops the maximum transport distance increased to 100 km. When considering the crop rotation value (Scenario 4b), grass-clover from large fields became the main ensiled crop in the optimized solution. For Örebro biogas plant the optimization in scenario 4a resulted in whole-crop cereal being replaced with grass-clover from large fields, green rye and cover crops.

Advanced biofuels crops such as sugarbeet tops, green rye and landscape conservation grass and grass-clover are interesting alternatives for biogas production but will increase substrate costs. In our analysis substrate costs increased with 26% compared to the current crops used at Jordberga biogas plant. Corresponding value for Örebro biogas plant was 17%.

Grass-clover was more competitive as a biogas crop in Örebro compared to in Jordberga. In Örebro, grass-clover was the main ensiled crop both in the advanced biofuel scenario (Scenario 4a) and when crop rotation values of grass-clover was considered (Scenario 4b). In Jordberga, the main ensiled crops in the advanced biofuel scenarios were green rye and grass-clover. Fresh grass-clover harvested with an adapted system with low capacity could not compete with costs with ensiled grass-clover harvested with a high capacity system, neither in Jordberga nor in Örebro.

Compared to the current crop based biogas production using only a few crops, the analysis of the advanced biofuel scenarios showed that the number of crops increased and both fresh and ensiled crops were included. This will increased complexity of the harvest-, transport- and storage system and the possible advantages and drawbacks of this need to be studied further.

The presented results are examples of the possibilities in using an optimization model as a tool for strategic planning and examining the trade-offs between cost savings and process and management related constraints for crop supply. Further work and site-specific tests are needed to study effects on the stability of the biogas process by feeding fresh substrates.

SAMMANFATTNING

För grödbaserade biogasanläggningar är kostnaden för att köpa grödorna en dominerande produktionskostnad och effektiva system för produktion, skörd, transport och lagring är därför av stor betydelse. Dessutom pågår en diskussion om konkurrens om åkermark för produktion av mat eller energi. EU har beslutat att kraftigt begränsa produktionen av drivmedel baserade på grödor som odlas på åkermark. För grödor till biogasproduktion är det därför mycket intressant att undersöka sätt att minska substratkostnader för grödor samt att använda grödor som inte konkurrerar med livsmedelsproduktion.

Detta projekt genomfördes som en fallstudie för två grödbaserade biogasanläggningar i Jordberga och Örebro som båda ägs av Gasum AB, tidigare Swedish Biogas International (SBI). Det övergripande syftet med projektet var att minska substratkostnaderna med minst 10 % genom att organisera tillförseln av grödor på ett nytt sätt som kombinerar färska och ensilerade grödor. Det underliggande antagandet är att substratkostnaderna kan minskas genom att under skördeperioden använda färska grödor i biogasprocessen och därigenom minska kostnaderna för lagring och undvika förluster av torrsubstans under ensilering och lagring.

Målet med projektet var att förbättra kostnadsberäkningarna och utveckla en optimeringsmodell för substrattillförsel för att analysera hur olika färska och ensilerade grödor bäst bör kombineras för att minimera substratkostnaderna under olika tider på året. I det tidigare f3-finansierade projektet ”Optimerad logistik för biogasproduktion” utvecklades en modell baserad på linjärprogrammering för optimering och strategisk planering av logistiken för biogasanläggningar. I detta projekt vidareutvecklades modellen för att optimera tillförseln under olika perioder av året i stället för på årsbasis som i det tidigare projektet.

I den första delen av projektet inventerades vilka grödor som ska inkluderas i fallstudierna samt deras egenskaper såsom skördetider, torrsubstansavkastning och metanutbyte. En geografisk inventering av fallstudieområdena genomfördes med hjälp av GIS och baserat på Jordbruksverkets blockdatabas. Åkermarken runt biogasanläggningarna delades in i två klasser, små fält (1-5 hektar) och stora fält (> 5 ha). För varje fält beräknades verkligt transportavstånd till biogasanläggningen. Fälten delades sedan in i 7 zoner med olika transportavstånd från 0-100 km och för varje zon summerades arealen för de två fältklasserna små och stora fält. Det genomsnittliga transportavståndet för alla fält i varje zon beräknades.

Baserat på inventeringen av grödor beräknades odlingskostnaderna. För att ta hänsyn till produktionspotentialen hos de grödor som annars odlas på fältet beräknades ett markvärde som också inkluderades i substratkostnaden. Skördesystem anpassade till om grödorna odlades på stora eller små fält togs fram. För varje avståndszon beräknades kostnader för transport med traktor eller lastbil och det billigaste alternativet användes sedan i optimeringsmodellen. För grödor skördade med hackvagn adderades sedan en förbehandlingskostnad (bioextrudering) för att tillräckligt reducera partikelstorleken. För ensilerade grödor beräknades en lagringskostnad för ensilering i plansilo. Hänsyn togs även till torrsubstansförlusterna under lagring.

En optimeringsmodell utvecklades som minimerar kostnaderna för tillförseln av färska och lagrade grödor under olika perioder av året för att producera 80% av den totala årliga metanproduktionen på biogasanläggningarna. Från perioden maj till november, när färska grödor fanns tillgängliga, delades tillförseln upp i perioder om en vecka, medan resten av året delades i två perioder när endast

lagrade grödor fanns tillgängliga, vilket återspeglar lagringsbehovet hos olika grödor. Baserat på de valda grödorna gjordes en lista över substrat, där grödans egenskaper för varje möjlig period för färsk skörd och varje period då en lagrad gröda fanns, representerades av en unik post. De lagrade grödorna antogs ha skördats vid den tidpunkt som resulterade i lägst substratkostnad per m^3 producerad metan. För fallstudien för Jordberga biogasanläggning fanns 27 olika grödkombinationer att välja mellan och eftersom många var tillgängliga under flera perioder resulterade det i en lista med 255 potentiella substrat. Motsvarande siffror för fallstudien för biogasanläggningen i Örebro var 15 grödor vilket resulterade i 237 potentiella substrat. Transportkostnaderna beräknades för 14 zoner där zon A1-A7 representerar åkermark på stora fält och B1-B7 åkermark på små fält.

Scenarier med olika villkor för markanvändning och grödkombinationer undersöktes och jämfördes med ett referensscenario (1) utan optimering innehållande de grödor som används idag vilket är ensilerad helsäd och majs i Jordberga och ensilerad helsäd och klövergräsvall i Örebro. I scenario 2 gjordes en optimering där endast ensilerade grödor inkluderades vilket möjliggjorde jämförelse av optimalt resultat med och utan färska grödor. I scenario 3 inkluderades såväl ensilerade som färska grödor med (3a) och utan (3b) restriktionen att maximalt 1/3 av grödorna som tillfördes fick vara färska, detta för att undvika eventuella negativa effekter av endast färska grödor på biogasprocessen. I scenario 4a undersöktes effekten av att endast tillåta grödor och restprodukter godkända för produktion av andra generationens biodrivmedel. I scenario 4b undersöktes om vall blir mer konkurrenskraftigt som biogassubstrat om hänsyn tas till det positiva värdet som vall har på andra grödor i spannmålsdominerade växtföljder. Resultatet av optimeringarna sammanfattas i nedanstående tabell.

Scenario	1, referens	2, ensilerad	3a, mixad	3b, mixad utan restriktioner	4a, avancerade drivmedel	4b, avancerade drivmedel med växtföljdseffekt
Jordberga						
Total årlig kostnad, MKr	46.9	46.1	44.3	42.0	59.2	56.5
Medelkostnad, Kr/Nm³	4.94	4.86	4.67	4.43	6.24	5.95
Medelkostnad, Kr/t TS	1349	1287	1274	1256	1594	1475
Besparing, % (jmf referens)	-	2	5	10	-26	-20
Örebro						
Total årlig kostnad, MKr	14.7	12.3	12.2	12.1	17.2	15.7
Medelkostnad, Kr/Nm³	4.38	3.67	3.64	3.61	5.11	4.67
Medelkostnad, Kr/t TS	1101	974	969	965	1 225	1 119
Besparing, % (jmf referens)	-	16	17	17	-17	-7

För Jordberga bestod den optimerade lösningen med endast ensilerade grödor (scenario 2) av endast helsäd som odlades på 2754 ha. Detta kan jämföras med 1000 ha majs och 1500 ha helsäd i referensscenariot. Om både färska och ensilerade grödor inkluderades i optimeringen utan begränsningar (scenario 3b) tillkom utöver ensilerad helsäd även färsk helsäd och färsk sockerbetsblast i den optimala lösningen. Årskostnaderna minskade till 90% av referensscenariot. Det innebar att projektets mål att sänka kostnadskostnaderna med 10% uppnåddes i detta scenario. När andelen färska grödor begränsades till maximalt 1/3 av behovet i varje period (scenario 3a) var de årliga substratkostnaderna 5.5% lägre än i referensscenariot. Maximalt transportavstånd var 15 km.

Biogasanläggningen i Örebro använder idag ensilerad helsäd och klövergräs (scenario 1). Den optimerade lösningen för endast ensilerade substrat (scenario 2) inkluderade helsäd odlad på 1219 ha i zon 1-3 upp till 15 km transportavstånd. När färska grödor inkluderades i optimeringen (scenario 3a) inkluderades förutom lagrad helsäd även färsk helsäd i den optimala lösningen och kostnaderna minskade med 17% jämfört med referensscenariot.

I den föreslagna uppdateringen av EU: s förnybarhetsdirektiv (RED) krävs att biogasanläggningar som idag producerar drivmedel från grödor hittar alternativa grödor godkända för produktion av s.k. avancerade biodrivmedel. I scenario 4a och 4b inkluderades därför endast klövergräsvall, naturmarksgräs, grönråg, mellangrödor och sockerbetsblast (endast i Jordberga) enligt Energimyndighetens definition av livsmedelsbaserade biodrivmedel Majs, helsäd och sockerbetor uteslöts. För Jordberga resulterade optimeringen i att ensilerad grönråg var huvudgröda följt av klövergräsvall från stora fält. Dessutom inkluderades de färska grödorna sockerbetsblast, naturmarksgräs och grönråg. För att förse biogasanläggningen med grödor ökade det maximala transportavståndet till 100 km. När klövergräsvallens växtföljdsvärde inkluderades (scenario 4b) blev istället vall den huvudsakliga ensilerade grödan i den optimerade lösningen. För Örebro biogasanläggning resulterade optimeringen i scenario 4a i att helsäd ersattes huvudsakligen med vall från stora fält samt en del grönråg och mellangrödor

Avancerade biobränslegrödor som sockerbetsblast, grönråg, naturmarksgräs och vall är intressanta alternativ för biogasproduktion men de innebär ökade substratkostnader. I vår analys ökade substratkostnaderna med 26% jämfört med nuvarande grödor som används vid Jordberga biogasanläggning. Motsvarande värde för Örebro biogasanläggning var 17%.

Vall var en mer konkurrenskraftig biogasgröda i Örebro jämfört med i Jordberga. I Örebro var den huvudgröda både i det avancerade biodrivmedelsscenariot 4a och i scenariot när vallens mervärden i växtföljden beaktades (4b). I Jordberga var grönråg och klövergräsvall huvudgrödor i scenariot med avancerade biodrivmedelsgrödor. Färsk vall skördad med ett anpassat system med låg kapacitet kunde inte konkurrera kostnadsmässigt med ensilerad vall skördad med ett system med hög kapacitet, varken i Jordberga eller Örebro.

Jämfört med de nuvarande systemen för grödbaserad biogasproduktion med endast ett fåtal grödor visade analysen av de avancerade biodrivmedelsscenarierna att antalet grödor ökade och innehöll både färska och ensilerade grödor. Detta ökar komplexiteten hos skörde-, transport- och lagringssystemet och möjliga för- och nackdelar med detta behöver studeras ytterligare.

De presenterade resultaten är exempel på hur en optimeringsmodell kan användas som verktyg för strategisk planering och för att undersöka avvägningar mellan kostnadsbesparingar och process- och hanteringsrelaterade begränsningar för tillförseln. Ytterligare arbete och specifika tester behövs för att studera effekter på biogasprocessens stabilitet vid användning av färska substrat.

CONTENTS

1 INTRODUCTION

In Sweden a minor part of the arable land is used to grow crops for energy production, ethanol from cereal grain, Agroetanol in Norrköping, being the largest example. There are also a few crop-based biogas plants. The biogas plants "Jordberga" in Skåne and "Örebro" are two biogas plants in Sweden that uses crops in the biogas production. These two plants are owned by Gasum AB (former Swedish Biogas International, SBI). For crop-based biogas plants, the cost of buying the substrates is a dominating production cost, and an efficient system in cultivation, harvest, transportation and storage that minimizes cost are therefore very important. Furthermore, there is on-going discussions about the sustainability of using arable crops to produce bioenergy and the competition on arable land between production of food and fuel. EU has decided that a minor part of the transportation fuel may come from crops grown on arable land. One argument against using crops for energy production is that it might cause so called ILUC-effects (Indirect land use change) when the crop otherwise produced on the arable land is compensated for by turning biologically valuable land in other parts of the world into crop production. For crop based biogas production it is therefore very interesting to find new alternative substrates.

Crops used for biogas production are normally handled in large-scale systems where the crops, in Sweden commonly whole-crop cereal, maize and grass-clover are harvested during a short period and stored as silage until fed into the biogas plant. These large-scale systems are adapted to crops grown on large fields. Grass grown on smaller fields are potentially available for biogas production but they are not suitable for the large-scale harvesting systems. Other potential biogas substrates are catch crops grown after the main crop or crop residues such as sugar beet tops. These crops might have high water content at harvest, which makes them difficult to preserve as silage. One possibility is then to feed these substrates to the digester as fresh plant material at harvest, without making silage of them and then reduce storage losses and storage costs.

Large fields normally have a high alternative value relating to the production potential of crops otherwise grown on the field. Crops grown on marginal land, crop residues and residual crops have no or a low alternative land value, which is favorable for the cost if the substrates are used for biogas production.

In the previous f3 financed project "Optimized logistics for biogas production" a model, based on linear programming, was developed for optimization and strategic planning of the logistics for biogas plants, both existing and planned plants (Ljungberg *et. al.*, 2013). Experiences from planning and design of logistic systems for biogas crops in Germany were considered when developing the model. The model was applied in a case study of a biogas plant planned to be built. Costs for growing and delivering crops at different distance from the biogas plant was calculated, and based on this the model optimized the most cost effective solution for crop supply and spreading of digestate.

In this project we examine if the harvest system can be adapted by using some of the crops fresh during the harvest season, May to November. We also examine if fresh crops or grown on smaller fields or on marginal land as well as crop residues can be used in combination with the large- scale ensiled crops used today. Fresh crops are available during limited times of the growing season so in order to examine how fresh crops can be combined with ensiled crops the optimization model will be developed to optimize the supply for several periods of the year, instead of on annual basis as in the previous project. The project includes substrate supply for the biogas plants, from the cultivation of crops in the field to pre-treatment prior to feeding the crop to the digester.

The project intends to address the following questions:

- Can the substrate cost in biogas production be decreased by using fresh crops in parallel with ensiled crops, and how should fresh and ensiled crops be combined to minimize costs?
- How is the substrate cost affected if the cultivated biogas crops are substituted with alternative advanced biofuel substrates like cover crops, sugar beet tops, grass-clover and crops from marginal land?
- Can grass-clover and landscape conservation grass harvested with a lower capacity harvesting system compete with ensiled crops grown on large fields?
- How should crops be allocated to fields near and far from the biogas plants, considering transport cost and other parameters?
- How is the choice of crops in the two studied regions around Jordberga and Örebro affected by differing growing conditions, price, yield and value of land?

These questions were examined in case studies for the biogas plants in Örebro and Jordberga with different pre-conditions concerning choice of crops, crop yields and value of land.

2 AIMS

The goal was to in two case studies analyze how different fresh and ensiled substrates should be best combined to minimize substrate costs, using improved production estimates, a further developed optimization model for substrate supply and optimized pretreatment during various times of the year. Based on the studies the goal was to develop general recommendations for how fresh and ensiled crops should best be combined to minimize the costs in crop based biogas production.

The overall aim of the project was to reduce substrate costs for biogas production by at least 10%, on an annual basis, by organizing the supply of crops in a new way, through a combination of fresh and ensiled crops.

3 MATERIALS AND METHODS

3.1 DESCRIPTION OF THE BIOGAS PLANTS

Jordberga and Örebro biogas plants both base their substrate supply on agricultural crops and waste products from agriculture and food/feed industry. Both biogas plants upgrade the biogas to vehicle fuel.

In the following sections the system storage and handling of the crops prior to feeding the substrate into the digester are described.

3.1.1 Jordberga

Figure 1 show the layout of Jordberga biogas plant. The production goal of Jordberga biogas plant for 2017 is 31 500 Nm^3 vehicle gas per day, i.e. biogas with 97% methane content. How much of this that can be produced from fresh crops depend on a number of different factors, such as price, methane potential, nutrient contribution to the biofertilizer etc. compared to other available substrates.

Figure 1 Overall layout of Jordberga biogas plant where 1. Weighing station, 2. Office and control room, 3. Bunker silos, 4. Roof covered area for dry substrates, 5. Tower silos, 6. Feeding containers, 7. Machine buildings. 8. Main digesters, 9. Post digesters, 10. Digestate storage, 11. Biogas upgrading, 12. Flare, 13. Propane tank for addition before injection to gas grid, 14. Storage for rain- leachate water, 15. Tank for liquid substrates.

Storage

At the Jordberga biogas plant there are several different storage options. Bunker silos for storage of silage, two tower silos for grain, one tank for liquid material, and one roof covered area, called “the barn", used for dry material that come in with short notice and are stored only for a shorter period at the plant.

Storage capacities:

- Bunker silos for silage: 4 x 4 000 m^2, each compartment holds approximately 20 000 tonnes.
- Tower silos for grain holds a total of 3 000 m^3
- Tank for liquid material holds 100 m^3
- "The barn", area 500 m^2

In addition to this there is one tank used for iron chloride with a volume of 50 m^3 and a basin with a volume of 2 000 m^3 for rainwater. The water is used for dilution in the digesters.

Feeding system

The feeding system consists of three parallel lines, one for each production line. The digestion process takes place in three production lines, each with one main digester and one post digester.

The solid substrates (i.e. everything that is not in the tank for liquid material) is mixed on the ground by a front loader, before loading it into one of the three feeding containers. In the containers, there is a mixer/blender, where some additional mixing occurs, but it is not enough to give a homogenous enough mix in itself, hence the "manual" mixing by the front loader before filling.

The grain stored in the tower silos is first crushed in a mill, after which it is mixed with the other material by the front loader and tilled into the feeding containers.

From the feeding containers the material is transported by a screw conveyor to a "power feeder", which feed it into a circulation loop on the digester. All material must be finely chopped before it is loaded into the containers, since no further cutting or crushing is available.

The exact proportions between different solid substrates, suitable average dry matter content in the mix etc. is difficult to define. The power feeder is sensitive to dry matter content in the incoming mix, as well as the proportions of different materials. Today there is about 50% dry matter in the mix, which seems to be the upper limit, although this may change if the materials change. Too wet mix is not good either, but a lot is possible to adjust to by changing the operating parameters, although all changes require stop of the feeding and time for adjustment and fine-tuning.

The feeding containers hold about 60 tonnes, and together the three feeding lines have a total maximum capacity of 340 tonnes per day.

The feeding is approximately 220-240 tonnes per day, amount depending on composition of substrate mix, which varies during the year depending on how much residues from different industries become available, for example grain residues, residues from food production such as waste carrots, onions etc. The amount of silage stored at the plant that is used per day is in the range of 150-170 tonnes.

3.1.2 Örebro

The layout of Örebro biogas plant is shown in Figure 2. The production goal for 2017 is 15 500 Nm^3 vehicle gas per day, i.e. biogas with 97% methane content. The amount that could be produced from fresh crops depends on a number of different factors, such as price, methane potential, nutrient contribution to the biofertilizer etc. compared to other available substrates.

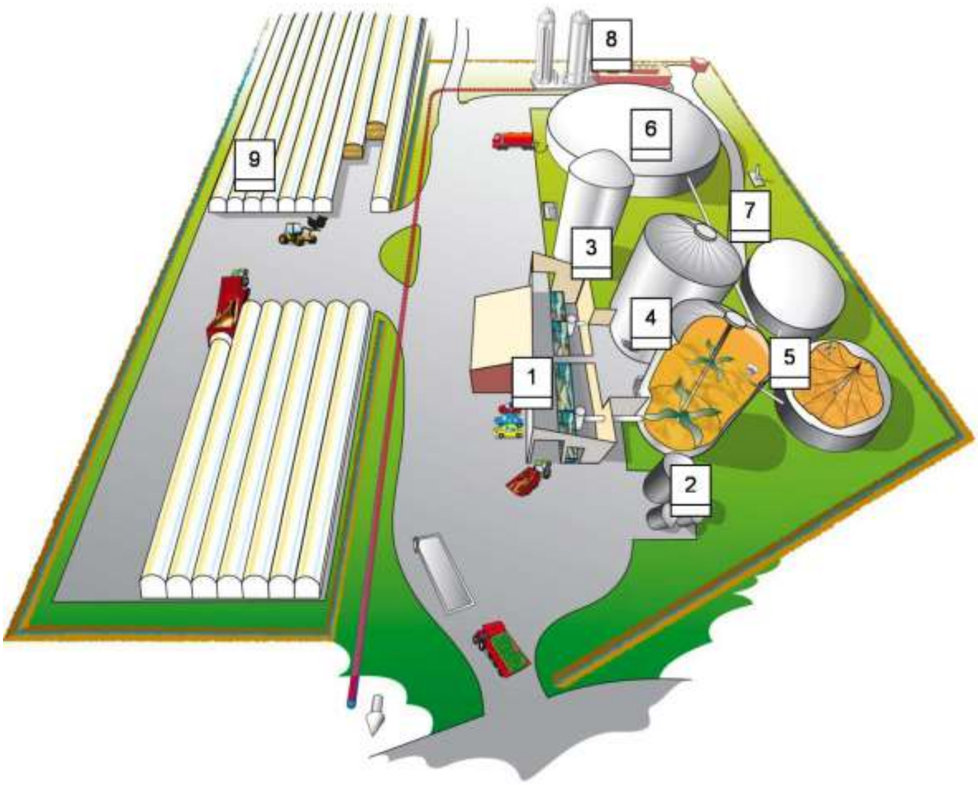

Figure 2 Overall layout of Örebro biogas plant where. 1. Reception building and office, 2. Buffer tanks for liquid substrates, 3. Silos for dry substrates, 4. Main digester, 5. Post digester, 6. Digestate storage, 7. Flare, 8. Biogas upgrading, 9. Silage storage.

Storage

The storage area at the Örebro plant is 11 250 m^2. About 2/3 of the whole area can be used for silage storage, the rest is used for materials that come in with shorter notice and are stored for a shorter time. From the beginning, the whole area was used for silage but the practice with a part open for short-term storage will probably be the same in the future.

Silage storage has so far been done in silage bags, but now trials are being done with storing in clamps instead. This may make it necessary to adapt the area to the new type of storage, for example in regard to runoff of water.

There is also a tower silo for grain with a capacity of 1 500 tonnes, and two tanks for liquid material with a volume of 100 and 300 m^3 respectively.

Feeding system

At the plant there is a mixer wagon where materials are mixed before being tipped into the feeding containers. All solid materials, which are not in the tower silo, are mixed in the wagon before being tipped into the containers. The mixer wagon is filled by a front loader, and from the mixer wagon the material is tipped directly into the feeding containers.

The feeding containers are indoor in a reception building, and consist of two containers per feeding line. The digestion process takes place in two production lines, each with a main digester and one post digester. The feeding containers are designed for 20 tonnes maize silage/container, which in practice mean 15-20 tonnes, depending on the materials. A cycle of loading, mixing and tipping into the containers take about 30 minutes. Each filling holds about 10 tonnes.

From the feeding containers the material is fed to mixer tanks by a screw conveyor. There is one mixer tank per production line, where the solid substrates are mixed with material from the digester, before being pumped into the digesters. The capacity of the feeding containers depends on the materials; the rate it is fed by today is close to maximum. Today it is set for feeding about 3 tonnes in a time frame of 1 hour and 15 minutes. Between these cycles the feeding rests for 0.5-1 hour.

The materials from the tower silo are fed to the mixing tanks through a mill where they are crushed. From the tanks for liquid substrates, the material is pumped straight to the digesters.

The operation of the feeding system is greatly affected of the mix of substrate. For example, solely grass is difficult to feed, but it also depend on how wet/dry the material is, straw length etc. Shorter straw length is better in general. The person operating the system tries out a suitable mix for the day, within the boundaries of the assigned feeding plan. Different materials also wear the components, for example the valves which make it difficult to regulate sludge flow.

The feeding is approximately 60-80 tonnes per day from the solid feeding system, 0-15 tonnes of material (low quality grain) from the tower silo and 20-40 ton liquid substrate per day. The exact amounts, and fractions of the different flows, depend on the quality of the material available at the time, to ensure a suitable total mix.

3.2 PRECONDITIONS FOR THE CALCULATIONS

3.2.1 Methane yield from fresh and ensiled biogas crops

Ensiling is a common method for preservation of animal forages and energy crops for biogas production (Weiland, 2010) in order to provide a high quality feed and substrates over the whole year. The production cost for fresh crops are lower compared with the corresponding ensiled crops because the cost for storage and ensiling is avoided (Björnsson and Lantz, 2013). As storage costs can be substantial (Gissén *et. al.*, 2014), the question is whether it could be possible to use fresh crops as a biogas substrate during the cropping season in order to reduce the costly ensiling and storage costs. Furthermore, the fermentation of sugars to lactic acid and acetic acid occurring in a proper ensiling process will to a small extent reduce the energy recovery of the crop (McDonald *et. al.*, 1973). At the same time, there are studies indicating that the methane yield (expressed as volume of methane gas per mass of volatile solids) is significantly higher after ensiling with additives (Amon *et. al.*, 2007; Pakarinen *et. al.*, 2008), which could be explained by an increase in organic acids and alcohols. However, Kreuger *et. al.* (2011) highlighted that the standard methods for determining total solids (TS) (dry matter (DM)) and volatile solids (VS) of silage with oven drying methods results in losses of volatile compounds. Thus, the analytical method will lead to an underestimation of the VS and consequently an overestimation of the methane yield when the measured methane production is related to less VS than actually are present. By correcting DM and VS of silage by the method of Porter and Murray (2001), Krueger *et. al.* (2011) this could show that the methane yield for maize, hemp, beets and beet tops before and after ensiling were not significantly different. However, without corrections of DM and VS, the methane yield was up to 51% higher for ensiled compared to fresh sugar beet. The authors conclude that ensiling process did not increase the methane yield of the studied crops and that published yields on silage without taking DM and VS losses into consideration, should be regarded with caution.

Based on these findings, there is no clear evidence that ensiling will increase the methane yield of energy crops and therefore no difference between the methane yield from fresh and ensiled crops is considered in this project.

3.2.2 Crop properties

Harvest periods for the crops included as biogas substrates for the biogas plants in Jordberga and Örebro are summarized in Figure 3.

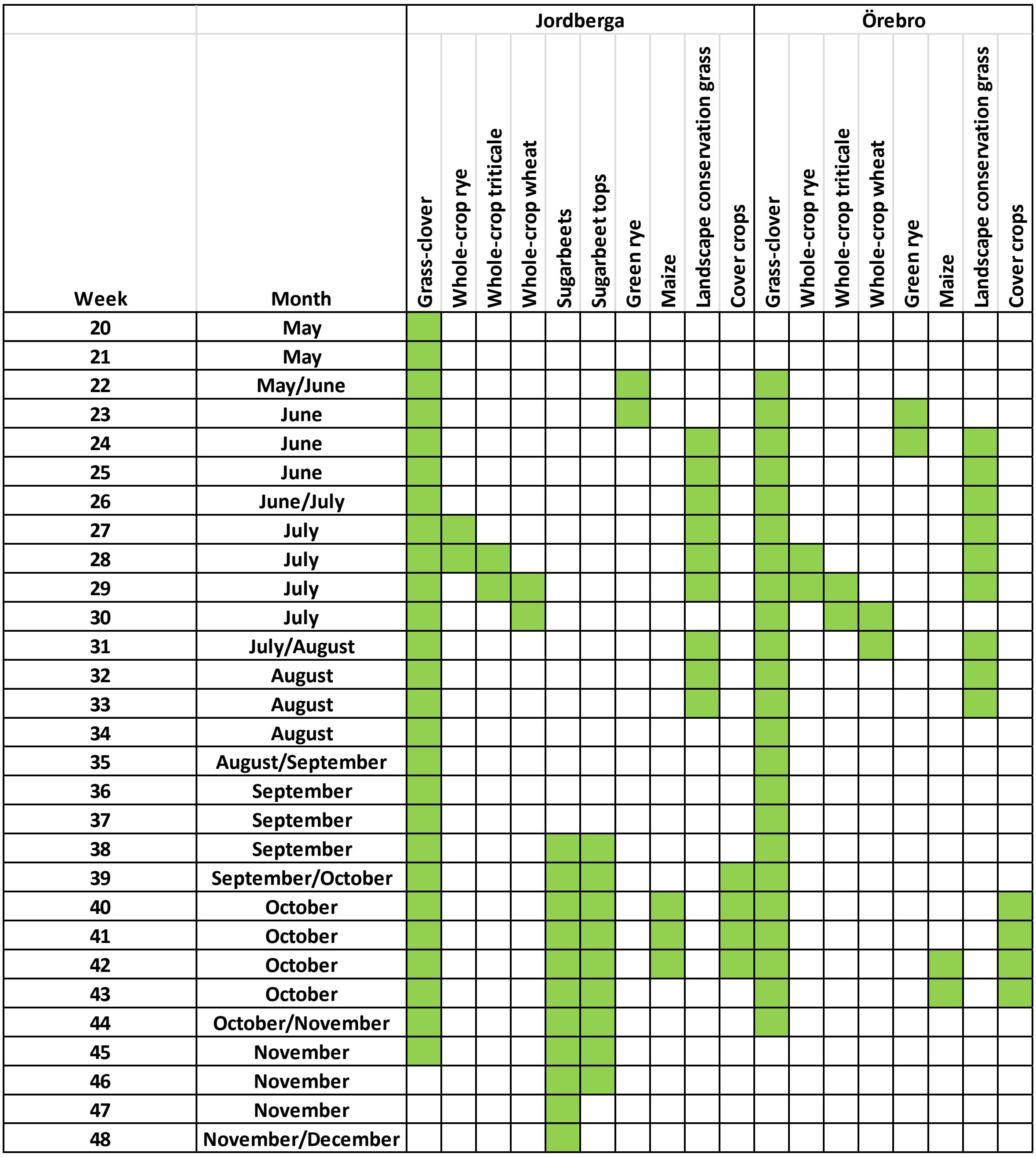

Figure 3. Harvest periods for the crops investigated as biogas substrate in Jordberga and Örebro.

Grass-clover crops

Grass-clover crops were assumed to be undersown in whole-crop cereal or green rye and being a main crop for two production years. The second production year was assumed to be shorter than the first (fewer cuts) to allow cultivation of an autumn crop, such as winter wheat or oil seed rape.

The biomass yield, methane potential and resulting methane energy yield were estimated for each week of the harvesting season and for both locations. For the calculations it was assumed 7, 8 and 8 weeks of regrowth before cut II, III and for the earliest harvested fields at the Jordberga plant even cut IV, respectively. Biomass yields and properties are presented in Appendix A (Table A1-Table A2).

For the Jordberga biogas plant, the potential harvest windows for cuts I-IV were assumed to be in weeks 20-27, weeks 27-34, weeks 35-42 and weeks 43-45, respectively. In the second production year, the potential harvest windows for cuts I-III were assumed to be in weeks 20-27, weeks 27-34 and weeks 35-38, respectively. As a result, grass-clover biomass is assumed to be available during weeks 20-45 (Figure 3).

For cut I, results from a recently published study with a 3-cut system in the region (Prade, et al. 2015) were linearly interpolated according to the date of the first day of each week. For this purpose the biomass increase rate was determined for the time between two sampling occasions as a linear relationship on the basis of biomass yield increase per day. Accordingly, for cut II and III, biomass yields were calculated from corresponding field data. For cut IV, the same growth rate as for cut III was assumed, but it was assumed that only 80% of the biomass yield of cut III was reached. In order to simulate decreasing growth rates at cuts later in the growing season, yields were decreased by 3% for each week of delay of each of cut II-IV. The resulting biomass yields represent the amount of recoverable biomass (Figure 4). For the second production year, a reduction of biomass yields with 10% was assumed.

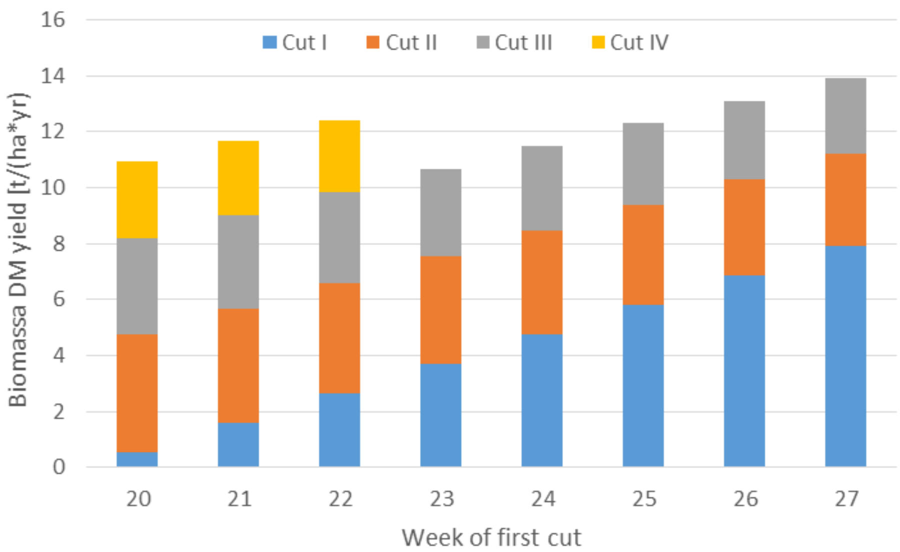

Figure 4. Biomass dry matter yields (DM) in the region of the Jordberga biogas plant for grass-clover crops over the harvesting season of the first of two production years. Regrowth periods were 7, 8 and 8 weeks for cuts II, III and IV, respectively.

For the Örebro biogas plant, in the first production year, the potential harvest windows for cuts I-III were assumed to be in weeks 22-29, weeks 29-36 and weeks 37-44. In the second production year, the potential harvest windows for cuts I-II were assumed to be in weeks 22-29 and 29-36, respectively. The biomass yields were assumed to be 10% lower compared to the biomass yields at Jordberga plant.

The fraction of volatile solids was calculated from the expect ash content of the biomass according to:

$$Volatile\ solid\ [\%] = 100 - Ash\ content\ [\%]$$

The ash content was calculated from a relationship presented by Prade *et al.* (2015):

$$Ash\ content\ [\%] = -0.0538 * Growing\ days + 12.035$$

Methane potential for grass-clover crops for all harvest weeks and cuts were calculated from a relationship presented by Prade *et al.* (2015):

$$Methane\ potential\ \left[\frac{Nm^3}{t_{VS}}\right] = -1.8418 * Growing\ days + 436{,}05$$

The use of these relationships are a simplification of development of ash content and methane potential that does not account for weather impact over the growing season, but was deemed sufficient for the purpose in this study.

Whole-crop cereal

Rye, triticale and wheat were assumed to be grown as an autumn crop for production of whole-crop biomass. These crops were assumed to be harvested when the dry matter (DM) content of the biomass reached approx. 35%, which results in rather narrow harvest windows of 2-3 weeks.

The mean biomass yield of 13 t DM/ha was taken from actual yields at the Jordberga biogas plant, which range between 8-18 t DM/ha (Olanders, 2014). The biomass yield in Örebro was assumed to be 20% lower than the biomass yield at the Jordberga plant. Biomass yields and properties are presented in Appendix A, Table A3.

Maize

Maize was assumed to be grown as a crop for production of whole-crop biomass and was assumed to be harvested when the dry matter content reached approx. 35%, which results in rather narrow harvest windows of 2-3 weeks.

The mean biomass yield of 15 t DM/ha was taken from typical yields at the Jordberga biogas plant. The biomass yield in Örebro was assumed to be 30% lower than the biomass yield at the Jordberga plant, due to a shorter growing season and lower temperatures in Örebro. Biomass yields and properties are presented in Appendix A, Table A4.

Sugarbeet and sugarbeet tops

Sugarbeet was assumed to be grown for use as biogas substrate around Jordberga but not Örebro. Harvest was assumed to be carried out in weeks 38-48. A constant dry matter yield of 15 t/ha during this harvest period was assumed. Use of sugarbeet tops as a biogas substrate was also assumed, with a harvest window weeks 38-46. Biomass yields were calculated for the time between two sampling occasions as a linear relationship on the basis of biomass yield increase per day from yield data presented by Kreuger *et al.* (2014). Biomass yields and properties are presented in Appendix A (Table A5Table A6).

Green rye

Green rye was assumed to be grown as an autumn crop for production of whole-crop biomass, but with a much earlier harvest date compared to whole-crop cereal. Green rye was assumed to be harvested in weeks 22 and 23 around Jordberga and Örebro biogas plant, respectively, with a dry matter content of 30%. Biomass yields for green rye in the Jordberga region were calculated from hand-harvested samples, from unpublished field experiments at SLU Alnarp, and corrected for machinery field losses (20%). Biomass yield varied between 6.8 and 9.4 depending on harvest time and location, see Appendix A (Table A7).

Landscape conservation grass

Grass harvested for reasons of landscape conservation was assumed to be used as biogas substrate in both locations. A biomass yield of 2.6 t DM/ha with one harvest and 2.3 and 1.2 t DM/ha for first and second harvest in the two-harvest system respectively was assumed, based on actual yields (Ola Rickardsson, personal communication). See Appendix A (Table A8).

Cover crops

Cover crops were assumed to be grown after early harvested crop such as whole-crop cereal (Jordberga and Örebro) or green peas (only Jordberga). A number of interesting cover crops are available which include oil radish, white mustard, buckwheat, phacelia or hairy vetch. Which cover crop is most suitable for cultivation depends on the other crops in the crop rotation and the crop sequence. Therefore, only general assumptions about potential biomass and methane yields were made. A biomass yield of 4 t DM/ha was assumed, based on typical biomass yields (Gunnarsson 2014). For Örebro, 20% lower biomass yields were assumed. Biomass yields and properties are summarized in Appendix A (Table A9).

3.2.3 Geographical analysis

The database on agricultural land receiving subsidies from the EU was used in a GIS analysis for calculating field size, arable area and transport distance from field to storage at the biogas plant. The transport distance is the average road distance from the middle point of the field to the site of the biogas plant. The arable land around the biogas plants was summarized in zones with different transport distance around the biogas plant of 0-5; 5,1-10; 10,1-15; 15,1-20; 20,1-30; 30,1-50; 50,1-100 km. The area was divided into fields smaller than 1 ha, fields 1-5 ha and fields larger than 5 ha. Fields smaller than 1 ha was excluded from the study. Fields classified as pasture for grazing on non-arable land, fruit and wetland where excluded from the summary.

Table 1 below shows the arable area in zones up to 100 km from the biogas plants in Jordberga and Örebro, average transport distance from field to the biogas plant for each zone as well as the average field size. The average field size for fields larger than 5 ha is somewhat larger in Jordberga (12.2 ha) compared with in Örebro (10.4 ha), as an average for all fields within 100 km from the biogas plants. The corresponding figures for fields 1-5 ha are 2.6 ha and 2.5 ha for Jordberga and Örebro respectively. Figure 5 and Figure 6 show images of the arable area zones for Jordberga and Örebro.

Table 1. Arable land area in zones up to 100 km from the biogas plants in Jordberga and Örebro, average transport distance from field to the biogas plant for each zone as well as the average field size.

Zone		Average transport distance (km)	Arable area (ha)	Average field size (ha)	Average transport distance (km)	Arable area (ha)	Average field size (ha)
		1-5 ha			>5 ha		
	Jordberga	**61.0**	**69 153**	**2.6**	**52.9**	**237 376**	**12.2**
1	0-5	3.7	238	3.1	3.5	3 222	14.6
2	5.1-10	7.8	1 132	2.8	7.5	8 274	13.4
3	10.1-15	12.9	1 505	2.7	12.6	9 494	13.7
4	15.1-20	17.7	1 985	2.7	17.6	10 344	13.5
5	20.1-30	25.0	4 614	2.7	25.2	23 789	13.0
6	30.1-50	41.3	10 228	2.7	41.2	50 709	12.7
7	50.1-100	72.2	49 452	2.5	69.6	131 543	11.6
	Örebro	**59.2**	**86 765**	**2.5**	**60.4**	**149 464**	**10.4**
1	0-5	3.9	433	2.7	3.9	579	10.5
2	5.1-10	7.6	1 151	2.5	7.8	2 715	12.0
3	10.1-15	12.9	2 309	2.5	12.9	6 473	11.8
4	15.1-20	17.7	4 414	2.6	17.7	8 189	10.6
5	20.1-30	24.9	9 513	2.6	24.6	18 131	10.3
6	30.1-50	40.5	13 796	2.4	40.6	16 771	9.5
7	50.1-100	76.1	55 148	2.5	79.1	96 607	10.5

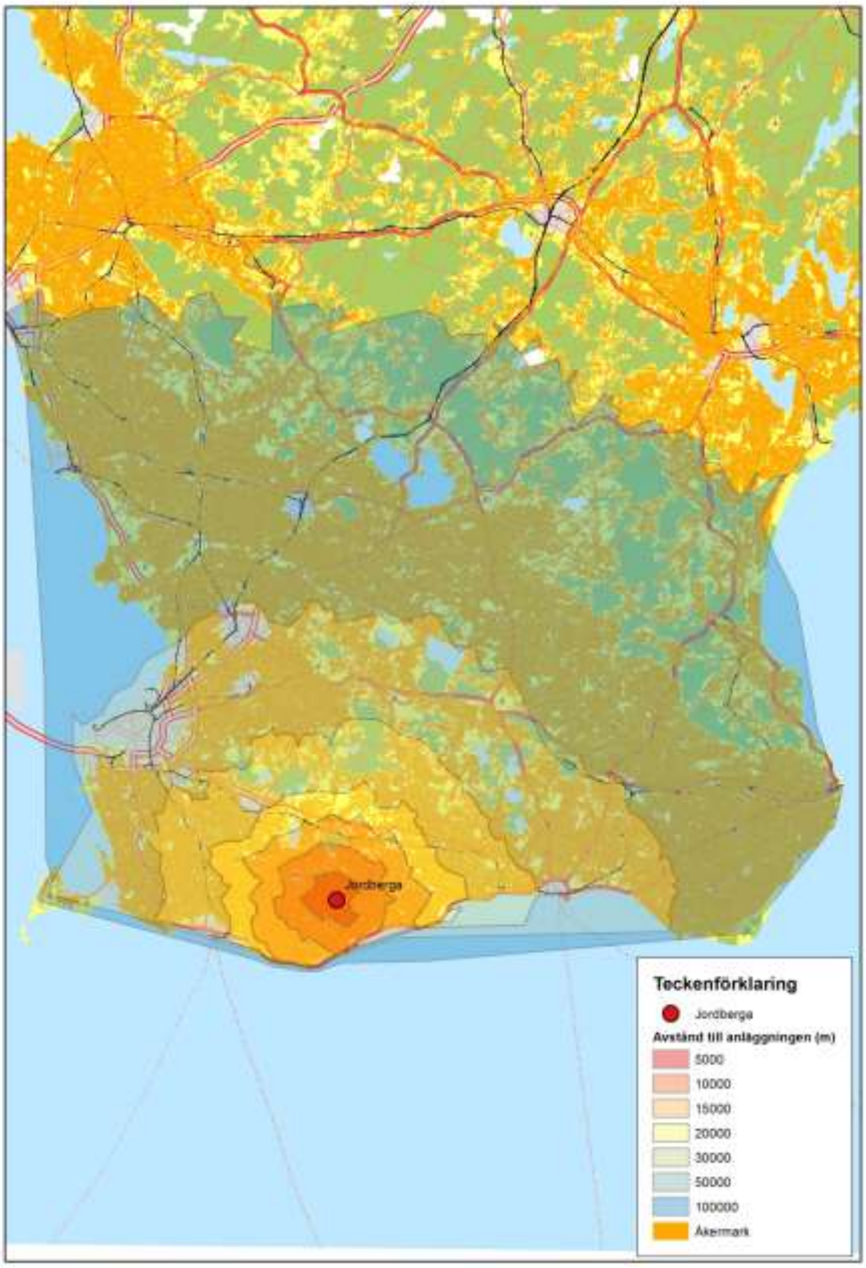

Figure 5. Transport distance zone up to 100 km for the arable land around Jordberga.

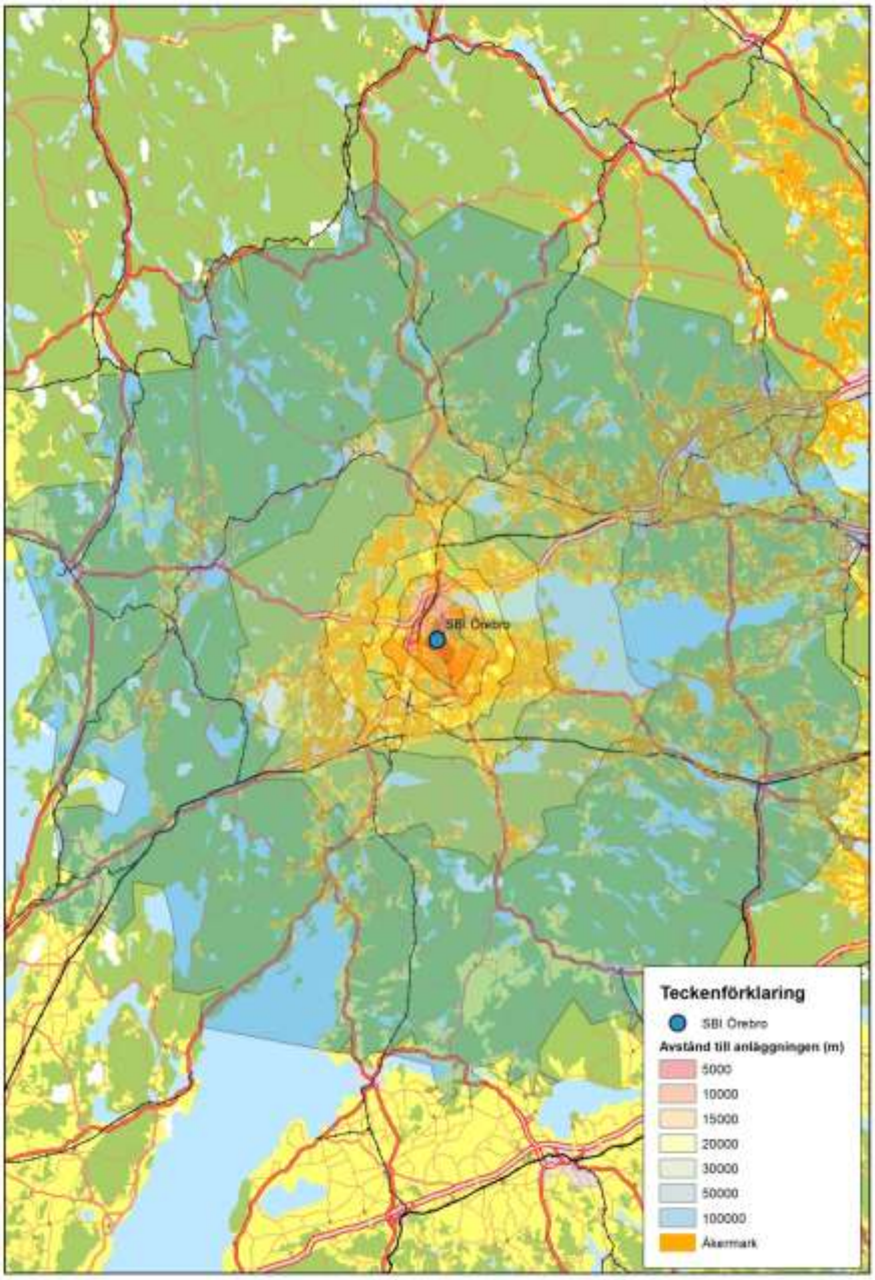

Figure 6. Transport distance zone up to 100 km for the arable land around Örebro.

3.3 COST CALCULATIONS

Substrate costs were calculated including cultivation of the crop to harvest, transport and pre-treatment before feeding the crop to the biogas plant. For ensiled crops, a cost for storage was also included. The following sections describe the cost calculations. Cultivation costs for each crop are shown in Appendix B (Table B3-Table B4 and Table B5-Table B6). Harvest- and transport costs are shown in Appendix C (Table C3-Table C8).

3.3.1 Cultivation

Cultivation costs per tonne were calculated by dividing all costs with the quantity produced. How much it costs to produce a product in relation to the expected price of the item is of interest for both the producer and the user.

Estimates published by the Swedish Board of Agriculture (Jordbruksverket, 2016) and established by Håkan Rosenqvist has formed the basis for the calculations. The estimates included all costs and revenues excluding subsidies. The estimates included common business expenses that could not be attributed to specific crop as driving, phones, accounting, road maintenance etc. Interest was considered in the calculations. The calculations are total step calculations where all costs are taken into account in the steps. By building up the calculations in steps they can be used both for short and long term analyzes (Rosenqvist, 1997; Rosenqvist, 2010, Jordbruksverket, 2016).

The calculations were based on the 2015 price level. The prices used in the calculations were a combination of different sources. Some of the most important sources were Agriwise, Vallåkra Lantmannaaffär (seed, pesticide and fertilizer prices), Svenska Foder (drying and analysis costs and grain prices), Maskinkalkylgruppen HIR (machine costs). The same prices were used for both case studies in Jordberga and Örebro.

3.3.2 Inputs and fertilization

Phosphorus (P) and potassium (K) fertilization was proportional to the crop yield while nitrogen (N) fertilization was largely linked to the crop yield but also had a hectare related fertilization. Fertilizer rates were calculated with respect to the amount of harvested crops according to Bertilsson *et. al*. (2005) and Jordbruksverket (2014). The fertilization of P and K corresponded to approximate the removal by the yield. Fertilization rates are shown in Table 2.

Table 2. Estimated fertilization rates in kg/ha and kg/tonne harvested (for grass-clover tonne DM) without regard to the preceding crop based on Bertilsson *et. al*. (2005), Jordbruksverket (2014) and Rosenqvist (2010).

	Nitrogen	Phosphorus	Potassium
Oats	17.5 kg/tonne	3 kg/tonne	5 kg/tonne
Winter wheat	25 kg/ha + 20 kg/tonne	3 kg/tonne	5 kg/tonne
Malting barley	17.5 kg/tonne – 20 kg/ha	3 kg/tonne	5 kg/tonne
Sugarbeet	120 kg/ha	0,4 kg/tonne	2 kg/tonne
Winter oilseed rape	110 kg/ha + 20 kg/tonne	5 kg/tonne	10 kg/tonne
Grass-clover	20 kg/ha +15 kg/tonne DM	3 kg/tonne DM	20 kg/tonne DM
Green rye	20 kg/ha +10 kg/tonne DM	1.5 kg/tonne DM	3 kg/tonne DM
Whole-crop cereal	20 kg/ha +10 kg/tonne DM	1.5 kg/tonne DM	3 kg/tonne DM
Maize	15 kg/tonne DM	5 kg/tonne DM	10 kg/tonne DM
Sugar beet tops	3 kg/tonne DM	3 kg/tonne DM	30 kg/tonne DM

The fertilizer prices used for N, P and K in the calculations were: N27; 2.58 SEK/kg, superphosphate P20; 3.70 SEK/kg and Kalisalt K50; 3.40 SEK/kg. Sugar beet was fertilized even with manganese nitrate (2 kg/ha à 22 SEK/kg) and Besal (160 kg/ha à 1.56 SEK/kg).

Machinery and work

Machinery costs were mainly calculated based on hourly rates from Maskinkalkylgruppen HIR (2014) and were well utilized machines on farms or cooperation covering a surface area of 400 hectares size class. The number of machine operations for each crop was the same for the different areas.

In addition to work in conjunction with the machine runs calculations also included 2 hours per ha other work, for sugar beet additionally 2 hours per ha was added for work by hand in the field.

Land use value

The land use value was calculated based the incomes from the land with 50% winter wheat, 25% barley and 25% rapeseed. The method and price level to calculate the land use value was the same as for the other crops.

For crops on large fields in Jordberga the land use value was calculated to 3201 SEK/ha. The corresponding value for Örebro was 493 SEK/ha. For crops on small fields the land use value was reduced with 1000 SEK/ha, resulting in 0 SEK/ha in Örebro. Sugar beet tops, landscape conservation grass and cover crops have no land use value. In Jordberga, the land use value for green rye was reduced to 25%, since it was assumed to be followed by establishing of a main crop in a two-crop system. In Örebro, the land use value for green rye was not reduced since the shorter growing season did not leave enough time to establish a main crop after the harvest of green rye. The calculations can be seen in Appendix B (Table B1-Table B2).

3.3.3 Harvest and transport

An overview of the identified harvest and transport systems for the crops included for Jordberga and Örebro are shown in Figure 7. Each system is described in more detail in the following section.

Specifications for the harvest and transport calculations are shown in Appendix C (Table C1-Table C2).

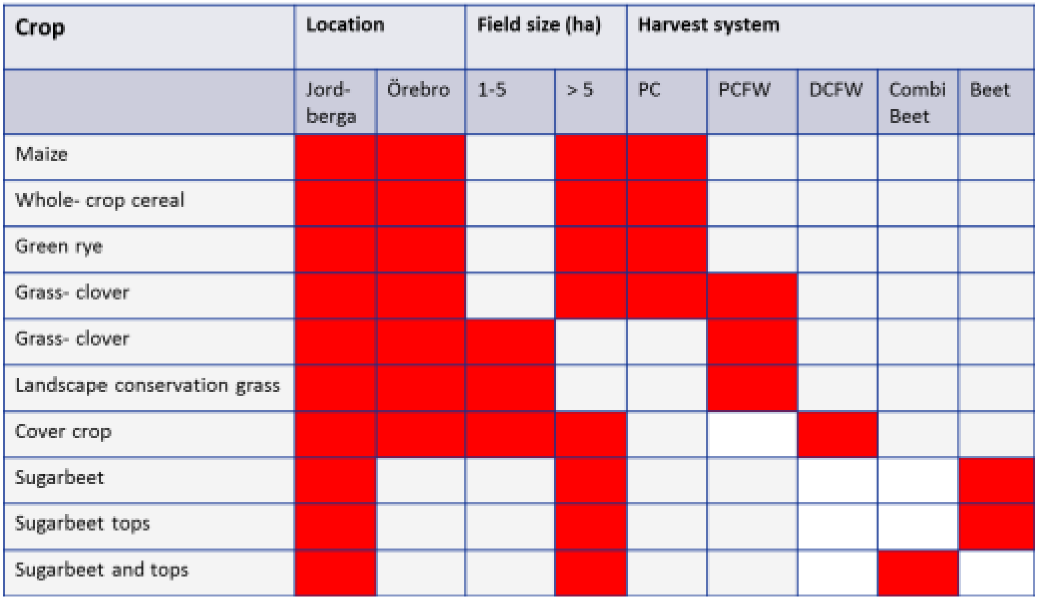

Figure 7. Overview of harvest systems for small and large fields for the crops for Jordberga and Örebro where PC equals Precision chopper , PCFW equals Precision chop forage wagon, DCFW equals Direct cut forage wagon, Combi beet equals the combined beet and top harvester and Beet equals the beet harvester.

Precision chopper

The self-propelled precision chopper was used for the harvest of maize, whole-crop cereal and green rye as well as grass-clover for ensiling grown on fields larger than 5 ha. For fresh crops both from small and large fields, the harvest system was adapted to using fresh crops that are harvested on a daily basis or 2-3 times a week depending on how long the grass can wait before feeding into the digester. For those crops, the precision chop forage wagon was chosen.

Whereas maize and whole crop silage were direct harvested, the grass-clover and green rye were mowed and wilted in the field before harvested. Compared with grass-clover for fresh use and on small fields a larger disc mower and swather were used, se Appendix C (Table C1). For green rye the smaller swather was used due to the high yield. The precision chopper was assumed to be adapted to harvesting crops for biogas by having a so called biogas drum with extra number of knifes for a shorter cutting length and no extra pre-treatment before feeding to the digester was needed.

For the crops harvested with the precision chopper, transport costs were calculated using tractor with single or double wagons and truck with trailer. In the system using a single wagon the tractor with wagon follows the harvester on the field and when the wagon is full it drives to storage where the wagon is unloaded. The system using tractor with double wagons consisted of a tractor with two wagons driving on the road to the storage, emptying the wagons and driving back. When arriving at the field edge the rear wagon is left on the field edge before the tractor drives to the harvester to fill up the front wagon. Parallel there is a tractor driving only on the field and loading rear wagons.

For the systems using truck transport, a tractor with a wagon with one container follows the precision chopper and when the container is full drives to the field edge or closest suitable place for unloading the container. The truck load the containers and drive to storage where the containers are unloaded and empty containers are loaded on the truck before returning to the field.

Precision chop forage wagon

Grass-clover and landscape conservation grass grown on fields of 1-5 ha as well as grass-clover for fresh use from both small and large fields was harvested using a tractor driven precision chop forage wagon where the harvester is integrated with the wagon. The forage wagon chop the crop in the swath, drives to the storage, unloads and drives back to the field. Calculations were also made for a container system where the forage wagon drove to the field edge where the container was unloaded and an empty container was loaded. The containers where then loaded to a truck and transported to storage.

Direct cut precision chop forage wagon

For the harvest of cover crops a direct-cut system was assumed consisting of a tractor with a mower in the front and a precision chop forage wagon in the rear. When the wagon is loaded it is left on the field edge where another tractor picks it up drives to the storage, unload the wagon and drives back to the field. Calculations were also made for a container system where the forage wagon drove to the field edge where the container was unloaded and an empty container was loaded. The containers where then loaded to a truck and transported to storage.

Sugarbeet systems

For Jordberga three alternatives were included for sugarbeets; beets only, combined harvest of beets and tops for biogas production and tops only from beets grown for sugar production.

For the alternative harvesting only beets a self-propelled 6 rows harvester was used that collected the beets on the container of the harvester. The harvester emptied the beets on the fly to a tractor with a high dump forage wagon driving up to the harvester. When loaded, the tractor drove to field edge and emptied the load to a container. Transport to the biogas plant was then made using trucks with the same container system as the described for the precision chopper. The beets that were stored for later use were stored in a clamp on the field edge.

When only tops were collected for biogas production during the harvest of conventional beets for sugar production the tops were collected by a tractor and a high dump forage wagon driving parallel to the harvester and emptying its load on the field edge to a single wagon for tractor transport or in containers for truck transport to storage. The cost of the harvester was charged the beets for sugar production. An additional harvest cost estimated to 150 SEK/ha in a study by Kreuger *et al.* (2014) was added to the beet tops due to reduced capacity of the beet harvest.

For the combined harvest of tops and beets, a tractor driven beet harvester (3 rows) was modified so that the tops were cut and transported with a conveyor belt to the container were beets and tops were gathered together. To avoid soil contamination of the tops they were handled separately from the beets until the beets have been mechanically cleaned from soil. The container was emptied on the run by a tractor with a high dump wagon driving up to the harvester. When loaded, the tractor drove to field edge and emptied the load to a container. Transport to the biogas plant was then made using trucks with the same container system as the described for the precision chopper.

Specifications for the calculations

Machinery costs were calculated based on hourly rates from Maskinkalkylgruppen HIR (2015) and correspond to well utilized machines. For mowing and swathing a constant speed independent of the yield was assumed resulting in a constant capacity and cost per hour. For the crops that were mowed and wilted on the field before harvesting the capacity of the harvest machine can be adjusted by the speed and the size of the swath. When the yield was low a swather was used to collect material from a larger area to get larger swaths. The effective capacity of the machines when working in the swath was calculated based on the crop yield and width and speed of the machine. For chopping the amount of biomass through the chopping device is limited and a maximum effective capacity was identified. Depending on the crop yield the speed was then adjusted to not exceed the maximum throughput capacity.

The practical capacity is describing how much biomass that is brought to the storage including unproductive time on the field for turnings etc. This unproductive time is also depending on the speed and on the field shape and field size. The practical capacity of each machine for each crop was calculated by dividing the crop yield with the time demand for operating one hectare. The time demand was calculated based on results from Nilsson *et. al.* (2014) simulating the time required for machine operations on fields with varying shape, size, implement width and speed. For operations on fields larger than 5 ha data for simulation on 15 ha field size was used. For operation on field 0-5 ha data from field of 2.5 ha was used.

Further, it was assumed that for all transport systems the practical capacity was not limited by transport capacity meaning that enough transport capacity was provided to avoid idle time for the harvester.

Transport costs were calculated using tractor with single or a double wagon (45 m^3) as well as for truck with trailer. For the truck transport a system with 3 containers each of a volume of 40 m^3 was assumed, one container on the truck and two containers on the trailer. This system requires separate tractors with a trailer with one container on the field. The container system requires extra containers available for a continuous harvest.

The load of the transport was assumed to be limited by the weight resulting in the same transport cost per volume for all crops within the same transport distance zone, unless the maximum weight was exceeded. Maximum load of the system with containers were set to 12 tonnes per container. For the tractor transport the maximum load was set to 20 tonnes with a single wagon and 36 tonnes when double wagons were used. The transport density of forage and whole crop silage was obtained from measurement done by SBI during harvest (Lingman, pers comm), 0.38 tonnes/m^3 for grass-clover and 0.42 tonnes/m^3 for whole crop silage. Maize was assumed to have the same density as whole crop silage and cover crops and green rye the same density as grass-clover. The density 0.36 tonnes/m^3 of beet tops was obtained from Kreuger et al. (2014). Densities for beets were set to 0.65 tonnes/m^3 and for beets and tops to 0.75 tonnes/m^3. Due to losses during turnings etc. on the sugar beet field 81% of the beet tops was assumed to be harvested (Kreuger *et. al.*, 2014).

3.3.4 Storage

For all crops except sugar beets the costs calculations were done for storing in bunker silos. Sugar beets were assumed to be stored in clamps. For Jordberga the calculations were done for the existing bunker silo based on experiences from filling and covering the silo (plastic, net straps, sand sacks and work). Since the biogas plant in Örebro does not have a bunker silo today a bunker silo adapted to the size of the biogas plant was assumed. The costs for packing the silo were based on the same cost per tonne DM as in Jordberga whereas costs for material and time for covering of the silo was related to the area of the silo by using the same cost per m^2 as in Jordberga. The bunker silo in Jordberga has 4 m high walls whereas for Örebro, bunker silos with 3 m high walls was assumed. Based on findings by Nilsson (2013) the density of the silage in the silo with lower height in Örebro was reduced with 9% compared with the density in Jordberga. Investment costs for the bunker silos were estimated by a manufacturer of bunker silos. The storage costs are summarized in Table 3 and details of the calculations are shown in Appendix D (Table D1).

Table 3. Costs per kg DM put into the silo for storage of silage in bunker silos in Jordberga and Örebro.

Costs (SEK/kg DM)	Jordberga	Örebro
Investment	0.021	0.039
Maintenance	0.002	0.003
Material and work for covering	0.008	0.015
Work packing	0.045	0.045
Total	0.076	0.102

Storage losses are affected by many factors such as type of crop, weather, time and technique of harvest, ensiling technique etc. and therefore show great variation. Storage losses can be divided into visible and invisible losses. After closing or covering the silo invisible losses of dry matter (DM) occur during fermentation of the crop. Leakage of air through the cover of the silo also causes invisible losses through oxidation. Air leakage also leads to spoilt silage in the outer layer. If the DM-content is low losses also occur through effluent. Visible losses also occur during take-out of the silo. Depending on the DM content Belotti (1990) mention storage and conservation DM losses for bunker silos of 16-22%. In a recently finished study of silage losses by Spörndly and Udén (2016) they analyzed losses in full scale bunker silos on farms and measured the invisible DM losses in the form of CO_2 and heat to 11% of DM on average. The losses occur during storage but probably also during take-out, especially in larger silos. When estimating DM losses for different silo systems they recommend using 20% DM-losses as an average for tower-, bunker- and bag silos. Other studies mention DM losses varying between 7-40% (McDonald *et. al.*, 1991)

Based on the model developed by Liljenberg *et. al.* (1995) and results from Spörndly and Udén (2016) the DM storage losses in the calculations done in this project were set to 10% and should cover for the invisible losses. The visible losses and the effluent are assumed to be collected and used for biogas production. In this project no differentiation between the methane yield of fresh and ensiled crops will be considered. This means that the energy losses are equal to the DM losses.

3.3.5 Pre-treatment by bio-extrusion

For crops harvested with the presisions chop forage wagon a pre-treatment cost was added to the substrate cost since the forage wagon is not equiped with the biogas drum for shorter cutting length.

According to Odhner *et. al.* (2015) the cost for pre-treatment of lignocellulosic substrates, such as grass from natural land areas and grass silage, by bio-extrusion is approx. 400 SEK/tonne VS (volatile substances) with a corresponding cost of approx. 360 SEK/tonne DM. In a bio-extrusion process lignocellulosic substrates will be disintegrated in an effective way. After the bio-extrusion it is normally easy to use such substrates in a biogas plant, which typically use more finely chopped substrates, such as maize and whole crop cereal, chopped by a normal precision chopper equipped with a biogas drum.

The methane yield increase by approx. 30% of grass from natural land areas, and the biogas production process is accelerated. After 30 days, nearly 70% of the readily available energy of the material is converted into methane gas, compared with about 50% of untreated raw materials at the same time. A great advantage of the bio-extrusion is that the residence time in the digester can be reduced and the production of methane gas from the substrate occurs over a much shorter time. The risk of floating layers or feeding problems in the digester also decreases significantly after bio-extrusion of fibre rich lignocellulosic substrates.

Bio-extrusion is used as a pre-treatment process of grass and grass silage at Karlskoga Biogas AB in Sweden. The bio-extruder on 74 kW is produced by Lehmann in Germany. The capacity is about 12 tonne DM per day, equivalent to about 4200 tonne of DM per year.

3.4 OPTIMIZATION

An optimization model was developed to minimize the cost of supply of fresh and stored crops during different periods of the year. The problem can be described as a mixing problem and a linear programming model was developed in Microsoft Excel, using the add-in module OpenSolver v2.8.5 (described in Mason, 2012) and the CBC optimization engine (COIN-OR: http://www.coin-or.org) which is an open source software with the capacity to handle larger (linear and non-linear) problems than the original Microsoft Excel Solver.

The period from May to November, when fresh crops could be available, was divided in one-week periods, while the rest of the year was divided into two periods for Jordberga and one period for Örebro, reflecting different storage capability of different crops. As a consequence, one year consists of 31 periods (p.1-p.31) in the model for Jordberga and 24 periods in Örebro. Based on the selected crops, a list of substrates was prepared, where the properties for every harvest opportunity for a fresh crop, and every period when a stored crop was available, was represented by unique list entries. Ensiled crops were assumed to be available in all periods in the year after harvest each crop was therefore represented by 31 and 24 list entries for Jordberga and Örebro, respectively. Fresh crops, which were harvested multiple times per year on the same field, were represented by one separate list entry for each alternative harvest schedule (e.g. grass-clover ley crops could be harvested 3-4 times depending on the starting week, resulting in 8 possible schedules). Sugarbeet could only be stored until February and was therefore only available in the first storage period and thus represented by one single list entry. It was assumed that the stored crops were harvested in the period resulting in lowest cost per methane production. For the Jordberga case, 19 crops were selected, and since many were available during several periods this resulted in a list of 255 potential substrates. For the Örebro case, 15 crops were selected, resulting in 237 potential substrates. Transport costs were calculated for 14 zones, where zones A1-A7 represented agricultural land in large fields and B1-B7 represented agricultural land in small fields.

The optimization model minimizes the substrate costs by allocating an optimized mix of substrates, under constraints related to land use, biogas production and possible combinations of crops. The decision variable, x_{spz}, denotes the land use (in ha) allocated to a substrate (s) in each period (p) and zone (z). The objective function of the model is to minimize the total cost to supply substrates from allocated land in each of the zones surrounding the plant, so that the demand for substrates for planned production rate is satisfied for each of the periods in the model:

Minimize

$$f(x_{spz}) = \sum_{s=1}^{S} \sum_{p=1}^{P} \sum_{z=A1}^{B7} x_{spz}\left[CLu_s + CCult_s + CHarv_{sp} + yield.DM_{sp}\left(dmc_{sp}^{-1} * CTrp_{sz} + CSto_s + CPre_s\right)\right]$$

where

s∈(1, …, S) is a list of available substrates

p∈(1, …, P) denotes time periods

z∈(A1, …, A7, B1, …, B7) denotes the land use zones with small and large fields (A/B) and at different distance intervals (1-7)

and where

x_{spz}	allocated land use for substrate *s* in zone z in period p, ha
CLu_s	Land use cost for substrate *s*, SEK/ha
$CCult_{sp}$	Cultivation cost for substrate *s* in period p, SEK/ha
$CHarv_{sp}$	Harvest cost for substrate *s* in period *p*, SEK/ha
$CTrp_{sz}$	Transport cost for substrate *s* from zone *z*, SEK/t WM
$CStor_s$	Storage cost for substrate *s*, SEK/t DM
$CPre_s$	Pre-treatment cost for substrate *s*, SEK/t DM
$Yield.DM_{sp}$	Dry matter yield of substrate *s* in period *p*, t DM/ha

Subject to constraints 1-6, where the set of constraints may be adapted to model different scenarios, which are described in Chapter 4, Results and discussion:

Constraint 1 states that the total substrate supply should satisfy the planned production of substrates for each period (after reduction for storage losses for the ensiled substrates), based on a set of substrates specific to each scenario. The designated values are based on 80% of the currently planned biomethane production for the plant. The agricultural land is classified in two types based on field size, but there is no differentiation based on soil types, land consolidation, or other field-specific characteristics.

Constraint 2 states that the land use for the supply of all substrates is limited to the accessible land in each zone; i.e. a set proportion (20%) of the total agricultural land in the area for each zone (as presented in Table 1). Since substrates are allocated based on land use, allocated land for residual products (e.g. sugarbeet tops), which do not compete with other substrates for land, is subtracted from the total land use in this constraint.

Constraint 3 controls the amount of fresh substrates supplied during each period, in order to avoid solutions with large volumes of fresh substrates in the substrate mix (which could negatively affect the digestion process, especially if the mix changes too rapidly). The constraint limits allocated land use for fresh substrates to one-third of the total dry matter supplied.

Constraint 4 limits the land use for specific substrates to a set proportion of the accessible land in each zone (25% for sugarbeet cultivation, 75% for cereal cultivation), in order to avoid solutions which are unrealistic due to crop rotational practice.

Constraint 5 states that the allocated land use for sugarbeet tops is limited to actual land use for sugarbeet production in the region (11%); assuming sugarbeet tops are collected from fields that are not accessible for other crops in the model.

Constraint 6 limits the land use for cover crops to a set proportion of land use for cereal crops (assuming that cover crops can be planted on 50% of all cereal crops in the region, corresponding with spring-sown cereal. With cereal production limited to 75% of arable land in the region, this limits the cover crops to 37.5% of total arable land in the region).

4 RESULTS AND DISCUSSION

Substrate costs were calculated from cultivation to pre-treatment before feeding the crops to the biogas plants. The cultivation-, transport- and harvest costs are presented for each crop in the Appendices. Also, land use costs were calculated. Substrate costs were used in the optimization model to find the crop combination with the lowest cost for producing the total annual methane production of the plant. Available substrates and constraints were combined into different scenarios, which were optimized based on the costs and properties of the crops described above. The following scenarios were analyzed:

1. Reference scenario based on current practice – in this scenario costs were calculated with the crop substrate mix used today at the biogas plants. No optimization was done in this scenario.

2. Ensiled scenario – in this scenario an optimization was done allowing only ensiled crops. Ensiling crops before feeding to the digester is currently normal practice and this scenario enables a comparison of optimized results with and without fresh crops.

3. a) Mixed scenario – in this scenario an optimization was done allowing both fresh and ensiled crops. To account for possible negative effects on the biogas process by feeding only fresh crops the contribution of fresh crops were limited to maximum one third of total crops in each scenario.
   b) Mixed unrestricted scenario – this scenario equal scenario 3a with the exception that no limitation was set to contribution of fresh crops. By doing this the production related constraints on the optimal solution could be investigated.

4. a) Advanced biofuels scenario – in this scenario, crops not classified as substrates for advanced biofuel production (maize, sugarbeets and whole-crop cereal) were not allowed, while crops considered as residues (sugarbeet tops) and cover crops and green rye (which are grown before or after a main crop) were allowed in the optimized solution. According to pending regulations, grass-clover is not considered to be a food-based crop and was therefore allowed in this scenario. Fresh crops were restricted to maximum one third of total substrate supply.
   b) Advanced biofuels scenario with crop rotation values – this scenario was based on the restrictions in 4a. In addition, the positive effect of grass-clover on subsequent crops in a cereal-based crop rotation was taken into account by reducing the land use value for grass-clover. Grass-clover has been considered as a suitable crop for biogas production but not always cost-competitive in relation to e.g. maize and whole-crop cereal. In this scenario, it is investigated how the cost comparisons would be altered by accounting for the positive effects on other crops in a cereal based crop rotation, like increased yield, decreased need for nitrogen fertilization and crop protection.

In the following section, results from optimizations are presented to explore how substrate mix and substrate costs for Jordberga and Örebro biogas plants could be affected by current and alternative strategies and combinations of fresh and ensiled crops. The basis for the calculations were that 80% of the total annual methane production of the biogas plants should be supplied from crop substrates. The residual 20% of the methane product was assumed to be produced from waste and other substrates that were not included in the calculations.

Out of the total arable land, 20% was assumed available for cultivation of crops for biogas production at Jordberga and Örebro biogas plants, respectively.

4.1 JORDBERGA BIOGAS PLANT

Total costs of evaluated crop substrates

The total substrate costs can be compared by entering one hectare of each substrate in each zone in the optimization model. Figure 8 presents total substrate costs per 1 ha of each substrate (as average values for all zones in the model), and their composition of land use, cultivation, harvest, transport, storage and pre-treatment costs for each substrate. For crops that can be harvested for more than one week or period, the figure shows an average value for all harvest periods.

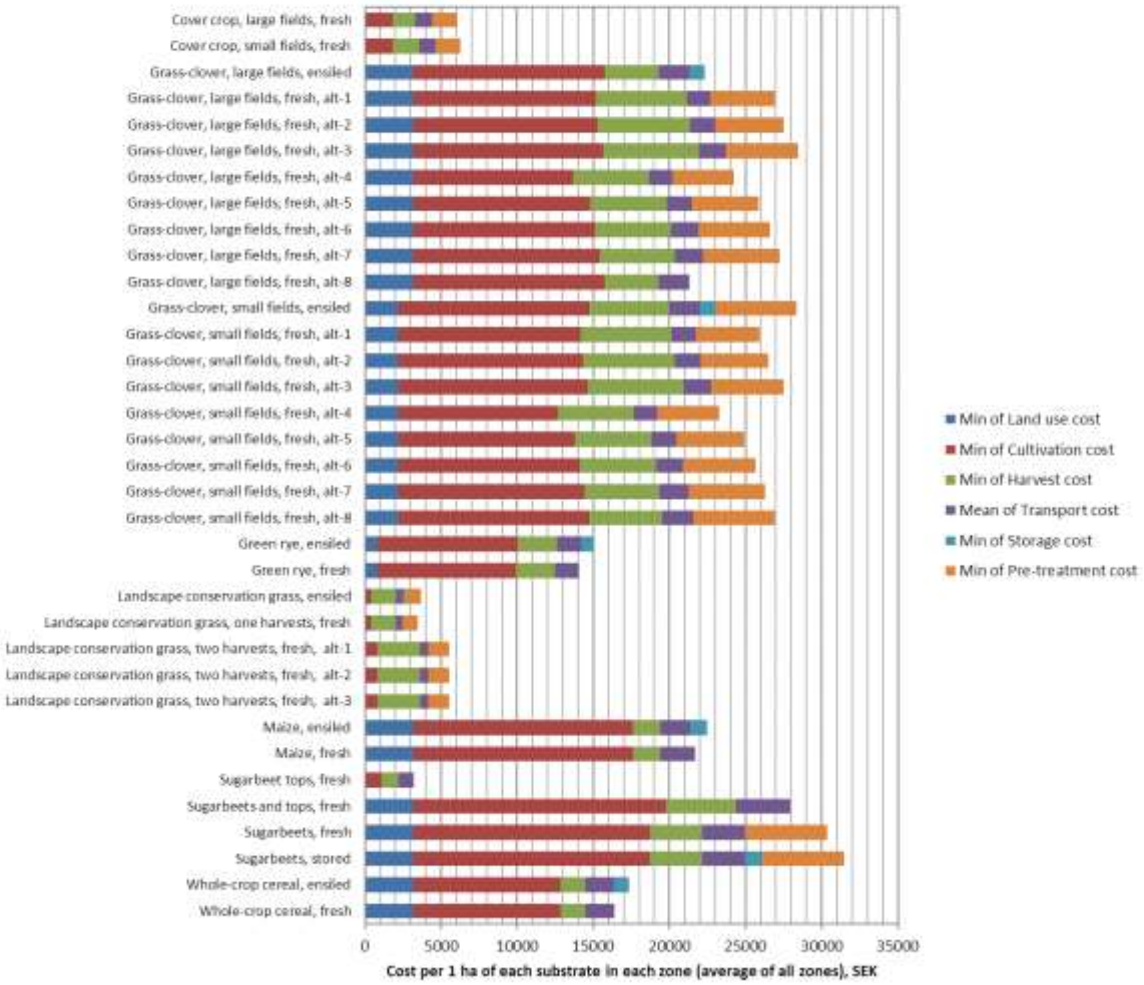

Figure 8. Total substrate cost (SEK/ha) based on cultivation of 1 ha of each substrate (as average values for all zones in the model), divided into costs for land use, cultivation, harvest, transport, storage and pre-treatment costs. For crops that can be harvested for more than one week/period the figure shows an average value for all harvest periods.

Costs per hectare show great variations between crops, costs are low for crops with no land use cost and no or low cultivation costs such as cover crops, landscape conservation grass and sugar beet tops. The landscape conservation grass has low costs based on the assumption that it is permanent without costs for establishment and no fertilization (the minimal cultivation costs mainly relate to over-head costs). The dominating cost for annual crops like maize and whole-crop cereal were cultivation costs whereas harvesting costs were a larger part of total costs for perennial grass-clover harvested 3 or 4 times per year. Grass-clover was undersown in a main cereal crop and kept for two years which reduced the cost for establishing the crop. The largest cost for cultivation of grass-clover was fertilizers.

The transport costs calculations were made for different transport alternatives using tractor or truck. For each zone the alternative with the lowest costs was chosen and used in the model. For all crops harvested with a self-propelled precision chopper, tractor with a single wagon had lowest costs within the two first zones up to 10 km. At distances above 10 km truck with trailer was the cheapest alternative.

For grass-clover and landscape conservation grass on small fields harvested with a precision chop forage wagon, transport with the forage wagon had lowest costs up to 5 km. At longer distances, truck transport was cheapest. The capacity of the system using a precision chop forage wagon is sensitive to increased transport distance since harvest and transport is done with the same machine and the harvest stops when the wagon leaves the field for the transport. For cover crops and all sugar beet systems, transport by truck was the cheapest alternative in all zones.

Figure 9 compares the total substrate costs per tonne DM for all substrates in each zone. Thus, 7 bars are displayed for each substrate (one for each zone) and the differences between these bars represent the difference in transport cost between zones. Figure 10 presents the same information expressed as cost per volume methane produced. The zones with different transport distances are A1-A7 representing large fields and B1-B7 representing small fields.

Expressed per Nm^3 methane produced, sugarbeet tops had lowest costs followed by fresh whole-crop cereal and maize. They were also among the cheapest of the ensiled crops. Grass-clover, both from large and small fields, could not compete with costs with the cheapest substrates.

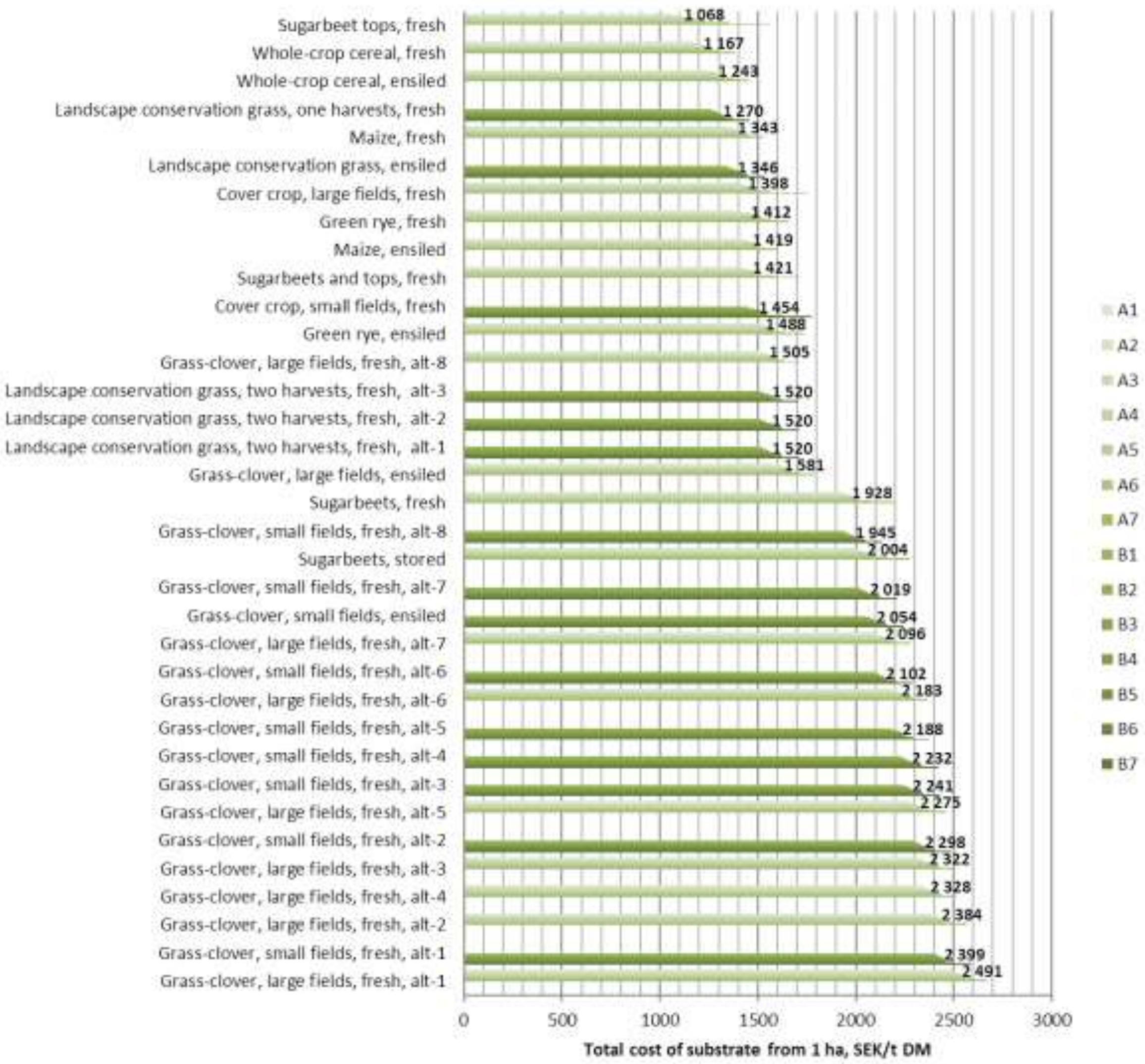

Figure 9. Substrate cost comparison for each zone in Jordberga, SEK/tonne DM (data labels indicate the lowest cost for each substrate; i.e. shortest transport distance).

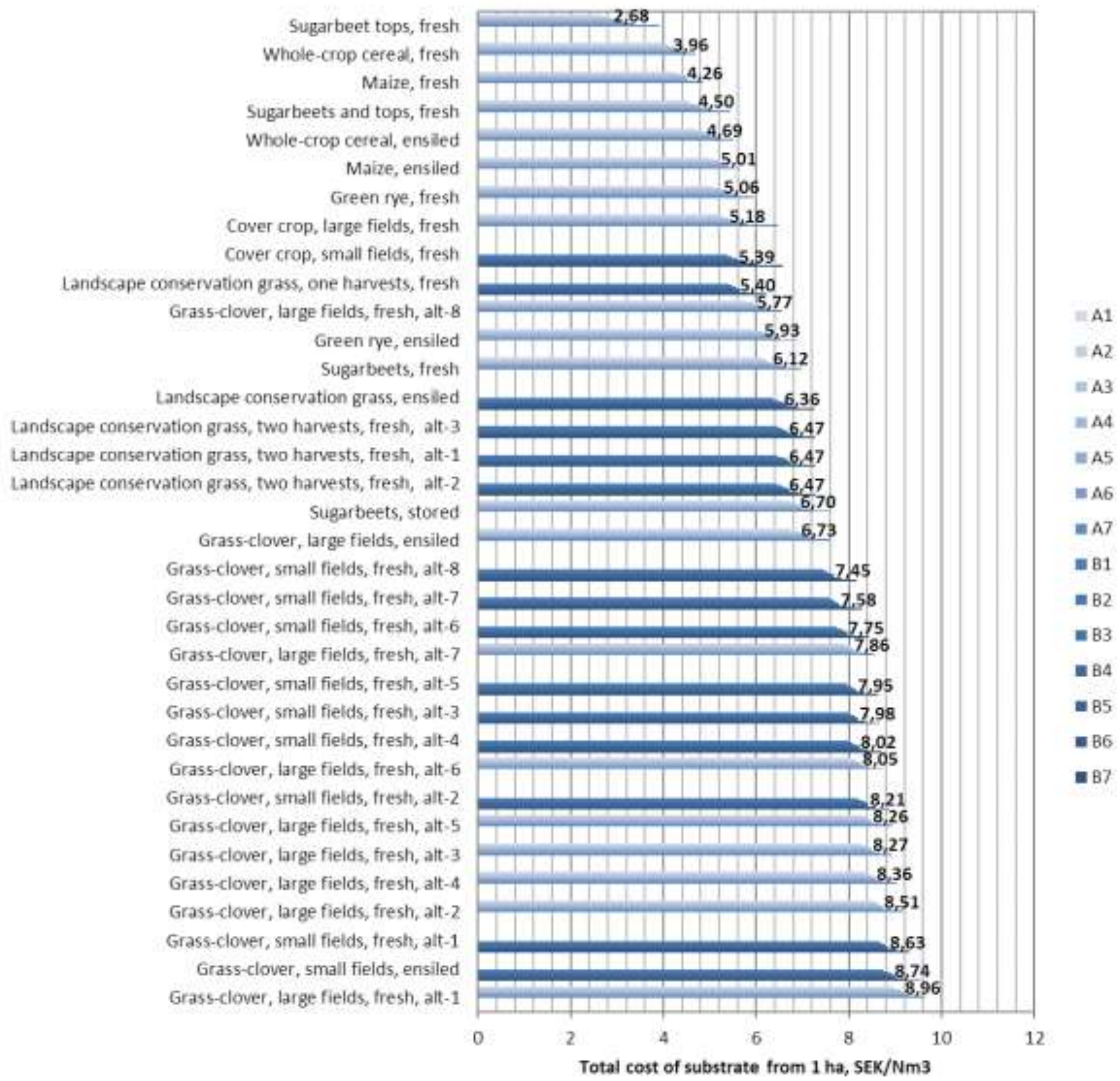

Figure 10. Substrate cost comparison for each zone, SEK/Nm^3 methane in Jordberga (data labels indicate the lowest cost for each substrate; i.e. shortest transport distance).

Scenario 1: Reference scenario based on current practices

In the reference scenario, we looked at the crop substrate mix supplied currently at Jordberga facility. The current practice for the crops used is to use a mix of ensiled crops consisting of 40% maize and 60% whole-crops cereal on wet weight basis. Figure 10 shows that these crops also have the lowest costs of ensiled crops in our calculations.

The agricultural land was manually allocated to satisfy the annual substrate demand and reflect the current proportions of ensiled maize to whole-crop cereal. The calculated biomethane production and land use demand for ensiled maize and whole crop cereal are presented in Table 4.

The reference scenario resulted in a total annual substrate cost of 46.9 MSEK, equivalent to 4.94 SEK/Nm^3 biomethane or 1349 SEK/tonne DM. The composition of the costs is shown in Figure 11. The distribution of land use for the include substrates is displayed in Figure 12. Since only stored substrates were used in this scenario, there was no case for optimizing the supply during different times of the year.

Table 4. Calculated land use for crops in the reference scenario in Jordberga.

	Methane production (%)	Substrate demand (tonnes w.m.)	Land use demand (ha)	Allocated land use per zone (ha)		
				A1	A2	A3
Total	100%	84 529	2 519	644	1 655	1 899
Maize, ensiled	40%	33 811	1 002	0	1297	220
Whole-crop cereal, ensiled	60%	50 718	1 517	644	358	0

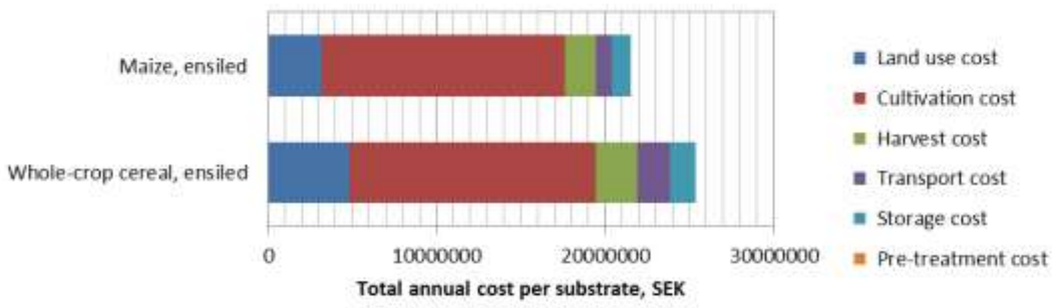

Figure 11. Composition of total annual substrate costs in the reference scenario calculation, SEK.

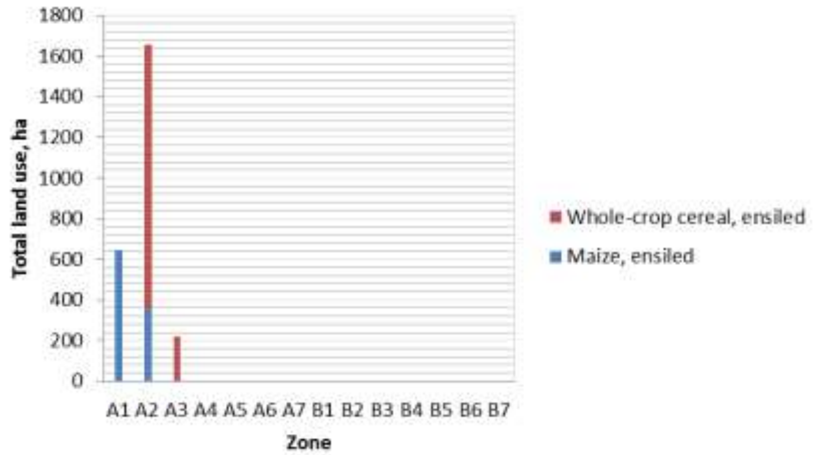

Figure 12. Supply of ensiled substrates to Jordberga; biomethane production (Nm^3) from substrates harvested in different zones (A1-A7 representing large fields, B1-B7 representing small fields) in the reference scenario calculation.

Scenario 2: Optimized solution based on ensiled substrates

In scenario 2 an optimization was done using only ensiled crops. The silage scenario resulted in a total annual substrate cost of 46.1 MSEK, equivalent to 4.86 SEK/Nm^3 biomethane. Compared with scenario 1, current practice, annual costs decrease of with 0.7 MSEK or 4.9%. Cost composition is shown in Figure 13. One single substrate, whole-crop cereal, was selected in the optimization.

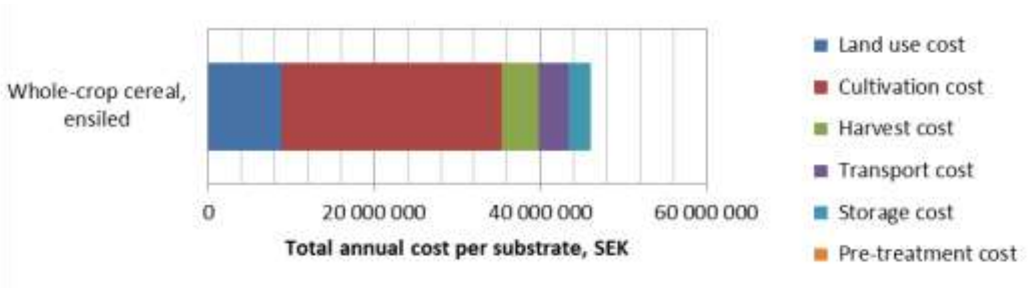

Figure 13. Composition of optimized total annual substrate costs, SEK, in the ensiled scenario in Jordberga.

To produce the annual amount of methane, crops were supplied from fields in zones 1-3, all within 15 km transport distance, see Figure 14.

Figure 14. Land use demand (ha) in different zones (A1-A7 representing large fields, B1-B7 representing small fields) for optimized supply of substrates to Jordberga in the ensiled scenario.

The result of this optimization differed from the current practice at Jordberga, where also maize is used as a biogas substrate. A reason for the use of maize could be that part of the arable land around Jordberga has light soils which are suitable for maize but not for whole-crop cereal. In the optimization model, effects of different soil properties of arable land were not accounted for, although this could be a possible further development.

Scenario 3a: Optimized scenario based on a mix of fresh and ensiled crop substrates

In this scenario the optimization was done allowing fresh crops to be used together with ensiled crops. In scenario 3a, contribution of fresh substrates was limited to maximum 1/3 of total crops in each period while scenario 3b was optimized without this limitation.

The mixed scenario 3a resulted in a total annual substrate cost of 44.3 MSEK, equivalent to 4.67 SEK/Nm^3 biomethane. Costs composition is shown in Figure 15.

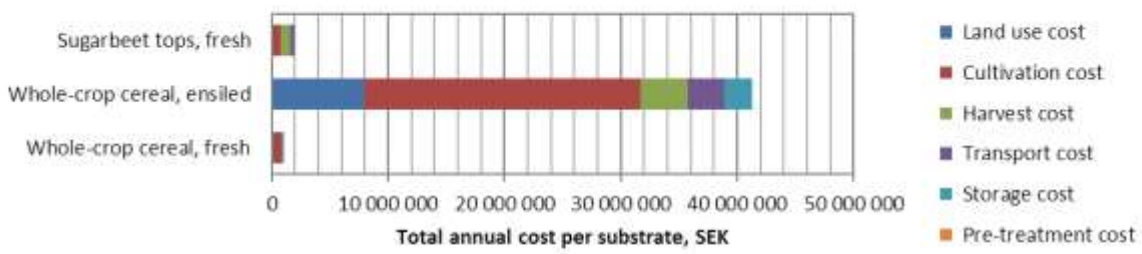

Figure 15. Composition of optimized total annual substrate costs, SEK, in the mixed scenario in Jordberga with fresh crops limited to 1/3 of the substrate mix.

The optimized solution included fresh sugarbeet tops during their whole harvest season, fresh whole-crops cereal during their whole harvest season and ensiled whole-crop cereal during the rest of the year, as seen in Figure 16. The limitation of maximum one-third of fresh crop in each period resulted in ensiled whole-crop cereal being used as a base in every period. Compared with scenario 1 (current substrate mix at Jordberga), the total substrate costs were 5.5 % lower for the mixed crop scenario. The distribution of land use for the included substrates is displayed in Figure 17. All crops were gathered from zones 1-3 at a maximum transport distance of 15 km.

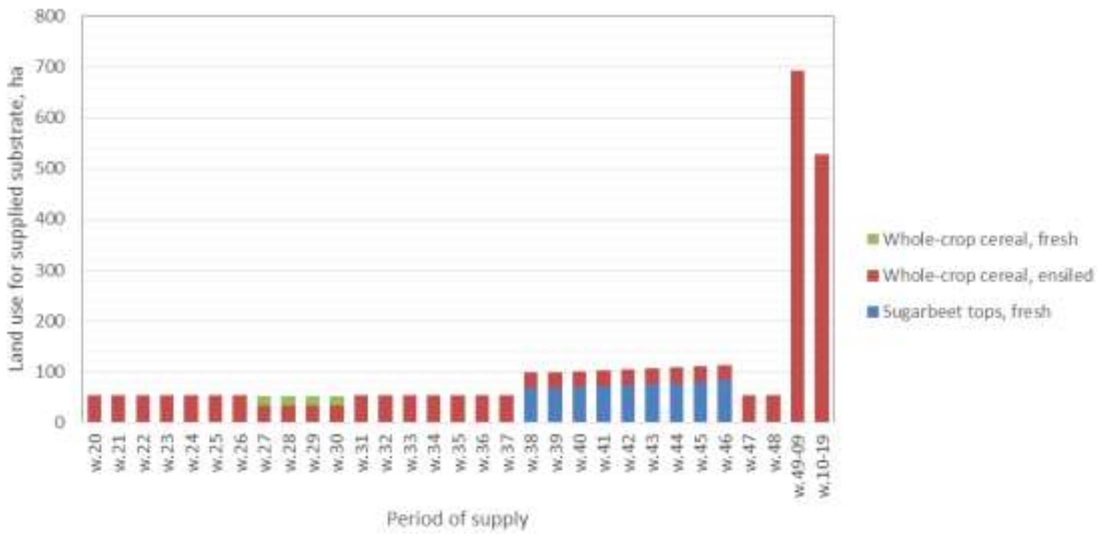

Figure 16. Supply of substrates to Jordberga in the optimized scenario using fresh and ensiled crops; land use demand (ha) distributed over the periods of the year. Note that fresh substrates are only available in the periods when they can be harvested, while stored substrates are assumed to be harvested when their total cost per biomethane potential is lowest and used when required as indicated in the figure.

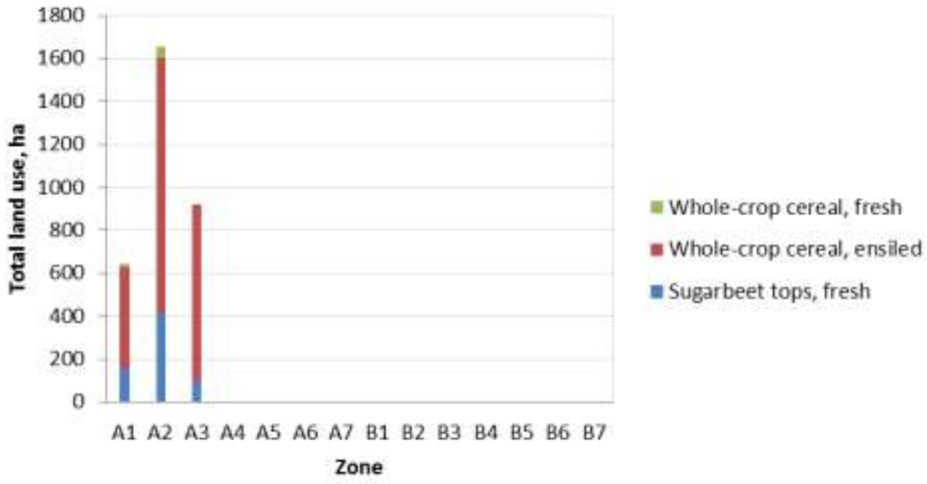

Figure 17. Land use (ha) in the optimized supply of fresh and stored substrates to Jordberga in the mixed scenario from different zones (A1-A7 representing large fields, B1-B7 representing small fields).

For fresh crops to be competitive, their costs need to be lower than the cheapest ensiled crop, which in our case was whole-crop cereal. When the crops were not competing for the same area, as for example sugarbeet tops and sugarbeets for sugar production, the fresh crops had to have lower substrate costs at the shortest transport distance compared to the cheapest ensiled crop with the longest transport distance used in the optimal solution.

Scenario 3b: Optimized scenario based on a mix of fresh and ensiled crop substrates without limitation on fresh substrates

In Scenario 3b, the restriction of fresh substrates to maximum 1/3 in the mix was removed in order to investigate this production related constraint on the optimized solution. After removing the restriction, the total annual substrate cost was reduced to 42.2 MSEK, equivalent to 4.44 SEK/Nm^3 biomethane. Costs composition is shown in Figure 18. The same three substrates were used in the mix but 100% was now allocated to one single crop in each period, and the selected fresh crops were used during the periods when they were available for harvest (Figure 19). The distribution of land use for the included substrates is displayed in Figure 20.

Compared with the reference scenario costs decreased with 10.1% in this scenario which corresponds to the goal of the project to reduce costs with 10% by using a combination of fresh and ensiled crops.

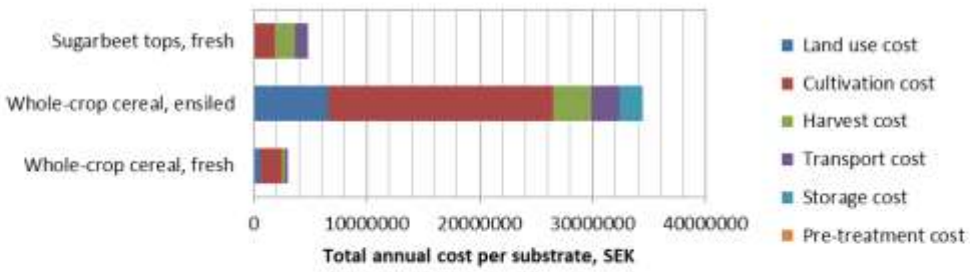

Figure 18. Composition of optimized total annual substrate costs, SEK, in the unrestricted mixed scenario.

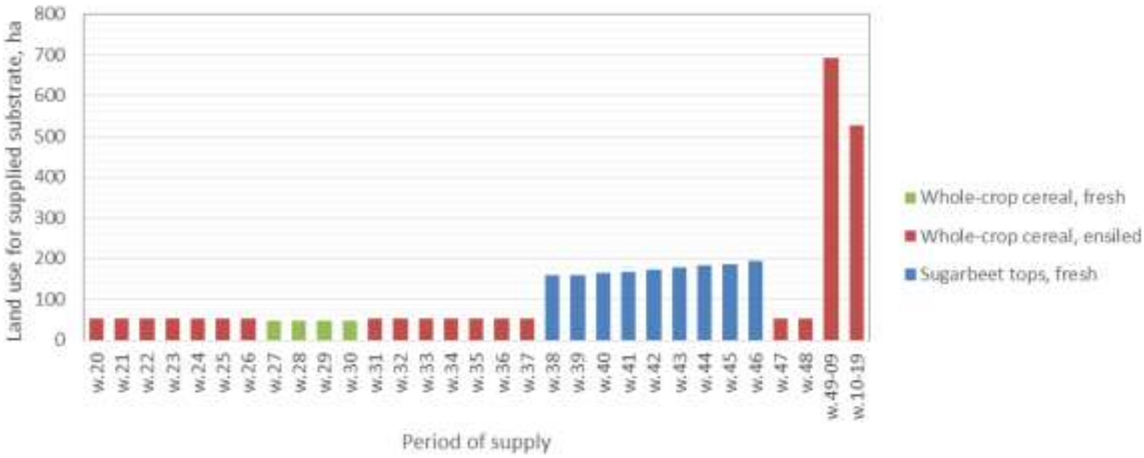

Figure 19. Supply of fresh and ensiled substrates to Jordberga in the unrestricted scenario 3b; land use demand (ha) distributed over the periods of the year (note that fresh substrates are only available in the periods when they can be harvested, while stored substrates are assumed to be harvested when their total cost per biomethane potential is lowest and used when required as indicated in the figure).

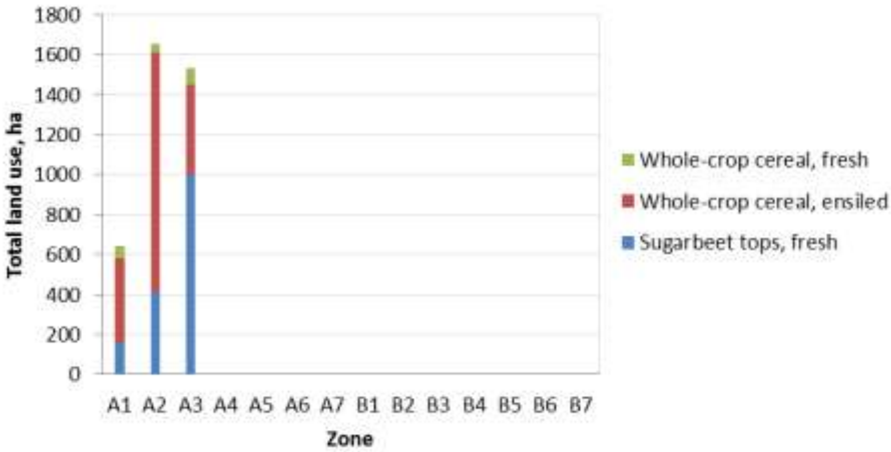

Figure 20. Land use (ha) in the optimized supply of fresh and stored substrates to Jordberga in the unrestricted mixed scenario from different zones (A1-A7 representing large fields, B1-B7 representing small fields).

One aspect of uncertainty for the small-scale system for harvest of fresh crops is the pretreatment cost associated with achieving a cutting length comparable to that of the large-scale system harvesting crops using a precision chopper equipped with a biogas drum. There are many types of machines for mechanical disintegration of crops, see for example Gunnarsson *et. al*. (2014). They calculated the cost for mechanical disintegration using a chipper to 100 SEK/tonne DM, which is much lower than the cost for the extruder used in this study (360 SEK/tonne DM). The degree of disintegration required is also depending on the feeding system and equipment available at the biogas plant and is therefore site-specific. Technique and cost for disintegration needs to be investigated further as well as the effect of the disintegration on the biogas yield of different crops.

Scenario 4a: Optimized scenario based on advanced biofuel crops

In scenario 4a we analyzed how substrate costs and choice of crops would be affected if Jordberga biogas plant would use only crops classified as substrates for advanced biofuel production, (EC, 2016; Energimyndigheten, 2015).

Crops included in this study regarded as suitable substrate for such advanced biofuels were sugar beet tops, cover crops, green rye, grass-clover and landscape conservation grass. Maize, whole-crop cereal and sugarbeet were excluded.

As in the scenario 3, fresh substrates were limited to 1/3 of the total supply for each period for all crops and zones. Green rye was assumed to be used in crop rotations with sugar beet and limited to 10% of accessible land, while landscape conservation grass was limited to 5% of accessible land.

When the model was forced to use 100% advanced biofuel crops, the annual production costs increased to 59.2 MSEK, 6.2 SEK/Nm^3 or 1594 SEK/tonne DM. This is an increase with 26.3% compared with the current situation in scenario 1. The crops included in the optimal solution and their composition of total costs are seen in Figure 21. The crop supply over the year is presented in Figure 22.

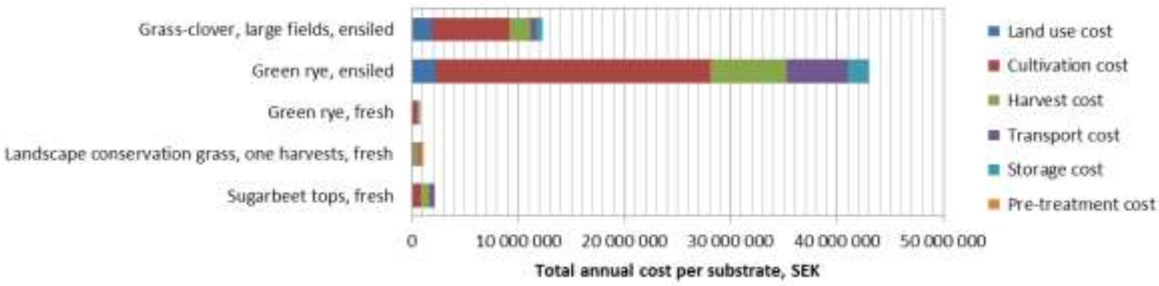

Figure 21. Composition of optimized total annual substrate costs (SEK) in the advanced biofuels scenario.

Whole-crop cereal (the main crop in the previous scenarios) was now substituted with green rye and grass-clover from large fields. This scenario also included landscape conservation grass from small fields. Landscape conservation grass represents a kind of crop that is very interesting for biogas plants as it is normally not used for food and feed production. Typically these crops have no cultivation costs and are often available for biogas producers to the costs of harvest, transport and pre-treatment to the right quality for feeding to the digester.

Another available area for this type of crop is the area set-aside from agricultural production according to the subsidies system to increase crop diversity and biological diversity. Farms larger than 15 ha in areas of Sweden with fertile soils (the plains in south and middle of Sweden) have to set at least 5% of the arable land out of normal production, the so-called ecological focus area. In the regions around Jordberga and Örebro this set-aside rule applies. There are different cropping alternatives for this land and some of them are interesting to use as biogas substrate.

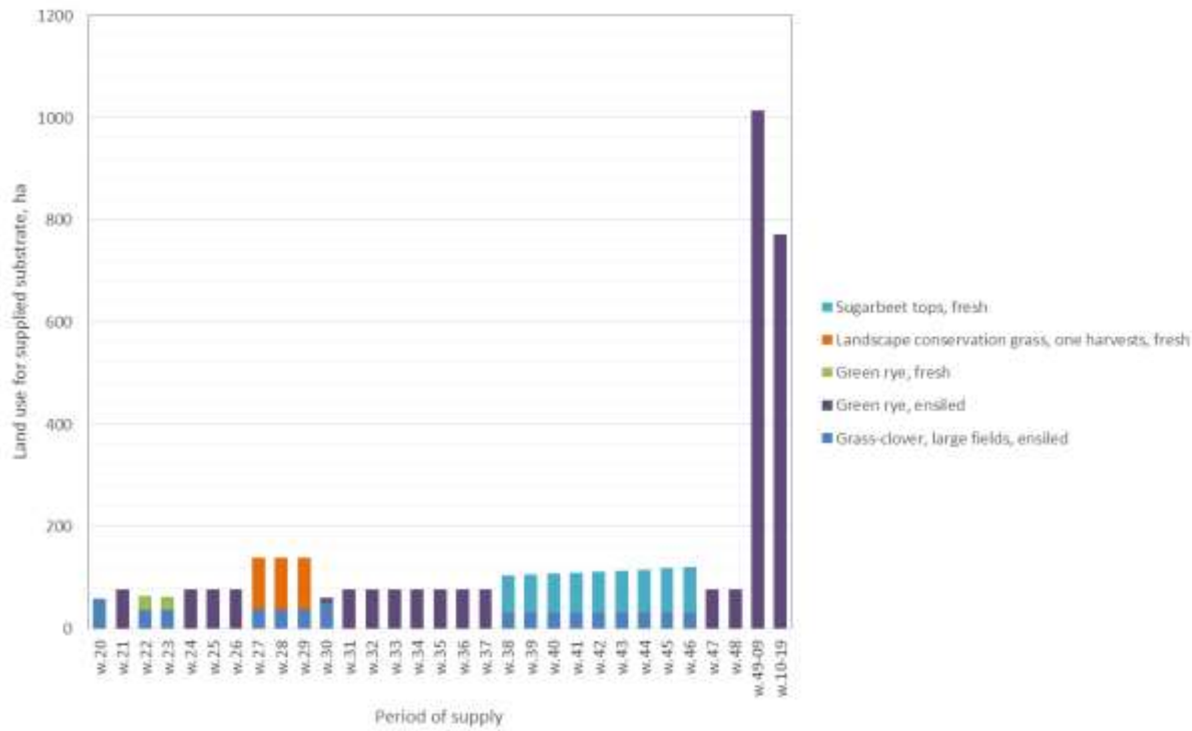

Figure 22. Supply of fresh and ensiled substrates to Jordberga in the advanced biofuels scenario (Scenario 4a); land use demand (ha) distributed over the periods of the year (note that fresh substrates are only available in the periods when they can be harvested, while stored substrates are assumed to be harvested when their total cost per biomethane potential is lowest and used when required as indicated in the figure).

To fulfil the substrate demand when applying the crop restrictions in this scenario, crops were collected from all available zones with transport distances up to 100 km, see Figure 23. When comparing different crops, the optimization resulted in grass-clover being was allocated to zones closer to the biogas plant, compared to sugarbeet tops and green rye. This result is also valid for the optimization in Scenario 4b (Figure 24), reflecting a higher sensitivity to transport cost for the grass-clover crops.

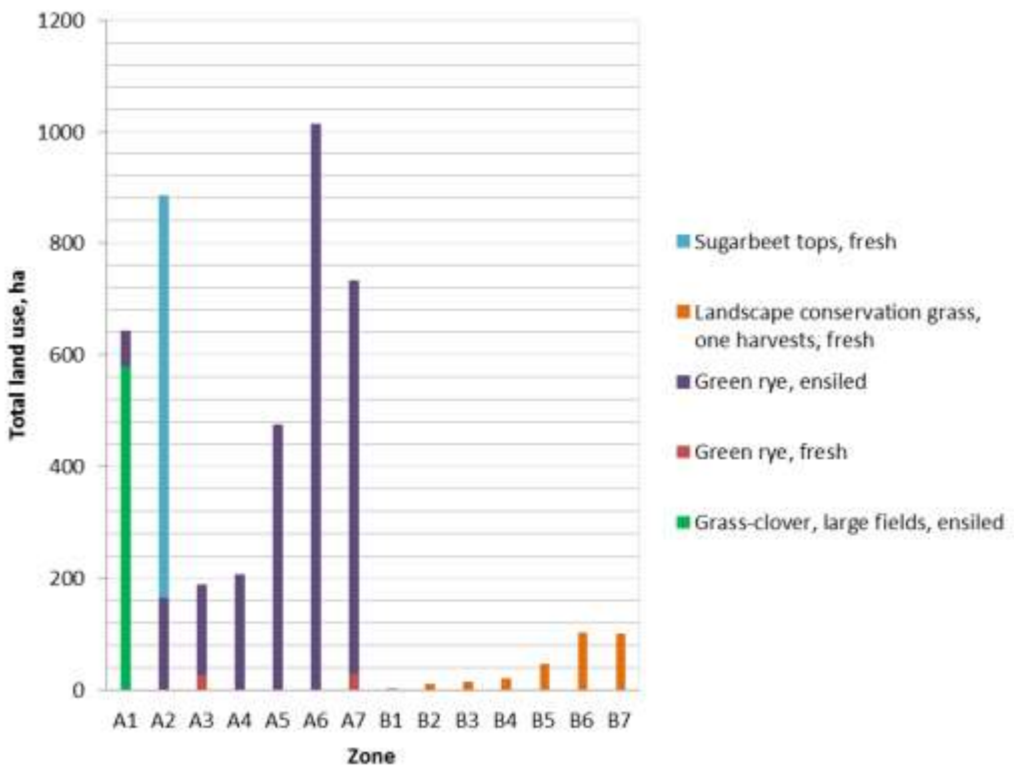

Figure 23. Land use demand (ha) in different zones (A1-A7 representing large fields, B1-B7 representing small fields) for optimized supply of substrates to Jordberga in the advanced biofuel scenario.

Scenario 4b: Optimized scenario based on advanced biofuel crops with crop rotation values

In this scenario, the positive value of grass-clover for the other crops in a crop rotation was studied by reducing the land use cost for grass-clover. The agricultural production in the studied region is dominated by cereal production. Introducing grass-clover in a cereal dominated crop rotation has many advantages such as increased yields of the crops following after grass-clover and decreased nitrogen leakage (Tidåker *et. al.*, 2016, Larsson *et. al.* 2005). In a recent study, Tidåker *et. al.* (2016) calculated the value of grass-clover in cereal based crop rotations. For a six-year crop rotation in Skåne with 2 years grass-clover and 4 years cereal, the difference in profitability for the other crops in the crop-rotation was calculated to 993 kr/ha. If this increased profitability is allocated to the grass-clover it results in a 1986 SEK/ha bonus annually.

In scenario 4b, the land use cost for grass-clover was reduced by 1986 SEK/ha. This resulted in a total annual substrate cost of 56.5 MSEK, 5.9 SEK/Nm^3 or 1475 SEK/t DM, distributed on the different crops as seen is Figure 24. The same crops as in scenario 4a were included in the optimized solution but the area of grass-clover increased from approx. 580 ha to 1900 ha. The cultivation of green rye decreased.

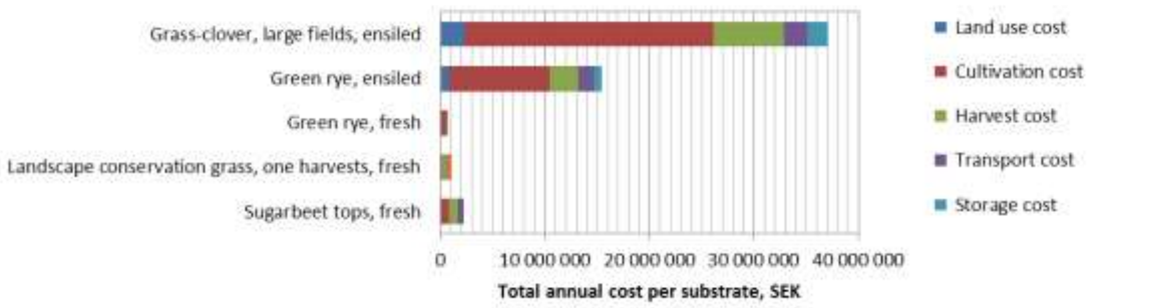

Figure 24. Composition of optimized total annual substrate costs, SEK, in the advanced biofuels scenario with crop rotation values of grass-clover.

A mixture of both fresh and ensiled crops was used in the substrate supply to the biogas plant during the different periods of the year as seen in Figure 25. The maximum transport distance reached 30 km (zone 1-5) for large fields, and up to 100 km for small fields (zone 7), see Figure 26.

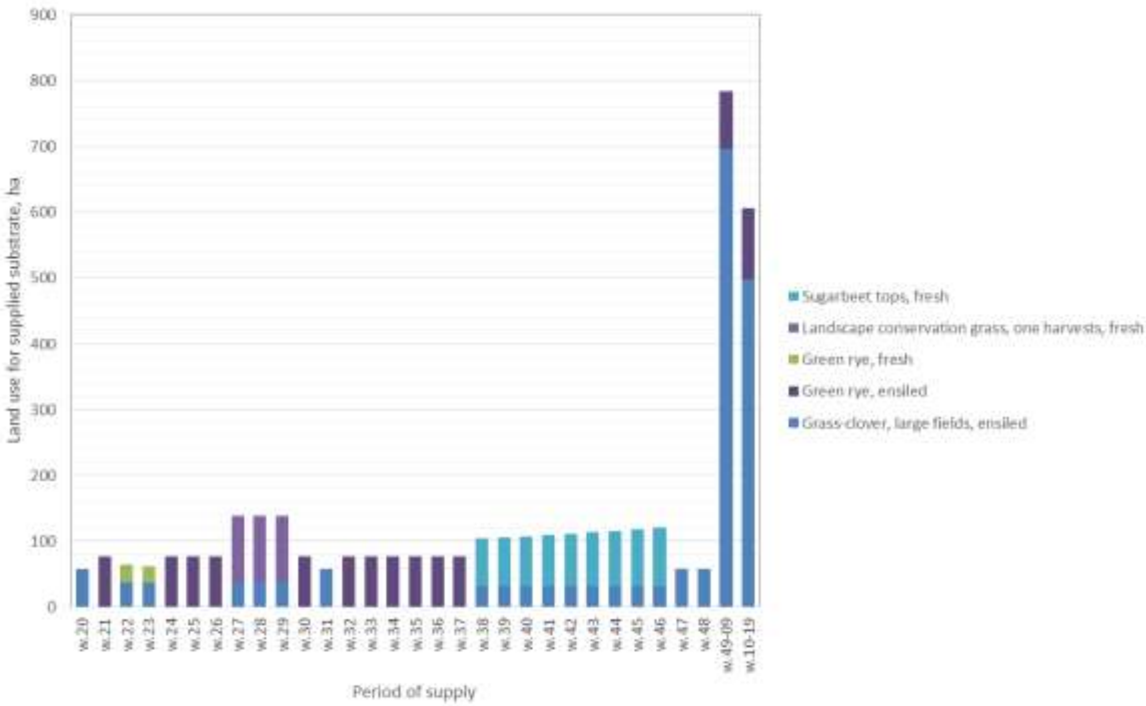

Figure 25. Supply of fresh and ensiled substrates to Jordberga in the advanced biofuels scenario with crop rotation values of grass-clover (Scenario 4b); land use demand (ha) distributed over the periods of the year (note that fresh substrates are only available in the periods when they can be harvested, while stored substrates are assumed to be harvested when their total cost per biomethane production is lowest and used when required as indicated in the figure).

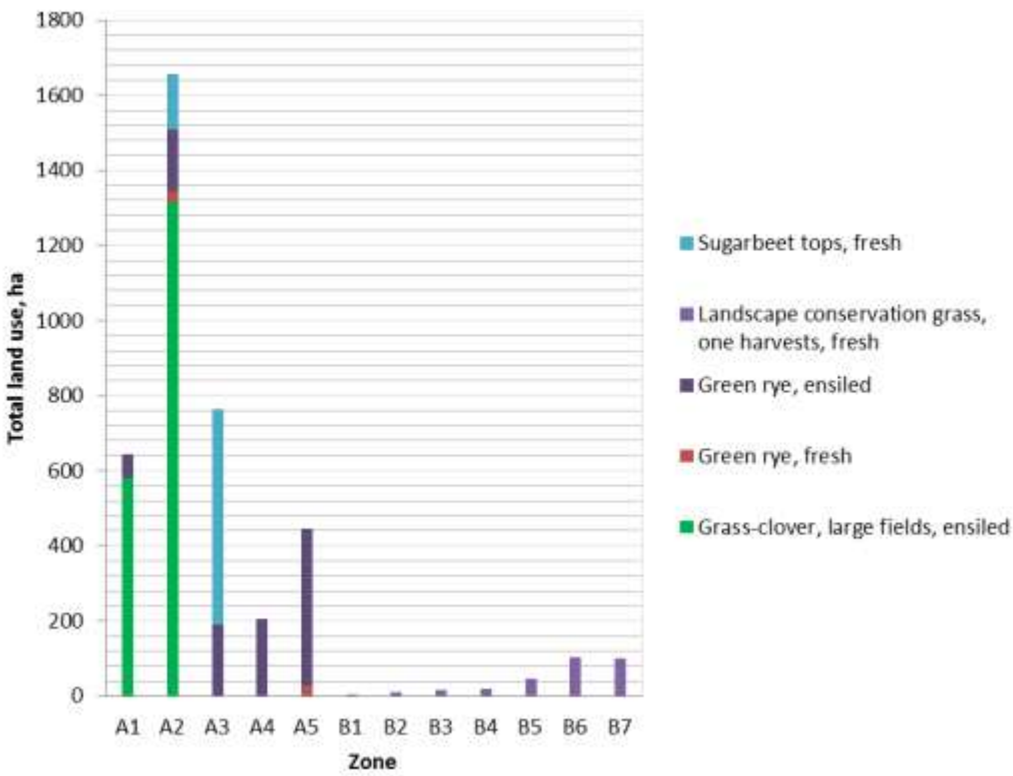

Figure 26. Land use demand (ha) in different zones (A1-A7 representing large fields, B1-B7 representing small fields) for optimized supply of substrates to Jordberga in the advanced biofuel scenario with crop rotation values of grass-clover (4b).

Compared to the current substrate mix at Jordberga biogas plant and scenarios 1-3 (without restrictions on the choice of crops), the number of crops included in the optimal solution in the advanced biofuel scenarios was higher. Such a system would increase the complexity of the harvest and storage system. Harvest would be done at a larger number of occasions instead of only at one or a few occasions, and the need for careful planning of the harvesting operations would increase. The whole-crop cereal and maize currently used at the Jordberga plant are adapted to the large-scale system used for harvest, transport and storage. The scenario with advanced biofuel crops included landscape conservation grass, grass-clover from small fields and cover crops, all assumed to be harvested using a system with lower capacity. If these crops are to be supplied in large volumes, the harvesting and transport chain may need to be adapted to the storage in large bunker silos to avoid queueing times and slow and inefficient unloading into the silo. Increased utilization of extensive crops from smaller fields needs to be analyzed further.

4.1.1 Summary of the optimization results

The results of the optimized scenarios are summarized in Table 5.

Table 5. Summary of studied scenarios at Jordberga biogas plant.

Scenarios	1	2	3a	3b	4a	4b
Total annual cost, MSEK	46.9	46.1	44.3	42.0	59.2	56.5
Average cost, SEK/Nm^3	4.94	4.86	4.67	4.43	6.24	5.95
Average cost, SEK/t DM	1349	1287	1274	1256	1594	1475
Substrates in resulting mix	2	1	3	3	5	5
Savings, SEK/Nm^3 (reference)	-	0.08	0.27	0.51	-1.30	-1.01
Savings, % (reference)	-	2	5	10	-26	-20
Savings, SEK/Nm^3 (ensiled)	-	-	0.19	0.43	-1.38	-1.09
Savings, % (ensiled)	-	-	4	9	-28	-23
Selected substrates	Whole-crop cereal en-siled, maize ensiled	Whole-crop cereal en-siled	Sugarbeet tops fresh, whole-crop cereal en-siled, whole-crop cereal fresh	Sugarbeet tops fresh, whole-crop cereal en-siled, whole-crop cereal fresh	Landscape cons. grass one harvest fresh, Green rye fresh, sugarbeet tops fresh, grass-clover large fields ensiled, green rye ensiled	Grass-clover large fields en-siled, green rye ensiled, green rye fresh, land-scape cons. grass one harvest fresh, sugarbeet tops fresh

4.2 ÖREBRO BIOGAS PLANT

Substrate costs for the crops included for Örebro biogas plant is shown in Figure 27. In the same way as for Jordberga biogas plant transport with tractor had lower costs than truck transport at short transport distance. For the system using the precision chopper for grass-clover truck transport was optimal to use already in the second zone from 6 km and onwards. For the system using precision chop forage wagon for grass-clover from small fields transport with truck had lowest cost in all zones. One reason for the difference between Jordberga and Örebro could be that up to 20 km transport distance around Jordberga the speed of truck transport was reduced due to small roads, which made the tractor transport more competitive. The speed restriction was not done for the roads around Örebro biogas plant.

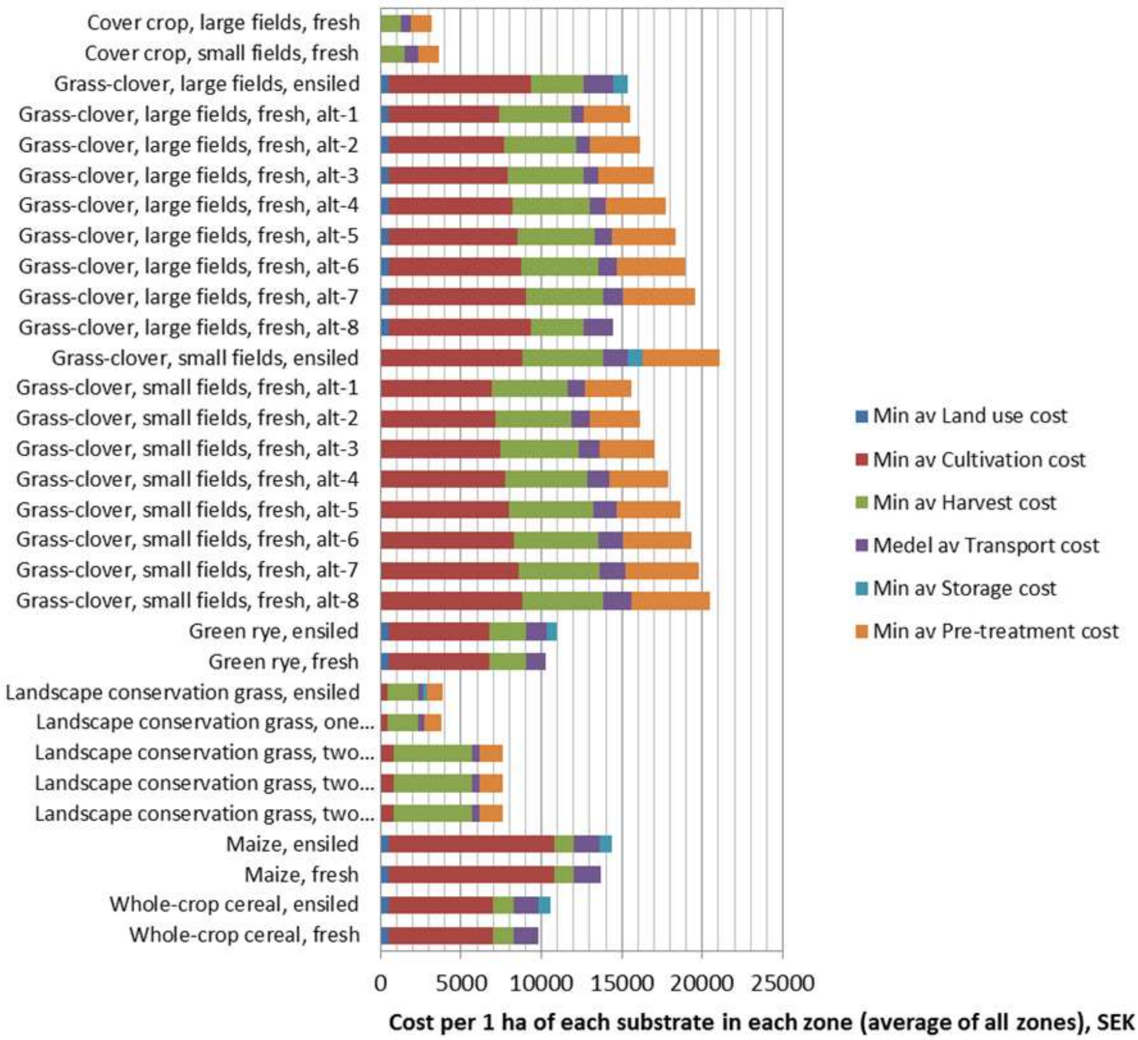

Figure 27. Total substrate cost (SEK/ha) based on cultivation of 1 ha of each substrate (as average values for all zones in the model), divided into costs for land use, cultivation, harvest, transport, storage and pre-treatment costs. For crops that can be harvested for more than one week/period the figure shows an average value for all harvest periods.

Figure 28 and Figure 29 show substrate costs per tonne DM of the crop and per Nm^3 biomethane produced. In the same way as for Jordberga, whole-crop cereal had lowest substrate costs. The cheapest substrate in Jordberga, sugarbeet tops, was not included in the case study for Örebro. For small fields cover crops had the lowest substrate cost, also that corresponds with result for Jordberga.

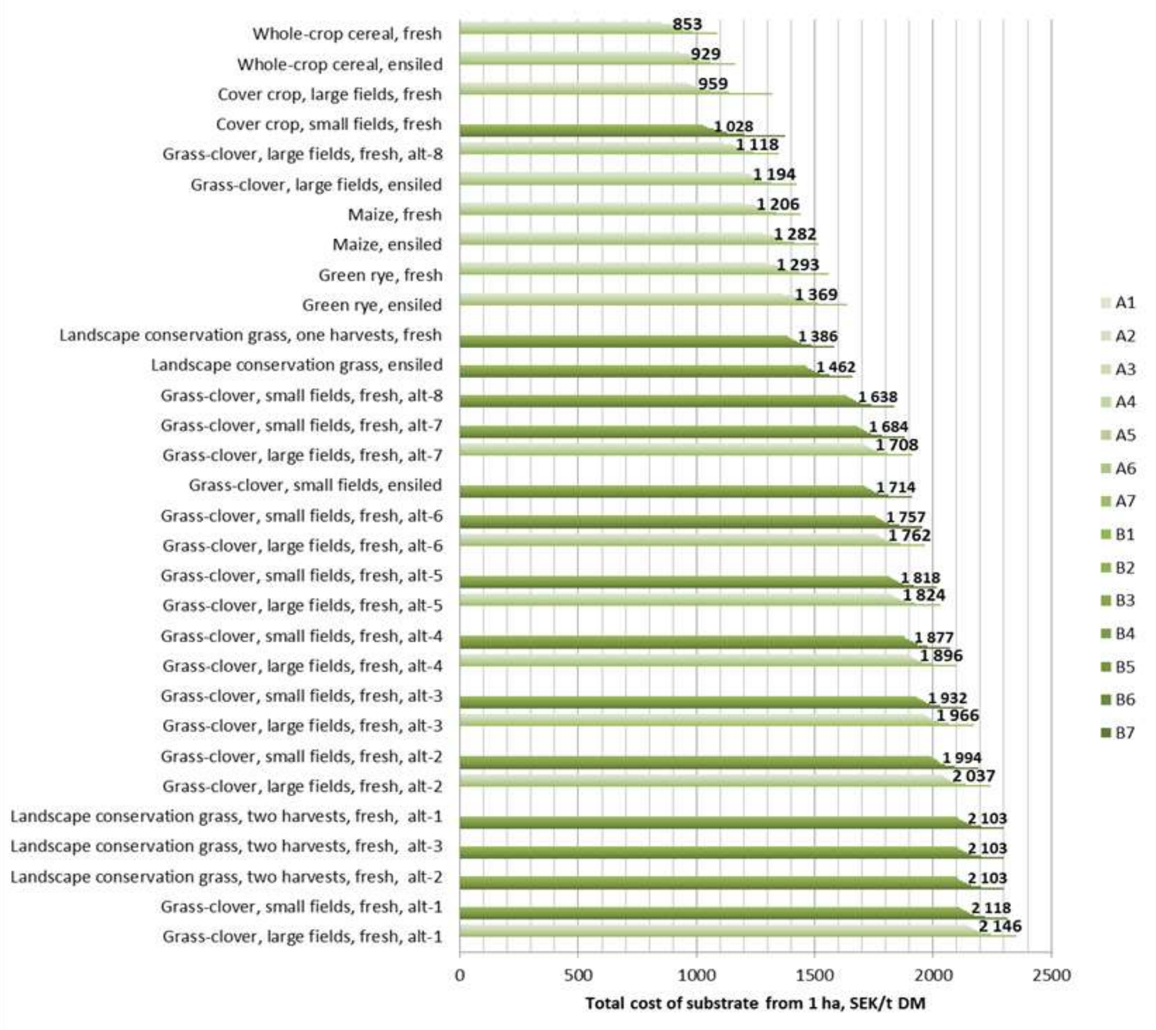

Figure 28. Substrate cost comparison for each zone in Örebro, SEK/tonne DM (data labels indicate the lowest cost for each substrate; i.e. shortest transport distance).

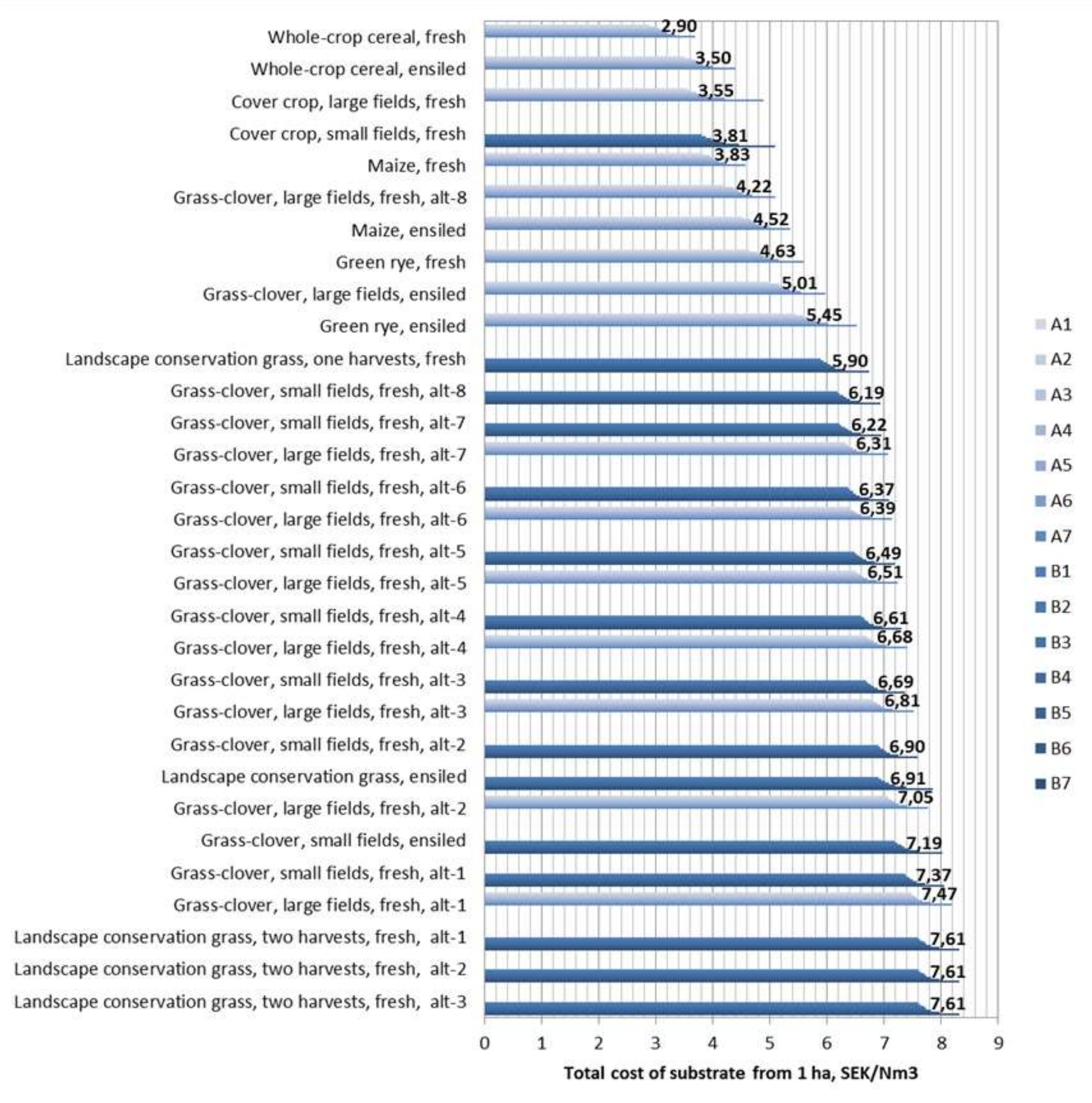

Figure 29. Substrate cost comparison for each zone, SEK/Nm³ methane in Örebro (data labels indicate the lowest cost for each substrate; i.e. shortest transport distance).

Scenario 1: Reference scenario based on current practices

The reference scenario for Örebro biogas plant is based on the current practice for the crops using a mix of ensiled crops consisting of 50% grass-clover and 50% whole-crop cereal on wet weight basis. The scenario resulted in a total annual substrate cost of 14.7 MSEK, equivalent to 4.4 SEK/Nm^3 biomethane or 1 101 SEK/tonne DM (Figure 30).

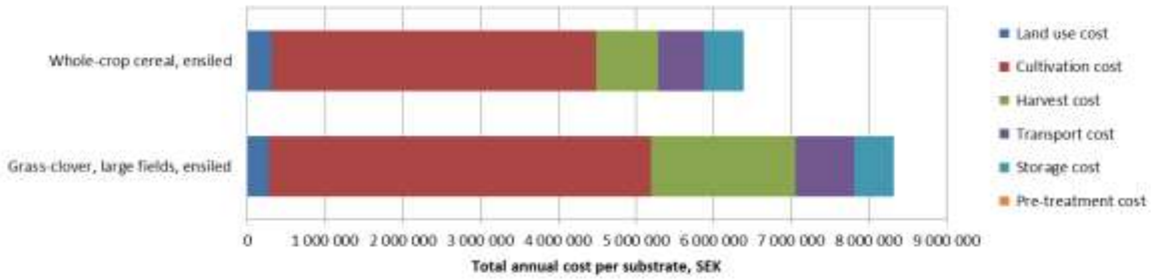

Figure 30. Composition of total annual substrate costs (SEK) in the reference scenario calculation for Örebro.

To fulfil the substrate demand crops were grown in the first 3 zones up to 15 km transport distance. The calculated biomethane production and the land use demand for ensiled whole-crop cereal and grass-clover for the reference scenario are presented in Table 6.

Table 6. Calculated land use for crops in the reference scenario in Örebro

	Methane production (%)	Substrate demand (tonnes w.m.)	Land use demand (ha)	Allocated land use per zone (ha)		
				A1	A2	A3
Total	100%		1197	116	543	538
Whole crop cereal, ensiled	52%	17118	660	116	524	
Grass-clover ley crop, ensiled	49%	17220	557		19	538

Scenario 2: Optimized solution based on ensiled substrates

One alternative for Örebro biogas plant is to continue using only ensiled crops. When the model was tested for this scenario allowing only ensiled crops the result was total annual substrate costs of 12.3 MSEK (Figure 31). This is equivalent to 3.7 SEK/Nm^3 or 974 SEK/tonne DM. This is a cost reduction with 16% compared with the reference scenario representing the current situation at Örebro biogas plant. The optimal solution includes only whole-crop cereal which is a difference to the current situation in Örebro, represented by scenario 1, where also grass-clover is used. The crop was supplied from 1219 ha in zone 1-3 within 15 km transport distance.

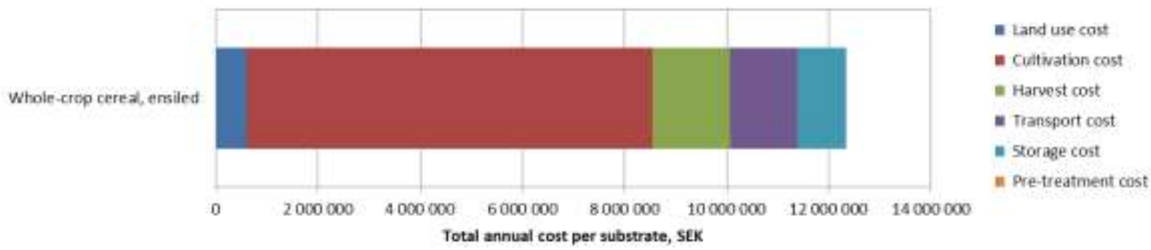

Figure 31. Composition of optimized total annual substrate costs (SEK) in the ensiled scenario in Örebro.

Scenario 3a: Optimized scenario based on a mix of fresh and ensiled crop substrates

In scenario 3a, an optimization was done allowing fresh crops to be used together with ensiled crops. The contribution of fresh substrates was limited to maximum 1/3 of total crops in each period while scenario 3b was optimized without this limitation.

The mixed scenario 3a, where fresh and ensiled crops were combined, resulted in a total annual substrate cost of 12.2 MSEK, equivalent to 3.6 SEK/Nm^3 biomethane or 969 SEK/tonne DM. (Figure 32). The result of this scenario only differs from the optimized scenario 2 in that fresh whole-crop cereal are used during 4 weeks to replace some of the ensiled whole-crop cereal (Figure 33). The effect on costs is marginal compared with scenario 2.

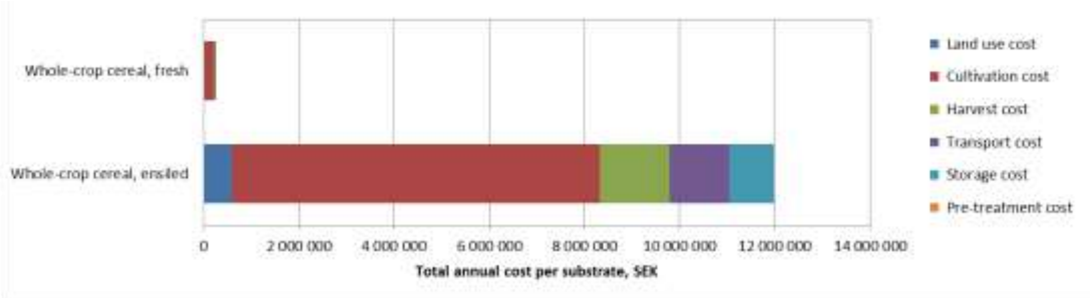

Figure 32. Composition of optimized total annual substrate costs, SEK, in the mixed scenario in Jordberga with fresh crops limited to 1/3 of the substrate mix.

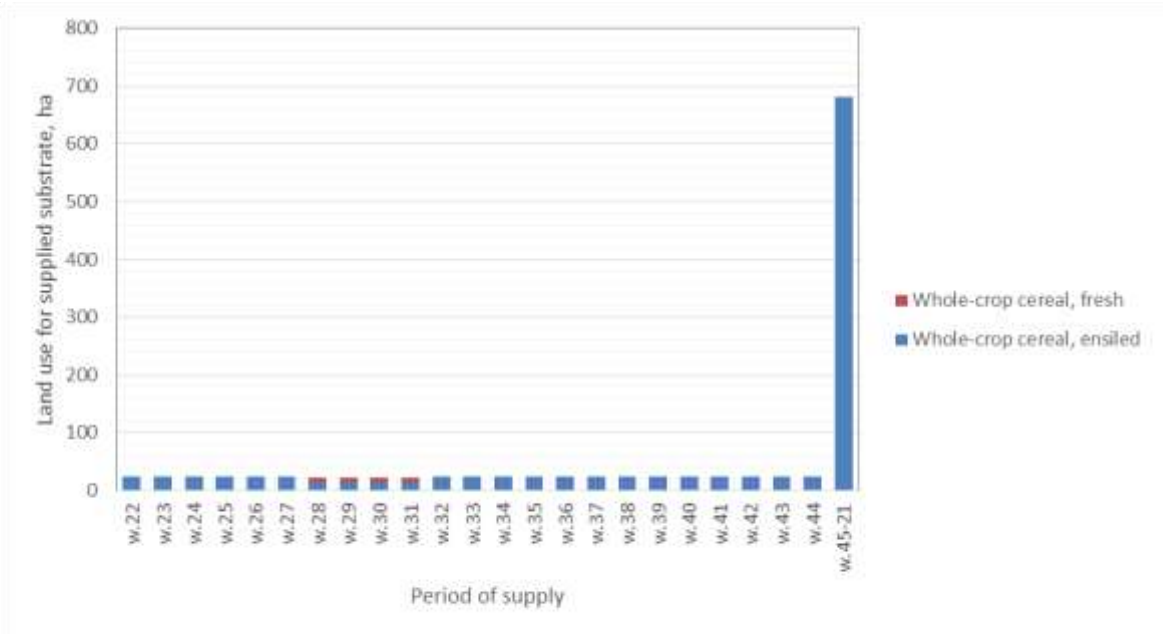

Figure 33. Supply of substrates to Örebro in the optimized scenario 3a using fresh and ensiled crops; land use demand (ha) distributed over the periods of the year. Note that fresh substrates are only available in the periods when they can be harvested, while stored substrates are assumed to be harvested when their total cost per biomethane potential is lowest and used when required as indicated in the figure.

As seen in Figure 34 the fresh crops are transported from the first zone with on average 5 km transport distance. To fulfill the demand up to zone 3 was used for the ensiled whole-crop cereal.

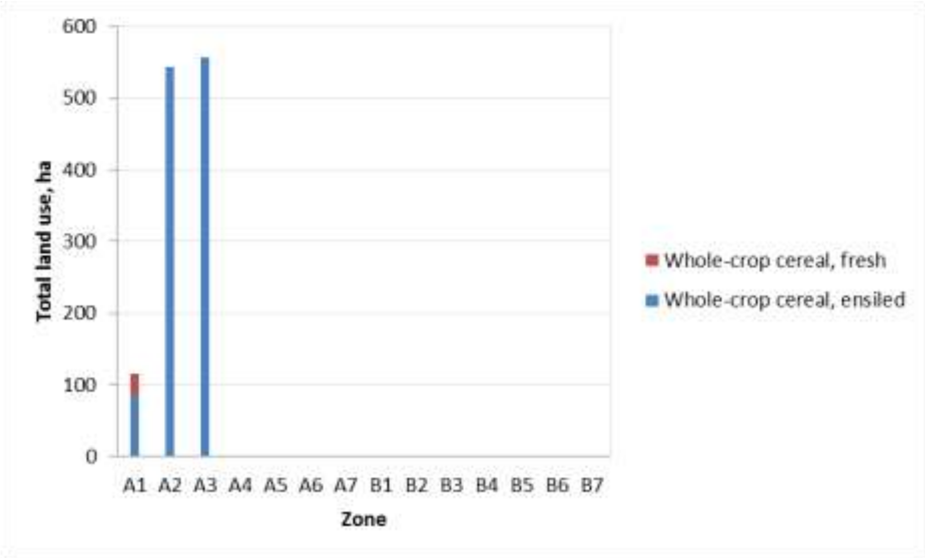

Figure 34. Land use [ha] in the optimized supply of fresh and stored substrates to Örebro in the mixed scenario from different zones (A1-A7 representing large fields, B1-B7 representing small fields).

Scenario 3b: Optimized scenario based on a mix of fresh and ensiled crop substrates without limitation on fresh substrates

In this scenario, the restriction on the amount of fresh crops was removed and resulted in a total annual substrate cost of 12.1 MSEK, equivalent to 3.6 SEK/Nm^3 biomethane or 965 SEK/tonne DM, Figure 35. The result is similar to that of scenario 3a. The difference is that whole-crop cereal are used to 100% during the period of 4 weeks when it is available for harvest (Figure 36 and Figure 37).

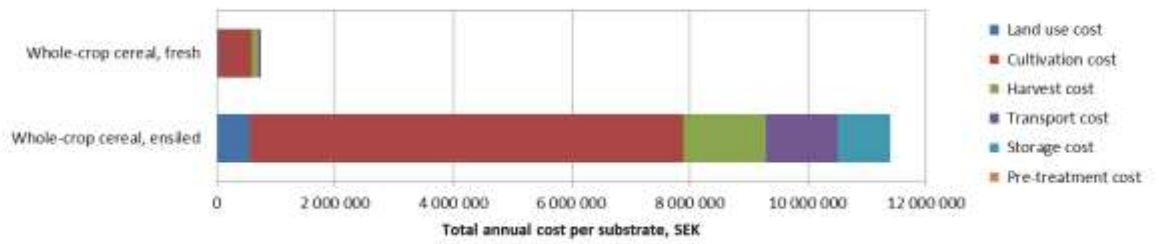

Figure 35. Composition of optimized total annual substrate costs (SEK) in the mixed scenario in Jordberga with unlimited use of fresh crops in the substrate mix.

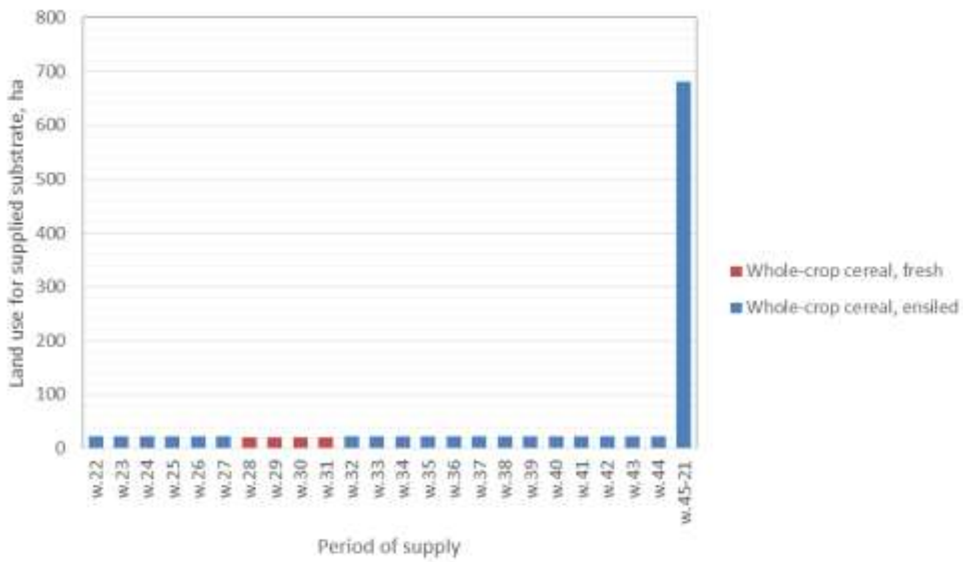

Figure 36. Supply of substrates to Örebro in the optimized scenario 3b using fresh and ensiled crops; land use demand (ha) distributed over the periods of the year. Note that fresh substrates are only available in the periods when they can be harvested, while stored substrates are assumed to be harvested when their total cost per biomethane potential is lowest and used when required as indicated in the figure.

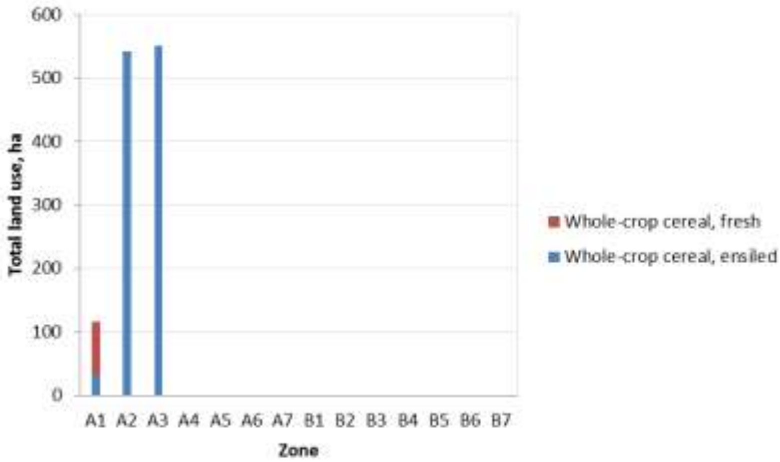

Figure 37. Land use [ha] in the optimized supply of fresh and stored substrates to Örebro in the mixed scenario from different zones (A1-A7 representing large fields, B1-B7 representing small fields).

The cost savings in SEK/Nm^3 biomethane using fresh crops compared with the optimized ensiled scenario were larger in Jordberga compared with Örebro. One reason for that could be that a large cost savings was done in Jordberga by using fresh sugarbeet tops that had lower costs than all other substrates.

Scenario 4a: Optimized scenario based on advanced biofuel crop

In Scenario 4, only advanced biofuel crops were allowed. Green rye was limited to maximum 10% and landscape conservation grass to maximum 5% in each zone.

It is possible to support Örebro biogas plant with substrate using advanced biofuel crops but costs will increase to an annual cost of 17.2 MSEK (Figure 38). This is an increase with 17% compared with the current situation (scenario 1) and 39% compared with the optimized scenario 2 using only ensiled crops. Substrate cost increased to 5.1 SEK/ Nm^3 or 1225 SEK/tonne DM. The main ensiled crop change from whole-crop cereal in scenario 2 and 3 to grass-clover from large fields (Figure 39 and Figure 40).

Stürmer (2017) analyses effects on costs of feedstock changes for biogas plants based on maize. A scenario to substitute maize with catch crops as 2nd generation biogas crops and thereby reduce the share of maize silage of total substrate supply from 90% to 30% was tested. The substrate cost including the price for the standing crop, harvest and transport increased with 13% for substrate supplying a biogas plant producing 4.2 GWh electricity annually. Compared with maize, alternative feedstock such as catch crops and material from landscape management have higher costs for harvest and transport due to low energy density. According to Stürmer (2017) digester volume and digestate storage tank volumes will increase. More lignocellulosic material also needs adaption of pretreatment, feeding systems and the need for stirring.

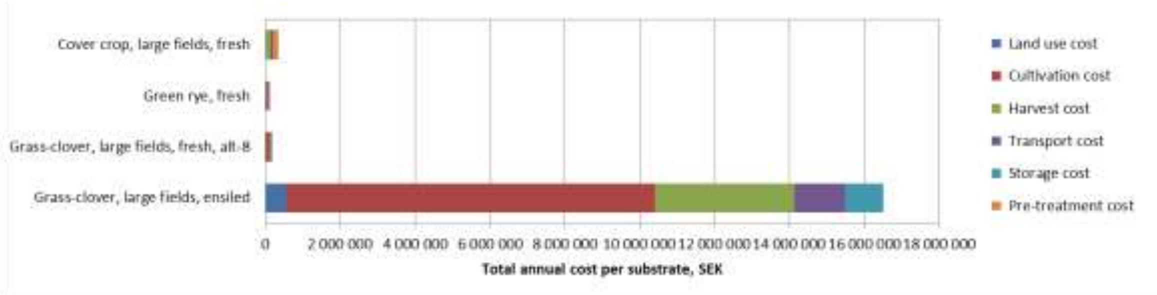

Figure 38. Composition of optimized total annual substrate costs, SEK, in the advanced biofuels scenario 4a.

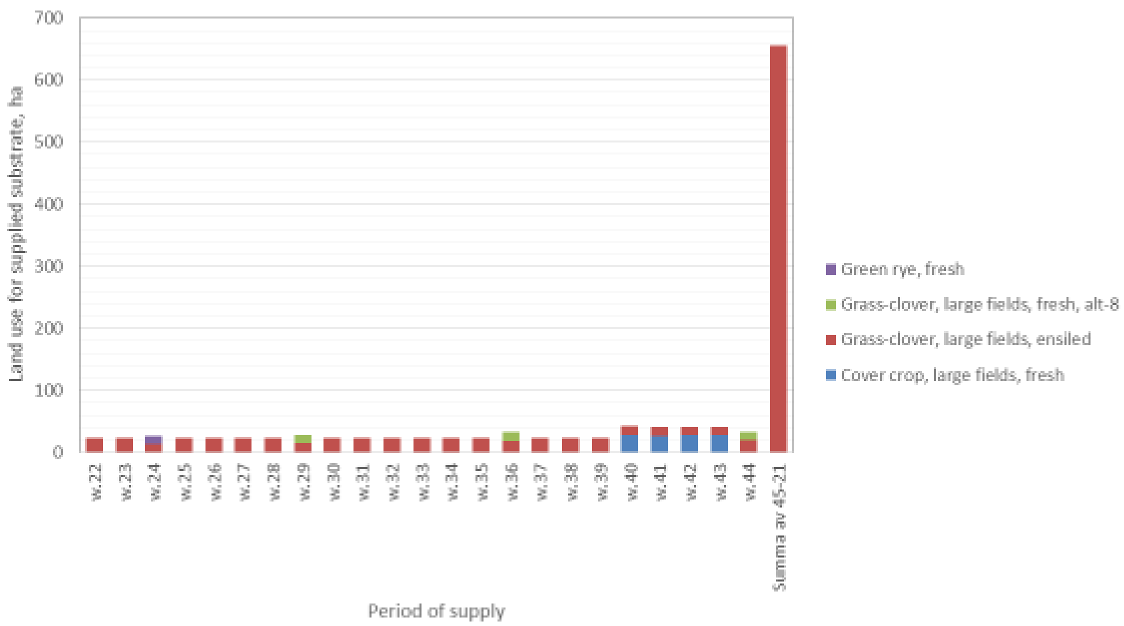

Figure 39. Supply of fresh and ensiled substrates to Örebro in the advanced biofuels scenario (Scenario 4a); land use demand (ha) distributed over the periods of the year (note that fresh substrates are only available in the periods when they can be harvested, while stored substrates are assumed to be harvested when their total cost per biomethane potential is lowest and used when required as indicated in the figure).

Crops from 1292 ha within zone 1-3 were used to cover the crop demand. All crops still can be gathered from the zone 1-3 up to 15 km. This is a difference from the corresponding scenario from Jordberga where the maximum transport distance increases to 100 km. In Jordberga, it was a cheaper alternative to use landscape conservation grass and green rye, both crops that have restricted availability which leads to increased transport distances to cover the substrate need. In Örebro, grass-clover without restricted availability was included in the optimal solution resulting in the same transport distance as in scenario 2 and 3.

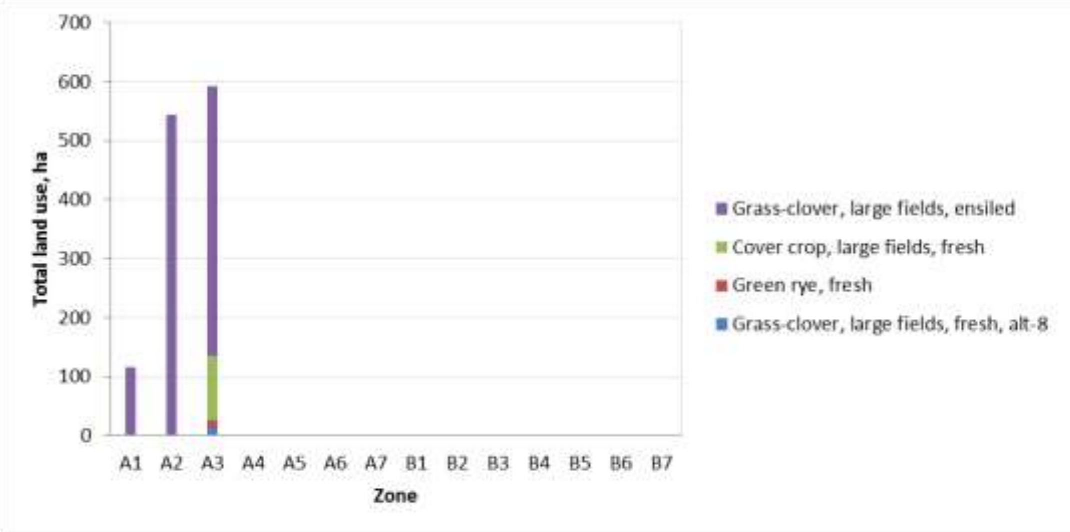

Figure 40. Land use demand (ha) in different zones (A1-A7 representing large fields, B1-B7 representing small fields) for optimized supply of substrates to Jordberga in the advanced biofuel scenario.

Scenario 4b: Optimized scenario based on advanced biofuel crops with crop rotation values

In this scenario the positive value of grass-clover for the other crops in a crop rotation was included by reducing the land use cost for grass-clover. Results from Tidåker *et. al.* (2016) showed that the value of grass-clover in a a six year crop rotation in Västra Götaland (in the south-west of Sweden) with 2 years grass-clover and 4 years cereal was 1406 SEK/ha. Corresponding value for Uppland in south-east of Sweden was 1188 SEK/ha for a 5 year crop rotation with 2 years of grass-clover. For Örebro, situated between Västra Götaland and Uppland, an average value of the two regions of 1298 SEK/ha was assumed.

This resulted in a total annual substrate cost of 15.7 MSEK, distributed on the different crops as seen in Figure 41 and Figure 42. Substrate cost was 4.7 SEK/ Nm^3 or 1119 SEK/tonne DM. Crop demand was cover from zones 1-3, Figure 43. Compared with the reference scenario the result of the optimization showed that Örebro biogas plant could be supplied with advanced biofuel crops at only 7% increased costs.

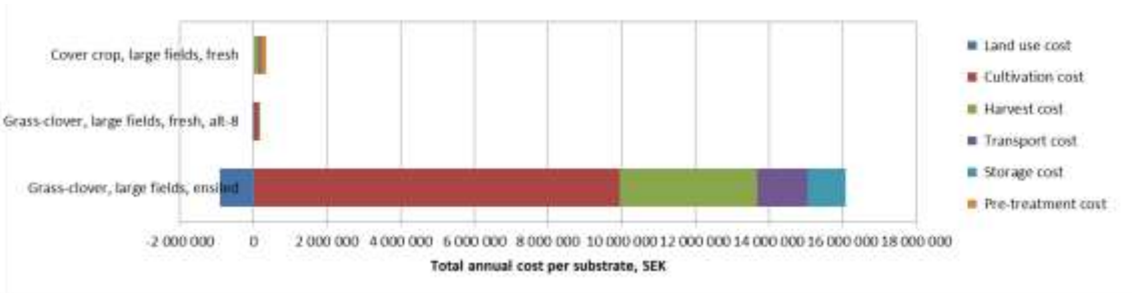

Figure 41. Composition of optimized total annual substrate costs, SEK, in the advanced biofuels scenario 4b.

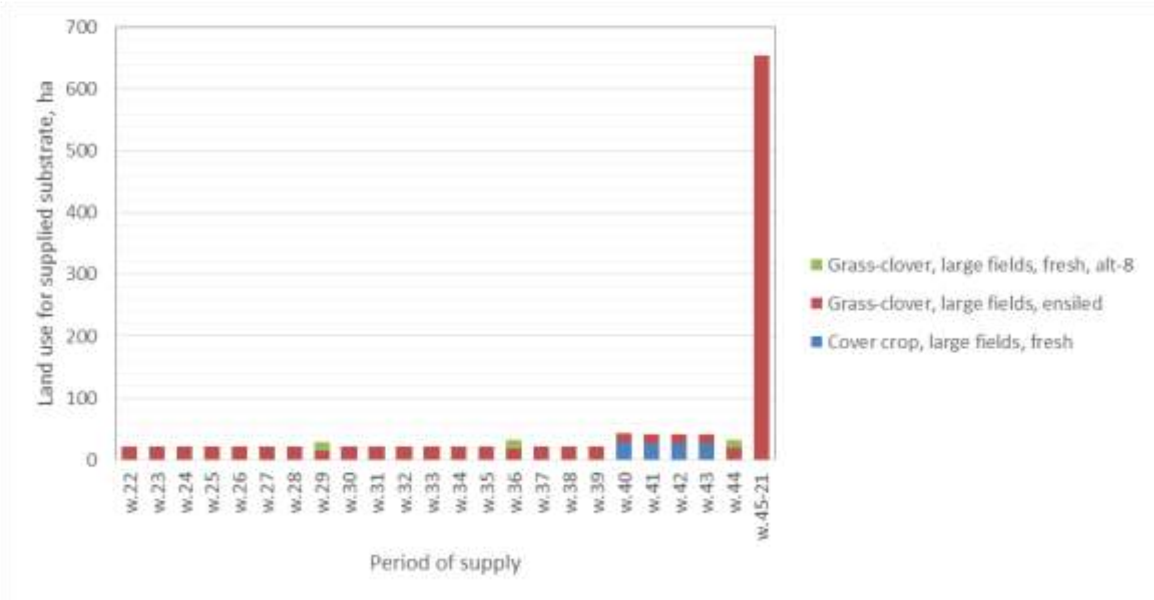

Figure 42. Supply of fresh and ensiled substrates to Örebro in the advanced biofuels scenario (Scenario 4b); land use demand (ha) distributed over the periods of the year (note that fresh substrates are only available in the periods when they can be harvested, while stored substrates are assumed to be harvested when their total cost per biomethane potential is lowest and used when required as indicated in the figure).

The crop supply is very similar to that of scenario 4a. Except for the main substrate grass-clover from large fields cover crops, only cover crops from large fields are in included. Fresh green rye is no longer in the optimal solution.

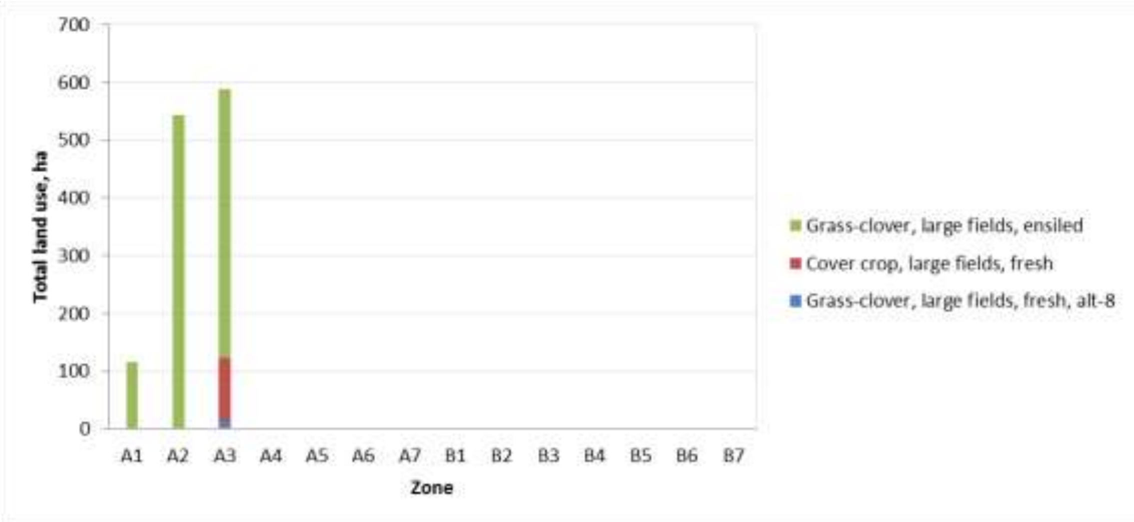

Figure 43. Land use demand (ha) in different zones (A1-A7 representing large fields, B1-B7 representing small fields) for optimized supply of substrates to Jordberga in the advanced biofuel scenario 4b.

In Örebro ensiled grass-clover could not compete with whole-crop cereal and was only included in the optimal solution in the advanced biofuel scenarios. The same result was achieved for Jordberga. One important question for biogas plants using ensiled crops are if fresh crops harvested and fed directly into the biogas plant is competitive to using ensiled crops. The high capacity harvest systems using self-propelled precision choppers used for harvesting crops to be ensiled are not suitable for harvesting small amounts corresponding with the feeding into the digester.

Therefore, on both large and small fields in this study fresh grass-clover was harvested with a low-capacity system using a precision chop forage wagon. The exception was for large fields during periods when the grass-clover was harvested for ensiling using large-scale harvest system with self-propelled precision chopper. The same system was then used also for harvesting of fresh crops from large fields. During all other weeks, grass-clover for fresh use was harvested with the low-capacity system using a precision chop forage wagon. In both scenarios 4a and 4b fresh grass-clover from large fields were only included in the optimal solution during the week when grass-clover for ensiling was harvested. This means that both grass-clover and landscape conservation grass harvested with the low capacity system was too expensive to be included in the optimal solution even in the advanced biofuel crop scenarios.

In this study, the substrate supply was optimized on a weekly level. But when using fresh substrates the harvest has to be done on a daily basis since the fresh crop has no storage stability and will start to heat up if left in a heap on the ground without cover or compaction resulting in temperature increase and losses of energy and dry matter. How fresh crops are to be handled on the biogas plant needs to be studied further. One question to look into is how much the substrate mix of fresh and ensiled crops can vary between the daily feeding occasions, and how long can the fresh crops be left on the ground before fed into the digester. This will have implications on how often fresh crops have to be harvested.

4.2.1 Summary of the optimization results

The results of the optimized scenarios are summarized in Table 7.

Table 7. Summary of studied scenarios at Örebro biogas plant.

Scenarios	1	2	3a	3b	4a	4b
Total annual cost (MSEK)	14.7	12.3	12.2	12.1	17.2	15.7
Average cost (SEK/Nm³)	4.38	3.67	3.64	3.61	5.11	4.67
Average cost (SEK/t DM)	1 101	974	969	965	1 225	1 119
Substrates in resulting mix	2	1	2	2	3	3
Savings, SEK/Nm³ (reference)	-	0.70	0.74	0.76	-0.73	-0.29
Savings, % (reference)	-	16	17	17	-17	-7
Savings, SEK/Nm³ (ensiled)	-	-	0.03	0.06	-1.44	-1.00
Savings, % (ensiled)	-	-	1	2	-39	-27
Selected substrates	Whole-crop cereal ensiled, grass-clover ensiled	Whole-crop cereal ensiled	Whole-crop cereal ensiled, whole-crop cereal fresh	Whole-crop cereal ensiled, whole-crop cereal fresh	Grass-clover large fields ensiled, grass-clover large fields fresh alt-8, green rye fresh, cover crop large fields fresh	Grass-clover large fields ensiled, grass-clover large fields fresh alt-8, cover crop large fields fresh

5 CONCLUSIONS

- The optimization model developed has proved a useful tool for strategic planning, examination of trade-offs between cost savings and process, and management related constraints for agricultural biomass substrate supply systems.

- Substrate costs could be decreased by using a mix of fresh and ensiled crops. Compared to the crops currently used at Jordberga biogas plant, the optimized solution with a mix of fresh sugarbeet tops and whole-crop cereal and ensiled whole-crop cereal reduced the substrate costs by 10%. When restricting the amount of fresh crops to maximum 1/3 of the crops used each week, annual substrate cost savings were 5.5% lower than in the reference scenario. In Örebro, costs decreased by 17% when fresh and ensiled whole-crop cereal were used instead of the reference scenario with whole-crop cereal and grass-clover. Furthermore, the optimization revealed possible cost savings for Örebro biogas plant when using whole-crop cereal as the only substrate, compared to the reference scenario where both whole-crop cereal and grass-clover crops were used.

- Grass-clover had higher substrate costs than whole-crop cereal and maize, both in Jordberga and Örebro, and only entered the optimized substrate mix in the advanced biofuel scenarios. Including crop-rotational benefits of grass-clover resulted in increased competitiveness for this crop. Even so, results indicated that some kind of subsidies might still be needed for grass-clover to be seen as a competitive biogas substrate. This is particularly true for Jordberga.

- Advanced biofuels crops such as sugarbeet tops, green rye and landscape conservation grass and grass-clover could be interesting alternatives for biogas production when adequate incentives are in place, but would increase substrate costs. In our analysis, the substrate costs increased with 26% compared to the current crops used at Jordberga biogas plant. Corresponding value for Örebro biogas plant was 17%.

- Grass-clover was more competitive as biogas crop in Örebro, compared to Jordberga. In Örebro, grass-clover was the main ensiled crop substrate, both in the advanced biofuel scenario and when crop rotation values of grass-clover were considered. In Jordberga, the primary ensiled crops in the advanced biofuel scenarios were green rye and grass-clover.

- Fresh grass-clover, harvested in an adapted low-capacity system, could not compete with costs with ensiled grass-clover, harvested with a high capacity system, neither in Jordberga nor in Örebro. However, it was found that choosing alternatives with as long growth periods as possible, and limited number of harvests per season, made the grass-clover crops more competitive in the studied systems. Therefore, it could also be of interest to further investigate the effects of a two-harvest system (rather than three to four-harvest systems) in Jordberga.

- Landscape conservation grass was more competitive in Jordberga than in Örebro, as an effect of the higher land use values in southern Sweden.

- Compared to current crop-based biogas productions with limited number of crops, the analysis of advanced biofuel scenarios introduced increased numbers of crops, including both fresh and ensiled crops. While this increased diversity may have positive effects in itself, it would also lead to increased complexity of the harvest-, transport- and storage system.

- Further work and site-specific tests are needed, in order to study the stability of the biogas process when feeding fresh substrates, to develop methods to manage the process, e.g. by adapting equipment and introduce stirring methodology, as well as for generating knowledge about critical limitations for fresh materials in the substrate mix.
- While a linear programming optimization model needs to reflect the complexity in the real system to a reasonable level, it necessarily includes simplifications to the system, such as a limited number of time periods and land use zones. Furthermore, stochastic and dynamic system parameters, such as unpredictable weather changes are not taken into account. Further development directions for the model could be to develop a more general planning tool with a user-friendly interface, to develop methods to differentiate between soil types in different zones, and to improve usability and speed of optimization.

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PERSONAL COMMUNICATION

Christer Lingman, Swedish Biogas International, 2015-11-04

Ola Rickardsson, Lantbrukare, Borgeby, 2015-10-02

APPENDIX A: CROP PROPERTIES

Table A1. Calculated biomass yields and properties from grass-clover crops, Jordberga. Assumed growth start was 15 April for Jordberga.

JORDBERGA, YEAR 1								
Cut I								
Week	**Date**	**Biomass yield [t DM/ha]**	**Growing days [d]**	**BMP, experimental [Nm³/tonne VS]**	**BMP, effective [Nm³/tonne VS]**	**Ash content [%]**	**VS [% of DM]**	**Methane yield [Nm³/ha]**
20	11 May	0,55	26	388	350	10,6	89,4	172
21	18 May	1,60	33	375	340	10,3	89,7	488
22	25 May	2,65	40	362	330	9,9	90,1	788
23	01 Jun	3,70	47	349	310	9,5	90,5	1 038
24	08 Jun	4,75	54	337	300	9,1	90,9	1 295
25	15 Jun	5,80	61	324	290	8,8	91,2	1 535
26	22 Jun	6,85	68	311	280	8,4	91,6	1 757
27	29 Jun	7,90	75	298	270	8,0	92,0	1 962
Cut II								
Week	**Date**	**Biomass yield [t DM/ha]**	**Growing days [d]**	**BMP, experimental [Nm³/tonne VS]**	**BMP, effective [Nm³/tonne VS]**	**Ash content [%]**	**VS [% of DM]**	**Methane yield [Nm³/ha]**
27	29 Jun	4,20	49	346	310	9,4	90,6	1 180
28	06 Jul	4,07	49	346	310	9,4	90,6	1 144
29	13 Jul	3,95	49	346	310	9,4	90,6	1 109
30	20 Jul	3,82	49	346	310	9,4	90,6	1 073
31	27 Jul	3,70	49	346	310	9,4	90,6	1 038
32	03 Aug	3,57	49	346	310	9,4	90,6	1 003
33	10 Aug	3,44	49	346	310	9,4	90,6	967
34	17 Aug	3,32	49	346	310	9,4	90,6	932

Table A1, continued.

JORDBERGA, YEAR 1								
Cut III								
Week	**Date**	**Biomass yield [t DM/ha]**	**Growing days [d]**	**BMP, experimental [Nm³/tonne VS]**	**BMP, effective [Nm³/tonne VS]**	**Ash content [%]**	**VS [% of DM]**	**Methane yield [Nm³/ha]**
35	24 Aug	3,43	56	333	300	9,0	91,0	936
36	31 Aug	3,33	56	333	300	9,0	91,0	908
37	07 Sep	3,22	56	333	300	9,0	91,0	880
38	14 Sep	3,12	56	333	300	9,0	91,0	852
39	21 Sep	3,02	56	333	300	9,0	91,0	823
40	28 Sep	2,91	56	333	300	9,0	91,0	795
41	05 Oct	2,81	56	333	300	9,0	91,0	767
42	12 Oct	2,71	56	333	300	9,0	91,0	739
Cut IV								
Week	**Date**	**Biomass yield [t DM/ha]**	**Growing days [d]**	**BMP, experimental [Nm³/tonne VS]**	**BMP, effective [Nm³/tonne VS]**	**Ash content [%]**	**VS [% of DM]**	**Methane yield [Nm³/ha]**
43	19 Oct	2,74	56	333	300	9,0	91,0	749
44	26 Oct	2,66	56	333	300	9,0	91,0	726
45	02 Nov	2,58	56	333	300	9,0	91,0	704

JORDBERGA, YEAR 2								
Cut I								
Week	**Date**	**Biomass yield [t DM/ha]**	**Growing days [d]**	**BMP, experimental [Nm³/tonne VS]**	**BMP, effective [Nm³/tonne VS]**	**Ash content [%]**	**VS [% of DM]**	**Methane yield [Nm³/ha]**
20	11 May	0,50	26	388	350	10,6	89,4	155
21	18 May	1,44	33	375	340	10,3	89,7	439
22	25 May	2,39	40	362	330	9,9	90,1	709
23	01 Jun	3,33	47	349	310	9,5	90,5	934
24	08 Jun	4,28	54	337	300	9,1	90,9	1 165
25	15 Jun	5,22	61	324	290	8,8	91,2	1 381
26	22 Jun	6,17	68	311	280	8,4	91,6	1 582
27	29 Jun	7,11	75	298	270	8,0	92,0	1 766

Tabel A1, continued.

JORDBERGA, YEAR 2								
Cut II								
Week	Date	Biomass yield [t DM/ha]	Growing days [d]	BMP, experimental [Nm³/tonne VS]	BMP, effective [Nm³/tonne VS]	Ash content [%]	VS [% of DM]	Methane yield [Nm³/ha]
27	29 Jun	3,78	49	346	310	9,4	90,6	1 062
28	06 Jul	3,67	49	346	310	9,4	90,6	1 030
29	13 Jul	3,55	49	346	310	9,4	90,6	998
30	20 Jul	3,44	49	346	310	9,4	90,6	966
31	27 Jul	3,33	49	346	310	9,4	90,6	934
32	03 Aug	3,21	49	346	310	9,4	90,6	902
33	10 Aug	3,10	49	346	310	9,4	90,6	871
34	17 Aug	2,99	49	346	310	9,4	90,6	839
Cut III								
Week	Date	Biomass yield [t DM/ha]	Growing days [d]	BMP, experimental [Nm³/tonne VS]	BMP, effective [Nm³/tonne VS]	Ash content [%]	VS [% of DM]	Methane yield [Nm³/ha]
35	24 Aug	3,09	56	333	300	9,0	91,0	842
36	31 Aug	2,99	56	333	300	9,0	91,0	817
37	07 Sep	2,90	56	333	300	9,0	91,0	792
38	14 Sep	2,81	56	333	300	9,0	91,0	766

Table A2. Calculated biomass yields and properties fro grass-clover crops, Örebro. Assumed growth start was 29 April for Örebro.

ÖREBRO, YEAR 1								
Cut I								
Week	Date	Biomass yield [t DM/ha]	Growing days [d]	BMP, experimental [Nm³/tonne VS]	BMP, effective [Nm³/tonne VS]	Ash content [%]	VS [% of DM]	Methane yield [Nm³/ha]
22	25 May	0,50	26	388	350	10,6	89,4	155
23	01 Jun	1,44	33	375	340	10,3	89,7	439
24	08 Jun	2,39	40	362	330	9,9	90,1	709
25	15 Jun	3,33	47	349	310	9,5	90,5	934
26	22 Jun	4,28	54	337	300	9,1	90,9	1 165
27	29 Jun	5,22	61	324	290	8,8	91,2	1 381
28	06 Jul	6,17	68	311	280	8,4	91,6	1 582
29	13 Jul	7,11	75	298	270	8,0	92,0	1 766

Table A2, continued.

ÖREBRO, YEAR 1								
Cut II								
Week	**Date**	**Biomass yield [t DM/ha]**	**Growing days [d]**	**BMP, experimental [Nm³/tonne VS]**	**BMP, effective**	**Ash content [%]**	**VS [% of DM]**	**Methane yield [Nm³/ha]**
29	13 Jul	3,78	49	346	310	9,4	90,6	1 062
30	20 Jul	3,67	49	346	310	9,4	90,6	1 030
31	27 Jul	3,55	49	346	310	9,4	90,6	998
32	03 Aug	3,44	49	346	310	9,4	90,6	966
33	10 Aug	3,33	49	346	310	9,4	90,6	934
34	17 Aug	3,21	49	346	310	9,4	90,6	902
35	24 Aug	3,10	49	346	310	9,4	90,6	871
36	31 Aug	2,99	49	346	310	9,4	90,6	839
Cut III								
Week	**Date**	**Biomass yield [t DM/ha]**	**Growing days [d]**	**BMP, experimental [Nm³/tonne VS]**	**BMP, effective**	**Ash content [%]**	**VS [% of DM]**	**Methane yield [Nm³/ha]**
37	24 Aug	3,09	56	333	300	9,0	91,0	842
38	31 Aug	2,99	56	333	300	9,0	91,0	817
39	07 Sep	2,90	56	333	300	9,0	91,0	792
40	14 Sep	2,81	56	333	300	9,0	91,0	766
41	21 Sep	2,72	56	333	300	9,0	91,0	741
42	28 Sep	2,62	56	333	300	9,0	91,0	716
43	05 Oct	2,53	56	333	300	9,0	91,0	691
44	12 Oct	2,44	56	333	300	9,0	91,0	665
ÖREBRO, YEAR 2								
Cut I								
Week	**Date**	**Biomass yield [t DM/ha]**	**Growing days [d]**	**BMP, experimental [Nm³/tonne VS]**	**BMP, effective**	**Ash content [%]**	**VS [% of DM]**	**Methane yield [Nm³/ha]**
22	25 May	0,45	26	388	350	10,6	89,4	139
23	01 Jun	1,30	33	375	340	10,3	89,7	395
24	08 Jun	2,15	40	362	330	9,9	90,1	638
25	15 Jun	3,00	47	349	310	9,5	90,5	841
26	22 Jun	3,85	54	337	300	9,1	90,9	1 049
27	29 Jun	4,70	61	324	290	8,8	91,2	1 243
28	06 Jul	5,55	68	311	280	8,4	91,6	1 423
29	13 Jul	6,40	75	298	270	8,0	92,0	1 590

Tabel A2, continued.

ÖREBRO, YEAR 2								
Cut II								
Week	Date	Biomass yield [t DM/ha]	Growing days [d]	BMP, experimental [Nm³/tonne VS]	BMP, effective [Nm³/tonne VS]	Ash content [%]	VS [% of DM]	Methane yield [Nm³/ha]
29	13 Jul	3,40	49	346	310	9,4	90,6	955
30	20 Jul	3,30	49	346	310	9,4	90,6	927
31	27 Jul	3,20	49	346	310	9,4	90,6	898
32	03 Aug	3,10	49	346	310	9,4	90,6	870
33	10 Aug	2,99	49	346	310	9,4	90,6	841
34	17 Aug	2,89	49	346	310	9,4	90,6	812
35	24 Aug	2,79	49	346	310	9,4	90,6	784
36	31 Aug	2,69	49	346	310	9,4	90,6	755

Table A3. Assumed biomass yields and properties for whole crop cereal: Jordberga and Örebro.

JORDBERGA							
Week	Date	Crop	Biomass yield [t DM/ha]	DM content [%]	BMP, effective [Nm³/tonne VS]	VS [% of DM]	Methane yield [Nm³/ha]
27	29 Jun	Rye	13,0	35	310	95	3 829
28	06 Jul	Rye	13,0	35	310	95	3 829
28	06 Jul	Triticale	13,0	35	310	95	3 829
29	13 Jul	Triticale	13,0	35	310	95	3 829
29	13 Jul	Wheat	13,0	35	310	95	3 829
30	20 Jul	Wheat	13,0	35	310	95	3 829
ÖREBRO							
Week	Date	Crop	Biomass yield [t DM/ha]	DM content [%]	BMP, effective [Nm³/tonne VS]	VS [% of DM]	Methane yield [Nm³/ha]
28	06 Jul	Rye	10,4	35	310	95	3 063
29	13 Jul	Rye	10,4	35	310	95	3 063
29	20 Jul	Triticale	10,4	35	310	95	3 063
30	27 Jul	Triticale	10,4	35	310	95	3 063
30	03 Aug	Wheat	10,4	35	310	95	3 063
31	10 Aug	Wheat	10,4	35	310	95	3 063

Table A4. Assumed biomass yields and properties for maize.

Location	Week	Date	Biomass yield [t DM/ha]	DM content [%]	BMP, effective [Nm³/tonne VS]	VS [% of DM]	Methane yield [Nm³/ha]
Jordberga	40	28 Sep	15,0	30	350	90	4 725
	41	05 Oct	15,0	35	350	90	4 725
	42	12 Oct	15,0	40	350	90	4 725
Örebro	42	12 Oct	10,5	30	350	90	3 308
	43	19 Oct	10,5	35	350	90	3 308

Table A5. Assumed biomass yields and properties for sugarbeets for Jordberga.

JORDBERGA (Sugarbeets)						
Week	Date	Biomass yield [t DM/ha]	DM content [%]	BMP, effective [Nm³/tonne VS]	VS [% of DM]	Methane yield [Nm³/ha]
38	14 Sep	15,0	23	350	90	4 725
39	21 Sep	15,0	23	350	90	4 725
40	28 Sep	15,0	23	350	90	4 725
41	05 Oct	15,0	23	350	90	4 725
42	12 Oct	15,0	23	350	90	4 725
43	19 Oct	15,0	23	350	90	4 725
44	26 Oct	15,0	23	350	90	4 725
45	02 Nov	15,0	23	350	90	4 725
46	09 Nov	15,0	23	350	90	4 725
47	16 Nov	15,0	23	350	90	4 725
48	23 Nov	15,0	23	350	90	4 725

Table A6. Assumed biomass yields and properties for sugarbeet tops for Jordberga.

JORDBERGA (Sugarbeet tops)						
Week	Date	Biomass yield [t DM/ha]	DM content [%]	BMP, effective [Nm³/tonne VS]	VS [% of DM]	Methane yield [Nm³/ha]
38	14 Sep	3,6	11,6	300	87	937
39	21 Sep	3,5	11,9	300	87	914
40	28 Sep	3,4	12,2	300	87	891
41	05 Oct	3,3	12,5	300	87	869
42	12 Oct	3,2	12,8	300	87	846
43	19 Oct	3,2	13,1	300	87	823
44	26 Oct	3,1	13,4	300	87	801
45	02 Nov	3,0	13,6	300	87	778
46	09 Nov	2,9	13,9	300	87	755

Table A7. Assumed biomass yields and properties for green rye.

Location	Week	Date	Biomass yield [t DM/ha]	DM content [%]	BMP, effective [Nm³/tonne VS]	VS [% of DM]	Methane yield [Nm³/ha]
Jordberga	22	25 May	8,6	30	310	90	2 399
	23	01 Jun	9,4	30	310	90	2 623
Örebro	24	08 Jun	6,8	30	310	90	1 897
	25	15 Jun	7,5	30	310	90	2 079

Table A8. Assumed biomass yields and properties for landscape conservation grass harvested either one or two times per year. Data was used for both Jordberga and Örebro.

Harvest	Week	Date	Biomass yield [t DM/ha]	DM content [%]	BMP, effective [Nm³/tonne VS]	VS [% of DM]	Methane yield [Nm³/ha]
1 of 1	27	29 Jun	2,6	35	250	94	611
	28	06 Jul	2,6	35	250	94	611
	29	13 Jul	2,6	35	250	94	611
1 of 2	24	08 Jun	2,3	35	300	94	640
	25	15 Jun	2,3	35	300	94	640
	26	22 Jun	2,3	35	300	94	640
2 of 2	31	27 Jul	1,2	35	300	94	328
	32	03 Aug	1,2	35	300	94	328
	33	10 aug	1,2	35	300	94	328

Table A9. Assumed biomass yields and properties for cover crops.

Location	Week	Date	Biomass yield [t DM/ha]	DM content [%]	BMP, effective [Nm³/tonne VS]	VS [% of DM]	Methane yield [Nm³/ha]
Jordberga	39	21 Sep	4,0	20	300	90	1 080
	40	28 Sep	4,0	20	300	90	1 080
	41	05 Oct	4,0	20	300	90	1 080
	42	12 Oct	4,0	20	300	90	1 080
Örebro	40	28 Sep	3,2	20	300	90	864
	41	05 Oct	3,2	20	300	90	864
	42	12 Oct	3,2	20	300	90	864
	43	19 Oct	3,2	20	300	90	864

APPENDIX B: CULTIVATION COSTS

LAND USE VALUE

The opportunity value of land depend of different factors like prices, crop combinations and a lot of other things which changes between different years and different farms.

The opportunity value was calculated as the average value of the result with 50% winter wheat, 25% barley and 25% rapeseed. This resulted in 3201 SEK/ha for Jordberga (Table B1) and 493 SEK/ha for Örebro (Table B2).

Table B1. Land use value for Jordberga.

	Yield (kg/ha)	Price (SEK/kg)	Results (SEK/ha)
Winter wheat, bread	10 000	1,4	2 697
Malting barley	7 000	1,47	547
Rapeseed	5 000	3,2	6 863

Table B2. Land use value for Örebro.

	Yield (kg/ha)	Price (SEK/kg)	Results (SEK/ha)
Winter wheat, bread	7 000	1,4	127
Malting barley	5 000	1,47	-1 138
Rapeseed	3 400	3,2	2 857

CALCULATED CULTIVATION COSTS

Table B3. Cultivation costs (SEK/ha) for the cultivation period from week 20 to week 34 for Jordberga.

JORDBERGA, WEEK 20-34															
Substrate name	**W 20**	**W 21**	**W 22**	**W 23**	**W 24**	**W 25**	**W 26**	**W 27**	**W 28**	**W 29**	**W 30**	**W 31**	**W 32**	**W 33**	**W 34**
Grass-clover, large fields, fresh, alt-1	2 161							3 547							
Grass-clover, large fields, fresh, alt-2		2 559							3 499						
Grass-clover, large fields, fresh, alt-3			2 959							3 451					
Grass-clover, large fields, fresh, alt-4				3 548							3 594				
Grass-clover, large fields, fresh, alt-5					4 329							3 929			
Grass-clover, large fields, fresh, alt-6						4 727							3 879		
Grass-clover, large fields, fresh, alt-7							5 126							3 831	
Grass-clover, large fields, fresh, alt-8								5 524							3 785
Grass-clover, small fields, fresh, alt-1	2 161							3 547							
Grass-clover, small fields, fresh, alt-2		2 559							3 499						
Grass-clover, small fields, fresh, alt-3			2 959							3 451					
Grass-clover, small fields, fresh, alt-4				3 548							3 594				
Grass-clover, small fields, fresh, alt-5					4 329							3 929			
Grass-clover, small fields, fresh, alt-6						4 727							3 879		
Grass-clover, small fields, fresh, alt-7							5 126							3 831	
Grass-clover, small fields, fresh, alt-8								5 524							3 785
Landscape conservation grass, two harvests, fresh, alt-1					408							408			
Landscape conservation grass, two harvests, fresh, alt-2						408							408		
Landscape conservation grass, two harvests, fresh, alt-3							408							408	

Table B3, continued.

JORDBERGA, WEEK 20-34															
Substrate name	**W 20**	**W 21**	**W 22**	**W 23**	**W 24**	**W 25**	**W 26**	**W 27**	**W 28**	**W 29**	**W 30**	**W 31**	**W 32**	**W 33**	**W 34**
Maize, fresh															
Whole-crop cereal, fresh								9 617	9 617	9 617	9 617				
Green rye, fresh			9 110	9 229											
Cover crop, large fields, fresh															
Sugarbeets and tops, fresh															
Sugarbeet tops, fresh															
Sugarbeets, fresh															
Landscape conservation grass, one harvests, fresh								408	408	408					
Cover crop, small fields, fresh															
Maize, ensiled	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409
Whole-crop cereal, ensiled	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617
Grass-clover, large fields, ensiled	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535
Green rye, ensiled	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229
Sugarbeets, stored															
Grass-clover, small fields, ensiled	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535
Landscape conservation grass, ensiled	408	408	408	408	408	408	408	408	408	408	408	408	408	408	408

Table B4. Cultivation costs (SEK/ha) for the cultivation period from week 35 to week 19 for Jordberga.

JORDBERGA, WEEK 35-19																
Substrate name	**W 35**	**W 36**	**W 37**	**W 38**	**W 39**	**W 40**	**W 41**	**W 42**	**W 43**	**W 44**	**W 45**	**W 46**	**W 47**	**W 48**	**W 49-09**	**W 10-19**
Grass-clover, large fields, fresh, alt-1	3 388								2 856							
Grass-clover, large fields, fresh, alt-2		3 215								2 824						
Grass-clover, large fields, fresh, alt-3			3 226								2 792					
Grass-clover, large fields, fresh, alt-4				3 328												
Grass-clover, large fields, fresh, alt-5					3 350											
Grass-clover, large fields, fresh, alt-6						3 306										
Grass-clover, large fields, fresh, alt-7							3 266									
Grass-clover, large fields, fresh, alt-8								3 226								
Grass-clover, small fields, fresh, alt-1	3 388								2 856							
Grass-clover, small fields, fresh, alt-2		3 215								2 824						
Grass-clover, small fields, fresh, alt-3			3 226								2 792					
Grass-clover, small fields, fresh, alt-4				3 328												
Grass-clover, small fields, fresh, alt-5					3 350											
Grass-clover, small fields, fresh, alt-6						3 306										
Grass-clover, small fields, fresh, alt-7							3 266									
Grass-clover, small fields, fresh, alt-8								3 226								
Landscape conservation grass, two harvests, fresh, alt-1																
Landscape conservation grass, two harvests, fresh, alt-2																
Landscape conservation grass, two harvests, fresh, alt-3																
Maize, fresh						14 409	14 409	14 409								

Table B4, continued.

JORDBERGA, WEEK 35-19																
Substrate name	**W 35**	**W 36**	**W 37**	**W 38**	**W 39**	**W 40**	**W 41**	**W 42**	**W 43**	**W 44**	**W 45**	**W 46**	**W 47**	**W 48**	**W 49-09**	**W 10-19**
Whole-crop cereal, fresh																
Green rye, fresh																
Cover crop, large fields, fresh					1 813	1 813	1 813	1 813								
Sugar beets and tops, fresh				16 805	16 775	16 746	16 716	16 686	16 686	16 657	16 627	16 597				
Sugar beet tops, fresh				1 284	1 254	1 225	1 195	1 165	1 165	1 136	1 106	1 076				
Sugar beets, fresh				15 521	15 521	15 521	15 521	15 521	15 521	15 521	15 521	15 521	15 521	15 521		
Landscape conservation grass, one harvests, fresh																
Cover crop, small fields, fresh					1 813	1 813	1 813	1 813								
Maize, ensiled	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409	14 409
Whole-crop cereal, ensiled	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617	9 617
Grass-clover, large fields, ensiled	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535
Green rye, ensiled	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229	9 229
Sugar beets, stored															15 521	
Grass-clover, small fields, ensiled	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535	12 535
Landscape conservation grass, ensiled	408	408	408	408	408	408	408	408	408	408	408	408	408	408	408	408

Table B5. Cultivation costs (SEK/ha) for the cultivation period from week 22 to week 33 for Örebro.

ÖREBRO,WEEK 22-33												
Substrate name	W 22	W 23	W 24	W 25	W 26	W 27	W 28	W 29	W 30	W 31	W 32	W 33
Grass-clover, large fields, fresh, alt-1	1 585							2 830				
Grass-clover, large fields, fresh, alt-2		1 943							2 788			
Grass-clover, large fields, fresh, alt-3			2 303							2 744		
Grass-clover, large fields, fresh, alt-4				2 660							2 702	
Grass-clover, large fields, fresh, alt-5					3 020							2 658
Grass-clover, large fields, fresh, alt-6						3 378						
Grass-clover, large fields, fresh, alt-7							3 738					
Grass-clover, large fields, fresh, alt-8								4 096				
Grass-clover, small fields, fresh, alt-1	1 585							2 830				
Grass-clover, small fields, fresh, alt-2		1 943							2 788			
Grass-clover, small fields, fresh, alt-3			2 303							2 744		
Grass-clover, small fields, fresh, alt-4				2 660							2 702	
Grass-clover, small fields, fresh, alt-5					3 020							2 658
Grass-clover, small fields, fresh, alt-6						3 378						
Grass-clover, small fields, fresh, alt-7							3 738					
Grass-clover, small fields, fresh, alt-8								4 096				
Landscape conservation grass, two harvests, fresh, alt-1			408							408		
Landscape conservation grass, two harvests, fresh, alt-2				408							408	
Landscape conservation grass, two harvests, fresh, alt-3					408							408
Maize, fresh												
Whole-crop cereal, fresh							6 521	6 521	6 521	6 521		
Green rye, fresh		6 240	6 240									

Table B5, continued.

ÖREBRO, WEEK 22-33												
Substrate name	**W 22**	**W 23**	**W 24**	**W 25**	**W 26**	**W 27**	**W 28**	**W 29**	**W 30**	**W 31**	**W 32**	**W 33**
Landscape conservation grass, one harvests, fresh						408	408	408				
Cover crop, small fields, fresh												
Maize, ensiled	10 293	10 293	10 293	10 293	10 293	10 293	10 293	10 293	10 293	10 293	10 293	10 293
Whole-crop cereal, ensiled	6 521	6 521	6 521	6 521	6 521	6 521	6 521	6 521	6 521	6 521	6 521	6 521
Grass-clover, large fields, ensiled	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842
Green rye, ensiled	6 240	6 240	6 240	6 240	6 240	6 240	6 240	6 240	6 240	6 240	6 240	6 240
Grass-clover, small fields, ensiled	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842
Landscape conservation grass, ensiled	408	408	408	408	408	408	408	408	408	408	408	408

Table B6. Cultivation costs (SEK/ha) for the cultivation period from week 34 to week 21 for Örebro.

ÖREBRO, WEEK 34-21												
Substrate name	**W 34**	**W 35**	**W 36**	**W 37**	**W 38**	**W 39**	**W 40**	**W 41**	**W 42**	**W 42**	**W 44**	**W 45-21**
Grass-clover, large fields, fresh, alt-1				2 475								
Grass-clover, large fields, fresh, alt-2					2 435							
Grass-clover, large fields, fresh, alt-3						2 399						
Grass-clover, large fields, fresh, alt-4							2 363					
Grass-clover, large fields, fresh, alt-5								2 327				
Grass-clover, large fields, fresh, alt-6	2 614								2 287			
Grass-clover, large fields, fresh, alt-7		2 572								2 251		
Grass-clover, large fields, fresh, alt-8			2 530								2 215	
Grass-clover, small fields, fresh, alt-1				2 475								
Grass-clover, small fields, fresh, alt-2					2 435							

Table B6, continued.

ÖREBRO, WEEK 34-21												
Substrate name	**W 34**	**W 35**	**W 36**	**W 37**	**W 38**	**W 39**	**W 40**	**W 41**	**W 42**	**W 42**	**W 44**	**W 45-21**
Grass-clover, small fields, fresh, alt-3						2 399						
Grass-clover, small fields, fresh, alt-4							2 363					
Grass-clover, small fields, fresh, alt-5								2 327				
Grass-clover, small fields, fresh, alt-6	2 614								2 287			
Grass-clover, small fields, fresh, alt-7		2 572								2 251		
Grass-clover, small fields, fresh, alt-8			2 530								2 215	
Landscape conservation grass, two harvests, fresh, alt-1												
Landscape conservation grass, two harvests, fresh, alt-2												
Landscape conservation grass, two harvests, fresh, alt-3												
Maize, fresh									10 293	10 293		
Whole-crop cereal, fresh												
Green rye, fresh												
Cover crop, large fields, fresh							0	0	0	0		
Landscape conservation grass, one harvests, fresh												
Cover crop, small fields, fresh							0	0	0	0		
Maize, ensiled	10 293	10 293	10 293	10 293	10 293	10 293	10 293	10 293	10 293	10 293	10 293	10 293
Whole-crop cereal, ensiled	6 521	6 521	6 521	6 521	6 521	6 521	6 521	6 521	6 521	6 521	6 521	6 521
Grass-clover, large fields, ensiled	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842
Green rye, ensiled	6 240	6 240	6 240	6 240	6 240	6 240	6 240	6 240	6 240	6 240	6 240	6 240
Grass-clover, small fields, ensiled	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842	8 842
Landscape conservation grass, ensiled	408	408	408	408	408	408	408	408	408	408	408	408

APPENDIX C: HARVEST AND TRANSPORT COST

Indata for the calculations of machine- and transport costs are shown in Table C1 and C2. Calculated harvest costs for the crops in Jordberga are shown in Tables C3-C4 and transport costs in Table C5. Corresponding costs for Örebro are found in Tables C6-C8.

Table C1. Specifications and machine costs excluding driver and fuel, except for truck where driver and fuel is included.

	Power req. (kW)	Fuel consumption (l/h)	Machine costs excl driver and fuel (SEK/h)	Max. capacity (tonne ww/h)	Max. speed (km/h)	Implement width (m)
Self propelled precision chopper	480		1 585			
Front pick-up (grass/clover)		0,8*	81	70	12	3
Direct cut header (whole crop silage)		0,7[1]	539	150	12	6
Circular cutting header, 10 rows (maize)		0,6[1]	890	180	12	7,5
Mower conditioner (front and rear monted)	170	26	665+242		12	9
Mower conditioner (rear monted)	100	15	510+164		12	3
Precision chop forage wagon, 40 m^3	130	20	822+204	30	12	4
Direct cut forage wagon (for intermediate crops)	170	26	822+220+242			3
Swather	70	11	387+128		10	7
Swather	110	17	660+177		10	13
Combined beet and tops harvester, 3 rows, tractor driven	130	20	1 151+204			1,5
Self propelled beet harvester 6 rows with separated tops harvest		50	1 307			3
Single transport wagon, 45 m^3	150	23	244+229			
Double transport wagon, 90 m^3	200	30	244+244+294			
Växlarvagn, chassi, 16/20 tonne samt containerflak (40 m^3)	150	23	220+79+229		15	
Truck with trailer (3x 40 m^3) incl. driver and fuel			950**			

*** l/tonne ww.**

**** including driver and fuel.**

Table C2. Data for calculation of transport capacities for the studied harvest and transport systems.

Specification	Time (min)
Tractor transport with single wagon	
Tractor unloading at storage	5
Tractor transport with double wagons	
Field tractor changing wagons at field edge	3
Tractor for road transport changing wagons at field edge	5
Tractor for road transport emptying double wagons at storage	15
Truck with containers	
Field tractor changing container in the field	3
Truck changing containers in field	20
Truck weighing and changing containers at storage	20
Tractor transport (intermediate crops)	
Changing wagons/container on field	3
Tractor for road transport unloading at storage	5
Precision chop forage wagon	
Tractor with forage wagon unloading at storage	5
Transport with tractor in beet systems	
Time for field tractor to emptying the load to a wagon at field edge	3
Time for tractor for road transport to change wagons on field edge	3
Tractor with wagon unloading at storage	5
Transport with truck in beet systems	
Filling up container on the run at harvester	3
Emptying the load to a container at field edge	3
Truck changing containers in field	20
Truck weighing, changing containers at storage	20

Table C3. Harvest costs (SEK/ha) for week 20 to week 34 for the crops in Jordberga.

JORDBERGA, WEEK 20-34															
Substrate name	**W 20**	**W 21**	**W 22**	**W 23**	**W 24**	**W 25**	**W 26**	**W 27**	**W 28**	**W 29**	**W 30**	**W 31**	**W 32**	**W 33**	**W 34**
Grass-clover, large fields, fresh, alt-1	1 179							1 700							
Grass-clover, large fields, fresh, alt-2		1 241							1 700						
Grass-clover, large fields, fresh, alt-3			1 494							1 700					
Grass-clover, large fields, fresh, alt-4				1 700							1 700				
Grass-clover, large fields, fresh, alt-5					1 700							1 700			
Grass-clover, large fields, fresh, alt-6						1 700							1 700		
Grass-clover, large fields, fresh, alt-7							1 700							1 604	
Grass-clover, large fields, fresh, alt-8								1 376							1 150
Grass-clover, small fields, fresh, alt-1	1 179							1 700							
Grass-clover, small fields, fresh, alt-2		1 241							1 700						
Grass-clover, small fields, fresh, alt-3			1 494							1 700					
Grass-clover, small fields, fresh, alt-4				1 700							1 700				
Grass-clover, small fields, fresh, alt-5					1 700							1 700			
Grass-clover, small fields, fresh, alt-6						1 700							1 700		
Grass-clover, small fields, fresh, alt-7							1 700							1 604	
Grass-clover, small fields, fresh, alt-8								1 700							1 604
Landscape conservation grass, two harvests, fresh, alt-1					1 528							1 282			
Landscape conservation grass, two harvests, fresh, alt-2						1 528							1 282		
Landscape conservation grass, two harvests, fresh, alt-3							1 528							1 282	
Maize, fresh															
Whole-crop cereal, fresh								1 641	1 641	1 641	1 641				

Table C3, continued.

JORDBERGA, WEEK 20-34															
Substrate name	**W 20**	**W 21**	**W 22**	**W 23**	**W 24**	**W 25**	**W 26**	**W 27**	**W 28**	**W 29**	**W 30**	**W 31**	**W 32**	**W 33**	**W 34**
Green rye, fresh			2 578	2 578											
Cover crop, large fields, fresh															
Sugar beets and tops, fresh															
Sugar beet tops, fresh															
Sugar beets, fresh															
Landscape conservation grass, one harvests, fresh								1 636	1 636	1 636					
Cover crop, small fields, fresh															
Maize, ensiled	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814
Whole-crop cereal, ensiled	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641
Grass-clover, large fields, ensiled	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563
Green rye, ensiled	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578
Sugar beets, stored															
Grass-clover, small fields, ensiled	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236
Landscape conservation grass, ensiled	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636

Table C4. Harvest costs (SEK/ha) for week 35 to week 19 for the crops in Jordberga.

JORDBERGA, WEEK 35-19																
Substrate name	**W 35**	**W 36**	**W 37**	**W 38**	**W 39**	**W 40**	**W 41**	**W 42**	**W 43**	**W 44**	**W 45**	**W 46**	**W 47**	**W 48**	**W 49-09**	**W 10-19**
Grass-clover, large fields, fresh, alt-1	1 604								1 494							
Grass-clover, large fields, fresh, alt-2		1 604								1 494						
Grass-clover, large fields, fresh, alt-3			1 604								1 494					
Grass-clover, large fields, fresh, alt-4				1 604												
Grass-clover, large fields, fresh, alt-5					1 604											
Grass-clover, large fields, fresh, alt-6						1 604										
Grass-clover, large fields, fresh, alt-7							1 604									
Grass-clover, large fields, fresh, alt-8								1 038								
Grass-clover, small fields, fresh, alt-1	1 604								1 494							
Grass-clover, small fields, fresh, alt-2		1 604								1 494						
Grass-clover, small fields, fresh, alt-3			1 604								1 494					
Grass-clover, small fields, fresh, alt-4				1 604												
Grass-clover, small fields, fresh, alt-5					1 604											
Grass-clover, small fields, fresh, alt-6						1 604										
Grass-clover, small fields, fresh, alt-7							1 604									
Grass-clover, small fields, fresh, alt-8								1 494								
Landscape conservation grass, two harvests, fresh, alt-1																
Landscape conservation grass, two harvests, fresh, alt-2																
Landscape conservation grass, two harvests, fresh, alt-3																
Maize, fresh						2 091	1 814	1 814								

Table C4, continued.

JORDBERGA, WEEK 35-19																
Substrate name	**W 35**	**W 36**	**W 37**	**W 38**	**W 39**	**W 40**	**W 41**	**W 42**	**W 43**	**W 44**	**W 45**	**W 46**	**W 47**	**W 48**	**W 49-09**	**W 10-19**
Whole-crop cereal, fresh																
Green rye, fresh																
Cover crop, large fields, fresh					1 516	1 516	1 516	1 516								
Sugar beets and tops, fresh				4 640	4 631	4 621	4 612	4 603	4 594	4 585	4 577	4 568				
Sugar beet tops, fresh				1 151	1 144	1 138	1 131	1 125	1 119	1 114	1 108	1 103				
Sugar beets, fresh				3 448	3 448	3 448	3 448	3 448	3 448	3 448	3 448	3 448	3 448	3 448		
Landscape conservation grass, one harvests, fresh																
Cover crop, small fields, fresh					1 748	1 748	1 748	1 748								
Maize, ensiled	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814	1 814
Whole-crop cereal, ensiled	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641	1 641
Grass-clover, large fields, ensiled	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563	3 563
Green rye, ensiled	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578	2 578
Sugar beets, stored															3 448	
Grass-clover, small fields, ensiled	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236	5 236
Landscape conservation grass, ensiled	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636	1 636

Table C5. Transport costs SEK/tonne ww for Jordberga where A1-A7 and B1-B7 represents transport intervals between for large and small respectively. 1 equals 0-5 km, 2 equals 5.1-10 km, 3 equals 10.1-15 km, 4 equals 15.1-20 km, 5 equals 20.5-30 km, 6 equals 30.1-50 km and 7 equals 50.1-100 km.

JORDBERGA														
Substrate name	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**
Grass-clover, large fields, fresh, alt-1	28	36	43	49	50	66	93							
Grass-clover, large fields, fresh, alt-2	28	36	43	49	50	66	93							
Grass-clover, large fields, fresh, alt-3	28	36	43	49	50	66	93							
Grass-clover, large fields, fresh, alt-4	28	36	43	49	50	66	93							
Grass-clover, large fields, fresh, alt-5	28	36	43	49	50	66	93							
Grass-clover, large fields, fresh, alt-6	28	36	43	49	50	66	93							
Grass-clover, large fields, fresh, alt-7	28	36	43	49	50	66	93							
Grass-clover, large fields, fresh, alt-8	21	36	44	51	52	67	94							
Grass-clover, small fields, fresh, alt-1								29	36	43	50	50	66	95
Grass-clover, small fields, fresh, alt-2								29	36	43	50	50	66	95
Grass-clover, small fields, fresh, alt-3								29	36	43	50	50	66	95
Grass-clover, small fields, fresh, alt-4								29	36	43	50	50	66	95
Grass-clover, small fields, fresh, alt-5								29	36	43	50	50	66	95
Grass-clover, small fields, fresh, alt-6								29	36	43	50	50	66	95
Grass-clover, small fields, fresh, alt-7								29	36	43	50	50	66	95
Grass-clover, small fields, fresh, alt-8								29	36	43	50	50	66	95
Landscape conservation grass, two harvests, fresh, alt-1								29	36	43	50	50	66	95
Landscape conservation grass, two harvests, fresh, alt-2								29	36	43	50	50	66	95
Landscape conservation grass, two harvests, fresh, alt-3								29	36	43	50	50	66	95
Maize, fresh	19	33	44	51	52	67	94							

Table C5, continued.

JORDBERGA														
Substrate name	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**
Whole-crop cereal, fresh	19	33	44	51	52	67	94							
Green rye, fresh	21	36	44	51	52	67	94							
Cover crop, large fields, fresh	33	38	45	51	52	67	104							
Sugar beets and tops, fresh	20	25	32	38	39	55	82							
Sugar beet tops, fresh	27	32	39	45	46	62	89							
Sugar beets, fresh	21	26	33	39	40	56	83							
Landscape conservation grass, one harvests, fresh								29	36	43	50	50	66	95
Cover crop, small fields, fresh								33	3	45	51	52	68	97
Maize, ensiled	19	33	44	51	52	67	94							
Whole-crop cereal, ensiled	19	33	44	51	52	67	94							
Grass-clover, large fields, ensiled	21	36	44	51	52	67	94							
Green rye, ensiled	21	36	44	51	52	67	94							
Sugar beets, stored	21	26	33	39	40	56	83							
Grass-clover, small fields, ensiled								29	36	43	50	50	66	95
Landscape conservation grass, ensiled								29	36	43	50	50	66	95

Table C6. Harvest costs (SEK/ha) for week 22 to week 33 for the crops in Örebro.

ÖREBRO, WEEK 22-33												
Substrate name	**W 22**	**W 23**	**W 24**	**W 25**	**W 26**	**W 27**	**W 28**	**W 29**	**W 30**	**W 31**	**W 32**	**W 33**
Grass-clover, large fields, fresh, alt-1	1 178							1 700				
Grass-clover, large fields, fresh, alt-2		1 210							1 700			
Grass-clover, large fields, fresh, alt-3			1 399							1 700		
Grass-clover, large fields, fresh, alt-4				1 605							1 605	
Grass-clover, large fields, fresh, alt-5					1 700							1 605
Grass-clover, large fields, fresh, alt-6						1 700						
Grass-clover, large fields, fresh, alt-7							1 700					
Grass-clover, large fields, fresh, alt-8								1 370				
Grass-clover, small fields, fresh, alt-1	1 282							1 746				
Grass-clover, small fields, fresh, alt-2		1 282							1 746			
Grass-clover, small fields, fresh, alt-3			1 528							1 746		
Grass-clover, small fields, fresh, alt-4				1 746							1 746	
Grass-clover, small fields, fresh, alt-5					1 854							1 746
Grass-clover, small fields, fresh, alt-6						1 854						
Grass-clover, small fields, fresh, alt-7							1 854					
Grass-clover, small fields, fresh, alt-8								1 854				
Landscape conservation grass, two harvests, fresh, alt-1			2 120							2 726		
Landscape conservation grass, two harvests, fresh, alt-2				2 120							2 726	
Landscape conservation grass, two harvests, fresh, alt-3					2 120							2 726
Maize, fresh												
Whole-crop cereal, fresh							1 243	1 243	1 243	1 243		

Table C6, continued.

ÖREBRO, WEEK 22-33												
Substrate name	**W 22**	**W 23**	**W 24**	**W 25**	**W 26**	**W 27**	**W 28**	**W 29**	**W 30**	**W 31**	**W 32**	**W 33**
Green rye, fresh		2 330	2 330									
Cover crop, large fields, fresh												
Landscape conservation grass, one harvests, fresh						1 932	1 932	1 932				
Cover crop, small fields, fresh												
Maize, ensiled	1 254	1 254	1 254	1 254	1 254	1 254	1 254	1 254	1 254	1 254	1 254	1 254
Whole-crop cereal, ensiled	1 243	1 243	1 243	1 243	1 243	1 243	1 243	1 243	1 243	1 243	1 243	1 243
Grass-clover, large fields, ensiled	3 325	3 325	3 325	3 325	3 325	3 325	3 325	3 325	3 325	3 325	3 325	3 325
Green rye, ensiled	2 330	2 330	2 330	2 330	2 330	2 330	2 330	2 330	2 330	2 330	2 330	2 330
Grass-clover, small fields, ensiled	5 018	5 018	5 018	5 018	5 018	5 018	5 018	5 018	5 018	5 018	5 018	5 018
Landscape conservation grass, ensiled	1 932	1 932	1 932	1 932	1 932	1 932	1 932	1 932	1 932	1 932	1 932	1 932

Table C7. Harvest costs (SEK/ha) for week 34 to week 21 for the crops in Örebro.

ÖREBRO, WEEK 34-21												
Substrate name	**W 34**	**W 35**	**W 36**	**W 37**	**W 38**	**W 39**	**W 40**	**W 41**	**W 42**	**W 42**	**W 44**	**W 45-21**
Grass-clover, large fields, fresh, alt-1				1 605								
Grass-clover, large fields, fresh, alt-2					1 605							
Grass-clover, large fields, fresh, alt-3						1 605						
Grass-clover, large fields, fresh, alt-4							1 605					
Grass-clover, large fields, fresh, alt-5								1 494				
Grass-clover, large fields, fresh, alt-6	1 605								1 494			
Grass-clover, large fields, fresh, alt-7		1 605								1 494		
Grass-clover, large fields, fresh, alt-8			1 034								922	
Grass-clover, small fields, fresh, alt-1				1 746								
Grass-clover, small fields, fresh, alt-2					1 636							
Grass-clover, small fields, fresh, alt-3						1 636						
Grass-clover, small fields, fresh, alt-4							1 636					
Grass-clover, small fields, fresh, alt-5								1 636				
Grass-clover, small fields, fresh, alt-6	1 746								1 636			
Grass-clover, small fields, fresh, alt-7		1 636								1 528		
Grass-clover, small fields, fresh, alt-8			1 636								1 528	
Landscape conservation grass, two harvests, fresh, alt-1												
Landscape conservation grass, two harvests, fresh, alt-2												
Landscape conservation grass, two harvests, fresh, alt-3												
Maize, fresh									1 529	1 254		
Whole-crop cereal, fresh												
Green rye, fresh												

Table C7, continued.

ÖREBRO, WEEK 34-21												
Substrate name	**W 34**	**W 35**	**W 36**	**W 37**	**W 38**	**W 39**	**W 40**	**W 41**	**W 42**	**W 42**	**W 44**	**W 45-21**
Cover crop, large fields, fresh							1 281	1 281	1 281	1 281		
Landscape conservation grass, one harvests, fresh												
Cover crop, small fields, fresh							1 501	1 501	1 501	1 501		
Maize, ensiled	1 254	1 254	1 254	1 254	1 254	1 254	1 254	1 254	1 254	1 254	1 254	1 254
Whole-crop cereal, ensiled	1 243	1 243	1 243	1 243	1 243	1 243	1 243	1 243	1 243	1 243	1 243	1 243
Grass-clover, large fields, ensiled	3 325	3 325	3 325	3 325	3 325	3 325	3 325	3 325	3 325	3 325	3 325	3 325
Green rye, ensiled	2 330	2 330	2 330	2 330	2 330	2 330	2 330	2 330	2 330	2 330	2 330	2 330
Grass-clover, small fields, ensiled	5 018	5 018	5 018	5 018	5 018	5 018	5 018	5 018	5 018	5 018	5 018	5 018
Landscape conservation grass, ensiled	1 932	1 932	1 932	1 932	1 932	1 932	1 932	1 932	1 932	1 932	1 932	1 932

Table C8. Transport costs SEK/tonne ww for Örebro where A1-A7 and B1-B7 represents transport intervals between for large and small respectively. 1 equals 0-5 km, 2 equals 5.1-10 km, 3 equals 10.1-15 km, 4 equals 15.1-20 km, 5 equals 20.5-30 km, 6 equals 30.1-50 km and 7 equals 50.1-100 km.

ÖREBRO														
Substrate name	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**
Grass-clover, large fields, fresh, alt-1	30	34	39	43	50	65	102							
Grass-clover, large fields, fresh, alt-2	30	34	39	43	50	65	102							
Grass-clover, large fields, fresh, alt-3	30	34	39	43	50	65	102							
Grass-clover, large fields, fresh, alt-4	30	34	39	43	50	65	102							
Grass-clover, large fields, fresh, alt-5	30	34	39	43	50	65	102							
Grass-clover, large fields, fresh, alt-6	30	34	39	43	50	65	102							
Grass-clover, large fields, fresh, alt-7	30	34	39	43	50	65	102							
Grass-clover, large fields, fresh, alt-8	23	35	40	44	51	66	103							

Table C8, continued.

ÖREBRO														
Substrate name	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**
Grass-clover, small fields, fresh, alt-1								30	33	39	43	50	65	99
Grass-clover, small fields, fresh, alt-2								30	33	39	43	50	65	99
Grass-clover, small fields, fresh, alt-3								30	33	39	43	50	65	99
Grass-clover, small fields, fresh, alt-4								30	33	39	43	50	65	99
Grass-clover, small fields, fresh, alt-5								30	33	39	43	50	65	99
Grass-clover, small fields, fresh, alt-6								30	33	39	43	50	65	99
Grass-clover, small fields, fresh, alt-7								30	33	39	43	50	65	99
Grass-clover, small fields, fresh, alt-8								30	33	39	43	50	65	99
Landscape conservation grass, two harvests, fresh, alt-1								30	33	39	43	50	65	99
Landscape conservation grass, two harvests, fresh, alt-2								30	33	39	43	50	65	99
Landscape conservation grass, two harvests, fresh, alt-3								30	33	39	43	50	65	99
Maize, fresh	21	34	40	44	51	66	103							
Whole-crop cereal, fresh	21	34	40	44	51	66	103							
Green rye, fresh	23	35	40	44	51	66	103							
Cover crop, large fields, fresh	32	36	40	45	52	67	104							
Landscape conservation grass, one harvests, fresh								30	33	39	43	50	65	99
Cover crop, small fields, fresh								32	35	40	45	52	67	101
Maize, ensiled	21	34	40	44	51	66	103							
Whole-crop cereal, ensiled	21	34	40	44	51	66	103							
Grass-clover, large fields, ensiled	23	35	40	44	51	66	103							
Green rye, ensiled	23	35	40	44	51	66	103							
Grass-clover, small fields, ensiled								30	33	39	43	50	65	99
Landscape conservation grass, ensiled								30	33	39	43	50	65	99

APPENDIX D: STORAGE COSTS

The total volume in Jordberga was calculated as the volume of the bunker walls plus an additional volume is over-filled in the center of the silo up to 4 m higher than the height of the walls. The volume of the silo in Örebro was assumed as the bunker volume plus additional volume with a height in the center of 1.4 m higher than the height of the walls.

Input data for the calculations are found in Table D1. The annual cost for the investment in the bunker silo (A) was calculated according to:

$$A = af\ (Inv - Rv)$$

Where *af* is the annuity factor, *Inv* is the investemetn cost and *Rv* is the residual value, which is assumed to be zero.

The annuity factor is calculated according to:

$$af = p\ /(1 - (1 + p)^{-t})$$

Where *p* is the interest rate and *t* is the depreciation time. The annuity factor was 0.0612 for the bunker silo and 0.1785 for net, sand sacks and straps for covering the silo.

Table D1. Specifications for the calculation of costs per compartment for storage in bunker silos.

	Jordberga	Örebro	Reference
Length per compartment; width; height	100; 38; 4	60; 20; 3	
Stored weight, tonne DM/compartment	7 000	1 260	Experience from SBI
Silo investment cost, SEK/compartment	2 400 000	800 000	Price from manufacturer
Annual maintenance cost (Inv), % of investment	0.5	0.5	
Interest rate (p), %	2	2	Maskinkostnader, 2015
Depreciation time silo (t), yr	20	20	
Depreciation time material for covering silo excl plastic sheets (t), yr	6	6	

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