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Location analysis for optimal collection of perennial forage crops to a biogas plant

– the case of ley crops in Uppsala, Sweden

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Abstract

Purpose: This study uses a location analysis technique to evaluate the optimal location of a biogas plant site primarily by optimizing the collection and transport of a mix of perennial forage crops (ley crops) for the production of biogas in Uppsala municipality.

Content: Ley crops together with organic waste from households and restaurants are used as substrates for biogas production in Västerås municipality in the county of Västmanland. The biogas plant in Västerås consist of a 4000m^3 digester tank, which is fed with a yearly total amount of 14000 tonnes of source-sorted food waste from households, 5000 tonnes of ley crops, and 2000 tonnes of sludge from grease separators. Previous studies have investigated the performance optimization of the biogas plant. It was found that the plant operates very well at full-scale and a feasible performance improvement of the biogas system was examined.

In the case of Uppsala, a municipality in east central Sweden, ley crops in the region are currently not used for biogas production, but are used for the production of animal feeds instead. 5000 tonnes of ley crops make up less than 1% of the total ley produced in Uppsala County. This study uses a GIS-based approach (ArcGIS Network Analyst tool for the closest facility and the Load-Distance (LD) technique) to optimise the logistics of collecting and transporting an annual amount of 5000 tonnes of ley crops as a substrate for biogas production in Uppsala municipality using a feedstock ratio and digester volume similar to the existing biogas plant in Västerås and then deciding the optimal location for a biogas plant.

The focus of this study is on the supply of biomass substrates to an optimal biogas plant site, under constraints related to the location of the biogas plant and filling stations since these are considered to have much higher cost in relation to the transport cost. The steps involve the following: proposing three candidate biogas plant sites in close proximity to road network and filling stations; identifying the biomass fields for the collection of an annual amount of 5000 tonnes of ley crops using three different land use scenarios (30%, 50%, and 70%); optimizing the collection and transport of ley crops from each field in each scenario to each candidate biogas plant site; determining the best land use scenario for the collection and transport of ley crops from the fields to the candidate biogas plant site and deciding the optimal location for the candidate biogas plant.

Results: Data from 2014 are used in this study and the results reveal that the location proposed for candidate biogas plant site-2 in scenario 3 (70% of land use) is the best location.

Abbreviations

CO_2e	Carbon dioxide equivalent
DM	Dry Matter
EU	European Union
GET	Geodata Extraction Tool
GHG	Greenhouse Gas
GIS	Geographic Information System
LD	Load-Distance
RED	Renewable Energy Directive
RNG	Renewable Natural Gas
SC_1	Scenario 1
SC_2	Scenario 2
SC_3	Scenario 3
SCB	Statistiska centralbyrån (Statistics Sweden)
SEK	Swedish Kronor
SMDM	Spatial Multicriteria Decision Making

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1. INTRODUCTION

The need to minimize the burning of fossil fuels and the associated impact of greenhouse gas emissions on the environment has led to the development of biofuels (Judd, Sarin, & Cundiff, 2012). The consumption of fossil fuel energy has increased the level of carbon dioxide in the atmosphere. Biofuels are environmentally friendly fuels, thus seen as attractive alternatives to fossil fuels. Biofuel use can play a vital role in energy security as well as contribute to the reduction of greenhouse gas emissions (Hagberg, Pettersson, & Ahlgren, 2016). Biofuels can be produced in the form of solid, liquid, or gases (Surriya, Saleem, Waqar, Kazi, & Öztürk, 2015). CO_2 and particulate emissions from biogas are the smallest of all vehicle fuels available on the market today and biomethane production seems to be a feasible means of substituting a significant portion of the entire fossil fuel energy consumed annually in Sweden (Biogas East, n.d.; Held, Mathiasson, & Nylander, 2008).

Over the past decade, Sweden has continuously increase the use of biogas as vehicle fuel, which now amounts to more than 1% of the entire fuel used in road transportation (Börjesson, Prade, Lantz, & Björnsson, 2015 in SEA, 2014). Following the Renewable Energy Directive (RED) of the European Union (EU), “the share of renewable fuels in the transportation sector in the EU should be 10% by 2020” (Börjesson et al., 2015, p. 6034 in European Union, 2009). Presently, most of the biogas produced uses organic waste such as food waste as a substrate. This indicates that there is a need to boost the production of biogas using other feedstocks like ley crops. Although the increasing biogas demand in the transport sectors has triggered the development of biogas systems that use energy crop as a substrate, since the quantity of organic waste and by-products obtainable for use as biogas substrates are limited (Börjesson et al., 2015).

It was found that the collection of biomass as well as transportation to a centralised processing plant incurs a significantly higher cost when compared with fossil fuels extraction from the earth (Biomass.net, n.d.). Location analysis for optimal collection of feedstocks to a biogas plant is crucial to the survival and profitability of a biogas business. It is vital to ensure that the location of a biogas facility is optimal enough. “Classical and neo-classical location theory prescribes the choice of firm location to be guided by cost factors and infrastructure in the region” (Christensen & Drejer, 2005, p. 807). In the case of a biogas facility location, the decision where to locate a biogas plant should include factors such as the proximity of the biogas plant site to filling stations, since filling station are required to provide the end users with fuel. Location analysis or the decision where to locate a facility puts into consideration crucial determinants such as availability of infrastructures as well as proximity to suppliers and customers (Bosona, 2013; Russel & Taylor, 2000). The Load-Distance (LD) technique for location analysis helps determine optimal facility location by evaluating potential sites using the LD value (Russel & Taylor, 2000).

Approximately 25% of global greenhouse gas (GHG) emissions are from the transport sector and road transport generates almost 75% of the emissions from the transport sector (Bosona, Nordmark, Gebresenbet, & Ljungberg, 2013 in IPCC, 2008 & Määttä-Juntunen, 2010). Greenhouse gases from transportation contribute significantly to global warming. Less travel times of fleets can minimize environmental impacts. Transportation takes approximately one-third of the total costs of logistics and the performance of logistics systems is heavily influenced by transport systems (Tseng, Yue, & Taylor, 2005). Distance is a primary factor influencing the cost of transport (Rodrigue & Notteboom, n.d.). In deciding on an optimal transport solution, distance must be taken into consideration. The LD technique for location analysis is used to evaluate the LD value of each potential facility site and the location with the minimum LD value is selected, since this would result in the lowest transportation cost (Russel & Taylor, 2000). The transport of biomass from fields to bioenergy plants requires an optimal approach. Therefore, minimizing the transport distance is one way to optimize the transport of biomass from the fields to the plant site. Through this, bioenergy industries will not only reduce greenhouse gas emissions from transportation, but also cut down their costs of biomass transportation.

This study investigates how an optimal biogas facility location can be determined as well as how biomass substrates specifically ley crops (perennial forage crops) can be supplied to the biogas plant site. The feedstock for the biogas plant includes a mix of organic waste, ley crops, and grease trap sludge. Organic wastes and some biomass crops are examples of second generation (2G) feedstocks. 2G feedstocks can overcome environmental and economic issues because they are biodegradable, non-food, and can be grown on marginal lands (Moncada, Aristizábal, & Cardona, 2016). It was found that "this leaves aside any ethical and social issue generated by first-generation approaches" (Scoma, Rebecchi, Bertin, & Fava, 2016, p. 175). 2G feedstocks for biofuel production helps avoid food versus fuel dilemma. Although "the competition of 2G feedstocks with feed and in some cases with fertilizing directly in the field can exist" (Moncada et al., 2016, p. 123). Perennial forage crops for biogas production can produce more energy and reduce greenhouse gas emissions than annual grain crops (Sanderson & Adler, 2008). Perennial forage crops such as ley crops, which are mostly a mix of legumes and grasses, are beneficial for the production of biogas.

1.1 Research Aim of the Study

Three candidate biogas plant sites will be proposed in this study and ArcGIS Network Analyst tool for the closest facility will be used to determine the best location for a biogas plant site. Even though the proposed candidate biogas plant will be fed with organic waste, ley crops, and grease trap sludge, the location of the biogas plant is based on the optimal collection and transport of only the ley crops to the biogas plant site. The rationale behind the decision is explained in detail in the limitation section of this paper (see chapter 3.2). This study involves optimizing the collection and transport of ley crops to three biogas plant locations and then selecting the most optimal biogas plant location. The main research questions of this study are:

- *What are the major factors to be considered when deciding the best location of a biogas plant in Uppsala municipality?*

- *What are the potential ley crops harvestable as feedstocks for biogas production in Uppsala municipality?*

- *How can network analysis in ArcGIS be used to determine the optimal location of a biogas plant site and the associated delivery routes from fields of ley crops to the plant site?*

An in-depth investigation of these questions will be carried out in this study.

1.2 Course of Research

This study will use geographic information system (GIS) to assess the exact locations of the hectares and the corresponding productivity (t/ha) of ley crops in Uppsala municipality. The possible mix of the ley crops includes red clover, white clover, mixed red and white clover, lucerne, other leguminous plants, and non-leguminous plants. This GIS spatial analysis and design, for example, through maps will help understand situations such as locations and the corresponding productivity of the ley crops. ArcGIS Network Analyst tool for the closest facility will be used to optimize ley crop collection for biogas production and also define the most optimal biogas facility location from three proposed candidate biogas plant sites. As a result, the possibility of collecting and transporting ley crops from fields to a biogas plant optimally can be achieved. The course of research is in line with the aim of this study, which is to determine optimal location of a biogas plant based on the collection of an annual amount of 5000 tonnes of ley crops substrate for biogas production in order to model the logistics of supplying the biogas plant with that specific quantity.

2. LITERATURE REVIEW

2.1 Ley Crops

Ley crops are perennial forage crops, a mix of grasses and/or legumes that can be grown together with annual crops. It was found that the mix of ley crops can be different grasses such as fescue, ryegrass, and timothy, and legumes such as alfalfa or lucerne and clover, et cetera (JTI / driv, 2016). Although the seeds of ley crops can be sown together with annual crops, but when the harvest of the annual crop is done, which is the end of its life cycle in a single growing season, the soil is left untilled and the ley crops continue to grow (Behrens, 2014). "Unlike annual crops, the need for soil tillage in perennial grasses is limited to the year in which the crops are established" (Lewandowski, Scurlock, Lindvall, & Christou, 2003, p. 336). Leaving the soil untilled for a long period can result in ecologic benefits such as a possible increase in the carbon content of the soil and reduced risk of soil erosion (Lewandowski et al., 2003 in Kahle, 2000 & Ma, Wood, & Bransby, 1999). The no-till system for ley farming is sustainable for the reason that it minimizes nutrient losses, controls surface runoff, reduces soil erosion, and intensifies soil organic carbon concentration (Jarecki & Lal, 2003).

In ley farming, it is beneficial to include legumes in the mix of ley crops because those legumes help improve the yields of crops grown after the leys. Forage legumes supply the succeeding or subsequent crops with more nitrogen than grain legumes (GRDC, 2010). The reason for this is because the majority of nitrogen fixed by grain legumes is used by the grains. Grain legumes use nearly all of their fixed nitrogen for themselves while forage legumes leave most of their fixed nitrogen for subsequent crops (Johnson & McKee, n.d.; GRDC, 2010). In addition to that, the nitrogen fixation efficiency is higher in pastures involving a mix of grasses and legumes, because the legumes are pressurized to fix nitrogen (GRDC, 2010). The deep root of the perennial ley crops help draw those nitrogen that has leached below the root zone of the leys and send the nitrogen back to the surface of the soil where it can be accessed again by crops (GRDC, 2010). Annual cropping systems have led to the decline of soil organic matter and one of the most effective ways to boost organic matter is growing ley crops, but grass ley crops are required to significantly boost organic matter, since forage legumes alone have minimal effect (GRDC, 2010). All these benefits of ley crops can last longer under the no-till cropping systems.

Ley crops are common protein crops in Sweden, which can revive soil fatigue, particularly on the plains, where almost nothing but grain is planted (JTI / driv, 2016). Growing ley crops help promote ecosystem services. Grasslands can promote biodiversity in the field and at the landscape level, improve the texture of the soil, enhance soil carbon sequestration, fix atmospheric nitrogen, and provide many other ecosystem services (Prade, Svensson, Mattsson, Carlsson, Björnsson et al., 2013). Root growth and the formation of litter impacts carbon sequestration, nitrogen fixation impacts the emission of greenhouse gas from mineral nitrogen needed for cultivation, and the yield of the biomass impacts the amount of crude oil substituted by biogas (Prade et al., 2013). The EU regulation states that 35% emission reduction has been achieved through the use of biogas vehicle fuel, which can be produced from sources including ley crops. This implies that greenhouse gas balance is directly influenced by some of these ecosystem services.

In the greenhouse gas performance analysis of biogas production from six agricultural crops including ley crops, hemp, sugar beet, triticale, wheat, and maize, it was found that the biogas systems of ley crops give the highest greenhouse gas emission reduction, which mostly results from the high soil carbon dioxide accumulation (Börjesson et al., 2015). Therefore, the net contribution of greenhouse gas emissions from the biogas systems of ley crops is negative. Less carbon dioxide emissions stem from harvesting of ley crops. The reason for this is that, after harvesting ley crops, the soil is left untilled until the end of the final season of the leys (Behrens, 2014). The final season of the ley crops is decided several or many years after the seeds are sown. The greenhouse gas emissions from ley crops compared with the other crops are shown below (see table 1).

Crop	Cultivation & harvest [2]	Biogenic N_2O [3]	SOC changes [4]	Storage [5]	Transport [5]	Total	Total–per GJ biomass [6]
Hemp	1430 (440)	742 (1220)	153 (−515)	111 (125)	136 (176)	2570 (1440)	17.4 (9.8)
Sugar beet	1970 (975)	798 (1310)	784 (115)	108 (122)	356 (397)	4010 (2920)	19.3 (14.0)
Maize	1470 (457)	845 (1310)	−875 (−1540)	151 (166)	140 (181)	1730 (566)	11.3 (3.7)
Triticale	1090 (559)	596 (868)	255 (−110)	102 (110)	131 (154)	2180 (1580)	18.1 (13.2)
Ley crops	1650 (639)	1460 (1910)	−2780 (−3450)	109 (123)	148 (188)	579 (−593)	4.1 (−4.2)
Wheat (grain)	1550 (543)	982 (1440)	−1340 (−2010)	243 (257)	45 (86)	1480 (324)	13.6 (3.0)

Table 1. Greenhouse gas emissions from biogas production systems of six different crops, expressed as kg carbon dioxide equivalents per hectare and year (Börjesson et al., 2015, p. 6039).

Notes for table 1 above: [1] Those numbers not in parentheses stand for production systems that are traced to 100% mineral fertilization, while those numbers in parenthesis show production systems that are traced to both digestate and mineral fertilization; [2] Life cycle greenhouse gas emissions (except biogenic nitrous oxide and carbon dioxide from soil) that stems from cultivation and harvest; [3] Nitrous oxide emissions from soil; [4] Net yearly changes of soil organic carbon content; [5] Life cycle greenhouse gas emissions from storage and transport; [6] Based on the lower heating value of crop dry matter (Börjesson et al., 2015).

As the support of renewable vehicle fuels continues to increase, the goal is to minimize the emissions of CO_2 by a minimum of 35% compared to crude oil, and further to 50% by 2017, and then improve to 60% by 2018 through the use the biofuels (Prade et al., 2013 in EC, 2009). It was also emphasized in another study that “a requirement is that the current biofuels lead to a 35% reduction in life cycle GHG emissions, compared to petrol and diesel, which will increase to a 50% and 60% reduction for biofuel systems implemented in 2017 and 2018, respectively” (Börjesson et al., 2015, p. 6034 in European Union, 2009). The least amount of ley crop biomass per hectare needed to meet these future requirements was investigated in a particular study. The study states that the emissions of carbon dioxide equivalent (CO_2e) decreases asymptotically as the biomass dry matter (DM) yield increases (Prade et al., 2013). The emissions are those that stem from cultivation, harvest, transport and storage of the ley crops.

Ley crops can be grown on different soils, including marginal soils (Prade et al., 2013). It was found that biomass DM yields above 3 Mg ha^{-1} a^{-1} can be attained unexpectedly on marginal lands with minimal or no fertilization and the intensity of the net greenhouse gas emissions that stem from this DM yield is reported to reach the currently acceptable limits (Prade et al., 2013). The quality of the soil as well as the quantity of fertilization strongly influences the DM yields of the ley crops. Therefore, to achieve the reduction goals of 50% by 2017, DM yields of around 5.5 Mg ha^{-1} a^{-1} will be needed, while the DM yield of about 10.5 Mg ha^{-1} a^{-1} will be required to achieve the reduction goal of 60% by 2018 (Prade et al., 2013). For that reason, the latter may require a shift from marginal lands to lands with better soils, which might lead to land competition between food and biofuel production.

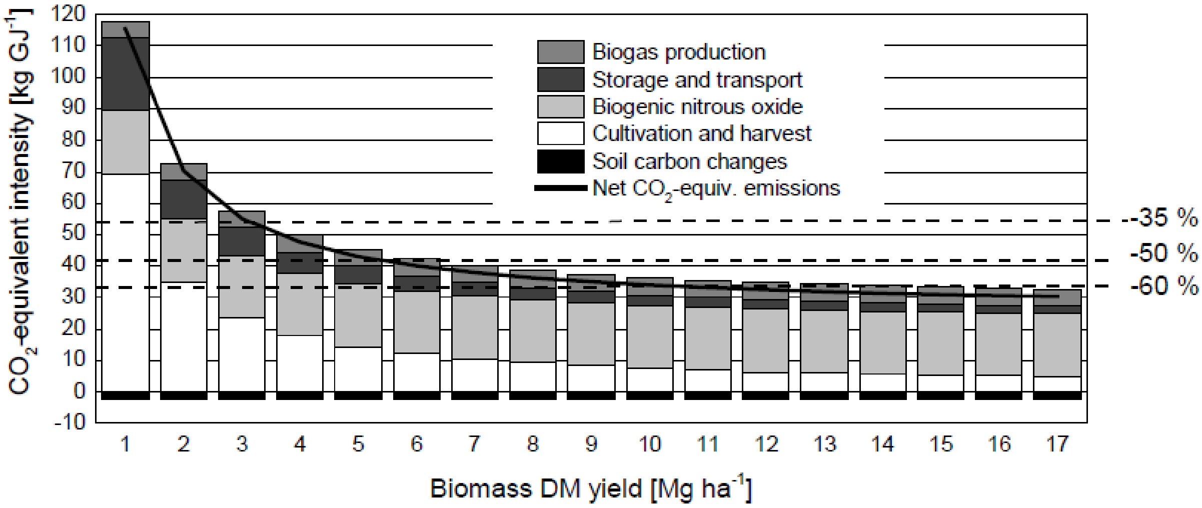

Figure 1. Concentration of CO_2-equivalents released during cultivation and harvest, use of digestate as fertilizer on the soil, storage and transport of biomass and production of biogas; negative emissions represent the carbon sequestered by the use of digestate; the bold lines represent the net emissions of CO_2-equivalent; the dashed lines represent European Union' emission reduction goals (Prade et al., 2013, p. 4).

Ley crops are considered as perennial forage species because they are allowed to grow for several or many years. Unlike annual crops which grow and are harvested and replaced within one year, ley crop can grow for many seasons. Ley crops are mostly harvested two or three times in a year, but in some regions of Sweden, it can be beneficial to harvest the crops four times a season (JTI / driv, 2016). During the harvest of ley crops, only the top grasses are cut, the roots are not removed so they are left to grow. In Sweden, when the ley crops are cut, it is then preserved as silage or dried as hay and a part of the crops are left for the cattle to graze (JTI / driv, 2016). "Ley crops can either be ploughed back into the soil, used as animal feed or anaerobically digested to produce biogas" (Behrens, 2014, p. 19). Therefore, ley crops are considered to be "multipurpose" crops, which in addition to their usefulness for biogas production, can also be used as silage, hay, as well as grazed by cattle.

2.2 Harvest and Storage of Ley Crops for Biogas Production in Västerås

The mix of the ley crops include clover (27%), fescue (25%), timothy (25%), ryegrass (13%), cocksfoot (10%), allowed to grow for 2 to 3 years and is part of crop rotation (JTi & AGROPTI-gas, n.d.; Vågström, 2005). Approximately 15% of the crops are planted on organic farms (JTi & AGROPTI-gas, n.d.). The harvesting of the ley crops for the production of biogas in Västerås happens 2 or 3 times in a year (JTi & AGROPTI-gas, n.d.). The harvesting is done in the same way as it is normally done for the large-scale production of silage for cattle (Held et al., 2008). During the harvesting period, the crops are dried, chopped, and then stored in 80 to 90m long air-tight plastic bag with 3.5m diameter (Held et al., 2008). Normally, the plastic bags are placed very close to the biogas plant. This is usually done to ease the fetching of the silage whenever it is needed for biogas production. In another study, it was found that the grass "is treated as ensilage in 80-90 m long plastic container and used in the fermentation process continuously during the year" (Nordberg & Rydén, 2012, p. 26).

As soon as the ley crops are chopped, they are transported to the silos for storage. The silage is collected from the bag silos and fed into the plant digester whenever it is needed for biogas production. The silage requires no pre-treatment when fed into the reactor (Held et al., 2008).

However, investigations on the performance optimization of the biogas plant reveals that the "pre-treatment of the ley crop substrate mechanically or with electroporation and using membrane filtration to treat the process water for recirculation of process water all has the potential to increase the biogas plant performance" (Thorin, Lindmark, Nordlander, Odlare, Dahlquist et al., 2012). The investigation further states that when compared with the electroporation pre-treatment method, the energy efficiency is highest for ley crops that undergo mechanical pre-treatment.

2.3 The Biogas Plant in Västerås

The biogas plant in Västerås started operations in the summer of 2005 (Held et al., 2008). The plant is installed in the outskirts of northern Västerås. It is situated at the Gryta Waste Treatment Plant (Held et al., 2008). The biogas plant was established for the anaerobic digestion of different feedstocks as biodegradable substrates for the production of biogas. The main feedstocks for biogas production include wastes from households as well as ley crops preserved as silage. Although there also exist another plant used for the treatment of sewage in Västerås. Food wastes, grass ley crops preserved as silage, and sludge from grease separators are fed into the biogas plant digester with a containing volume of $4000m^3$ (Held et al., 2008).

The substrates used for the biogas plant are mix of source-sorted (separated) solid food waste from households, a yearly total amount of 14000 tonnes, and 5000 tonnes of grass ley crop silage, which are fed into the plant for treatment in the digester (Nordberg & Rydén, 2012). In addition to that, a total of 2000 tonnes of sludge from fat separators are also received by the digester (Nordberg & Rydén, 2012). Therefore, an average of 20 tonnes of silage is required for daily biogas production. This indicates that the plant operates for approximately 250 days in a year. Yearly inputs for the biogas plant are shown below (see table 2).

Substrates:	
Source-sorted organic household waste	14000 tonnes
Silaged ley crop	5000 tonnes
Sludge from grease separators	2000 tonnes

Table 2. Substrates for the biogas plant in Västerås (Held et al., 2008, p. 56 - 57).

The biogas plant treats exclusively organic waste from households in Västerås, ensiled ley crops from local farmers, and grease trap sludge from restaurants (Vågström, 2005). The feedstocks are treated inside a 37 degree Celsius (°C) mesophilic digester, which is continuously-mixed in a one-step process (Held et al., 2008). The household waste is source-sorted, packed in paper bags and placed in ventilated containers for collection (Held et al., 2008). The municipality of Västerås distributes paper bags to households. Almost 129600 households, which correspond to 90% of the entire 144000 households in Västerås, participate in source sorting organic waste (Nordberg & Rydén, 2012; Monson, Esteves, Guwy, & Dinsdale, 2007). In addition to that, approximately 7% of 144000 households in the municipality participate in home composting the organic waste, while about 3% generate mixed wastes from their households that are treated via incineration (Monson et al., 2007).

The ley crops are grown by the local farmers in Västerås - just like the organic waste collected for the biogas production comes solely from the municipality (Vågström, 2005). Around 300 hectares of land are used to grow the grass ley crops (predominantly clover) for use as feedstock for biogas production

(Nordberg & Rydén, 2012). The biogas plant has since been operating at full capacity and full production of biogas is realised from the system. It was found that the biogas system comprises of a gas production plant, a plant for upgrading the biogas, gas pipelines for transportation of fuel, and two gas filling stations (one station supplies biomethane for buses and refuse vehicles, while the other biomethane station is open to the public) (Biogas East, n.d.; Vågström, 2005). A schematic diagram of the gas distribution system in Västerås is shown below (see figure 2).

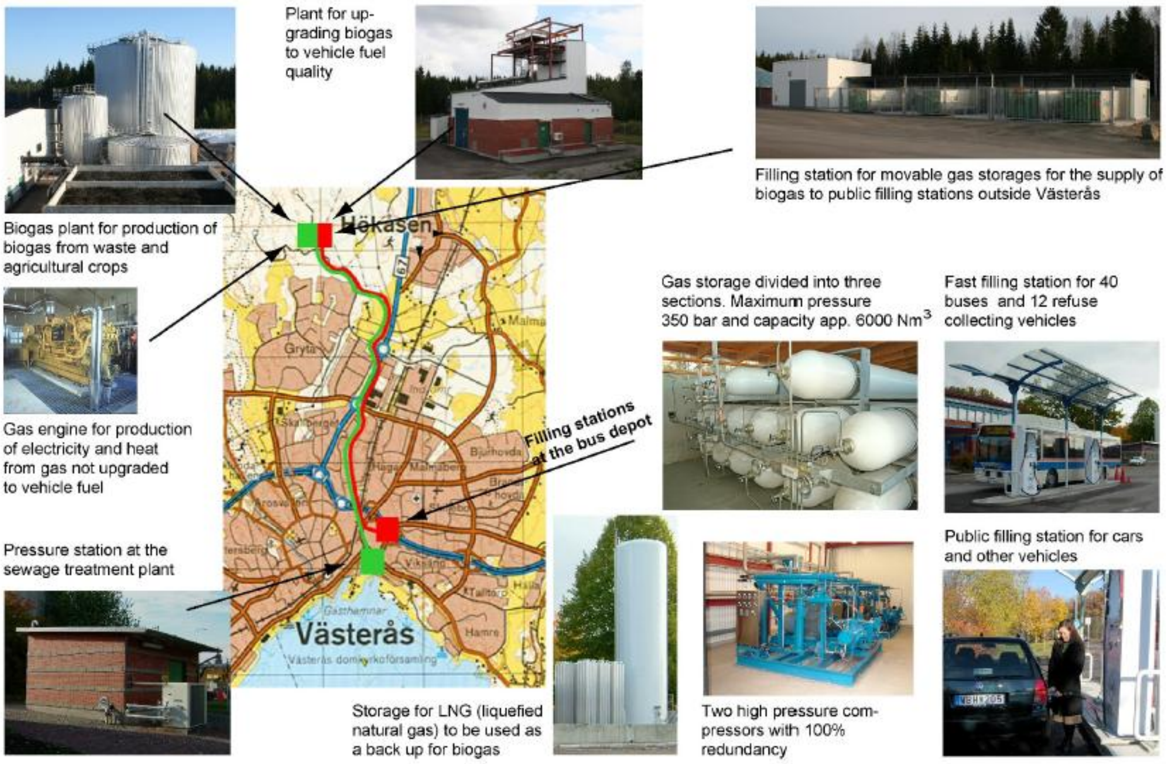

Figure 2. "Schematic diagram of the system for gas distribution in Västerås" (Held et al., 2008, p. 55).

2.4 Biogas Production Processes, Upgrading and Use in Västerås

Biogas consist of methane (45-85%) and carbon dioxide (15-45%) (Held et al., 2008). Although the percentage of the individual gases can vary depending on production conditions. Biogas, which is mainly composed of methane and carbon dioxide, is formed through anaerobic digestion of biological materials (Avfall Sverige, 2009). It is "formed when organic material is decomposed by microorganisms in an oxygen-free environment" (Energigas Sverige, 2011, p. 2). In the process of biogas production, numerous distinct microorganisms interact within a complex web. The interacting process triggers "the decomposition of complex organic compounds such as carbohydrates, fats and proteins to the final products methane and carbon dioxide" (Energigas Sverige, 2011, p. 2). Anaerobic digestion occurs naturally in a lot of oxygen-limited environments such as the digestive tract of ruminants, i.e. cows. The conversion process of biomass differs depending on the biomass type (see figure 3).

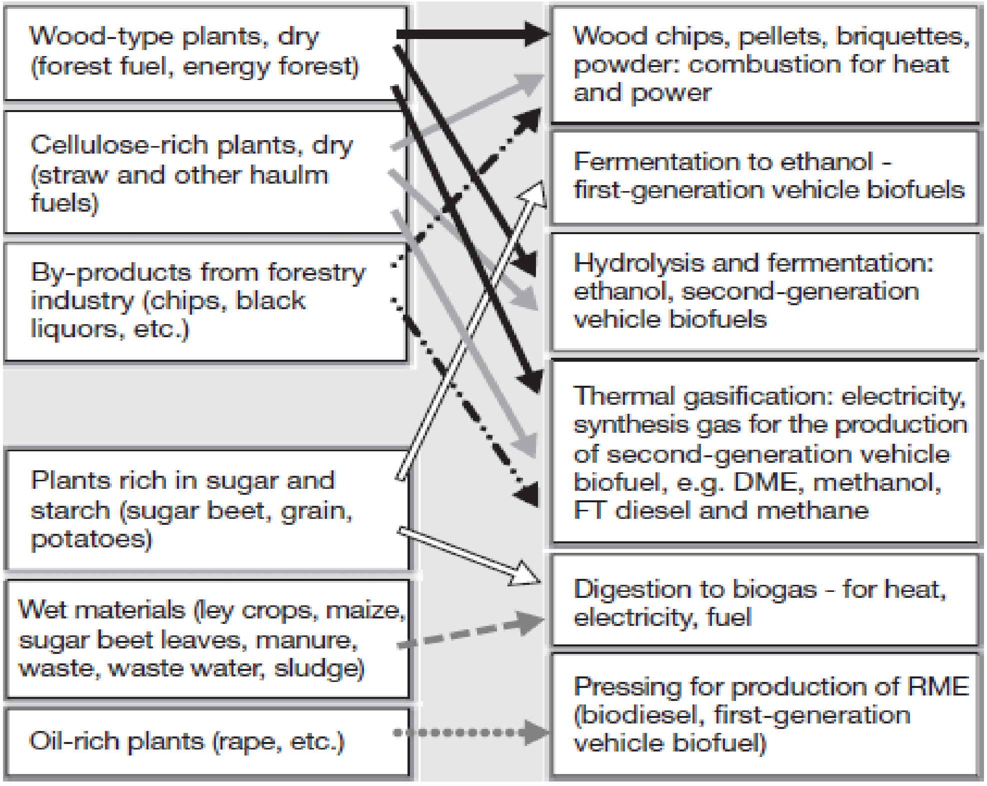

Figure 3. Conversion process of different biomass types to various energy carriers useful for different applications (Johansson, 2008, p. 45).

One of the first stages of biogas production in Västerås is the transport of the ley crop silage and the organic waste to the deep bunker (see figure 5). It was found that “at the biogas plant, the waste is chopped up, mixed with water and pasteurized at 70°C for one hour, before it is fed into the reactor” (Held et al., 2008, p. 53). Trucks are first used to transport the substrate, and then by the conveyor belts attached to the equipment that breaks up and then mixes the substrate (Nordberg & Rydén, 2012). The receipt and treatment of the substrate occurs in three distinct halls. The substrate is refined by removing impurities and separating the heavy particles. Plastic and sand are examples of unwanted materials that are removed. Water is used to dilute the mixture. A macerator is then used to treat the suspension so as to minimise the particle size. The processed suspension is then transported to one of the three tanks for hygienisation, which involves treating the suspension for one hour at 70 degree Celsius (˚C) (Nordberg & Rydén, 2012).

The process proceeds by pumping the suspension into the fermentation chamber (Nordberg & Rydén, 2012). The mixing of the suspension takes place at the same time that gas is continuously pumped through the chamber. Sufficient heat is produced by the process and this heat helps ensure that a mesophilic process is maintained at 37˚C. The fermentation period takes approximately 20 days and new substrate is continuously added to the mix during 6 days every week throughout the year. A gas dome receives the produced biogas. The biogas is then treated inside a water scrubber, which operates at a capacity of 150-550 Nm^3 gas per hour (Nordberg & Rydén, 2012). During this purification process, contaminants such as nitrogen compounds and sulphur are removed. In another study, it was found that the biogas is pumped into a pressurized water wash, where re-circulation occurs in a 150 to 550 Nm^3 per hour capacity (Held et al., 2008).

When operating at full capacity, a little less than $1m^3$ of fresh water is added to the system every hour. The biogas is then dried and pumped into the upgrading facility at Gryta (Nordberg & Rydén, 2012).

The majority of the biogas produced is upgraded into vehicle fuel at the upgrading plant (Held et al., 2008). The remaining portion is used for the production of heat and electricity. The biogas plant also produces solid bio-manure equivalent to 3500 tonnes and liquid bio-manure equivalent to 13000 tonnes for agricultural use (Nordberg & Rydén, 2012). The mould and bio-fertilizer produced are used for improving the topsoil of agricultural lands in the region (see figure 4). Farmers receive the digestate produced from the process for use as fertilizer in order to achieve a re-circulation process, since the aim of the farmers who provided the ley crop is to be self-sufficient in fertilizer use on their farms. The digestion residuals allocated to the farmers are according to the acreage of ley crops (JTi & AGROPTI-gas, n.d.).

Figure 4. The spread of liquid digestate on farmland (left) and a truck unloading a container of solid digestate on farmland (right) (Monson et al., 2007, p. 21 & 23).

An 8.5 kilometre pipe transports the gas from the sewage treatment plant to Gryta, where the gas is upgraded together with the gas from the biogas plant (Vågström, 2005). The plant produces biogas estimated to contain 15000 MWh of energy annually, added to this is the biogas produced from digestion at the existing municipal sewage treatment plant, which is equivalent to 8000 MWh of biogas energy (Nordberg & Rydén, 2012). Each year the biogas produced from both silage and food waste at the Gryta plant is calculated to have an energy content of 15000 MWh, which is the biogas equivalent of more than 1.6 million litres of petrol (Held et al., 2008).

The biogas generated from the treatment of sewage (the municipal sewage treatment plant), which is equivalent to 8000 MWh is also pumped into the upgrading plant (Held et al., 2008). The energy from both the biogas plant and the sewage treatment plant is then upgraded into vehicle fuel. Therefore, the aggregate amount of gas usable as vehicle fuel corresponds to 2.5 million litres of petrol (Held et al., 2008). The quality of the vehicle fuel produced is 97% methane (Nordberg & Rydén, 2012). The process flow of the biogas plant in Västerås is shown below (see figure 5).

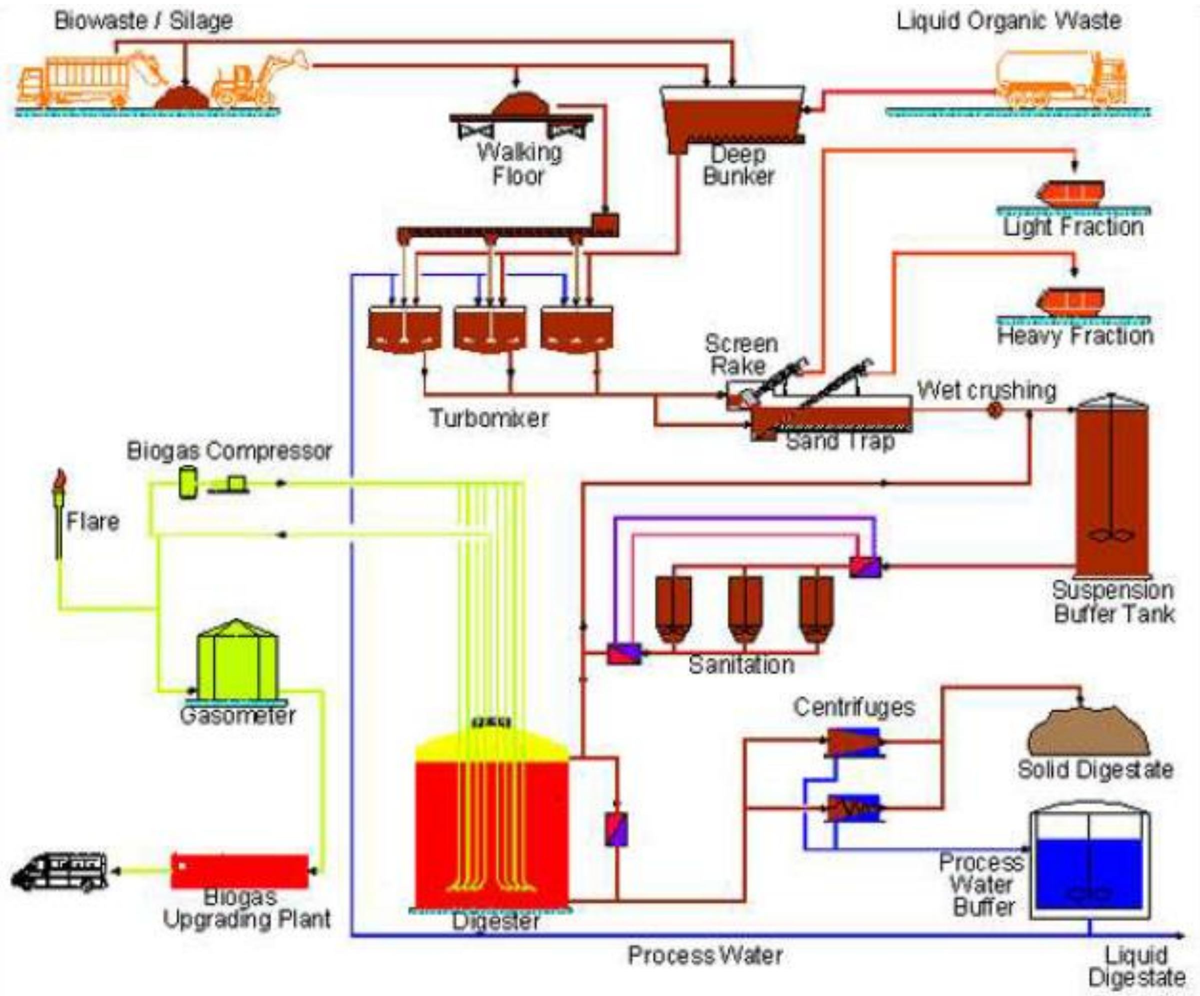

Figure 5. Process flow diagram of the biogas plant in Västerås (Monson et al., 2007, p. 12).

The energy content in 1Nm^3 of biogas (97% methane) is 9.67 kWh (Energigas Sverige, 2011). Pipes are then installed and used to transport the fuel to the filling station. The filling station in the municipality is equipped with compressors, gas tanks, and other equipments. The yearly outputs from the biogas plants are shown below (see table 3).

Biogas:	
From the biogas plant	15000 MWh
From the sewage treatment plant	8000 MWh
Upgraded biogas	23000 MWh
Bio-manure:	
Solid bio-manure	3500 tonnes
Liquid bio-manure	13000 tonnes

Table 3. Biogas produced from the biogas and sewage treatment plant and the digestates produced (Held et al., 2008, p. 57).

The total yield of 23000 MWh of upgraded biogas produced is for use by city buses (Nordberg & Rydén, 2012). Approximately 80 city buses and 20 waste transport vehicles in the municipality runs on biogas. The plan for the municipality is to use biogas to run all the city buses by the year 2020. The total number of buses in Västerås is approximately 150.

2.5 Benefits of the Biogas Plant Project in Västerås

Both the project owners and society see the project as a win-win situation (Nordberg & Rydén, 2012). The activities have benefited the environment in so many ways. The production of renewable energy has been developed and the recirculations of resources have been established (Nordberg & Rydén, 2012). The project has resulted in savings of energy, which has been estimated to be equivalent to 2.5 million litres of petrol per year (Held et al., 2008). The emissions of carbon dioxide (CO_2) from fossil fuel have been reduced by 5500 tonnes per year. The bio-manure produced from the process delivers approximately 1000 tonnes of organic matter, 60 tonnes of potassium, 11 tonnes of phosphorus, and 100 tonnes of nitrogen to arable land each year (Held et al., 2008). Moreover, the quantity of organic waste incinerated every year has reduced by 14000 tonnes (Held et al., 2008). The reduction in the incineration of wastes has a huge environmental benefit. Air pollution in the municipality has been significantly reduced.

2.6 Benefits of Biomethane

Once biogas is produced, it is upgraded to biomethane by extracting CO_2 from the gas so as to achieve nothing less than 97% methane content in the upgraded gas (EBA, 2016). Biomethane means a gas that chiefly consists of methane, which is produced from biological materials (Held et al., 2008). Methane is not poisonous, so the fuel is safer than petrol or diesel. In the case of a methane leak, the gas will speedily rise through the surrounding air and get diluted, since methane is lighter than air (Held et al., 2008). Although leaks should be avoided during biogas handling and treatment, since methane still remains a greenhouse gas (Held et al., 2008). The chemical content of biomethane is similar to natural gas, thus gas-powered engines can run on both biomethane and natural gas (Biogas East, n.d.). Biomethane is essentially renewable natural gas (RNG). RNG is a drop-in fuel, which together with conventional natural gas can be transported in the same pipelines, stored in the same storage tanks, dispensed at the same filling stations, and can be used to run natural gas-powered engines without any engine modifications (Clean Cities, 2015).

2.7 Uppsala

Uppsala is a municipality in Uppsala County. As at 2014, Uppsala municipality has a population of 207362, land area of 2182.41 sq. km, and a population density of 95 per sq. km (SCB, 2017). The population is recorded as at 31st of December each year and by land area it is as at 1st of January the following year.

2.8 Ley Crops in Uppsala

Statistics Sweden (SCB) collects data on ley crops in Uppsala County. According to SCB, the data on the crops were obtained from different farmers within the county. Therefore, information such as the exact composition of the mix of ley crops and the number of years that the forage is left to grow varies among different farms. The choice of the farmers and the use of the ley crops are some factors that might cause variations. Also, the harvest period differs among farms, for example, the harvest periods (months) of first cut and re-growth varies a lot among different farms in Uppsala. (personal message 1).

2.9 Mix of Ley Crops in Uppsala

The data obtained from SCB provides information on the mix of ley crops in Uppsala County. Since Uppsala municipality belongs to Uppsala County. It is assumed that the mix of ley crops in Uppsala municipality is similar to that of Uppsala County. Information on the different mix of ley crops and the corresponding land area in Sweden's agricultural production areas (PO) is shown below (see table 4).

PO [1]	Number of farms [2]	Area of ley crops (Hay & Silage)	Percentage of land area with:					
			Only red clover	Only white clover	Mixed red- and white clover [3]	Only lucerne	Others and mixed [4]	Without leguminous plants
		Ha	% ci [5]	% ci [5]	% ci [5]	% ci [5]	% ci [5]	% ci [5]
GSS	84	36 600	9 ± 7	0 ± 0	52 ± 17	0 ± 1	8 ± 8	30 ± 14
GMB	103	103 200	7 ± 5	2 ± 2	13 ± 8	18 ± 11	47 ± 17	15 ± 8
GNS	133	93 000	5 ± 4	2 ± 2	43 ± 17	3 ± 5	33 ± 22	14 ± 8
SS	162	133 100	7 ± 4	1 ± 2	58 ± 12	2 ± 4	6 ± 6	26 ± 9
GSK	108	261 900	10 ± 6	2 ± 2	49 ± 13	0 ± 0	12 ± 9	29 ± 12
SSK	100	88 100	6 ± 6	0 ± 0	52 ± 17	0 ± 0	8 ± 9	34 ± 17
NN	104	95 600	19 ± 12	0 ± 0	59 ± 13	0 ± 0	0 ± 0	23 ± 10
NÖ	92	66 100	41 ± 13	0 ± 1	31 ± 13	0 ± 0	4 ± 8	23 ± 9

Table 4. Land area of ley crops (hay and silage) by type of leguminous plants in the seed mixture in 2014 (SCB, 2015, p. 13).

Notes for table 4 above: [1] Agricultural production area (GSS: Plain districts in Southern Götaland; GMB: Central districts in Götaland; GNS: Plain districts in Northern Götaland; SS: Plain districts in Svealand; GSK: Forest districts in Götaland; MSK: Forest districts in Central Sweden; NN: Lower parts of Norrland; NÖ: Upper parts of Norrland); [2] Number of farms included in the calculations; [3] Special reports from 2014; [4] Other leguminous plants and mixture of leguminous plants; [5] ci: 95-per cent confidence interval as an estimate of values (SCB, 2015). The table does not include data on ley crops used for grazing. (personal message 2).

As shown in table 4 above, Uppsala is located in the PO-region "Plain districts in Svealand: SS" and a mixture of seeds containing both red and white clover were sown on 58% of the ley area (133 100 ha) in the PO-region "SS" in 2014. (personal message 3). The land area of ley crops containing mixed red and white clover in the PO-region "SS" has a value of 58% ± 12 in 2014. Therefore, 95% confidence interval is then given by [46; 70]. This means that with 95% probability, the value is between 46% and 70% (SCB, 2015). Since the data on the type of ley crop seeds for the entire PO-region "SS" is known, It is assumed that the mix of different varieties of forage that make up the ley crops grown in Uppsala municipality is similar to the seed mixture shown for the PO-region "SS".

Moreover, the percentage of the leguminous crop in the ley seed mixture at the time of planting in 2014 is shown below (see table 5).

personal message 1 Cf. (Gerda Ländell, personal message, 2017-04-23).
personal message 2 Cf. (Ylva Andrist Rangel, personal message, 2017-03-17).
personal message 3 Cf. (Gerda Ländell, personal message, 2017-03-15).

PO [1]	Proportion of leguminous plants in the seed mixture:									
	Only red clover		Only white clover		Mixed red-and white clover [2]		Only lucerne		Other and mixed [3]	
	%	ci [4]	%	ci [4]	%	ci [4]	%	ci [4]	%	ci [4]
GSS	..	± ..	..	± ..	14	± 2	..	± ..	..	± ..
GMB	..	± ..	..	± ..	20	± 5	..	± ..	..	± ..
GNS	..	± ..	..	± ..	23	± 7	..	± ..	..	± ..
SS	..	± ..	..	± ..	22	± 7	..	± ..	..	± ..
GSK	..	± ..	..	± ..	17	± 2	..	± ..	..	± ..
SSK	..	± ..	..	± ..	20	± 4	..	± ..	..	± ..
NN	..	± ..	..	± ..	21	± 6	..	± ..	..	± ..
NÖ	..	± ..	..	± ..	20	± 4	..	± ..	..	± ..

Table 5. "Share of leguminous plants in the seed mixture 2014 by leguminous species" (SCB, 2015, p. 14).

Notes for table 5 above: [1] Agricultural production area (GSS: Plain districts in Southern Götaland; GMB: Central districts in Götaland; GNS: Plain districts in Northern Götaland; SS: Plain districts in Svealand; GSK: Forest districts in Götaland; MSK: Forest districts in Central Sweden; NN: Lower parts of Norrland; NÖ: Upper parts of Norrland); [2] Special reports from 2014; [3] From 2014 does not include mixture with only red and white clover; [4] ci: 95-percent confidence interval as an estimate of values (SCB, 2015). Two dots in the table represent unavailable data. Other values were not shown because it contains too few information. The table only include data on ley crops used for hay and silage. Data on ley crops used for grazing is not included. [(personal message 4).]

The information in table 5 above shows the composition of the seed mixture to be sown as ley crops. For the PO-region "SS" in 2014, the seed mixture containing both red and white clover makes up an average of 22% of the total seeds in the bag. [(personal message 5).] Pure stand of leguminous plants are rare in Sweden, therefore grass species make up the rest of the respective seed mixture shown in table 5 above. [(personal message 6).]

[personal message 4] Cf. (Ylva Andrist Rangel, personal message, 2017-03-17).
[personal message 5] Cf. (Ylva Andrist Rangel, personal message, 2017-03-17).
[personal message 6] Cf. (Gerda Ländell, personal message, 2017-03-15).

2.10 Yield, Production, Dry Matter Content, and Land Area of Ley Crops in Uppsala

The yield (kg per hectare), production (tonnes), dry matter content, and land area of ley crops reported by farmers in Uppsala County is shown below (see table 6).

Yield of ley crops per year, kg/hectare, in **Uppsala County** (16.5% moisture content)							
Year	2009	2010	2011	2012	2013	2014	2015
Hay and silage (*first cut*)	3400	3700	2390	3360	2920	**4130**	3140
Hay and silage (*re-growth*)	2080	1690	1670	2580	..	**..**	2120
Hay and silage (*total*)	5490	5400	4060	5940	4390	**6850**	5250
Total production of ley crops per year, tonnes, in **Uppsala County** (16.5% water content)							
Year	2009	2010	2011	2012	2013	2014	2015
Hay and silage (*first cut*)	113300	136800	83900	131300	119000	**147700**	106400
Hay and silage (*re-growth*)	69400	62500	58500	100700	..	**..**	71800
Hay and silage (*total*)	182700	199300	142400	232000	178600	**244900**	178200
Crop area of ley crops per year, hectares, in Uppsala County							
Year	2009	2010	2011	2012	2013	2014	2015
Hay and silage (*first cut*)	-	-	-	-	-	**35770**	-
Hay and silage (*re-growth*)	-	-	-	-	-	**35770**	-
Acreage distribution of ley crops per year, hectares, in Uppsala County							
Year	2009	2010	2011	2012	2013	2014	2015
Area of ley field (*hay and silage*)	-	-	-	-	-	**35770**	-
Area of ley field (*grazing*)	-	-	-	-	-	**8190**	-
Area of unutilized ley field	-	-	-	-	-	**3160**	-
Area of ley field (*hay, silage, and grazing*)	-	-	-	-	-	**47130**	-

Table 6. The yield (kg per hectare), production (tonnes), dry matter content, and land area of ley crops in Uppsala County (SCB, 2016).

Notes for table 6: Hyphen in the table represents uncalculated data. Two dots in the table represent too low number of survey units (SCB, 2016).

In table 6 above, the harvest periods (months) of first cut and re-growth varies among different farms, therefore no specific data is available on this. For year 2009, 2010, and 2015 in table 6, the sum of the yield from the first cut and the re-growth does not match the total value recorded. This is due to rounding effects. (personal message 7). As shown in table 6, the division of "ley crops used for hay, silage, and grazing" into "ley crops for hay and silage" and "ley crops for grazing" and "unutilized ley crops" respectively, is based on a sample survey of 35 farms in Uppsala County, therefore uncertainty may occur due to sampling errors (SCB, 2016). The data reported in table 6 was converted to the standard water content of 16.5% (83.5% dry matter content), which means that all harvests were converted to weight in the form of hay. (personal message 8). Ley crops for biogas production can require a dry matter content of around 35%, therefore a re-calculation is shown in the results and discussion chapter (see formula 4).

2.11 The Biogas Plant in Uppsala

There is an existing biogas plant in Uppsala municipality, which was built in 1996 and undergoes continuous development (Hellstedt, Cerruto, Nilsson, & McCann, 2014). The company, Uppsala Vatten owns the biogas plant. The substrates for the biogas plant include municipal waste and industrial waste (Rydén, 2012). The municipal waste is source-separated organic waste, also known as food waste, from households and restaurants, while the industrial waste includes organic waste from food companies like slaughterhouses (Rydén, 2012; Hellstedt et al., 2014). The plant has a capacity of 40000 tonnes of waste per year with 2 digesters each of size 2400 m^3 (EBA, 2016). At present, 85% of the substrates for the plant are municipal waste, while slaughterhouse waste makes up the remaining 15%. Year 2014 report reveals that the biogas plant in Uppsala produced 4.7 million Nm^3 of raw biogas per year, 3 million Nm^3 of biomethane per year, and 43000 tonnes of digestate per year (EBA, 2016). The digestate is bio fertilizer, also known as organic fertilizer.

Presently, the entire organic waste available for use in Uppsala is a combination of organic waste collected within the municipality and those obtained from neighbouring municipalities. Waste management service in Uppsala is handled by Uppsala Vatten. It was found that "although located in Uppsala, Uppsala Vatten also receives waste from neighbouring municipalities, as well as slaughterhouses and other producers of biowaste" (EBA, 2016, p. 1). Food waste and slaughterhouse waste in Uppsala are transported directly to Uppsala biogas plant situated at Kungsängens Gård. (personal message 9). In the case of the food waste from Täby, one of the neighbouring municipalities that provides Uppsala Vatten with waste, it was found that the waste is first transported to Hagby recycling center located at Frestavägen (the collection center for food waste in Täby) and later transported to the biogas plant in Uppsala (Täby kommun, 2017). A total of 30 tonnes of material are carried in each transport from the collection center in Täby to the biogas plant in Uppsala. (personal message 10). The data on organic waste used for biogas production is shown below (see table 7).

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personal message 7 Cf. (Gerda Ländell, personal message, 2017-04-23).
personal message 8 Cf. (Gerda Ländell, personal message, 2017-04-23).
personal message 9 Cf. (Lennart Nordin, personal message, 2017-05-22).
personal message 10 Cf. (Lennart Nordin, personal message, 2017-05-22).

Year	2009	2010	2011	2012	2013	2014	2015	2016
Food waste (tonnes)	7753	6274	17636	21532	22632	**26216**	25883	23843
Slaughterhouse waste (tonnes)	1144	1262	2136	3704	3981	**4024**	4528	4320
Total waste (tonnes)	8897	7536	19772	25236	26613	**30240**	30411	28163

Table 7. Amount of food waste and slaughterhouse waste collected in Uppsala and neighbouring municipalities between 2009 and 2016. (personal message 11).

There are two receiving bays at the biogas plant in Uppsala: one receives the household food waste, which is always packed in paper bags, while the other receives the unpackaged food waste, which is the slaughterhouse waste (Hellstedt et al., 2014). The paper bags are separated from the food waste using a special machine. Large screws aid the transfer of the food waste to a facility where it is blended with the unpackaged food waste, diluted with water, and then undergoes a series of processes for biogas production (Hellstedt et al., 2014). A view of the biogas plant in Uppsala is shown below (see figure 6). The biogas produced at the Uppsala biogas plant is transported to a biomethane filling station installed downtown (EBA, 2016). At the filling station, biomethane is made available for fuelling vehicles.

Figure 6. “Anaerobic digestion plant in Uppsala, Sweden” (Hellstedt et al., 2014, p. 70).

personal message 11 Cf. (Lennart Nordin, personal message, 2017-05-22).

2.12 Previous Studies on Logistics of Silage

The logistics of silage have been investigated by several authors, for example, Vågström (2005) discusses the handling of forage and the chain of operations involved such as mowing, wilting, chopping, transport, and ensiling of the ley crops. In order to obtain a high yield and quality of ley crops, it is best to ensure that the harvest is done at the right time. The right or optimal time to harvest might sometimes depend on the weather condition, soil condition, the mix of ley crops, and several other factors. Although certain factors can hinder the completion of ley crops harvest at the optimal time (Vågström, 2005). As a result, there might be costs incurred. Costs that occur when the ley crop harvest is not carried out at the optimal time are known as timeliness costs (Vågström, 2005). In another study, it was found that "timeliness costs are the economic consequences of performing a field operation at a non-optimal time" (Nilsson, 2012, p. 8 in Gunnarsson, 2008).

The use of a mower-conditional (see figure 7) for mowing the ley crops is most desirable for the reason that the machinery also expedites the wilting of the crop, but in most cases, the mower capacity is higher than for the operations that follow such as chopping, transport, and ensiling, therefore it is optimal to ensure that the ley crops mowed daily are not more than what can be handled by the subsequent operations (Vågström, 2005). Regular mowing of the ley crops is beneficial because it helps control the emergence of weeds (Ringselle, 2015). When the ley crops are grown together with annual crops, cutting the leys frequently for silage or hay can effectively control those weeds prevalent to annual crop systems. Even though mowing of the leys is mostly beneficial when done at the optimal time.

Freshly mowed ley crops are always wet and the water content can be as high as 75% to 80%, but wilting the crop to have around 35% dry matter (65% water) in the content is suitable for high quality silage, which can be used for biogas production (Vågström, 2005). If the ley crops mowed in a day are more than what can be handled by the chopper, transport trucks, and bag silos, part of the leys might be left to lie in the field for a long time resulting in a too high dry matter content of the crop. As a result, silaging may become problematic due to quality and material losses encountered. Common data relevant to mower-conditioning of ley crops for biogas production in Västerås is shown below (see table 8).

Common data	**Value**
Capacity of the mower-conditioner	10 ha/h
Working width of the mower-conditioner	9m
Working width equivalent to swath	9m width ⇔ 1 swath

Table 8. Data specific to mower-conditioning of ley crops for biogas production in Västerås (JTi & AGROPTI-gas, n.d., p. 8).

The chopping can be done in less than 24 hours after wilting on the condition that the weather condition is good enough (Vågström, 2005 in Witney, 1996). When the chopping starts, the ley crop will preferably contain 35% dry matter content (Vågström, 2005). "The dry matter content is the percentage of the material that is not water" (Vågström, 2005, p. 5). A self-propelled forage harvester is desirable to chop ley crops finely so as to facilitate the process of silaging and also to ensure that they are suitable for the production of biogas. "Harvesting for biogas means you need to chop shorter for closer packing (typically 5 – 7 mm) which increases fuel consumption and reduces throughput" (John Deere SPFH, n.d., p. 11).

The energy yield and the methane potential of ley crops vary depending on when the harvesting of the crops take place and how finely the crops are chopped (Prade, Svensson, Kreuger, Hörndahl, & Mattsson, 2015). It was found that the specific methane potential reduces as the chopping length settings are reduced. Also, it is not always beneficial to chop ley crops finely because the energy yield can be reduced due to too small cutting length settings (Prade et al., 2015). A precision chopper (see figure 7) is a self-propelled forage harvester, which facilitates the efficiency of harvest operations. Although the precision chopper puts more demand on the management of transport to ensure that the capacity of harvest is high enough and to avoid idle time on the part of the chopper (Vågström, 2005 in Hertwig et al., 1996). This is one main drawback with using a chopper. Common data relevant to precision chopping of ley crops for biogas production in Västerås is shown below (see table 9).

Common data	**Value**
Size of containers used	40 m³
Chopper capacity	7 containers/h
Container equivalent to hectare	1 container ⇔ 1 ha
Container equivalent to tonne	1 container ⇔ 11 tonnes

Table 9. Data specific to precision chopping of ley crops for biogas production in Västerås (JTi & AGROPTI-gas, n.d., p. 9).

The forage harvester used in a large scale farm often blows the forage into a truck or a tractor-trailer running beside the harvester. In the case of the ley crop harvest process in Västerås, the movable spout on the precision chopper blows the chopped ley into $40m^3$ containers (Vågström, 2005). The container is towed or hauled in the field by the chopper (see figure 7). As soon as the precision chopper fills up the container with ley crops, the chopper tows the container to the side of the field, where the container is detached from the chopper, and then loaded to truck (see figure 8). Once the filled container is detached from the precision chopper at the side of the field, another empty container is immediately attached to the chopper and the harvesting continues. This helps prevent idle time, thus enhancing a smooth chopping operation without any delay.

The changeovers from full to empty containers connect the harvesting and transport cycles (Vågström, 2005 in Witney, 1996). The ley collection center is the place at the side of the field where the containers are gathered before they are loaded to trucks and then transported to the plant area. The trucks transport the containers directly to the storage area (silo). Each truck can be loaded with 3 containers (see figure 8) for transport at a time to the plant area (JTi & AGROPTI-gas, n.d.). A maximum load of 40 tonnes of ley crops can be loaded to a truck and transported. Once the trucks arrive at the plant area, the containers of ley crops are unloaded into the silos and empty containers are returned back to the field. A minimum of 2 trucks with trailers must be available on the transport system of ley crops for the production of biogas in Västerås (Vågström, 2005). This is vital to avoid bottlenecks.

Figure 7. A mower-conditioner with nominal width of 9m (left) and a 40m^3 container pulled by a Claas Jaguar precision chopper in the ley field (right) (Vågström, 2005, p. 6).

Moreover, certain activities take place during the harvesting and transport cycles such as changing of the container for the chopper, as well as the loading and unloading of the truck. The time taken for each activity varies sometime depending on the expertise of the workforce involved and the type of vehicle used. For example, it was found that the loading and unloading time for a truck with a trailer is 20 minutes (Vågström, 2005). Another study states that it takes approximately 20 to 30 minutes to load the containers to a truck (JTi & AGROPTI-gas, n.d.). The data taken into consideration in the ley crop harvest for biogas production in Västerås is shown below (see table 10).

Specifications	**Value**
Container volume (m³)	40 [a]
Transport speed of chopper (km/h)	25 [b]
Maximum capacity of chopper (t DM/h)	40 [c]
Time it takes the chopper to change container (min)	3 [d]
Average speed (high) of trucks (km/h)	70 [e]
Average speed (low) of trucks (km/h)	40 [f]
Loading/unloading time of truck with trailer (min)	20 [g]

Table 10. Specifications based on experience and assumptions for the ley crop harvest in Västerås (Vågström, 2005, p. 17).

Notes for table 10 above: [a] Value based on actual work of the harvest company; [b] Value based on the experience; [c] Value based on the experience; [d] Value based on the experience; [e] Value based on assumption; [f] Value based on assumption; [g] Value based on the experience (Vågström, 2005).

The time it takes to load the containers to a truck, transport the containers to the storage area or silos, unload the containers at the storage area, and return empty containers back to the field is calculated starting from the time when the loading begins. This is the inception of loading the 3 containers to the truck at the ley collection center, not when the containers are hauled by choppers in the field. A total of 3 containers of leys crops are loaded to a truck singly. The unloading time is the time it takes the truck to unload the ley crops from the containers, while at the same time loading the crops directly into the silo through a bagging machine (see figure 9). The transport time of the truck (see formula 1) is based on how the ley crops in Västerås are transported from the ley collection center to the biogas plant.

Figure 8. Loading of containers to truck at the side of the ley crop field (left) and a truck transporting 3 containers of ley crops to the biogas plant in Västerås (right) (JTi & AGROPTI-gas, n.d., p. 10 & p. 11).

$$\text{Transport time of a truck} = 2 \times \frac{\text{distance}}{\text{average speed}} + \text{loading time} + \text{unloading time} \quad (1)$$

Formula 1: Transport time of a truck (Vågström, 2005).

Common data relevant to transport of ley crops to the biogas plant in Västerås is shown below (see table 11).

Common data	**Value**
Number of containers of ley crops per truck for transport to the plant area	3
Maximum weight of 3 containers per truck	40 tonnes
Total number of trucks used for transport of ley crops to the plant area	2
Transport time of each truck from ley collection center to the silo	ca. 20 min

Table 11. Data specific to transport of ley crops to the biogas plant in Västerås (JTi & AGROPTI-gas, n.d., p. 11).

Bag silos (see figure 9) are advantageous to ensile the ley crops. The bagged silage is beneficial because of the following factors: not as many safety hazards compared to piles, bunkers, and towers; requires no specialized equipment for unloading the silage; less susceptible to damage from weather during filling compared to pile and bunker silage; a very flexible system due to the possibility to adjust the storage capacity of the silos to fit crop yields; minimal dry matter loss (less than 10%) if management is carried out properly (Bolsen & Bolsen, 2006). In another study, it was found that the losses in bagged silage are not more than 6 or 8%, as against bunkers with 12 to 25% losses (Garvey, 2010). A bagging machine is more commonly used to load the ley crops into the bags. This is usually because the cost is cheap. Common data relevant to ensiling of ley crops for biogas production in Västerås is shown below (see table 12).

Common data	Value
Diameter of the bag silo	3.5 m
Length of the bag silo	90 m
Capacity of self-propelled packing machine	100 tonnes/h
Size of the storage place for ensiling at the biogas plant	7000 m^2

Table 12. Data specific to ensiling of ley crops for biogas production in Västerås (JTi & AGROPTI-gas, n.d., p. 12).

Moreover, a bagging machine can ensure a consistent fill and density. Although achieving a uniform fill and density during bagging is contingent on the skill level of the bagging operator (Bolsen & Bolsen, 2006). The bags are allowed to lie on asphalt laid on a site very close to the biogas plant, as it is done at the plant area in Västerås (Vågström, 2005). Bags can also be placed on a concrete surface. The most important factor is that the surface must be firm and well-drained. The daily quantity of ley crops required for biogas production is collected from the bag silos. The biogas plant in Västerås is equipped with tractors, wheel loaders, and some in-house vehicles used to transport ley crops within short distances in the plant area.

Figure 9. Packing the ley crops in a plastic bag silo (Held et al., 2008, p. 54).

Vågström (2005) propounds in the analysis of the ley crop harvest for biogas production in Västerås that factors such as throughput capacity (the quantity of ley crops harvested in one hour), material density, total chopping time, the number of containers, the cost for mowing, chopping, transport, and bagging were investigated using a model for the calculations. In addition to that, JTi & AGROPTI-gas (n.d.) states in their report certain data specific to some of the above-listed factors. Therefore, the methodology of this thesis will focus on the logistics of collecting and transporting ley crops to a biogas plant site using the assumption that the ley has already been chopped and gathered at the different ley collection center in different fields. Factors that will be taken into consideration in this study include the collection of a yearly amount of 5000 tonnes of ley crops and transporting the crops to the biogas plant site optimally.

2.13 Location Analysis

In the design of biofuel supply chain, one study proposes a linear programming model for deciding optimal locations of depots and biorefineries that uses corn stover and switch grasses as substrates. The authors found that as the distance between the biorefinery and harvesting fields increase, the cost of transportation increases (Ng & Maravelias, 2017). Therefore, it is essential to minimize distance as much as possible. In this study, location analysis technique is used to evaluate the most optimal location of a biogas plant site primarily by optimizing the collection and transport of ley crops from the fields to the biogas plant site. An optimal transport can also mean the shortest distance possible. The shorter the distance between the fields of ley crops and the biogas plant site, the closer the proximity of the ley fields to the biogas plant site.

The biogas plant site in this study will consist mainly of the gas production plant, the upgrading plant, and the silos. First, in deciding on the location of a biogas plant, care must be taken to ensure that the distance between the plant area and field is optimal enough. The rationale for locating a biogas plant in proximity to the biomass field is to contribute to making biogas a viable alternative to fossil fuel economically and environmentally. The judicious location of a biogas plant can facilitate the logistics of collecting and transporting biomass from the fields to the plant area.

Second, if the site of the biogas plant is along existing truck transportation networks, therefore, the transport of ley crops takes place on the existing road network. However, if the biogas plant site is located far away from an existing truck transportation network, this might lead to constructing new roads and infrastructures, thus putting a higher cost on the project. Third, facilities such as filling stations will be required to provide end users with fuel. Therefore, the site of the biogas plant must be in proximity to such facilities. Location analysis helps to identify optimal facility location by assessing location factors such as proximity to suppliers, transportation services, nearness to customers, availability of infrastructures, et cetera (Bosona, 2013).

Other factors that might be vital to take into consideration when deciding a facility location is to ensure that the choice of location does not negatively impact other potential factors, for example, the choice of any particular location should not lead to high environmental costs. It was found that environmental costs "takes into account human and ecological health (wildlife, soil and water), and also pollution, habitat biodiversity and disturbance" (Haddad & Anderson, 2008, p. 1103). Although environmental costs are costs associated with the negative impacts of certain operations or activities on the environment, but at the same time, the locations where those activities take place also contributes to the degree of such impact on the environment. Therefore, it is vital to strike a balance between the choice of location and any potential factors. In a particular study, the use of satellite storage locations is proposed for the development of the logistics system of a feedstock. The authors use a system cost approach to locate the storage locations by striking a balance between the costs of loading biomass, transporting biomass from fields to storage locations, and developing the storage locations (Judd et al., 2012).

3. METHODOLOGY

3.1 Materials and Methods

The data used in this study was collected by several means. GIS block data from 2015 together with ley crop data from 2014 was combined together. The GIS data was obtained from Statistics Sweden (SCB). The GIS road network data was taken from the database of Swedish University of Agricultural Sciences (SLU) using the Geodata Extraction Tool (GET). The data on mix, yield, production, and land area of ley crops in Uppsala was also gotten from SCB. Data on food waste and slaughterhouse waste in Uppsala was gotten from Uppsala Vatten.

This focus of this study involves the following: proposing three candidate biogas plant sites in close proximity to road network and filling stations; identifying the biomass fields for the collection of an annual amount of 5000 tonnes of ley crops using three different land use scenarios (30%, 50%, and 70%); optimizing the collection and transport of ley crops from each field in each scenario to each candidate biogas plant site; determining the best land use scenario for the collection and transport of ley crops from the fields to the candidate biogas plant site and deciding the best location for the candidate biogas plant. This study uses a GIS-based approach to optimise the logistics of collecting and transporting an annual amount of 5000 tonnes of ley crops as a substrate for biogas production in Uppsala municipality using a feedstock ratio and digester volume similar to the existing biogas plant in Västerås municipality and then selecting an optimal location for the biogas plant. ArcGIS Network Analyst tool for the closest facility is used in this study.

3.2 Limitations

Even though the proposed biogas plant will be fed with three different feedstocks (silaged ley crops, organic household waste, and sludge from grease separator), the location of the biogas plant is based on the optimal collection and transport of only the ley crops to the biogas plant site. The rationale behind the decision is that the lands on which the ley crops grow are fixed. A set of highly productive fields that are at least some years used for growing ley crops have been identified. The actual number of years that the ley crops are left to grow varies among different farms in Uppsala. The same fields will be used for growing ley crops again. The crop rotation system in practice will then have an influence on which scenario comes into practice, i.e. 30%, 50%, or 70%. Also, the amount of ley crops that can be obtained in the fields is known and there exist ley collection centers in the fields. After the ley crops are mowed, a self-propelled forage harvester is used to chop the crops. As soon as the precision chopper fills up the containers with ley crops, the containers are towed to a place in the field, where they are loaded to trucks and then transported to the plant area. It is assumed that those places where the ley crops are gathered together in the fields are ley collection centers. In this study, ley collection centers are defined in GIS space as points in the middle of each field.

In the case of the other feedstocks (organic household waste and grease separator sludge), the wastes are obtained from different locations and there are no defined collection centers for these feedstocks. Once the organic waste and sludge are obtained from different households, restaurants and big kitchens, slaughterhouses, and other food industries in Uppsala, they are transported directly to biogas plant. The way of collecting and transporting organic waste and sludge as described above is the condition that will be assumed for the proposed candidate biogas plant. Since organic waste will also be required for the proposed candidate biogas plant, the assumption in this study is that the quantity of organic waste collected in Uppsala will increase in the future in order to have adequate organic waste substrates for the biogas plant.

3.3 Empirical Studies

"Site suitability modelling is broadly used in a variety of fields mainly because it helps capture geographic variation for different ends" (Haddad & Anderson, 2008, p. 1099). In the identification of suitable collection sites for corn stover, one study applies GIS technology in the methodology. The authors use spatial multicriteria decision making (SMDM) model in decision-making situations (Haddad & Anderson, 2008). In the study, six components are proposed, which involves the following: first, the goal is to identify potential sites for the collection facilities in a particular region; second, the decision makers involved in the process falls into two categories, namely farmers who would like to increase their profit and environmentalist who would like to reduce environmental impacts; third, two models are created for the objectives, one is to increase profit through an increase in productivity and the other is to reduce environmental costs; fourth, each model has separate weights assigned to it, which generated a series of decision alternatives; fifth, there are variables that are uncontrollable such as "economic recession or bad weather or any other factor over which decision makers have no control" (p. 1099); sixth, the series of outcomes generated are linked with each scenario (Haddad & Anderson, 2008).

The authors developed a SMDM framework for identifying potential sites for collection facilities (see figure 10). Decision maker 1 and 2 as shown in figure 10 represents the farmers and environmentalist respectively. The resulting scenarios are based on the outcomes, which are the results of assigning different weights to each of the models (Haddad & Anderson, 2008). The authors assign different weights to the attributes of each of the objectives, which are presented as two different models, under three different scenarios: scenario I represents an equivalent weight, therefore assigns the same value to both models; scenario II gives priority to productivity, therefore assigns higher value to productivity; scenario III gives priority to environmental, therefore assigns higher value to environmental cost. The guidelines of the SMDM process involves assigning weights to each attribute according to the significance of each of the model and decision makers analyse scenarios I, II and III, and according to their preferences, they select the scenario that they consider most suitable, as well as best fits their objectives (Haddad & Anderson, 2008).

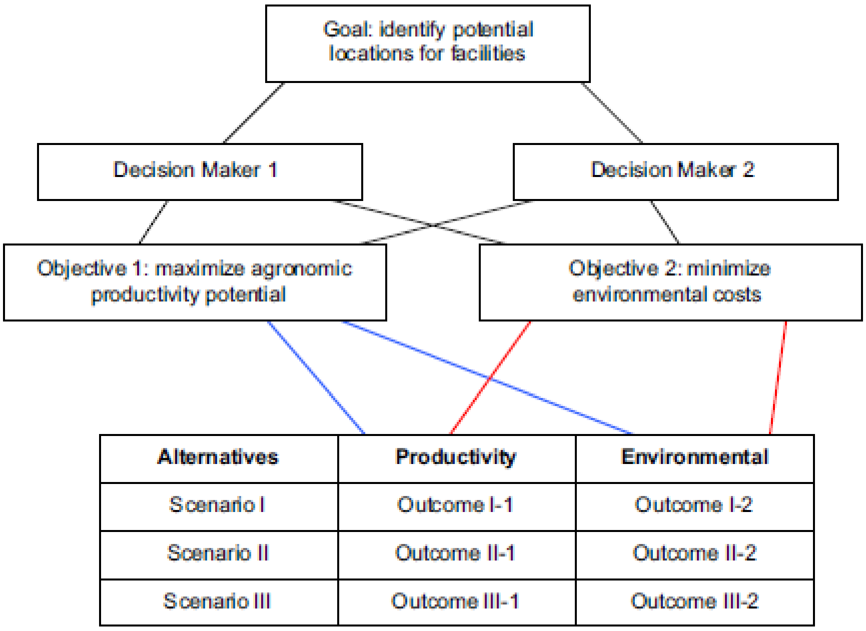

Figure 10. The spatial multicriteria decision making (SMDM) framework (Haddad & Anderson, 2008, p. 1100).

The SMDM model is one approach in GIS technology. Other GIS technologies and techniques used to determine an optimal facility location includes the Center-of-Gravity method and Load-Distance method (Bosona et al., 2013 in Russell & Taylor, 2009). The Center-of-Gravity technique involves the use of travel distance and the weight of goods to determine the optimality of a location, i.e. distribution centre (Bosona et al., 2013). The mathematical formula is shown below (see formula 2).

$$x = \frac{\sum_{i=1}^{n} x_i w_i}{\sum_{i=1}^{n} w_i}, \qquad y = \frac{\sum_{i=1}^{n} y_i w_i}{\sum_{i=1}^{n} w_i} \qquad (2)$$

Formula 2: Formula for Center-of-Gravity technique (Bosona et al., 2013).

x, y represents the coordinates of new location, i.e. distribution centre; x_1, y_1 in decimal degrees represent the coordinates of delivery point *i*; w_1 in tonnes represent the weight of load transported to delivery point *i* in a year (Bosona et al., 2013).

The Load-Distance (LD) technique involves the selection of different candidate locations and evaluating those locations using a product of load and distance as the value for measurement (Bosona et al., 2013). The mathematical formula is shown below (see formula 3).

$$LD = \sum_{i=1}^{n} w_i d_i \qquad (3)$$

Formula 3: Formula for Load-Distance (LD) technique (Bosona et al., 2013).

LD in tonnes-km represents the product of load and distance; n represents the number (sum) of collection and delivery points *i*; w_1 in tonnes represents the demand at the delivery point *i* in a year; d_1 in km is the distance between the proposed candidate sites and delivery point *i* (Bosona et al., 2013).

3.4 Study Area

The focus area in this study is Uppsala municipality. Even though most of the data is provided on a County basis, only a subset of the data is used for the research in this study. For example, the GIS block and ley crop data, the data on mix, yield, production, and land area of ley crops provided by SCB represents the entire Uppsala County. Only those data that represents Uppsala municipality is used in this study. For the GIS data, a smaller subset data set for Uppsala municipality is created out of the larger data set for Uppsala County.

3.5 Sensitivity Analysis in GIS

Sensitivity analysis is the evaluation of potential changes in the assumptions and values of any model and the impacts of these changes on the conclusions, decisions, or recommendations that are to be drawn from the model (Pannell, 2017). The use of sensitivity analysis in a solution methodology is beneficial for any scientific work. There are numerous uses of sensitivity analysis, which includes the following: comparing simple and complex assumptions or strategies; using circumstances to make flexible recommendations; determining vital or sensitive variables; examining the robustness of a result or optimal solution; investigating solutions that are sub-optimal; communicating no commitment to a particular strategy; allowing decision makers to choose from various assumptions; making conclusions more understandable and credible; increasing the understanding of the system; et cetera (Pannell, 2017). A sensitivity analysis of different assumptions (land use scenarios) is used in order to identify the most feasible assumption and to know the assumption that provides more benefits. The assumptions involve changes in land use. The input data in GIS is the land area. Sensitivity analysis is performed by changing the input data.

3.5.1 Evaluating optimal location of a biogas plant site

In this study, the methods used to determine the optimal location of a biogas plant involves the following:

1. Proposing three candidate biogas plant sites in close proximity to road network and filling stations. This involves first identifying the existing filling stations and road network in Uppsala municipality and then proposing three candidate biogas plant sites in close proximity to those infrastructures.

2. Identifying the biomass fields for the collection of an annual amount of 5000 tonnes of ley crops under three different land use scenarios (30%, 50%, and 70%). The total number of hectares that can produce 5000 tonnes of ley crops under three different land use scenarios is first calculated. For each scenario, the ley fields (blocks) bigger than or equal to 5ha that together make up the equivalent total number of hectares calculated for that particular scenario is selected around the proposed locations of the candidate biogas plant sites.

3. Optimizing the collection and transport of ley crops from each field in each scenario to each candidate biogas plant site. Network Analyst tool for the closest facility in ArcGIS is used to optimize the collection and transport of ley crops and also calculate the distances from each field in each scenario to each candidate biogas plant.

4. Determining the best land use scenario for the collection and transport of ley crops from the fields to the candidate biogas plant site and deciding the best location for the candidate biogas plant. The load (quantity) in tonnes from each field in each scenario is calculated in ArcMap as follows: total land area in each field * tonnes per hectare * percentage of the total land use. A Load-Distance (LD) computation in excel is used to calculate the sum of the products of load and distance from each field in each scenario to each candidate biogas plant and the proposed biogas plant location with the lowest LD value is selected as the most optimal location.

4. RESULTS AND DISCUSSIONS

The locations of the proposed candidate biogas plant sites are characterized by two major factors:

a) The candidate biogas plant sites will be located in proximity to filling stations. There are three existing biomethane public filling stations in Uppsala municipality. The assumption here is that new filling stations will not be installed, but the infrastructures at the existing biomethane filling stations will be used instead. The total cost (excluding upgrading or reconstruction cost) of installing one of the existing filling stations and connecting the station to the biogas upgrading plant through a gas pipe was around 5 million SEK (Biogas East, n.d.). It is assumed that the cost of installing new filling stations can be saved, thus the biomethane produced at the candidate biogas plant site will be transported to the existing filling stations in siktargatan/kungsängsgatan, kungsängsgatan/stallängsgatan, and kumlagatan in Uppsala. Although there might be a need to upgrade facilities such as increase the fuel storage capacity at the existing filling stations.

b) The candidate biogas plant sites will be located along existing transportation network. This will facilitate the transportation of ley crops from the “ley collection center” in the field to the “silos” at the biogas plant site.

4.1 Location Analysis for Optimal Biogas Plant Site

The following steps are used in location analysis in order to evaluate the optimality of a biogas plant site and the results of each step are also shown as follows:

I) Step 1: Location of existing filling stations

Three candidate biogas plant sites are proposed and located around the existing biogas public filling stations in Uppsala municipality. An excel file is used to create the attribute table for the three existing filling stations in ArcGIS (see table 13). The view in GIS Space is shown below (see figure 11).

No	Name	Address	Latitude	Longitude
1	Filling Station-1	siktargatan 8 - kungsängsgatan 66, Uppsala Vatten & Avfall AB	59.852	17.653
2	Filling Station-2	kungsängsgatan / stallängsgatan, AGA Gas	59.847	17.667
3	Filling Station-3	kumlagatan 4, OKQ8/E.ON	59.844	17.731

Table 13. The attribute table used to locate the three existing filling stations in GIS Space.

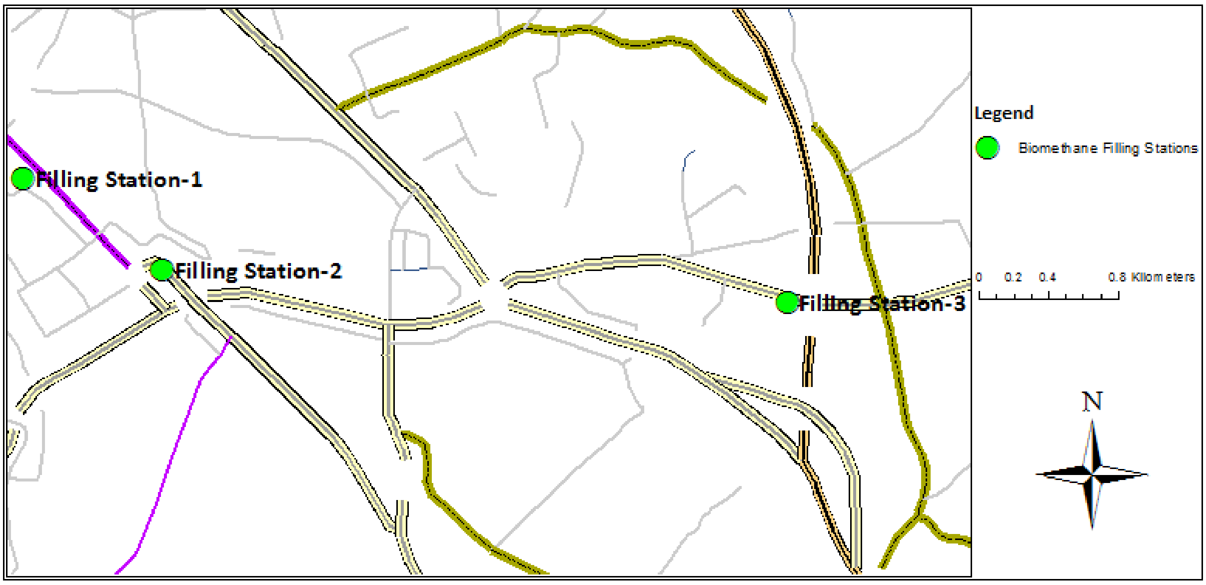

Figure 11. A view of the three existing filling stations in GIS Space.

Notes for figure 11 above: All lines shown on the map represents road network within Uppsala. Road data source: © Lantmäteriet.

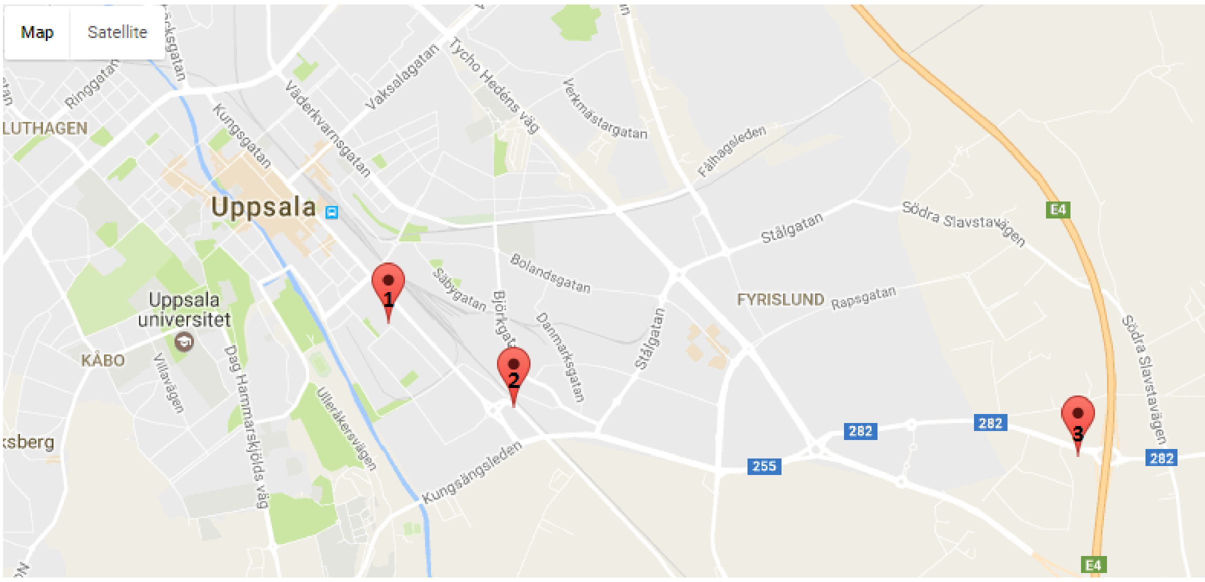

Figure 12. Locations of three existing biomethane filling stations in Uppsala (Energigas Sverige, 2017).

Notes for figure 12 above: Filling station 1: siktargatan 8 - kungsängsgatan 66, Uppsala Vatten & Avfall AB; Filling station 2: kungsängsgatan/stallängsgatan, AGA Gas; Filling station 3: kumlagatan 4, OKQ8/E.ON (Energigas Sverige, 2017). Uppsala Vatten supplies biomethane to filling station 1 & 2 and E.ON supplies a mix of biogas and natural gas to filling station 3. (personal message 12).

II) Step 2: Proposing the locations of three candidate biogas plant sites

Three locations are proposed for the three candidate biogas plant sites. The location of the existing biogas plant in Uppsala municipality is considered as one of the proposed locations. An excel file is used to create the attribute table in ArcGIS for the existing biogas plant in Uppsala (see table 14). The location of the existing biogas plant is in proximity to Filling Station-2. The existing biogas plant is

personal message 12 Cf. (Lennart Nordin, personal message, 2017-05-24).

marked as Plant-2 in GIS space (see figure 13). Plant-1 is located 500 meters away from Filling Station-1 (see figure 13). Plant-3 is located 500 meters away from Filling Station-3 (see figure 13). The locations of the candidate biogas plant sites are close to road network.

Plant_Name	Address	Latitude	Longitude
Plant-2	Kungsängens Gård, Uppsala	59.843	17.672

Table 14. The attribute table used to locate the existing biogas plant site in GIS Space.

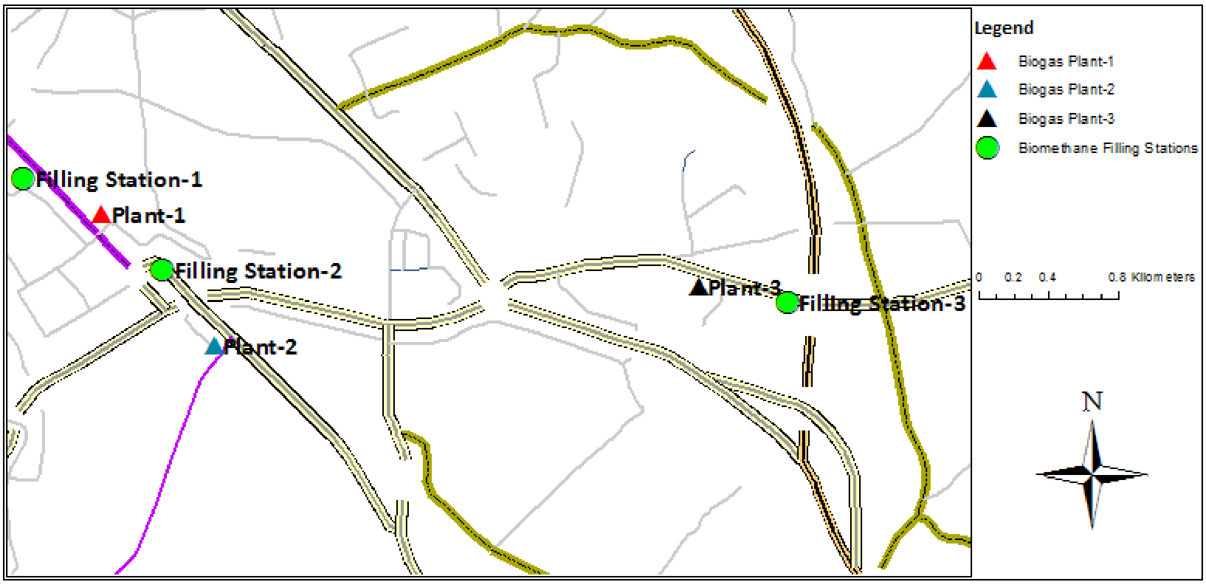

Figure 13. A view of the locations of three candidate biogas plant sites in GIS Space.

Notes for figure 13 above: All lines shown on the map represents road network within Uppsala. Road data source: © Lantmäteriet.

III) Step 3: Identification of ley crop fields

The original data obtained for use in this study is the data on ley crops in Uppsala County. The data for Uppsala County is subsetted to Uppsala municipality. Within Uppsala municipality, only hectares of land that can produce 5000 tonnes of ley crops under three land use scenarios are considered for use (see table 15). The number of hectares that can produce 5000 tonnes of ley crops is first calculated. Data for 2014 reveal that 6.85 tonnes per hectare with 16.5% moisture content is produced on 35770 hectares of crop land (see table 6). To calculate the equivalent number of hectares that can produce 5000 tonnes of ley crops with 65% water content, the formula for conversion of quantities between different water content is used (see formula 4). It is assumed that the ley crops used for biogas production will have exactly 65% water content.

Harvest with standard or required water content =

$$\frac{\text{harvest with reported water content} * (100 - \text{reported water content})}{(100 - \text{standard or required water watent})} \quad (4)$$

Formula 4: Conversion of quantities between different water content. *(personal message 13).*

personal message 13 Cf. (Gerda Ländell, personal message, 2017-04-24).

Therefore, the conversion of 6.85 tonnes per hectare with 16.5 % moisture content to 65% moisture content is calculated as follows:

$$\frac{6.85 \text{ tonnes per hectare} * (100-16.5\%)}{(100-65\%)} = 16.34 \text{ tonnes per hectare}$$

To calculate the equivalent land area of 5000 tonnes with 65% moisture content

$$\frac{5000 \text{ tonnes}}{16.34 \text{ tones per hectare}} = 306 \text{ hectares}$$

A calculation of the hectares of land that can produce 5000 tonnes of ley crops under three land use scenarios is shown below (see table 15).

Land use scenario (SC)	Ley fields in hectares (ha)	Annual amount (tonnes)
100% = reference	306	5000
30% = SC_1	1020	5000
50% = SC_2	612	5000
70% = SC_3	437	5000

Table 15. Crop area, hectares that can produce 5000 tonnes of ley crops under three different land use scenarios.

The calculation in table 15 reveals that as the portions of land to be used in each field area increases, the total hectares of fields where 5000 tonnes of ley crops will be collected decreases. In the case of scenario 3, the total hectares of fields where ley crops will be collected decreases to 437 hectares. An area of land is marked around the proposed locations for the candidate biogas plant sites. Within this area, three land use scenarios are created using the select by attributes tool in ArcGIS to select only the land hectares that are bigger than or equal to 5ha. Hectares of land bigger than or equal to 5ha are defined as areas with high productivity (see figure 14). For scenario 1, 30% of each ley field (block) bigger than or equal to 5ha with an equivalent total number of 1020 hectares are selected for the collection of 5000 tonnes of ley crops annually (see figure 15). For scenario 2, 50% of each ley field (block) bigger than or equal to 5ha with an equivalent total number of 612 hectares are selected for the collection of 5000 tonnes of ley crops annually (see figure 16). For scenario 3, 70% of each ley field (block) bigger than or equal to 5ha with an equivalent total number of 437 hectares are selected for the collection of 5000 tonnes of ley crops annually (see figure 17).

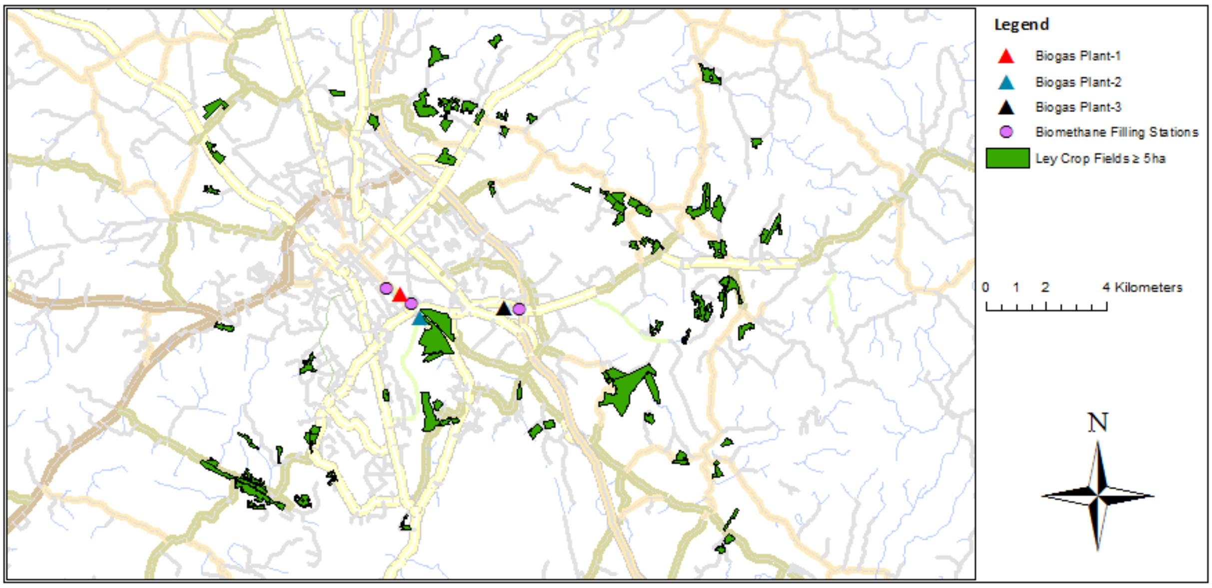

Figure 14. Hectares of land bigger than or equal to 5ha selected around the proposed locations for the candidate biogas plant sites.

Notes for figure 14 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

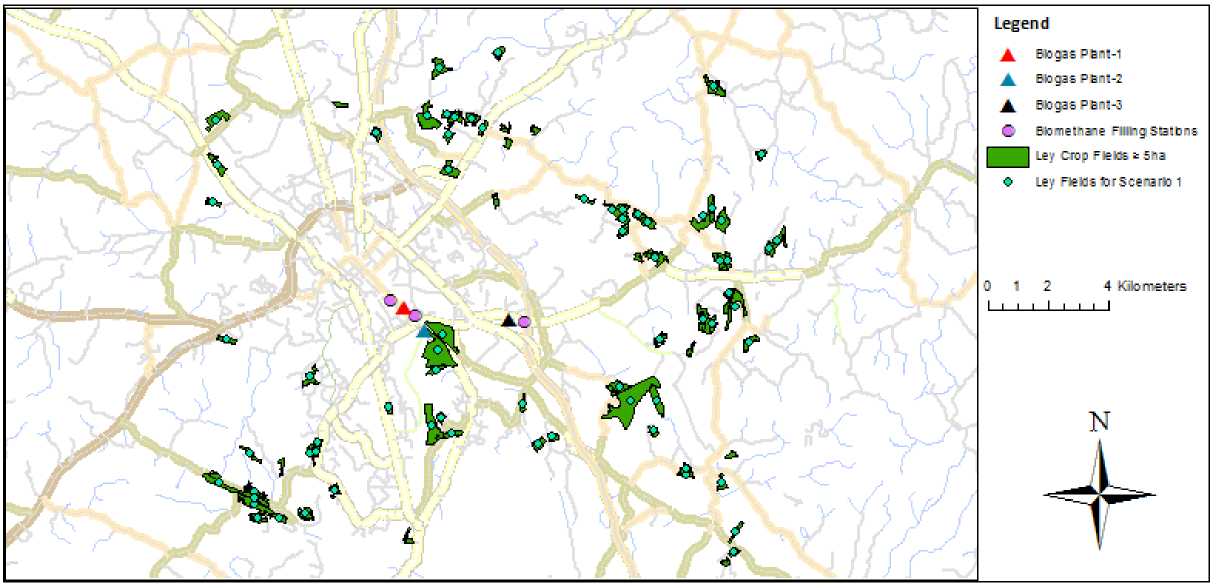

Figure 15. Ley crop fields marked for scenario 1 (SC_1) 30% land use.

Notes for figure 15 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

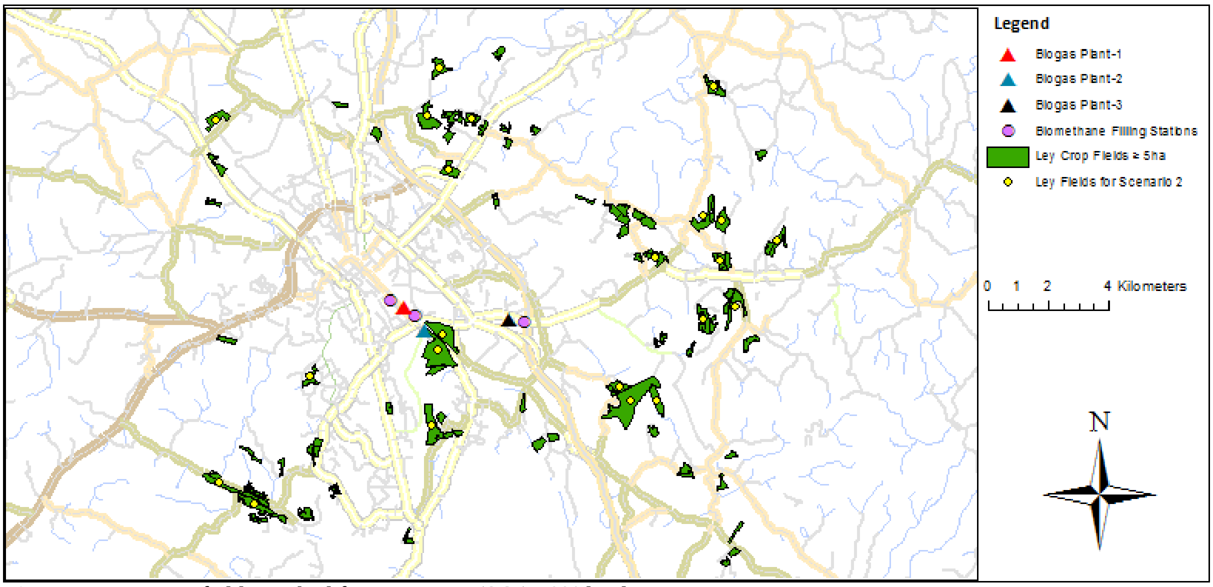

Figure 16. Ley crop fields marked for scenario 2 (SC_2) 50% land use.

Notes for figure 16 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

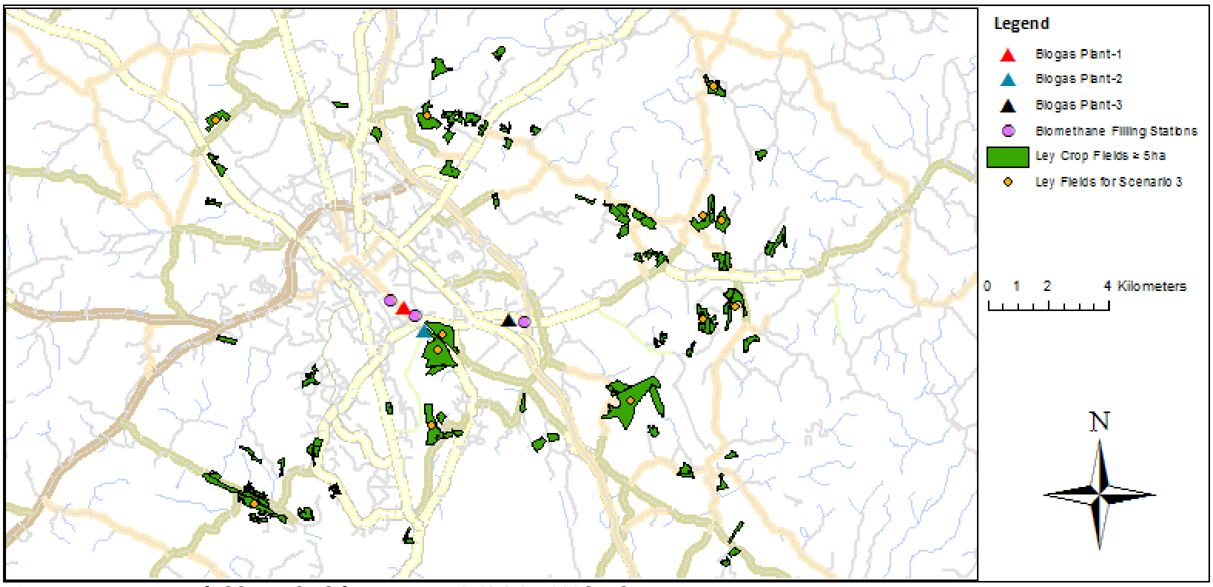

Figure 17. Ley crop fields marked for scenario 3 (SC_3) 70% land use.

Notes for figure 17 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

IV) Step 4: Optimizing the collection and transport of ley crops

ArcGIS Network Analyst tool for the closest facility and the Load-Distance (LD) technique are used in this study. The reason for using the LD techniques is because the load (quantity) in tonnes and detailed distance information in kilo meters can be calculated. The load, L is the amount of ley crops in each of the three land use scenarios (30%, 50%, and 70%) that is collected and transported from each ley crop field in each scenario to each of the three proposed candidate biogas plant sites. D is the length, which is the distance from each ley crop field in each scenario to each of the three proposed candidate biogas plant sites.

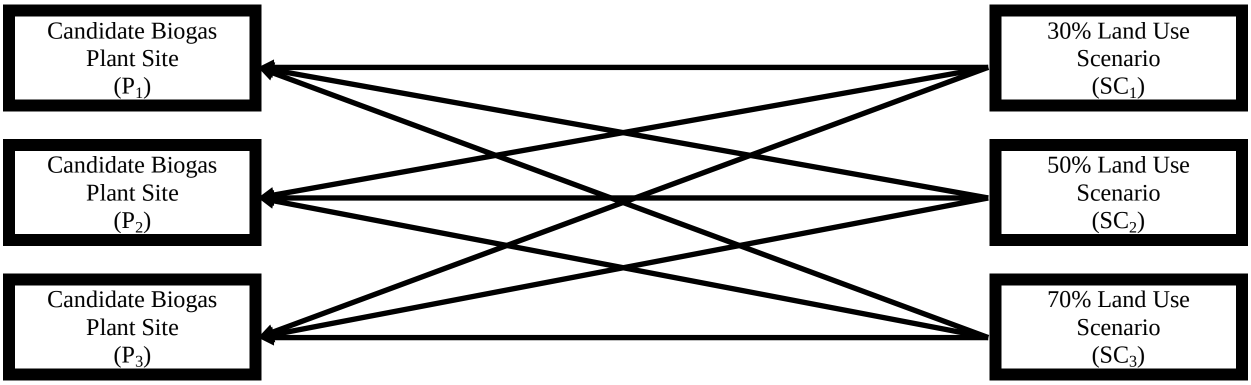

Figure 18. Ley crops are collected and transported from each ley crop field in each scenario to each candidate biogas plant site.

The load (quantity) in tonnes from each field in each scenario to each candidate biogas plant is calculated as (total land area in each field * tonnes per hectare * percentage of the total land use) (see table 16). This is the annual amount of ley crops that will be collected from each field in each scenario.

Scenario	SC_1 (30%)	SC_2 (50%)	SC_3 (70%)
Load (t)	Land area*16.34t/ha*0.3	Land area*16.34t/ha*0.5	Land area*16.34t/ha*0.7

Table 16. Annual collection of ley crops from each field in each scenario.

The distance from each field in each scenario to each candidate biogas plant is measured. The assumption here is that the ley crops collected from each field will be gathered at the center of the field. Therefore, distance is measured starting from the mid-point in the field. The mid-point of each field in each scenario is calculated. This is done by adding both x and y coordinates to the attribute table of the layer representing each of the scenarios in ArcMap. The attribute table of the layers in ArcGIS contains information on each field in each scenario. Network Analyst tool for the closest facility in ArcGIS is used to calculate the distances from each field in each scenario to each candidate biogas plant.

Collection and transport of ley crops from each field in scenario 1 to Plant-1 is shown below (see figure 19).

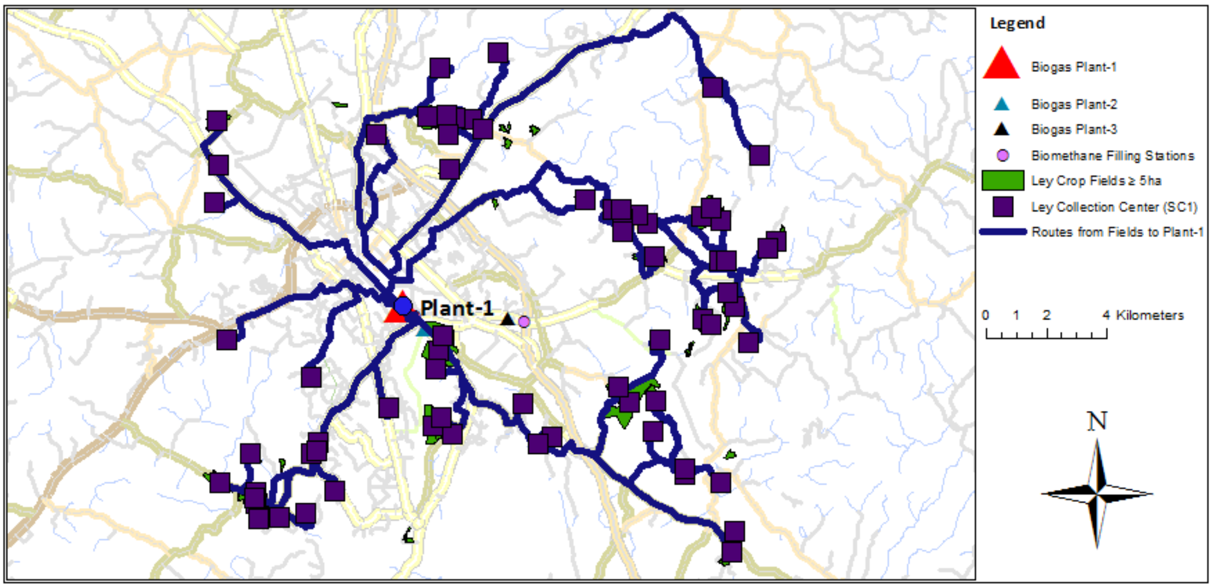

Figure 19. Collection and transport of ley crops from each field in scenario 1 to Plant-1.

Notes for figure 19 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

Collection and transport of ley crops from each field in scenario 1 to Plant-2 is shown below (see figure 20).

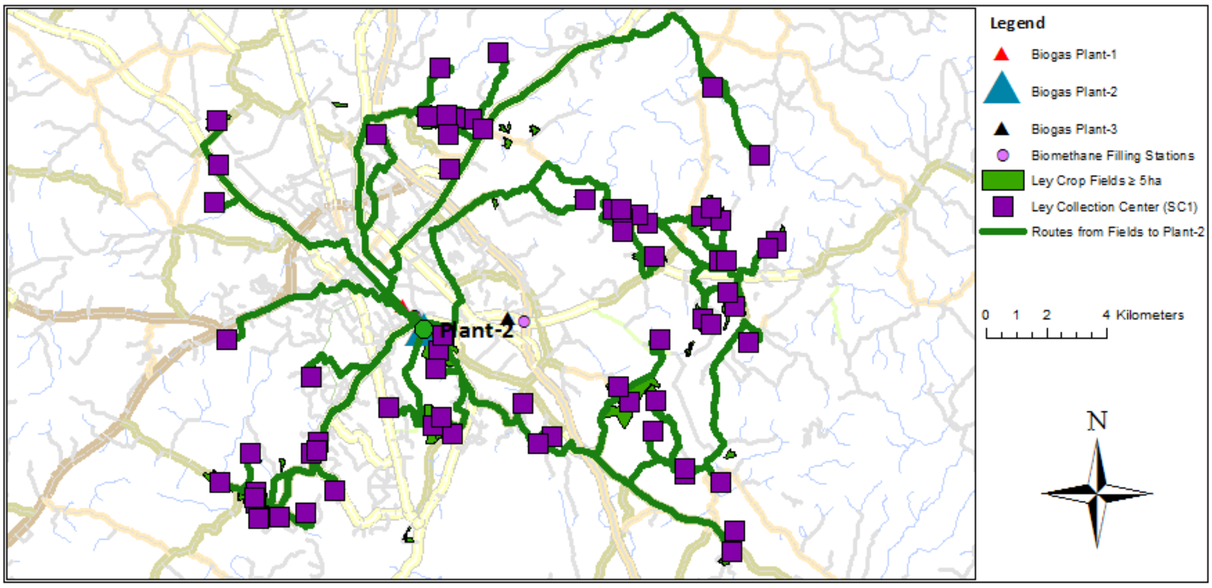

Figure 20. Collection and transport of ley crops from each field in scenario 1 to Plant-2.

Notes for figure 20 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

Collection and transport of ley crops from each field in scenario 1 to Plant-3 is shown below (see figure 21).

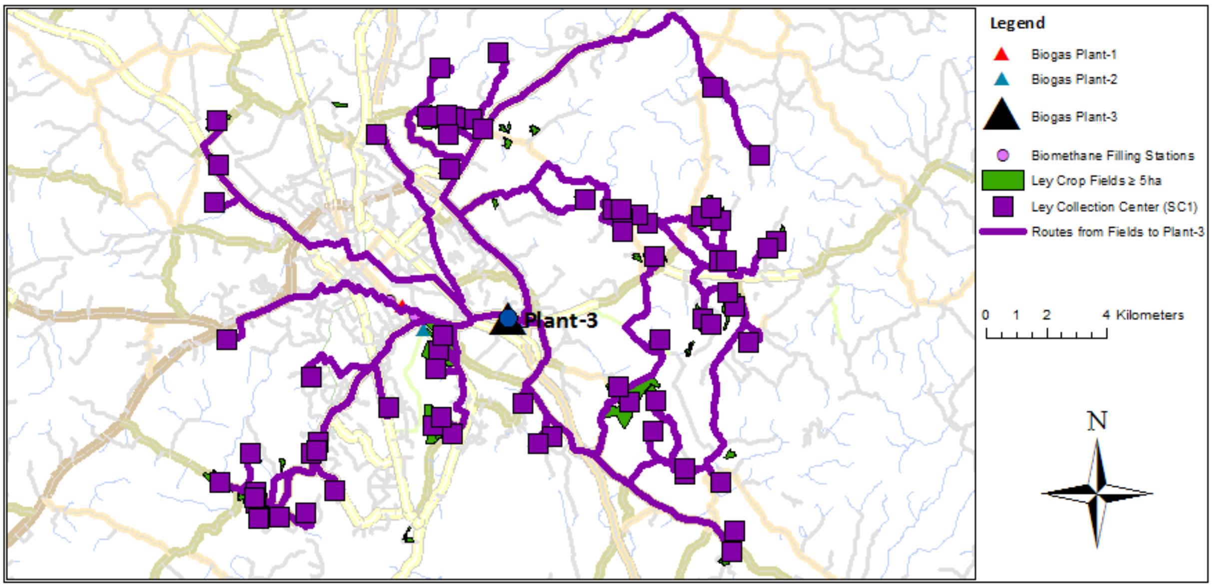

Figure 21. Collection and transport of ley crops from each field in scenario 1 to Plant-3.

Notes for figure 21 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

Collection and transport of ley crops from each field in scenario 2 to Plant-1 is shown below (see figure 22).

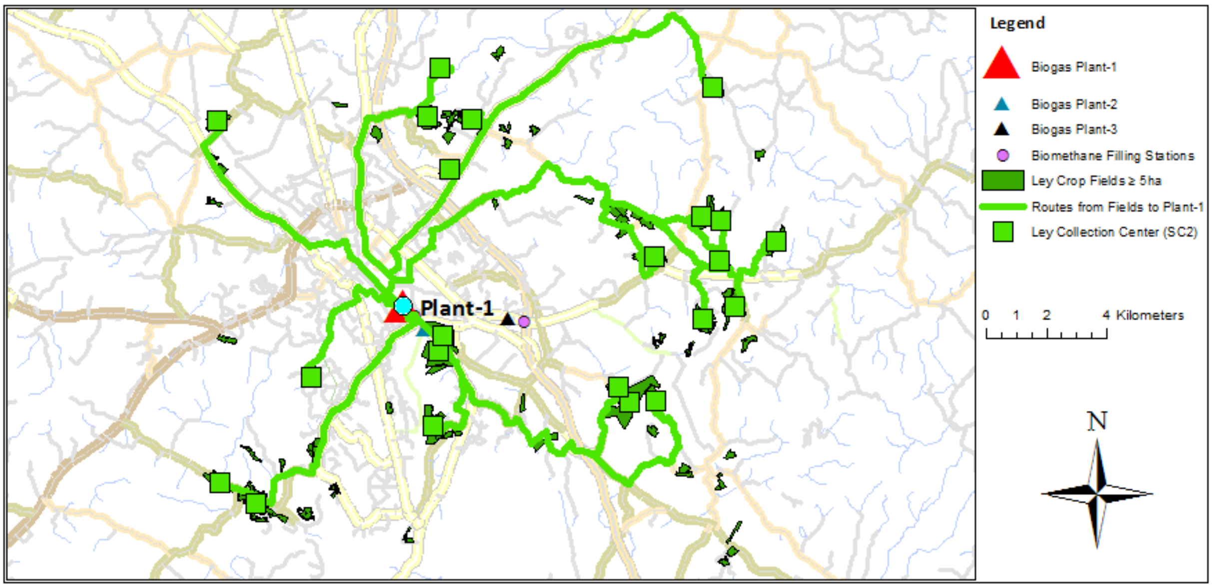

Figure 22. Collection and transport of ley crops from each field in scenario 2 to Plant-1.

Notes for figure 22 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

Collection and transport of ley crops from each field in scenario 2 to Plant-2 is shown below (see figure 23).

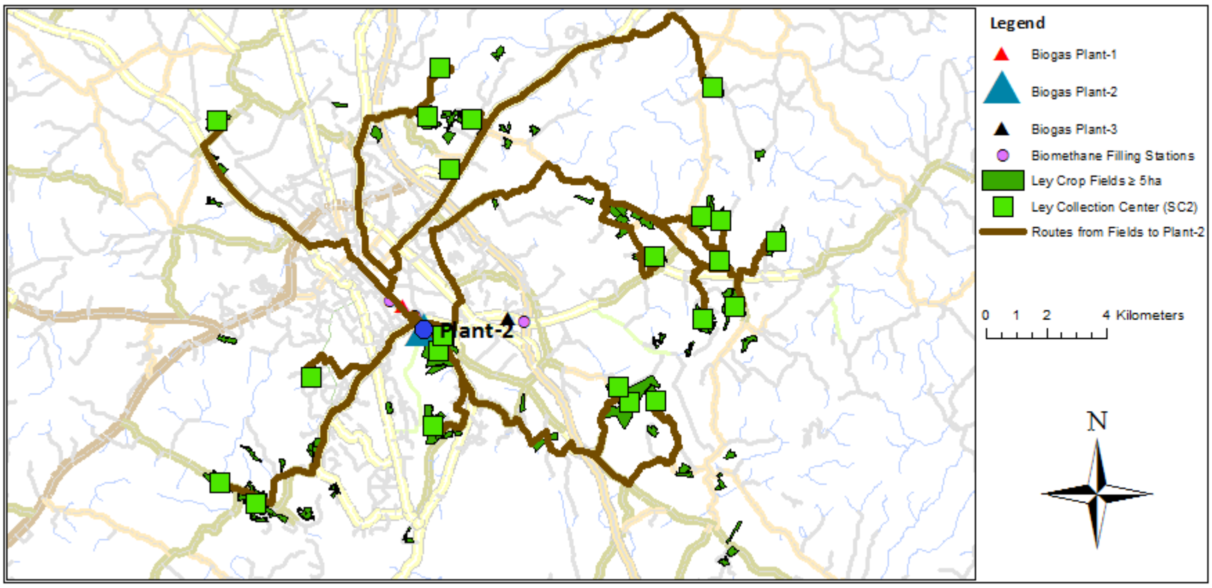

Figure 23. Collection and transport of ley crops from each field in scenario 2 to Plant-2.

Notes for figure 23 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

Collection and transport of ley crops from each field in scenario 2 to Plant-3 is shown below (see figure 24).

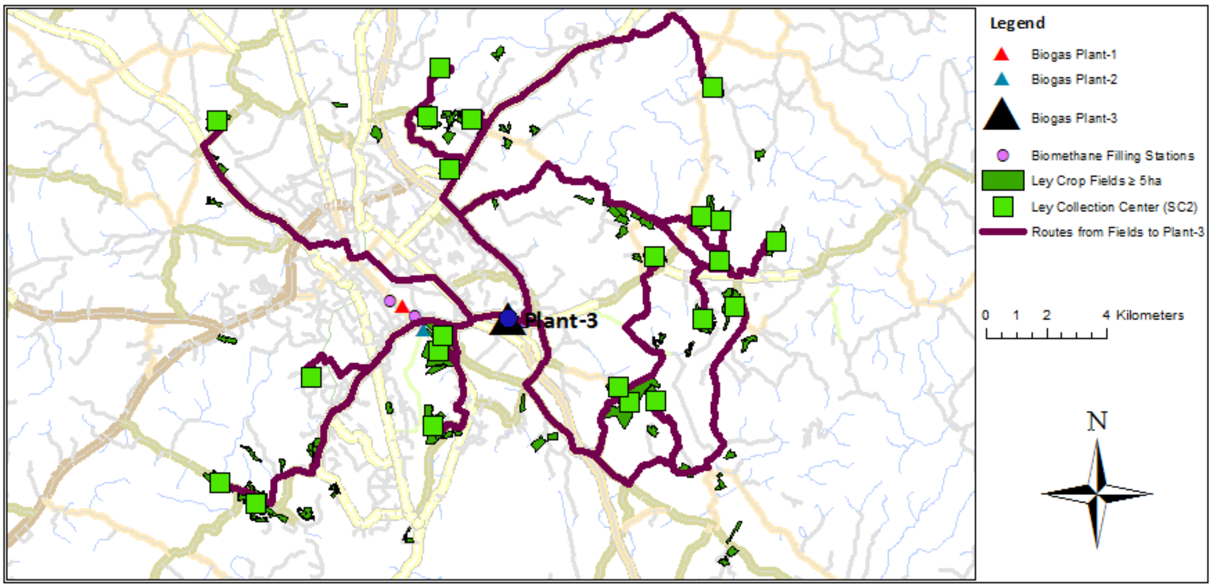

Figure 24. Collection and transport of ley crops from each field in scenario 2 to Plant-3.

Notes for figure 24 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

Collection and transport of ley crops from each field in scenario 3 to Plant-1 is shown below (see figure 25).

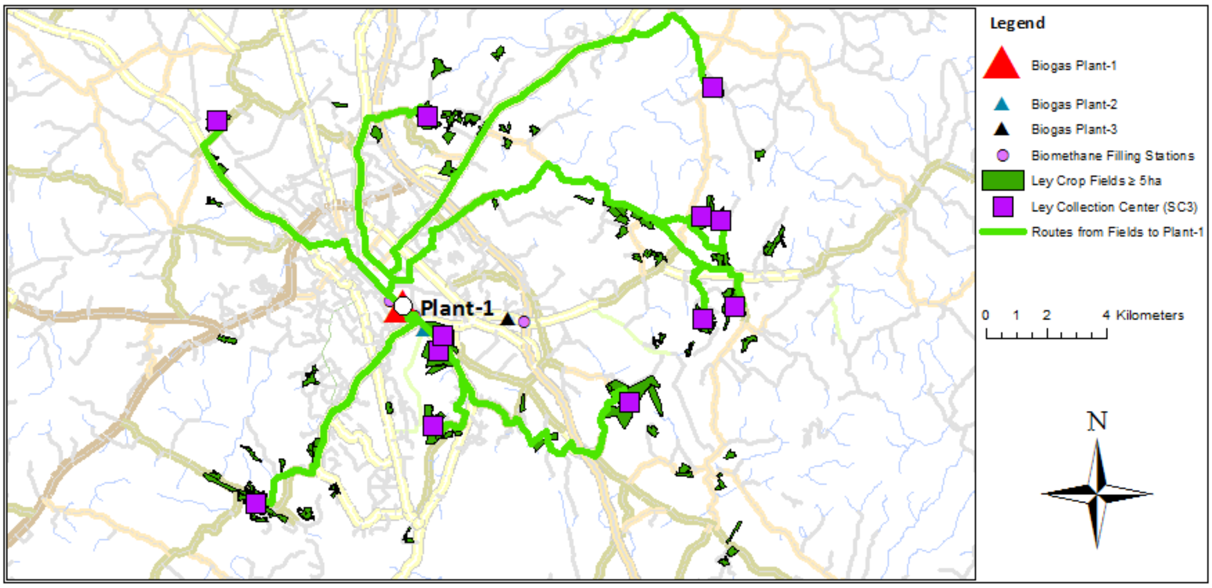

Figure 25. Collection and transport of ley crops from each field in scenario 3 to Plant-1.

Notes for figure 25 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

Collection and transport of ley crops from each field in scenario 3 to Plant-2 is shown below (see figure 26).

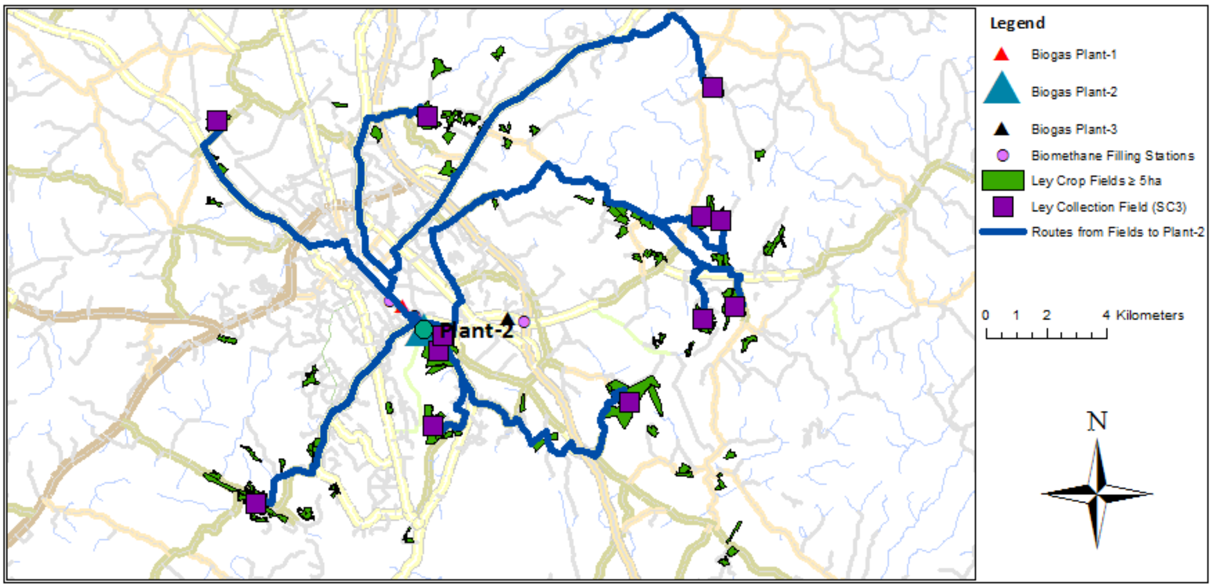

Figure 26. Collection and transport of ley crops from each field in scenario 3 to Plant-2.

Notes for figure 26 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

Collection and transport of ley crops from each field in scenario 3 to Plant-3 is shown below (see figure 27).

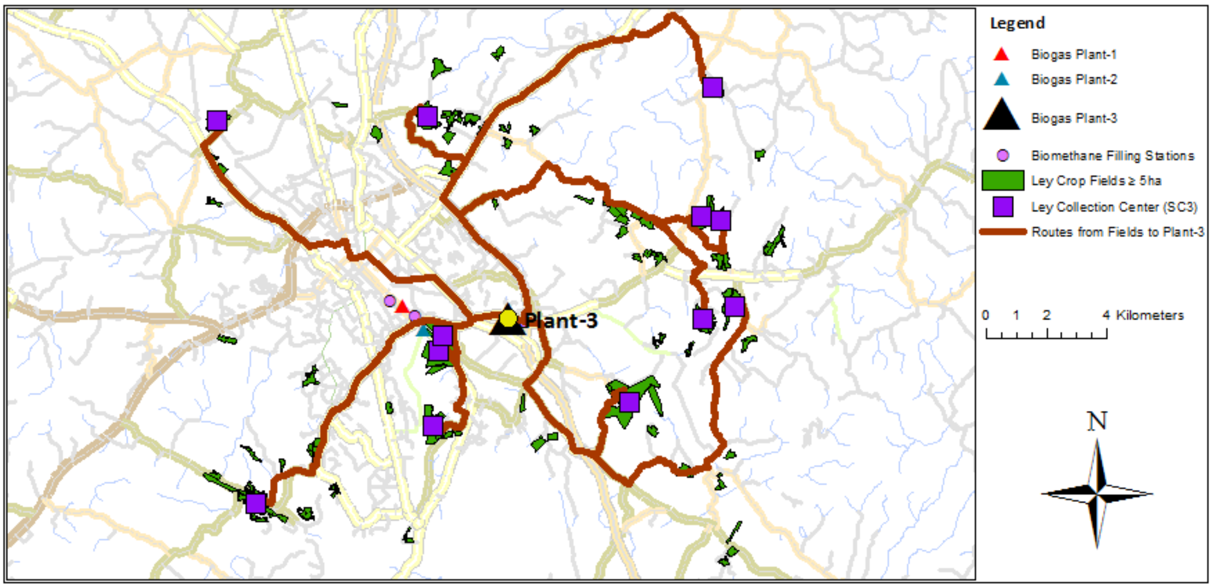

Figure 27. Collection and transport of ley crops from each field in scenario 3 to Plant-3.

Notes for figure 27 above: All lines shown on map represents road network within Uppsala. Road data source: © Lantmäteriet.

V) Step 5: Deciding the best location for the biogas plant

The load (quantity) in tonnes from each field in each scenario is calculated in ArcMap. Network Analyst tool for the closest facility is used to calculate the distances from each field in each scenario to each candidate biogas plant. A computation in excel is used to calculate the sum of the products of load and distance from each field in each scenario to each candidate biogas plant. The best option is determined from the Load-Distance (LD) calculations. "The load-distance technique is applied by computing a load-distance value for each potential facility location. The implication is that the location with the lowest value would result in the minimum transportation cost and thus would be preferable" (Russel & Taylor, 2000, para. 19).

4.2 Analysis of Results

L is the quantity in tonnes from each field in each scenario. D is the distance in kilo meters from each field in each scenario to each candidate biogas plant. LD is the product of L and D. The final result is the sum of the products of load and distance from each field in each scenario to each candidate biogas plant. In scenario 1, the results are: 54134.06tkm for Plant-1; 54835.94tkm for Plant-2; 55817.08tkm for Plant-3. Therefore, in scenario 1, the location of Plant-1 is the best option because it gives the lowest value. In scenario 2, the results are: 53156.62tkm for Plant-1; 53256.64tkm for Plant-2; 54591.30tkm for Plant-3. Therefore in scenario 2, the location of Plant-1 is the best option because it gives the lowest value. In scenario 3, the results are: 41135.79tkm for Plant-1; 40556.11tkm for Plant-2; 47201.55tkm for Plant-3. Therefore, in scenario 3, the location of Plant-2 is the best option because it gives the lowest LD value.

Moreover, in scenario 1 (30% of land use), there are 69 routes. In scenario 2 (50% of land use), there are 22 routes. In scenario 3 (70% of land use), there are 12 routes. Each route connects each ley collection center to a biogas plant. Scenario 3 has the lowest number of routes. Considering all scenarios, the location of Plant-2 in scenario 3 (70% land use) is the overall best option because it gives the lowest LD value in all the scenarios. Therefore the location proposed for candidate biogas plant-2 is the most optimal, because it would result in the lowest transportation cost.

The result of LD in each scenario is shown below.

	Plant-1	**Plant-2**	**Plant-3**
Scenario 1 (30%)	54134.06tkm	54835.94tkm	55817.08tkm
Scenario 2 (50%)	53156.62tkm	53256.64tkm	54591.30tkm
Scenario 3 (70%)	41135.79tkm	40556.11tkm	47201.55tkm

Table 17. LD values of the three biogas plant locations considering three land use scenarios.

Notes for table 17 above: see appendix VI, VII, & VIII for detailed calculations.

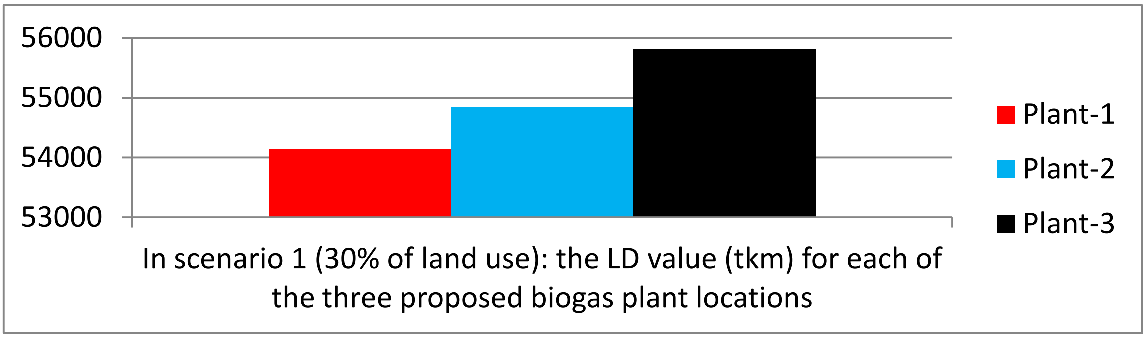

Figure 28. Chart showing the LD value (tkm) for each of the three proposed biogas plant locations in scenario 1.

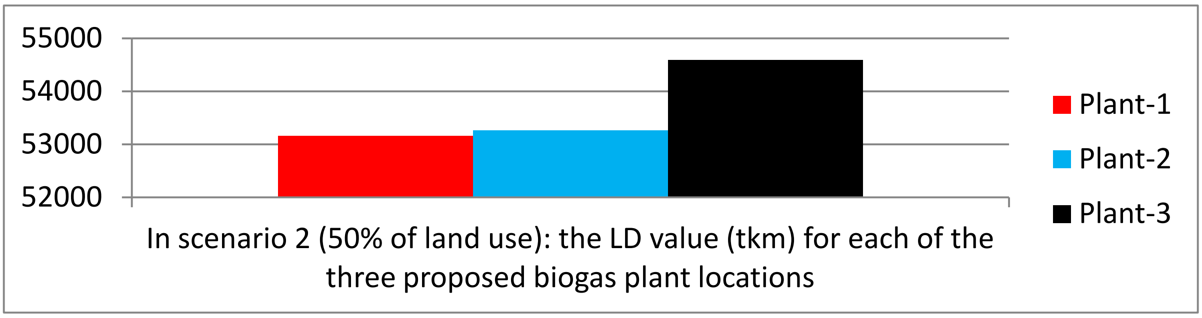

Figure 29. Chart showing the LD value (tkm) for each of the three proposed biogas plant locations in scenario 2.

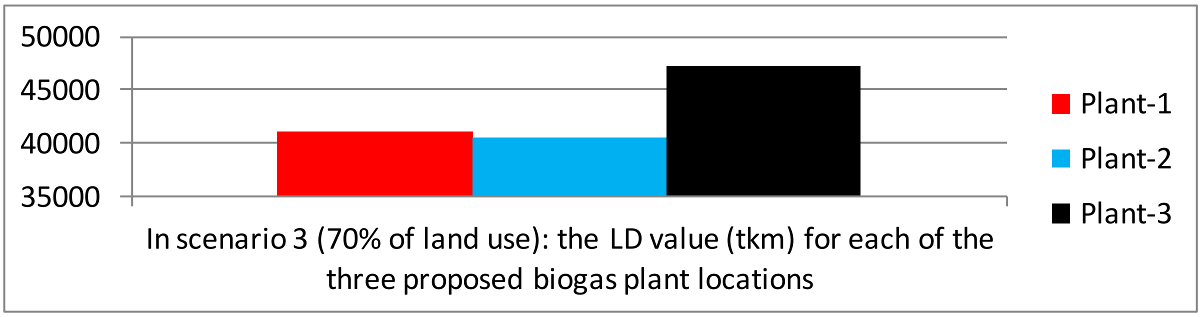

Figure 30. Chart showing the LD value (tkm) for each of the three proposed biogas plant locations in scenario 3.

Therefore, the best plant site location in each of the three scenarios (30%, 50%, and 70%) is shown below (see table 18).

Scenario	Scenario 1 (30%)	Scenario 2 (50%)	Scenario 3 (70%)
Lowest LD value	54134.06tkm	53156.62tkm	40556.11tkm
Plant	Plant-1	Plant-1	Plant-2

Table 18. LD value of the best plant site location in each of the three scenarios (30%, 50%, and 70%).

The location of biogas plant-2 in scenario 3 is the most optimal. Therefore, the best location is the location proposed for candidate biogas plant-2.

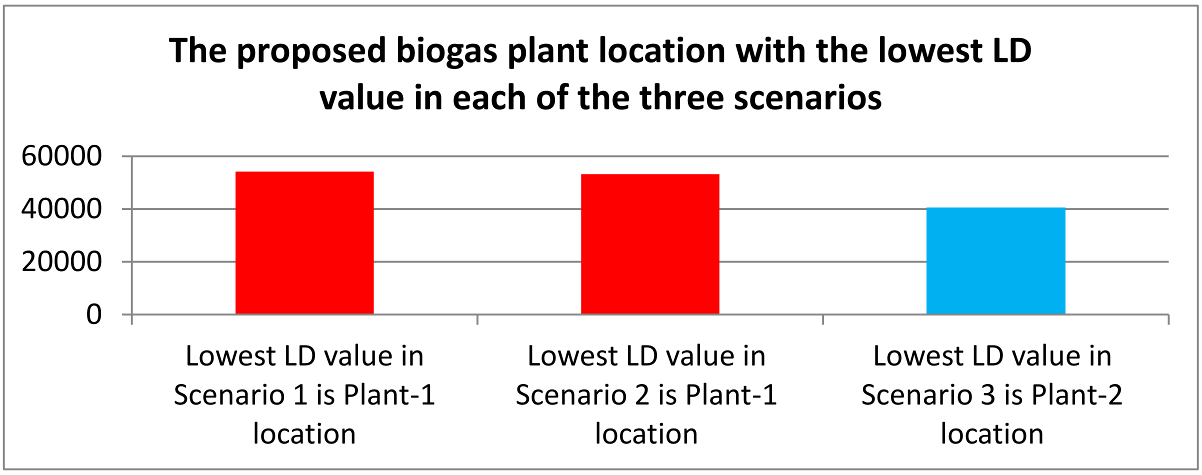

Figure 31. Chart showing the proposed biogas plant location with the lowest LD value in each of the three scenarios.

The results of the analysis reveal that the location of candidate biogas plant-2 in scenario 3 is the most optimal. Therefore, the best location is the location proposed for candidate biogas plant-2. This implies that the location of biogas plant-2 would minimize the transportation cost.

4.3 Effect of Proximity of Biogas Plant to Filling Station

The proximity of the biogas plant to filling station and the amount (5000 tonnes) of ley crops to be collected from each field are considered as major factors for location analysis in this study. Since the three filling stations are not very far from one another, the results of the load-distance (LD) values vary slightly. This indicates that if the filling stations are neglected (not considered as factors in the initial proposal of the biogas plant locations), the best location might be shifted towards the area producing more ley crops. This means that the biogas plant location might be far away from the city centre. In that case, the efficiency will depend on the way and how the biogas produced will be distributed to the filling stations.

4.4 Impact of Location and Land Use

When selecting the most optimal location for the biogas plant the location with the lowest LD value is chosen. In this study, the location of Plant-2 in scenario 3 (70% land use) is selected as the most optimal location because it gives the lowest LD value. Another major observation is that scenario 3 has the lowest number of routes. Consequently, the location of Plant-2 in scenario 3 would result in the lowest transportation cost. The proximity of ley fields to the biogas plant site influences the distance between the fields and the plant site. As the transport distance decreases, the transportation cost and time will decrease. Scenario 3 takes the largest land use scenario (70%) when compared with the other scenarios. This indicates that as the proportion of land use increases, the LD value decreases.

Moreover, chain of operations such as mowing, wilting, and chopping of the ley crops will take place before the leys are transported to the biogas plant site. It is justifiable to state that it takes less time to mow and chop fewer and larger ley crop fields than those fields that are somewhat smaller and many. It was found that it takes a shorter time to chop fewer and larger fields, since less travel time is spent as the chopper moves from one field to another (Vågström, 2005). Scenario 3 (70% land use) has fewer and larger ley crop fields, and consequently the lowest number of routes. The few routes makes scenario 3 more beneficial than the other land use scenarios.

4.5 Effect of Crop Rotation

A set of highly productive fields that are at least some years used for growing ley crops are identified in this study. The actual number of years that the ley crops are left to grow varies among different farms in Uppsala. The same fields will be used for growing ley crops again. In ley farming, the mix of forage is grown in rotation with crops (Jarecki & Lal, 2003). The farmer decides the number of years to grow ley crops, but in most cases, the crops are allowed to grow for several or many years before they are rotated with another crop. The rotation of grasses and legumes with crops in a ley farming system is one of the most economical and eco-friendly farming method (Bouton, 1996). "Having a ley crop in the rotation brings what we call the preceding crop effect. This increases yields of the crops grown after the ley crop" (JTI / driv, 2016, p. 19). Crop rotations with ley crops have the potential to boost nutrient cycling and soil fertility, reverse a declining soil structure, restore failing soil health, and minimize deep drainage (GRDC, 2010). Including legumes in the mix of ley crops will boost the fertility of the soil as well as the yields of crops grown after the leys.

4.6 Optimal Harvest Time

The optimal time to harvest is when the ley crops have its peak value. Therefore, if the ley crops are not harvested at the optimal time, losses will occur due to the delay of the harvest. The time it takes to harvest is determined by the harvesting operation with the minimum capacity. The timeliness costs are affected by farm-specific conditions such as the length of the working day and non-productive time, availability of labour, and transport distances to the field (Nilsson, 2012). Although the costs are also partly influenced by the efficiency of the field operations through planning. Optimal farm conditions and efficient machineries can help minimize the timeliness costs. It can be very difficult to calculate the timeliness coefficients. Not only is it very demanding to determine the optimal date, but also the difference in the value of the crop due to the delay in operation is difficult to determine (Vågström, 2005). In the case of ley crops for the production of biogas, the yield and market value of methane is affected by the change in the crop value due to harvest operations carried out at an unseasonable time. The timeliness costs for an operation are calculated using the timeliness factors taking into consideration the losses that occur from the delay of an operation every day (Nilsson, 2012 in Gunnarsson, 2008).

5. CONCLUSIONS AND RECOMMENDATIONS

The capacity of the candidate biogas plant proposed in this study is 4000 m^3. The yearly total amount of substrates for the biogas plant are 14000 tonnes of organic household waste, 5000 tonnes of silaged ley crops, and 2000 tonnes of grease separator sludge. The location of the biogas plant is based on the optimal collection and transport of only the ley crops to the biogas plant site. Therefore, 5000 tonnes of ley crops will be collected and transported as substrates for a biogas plant annually. The yearly ley crops to be collected and transported from the fields in each scenario do not vary, but the field area will vary according to the scenario. The area requirement is a simplification and all fields will have unique conditions. 5000 tonnes of ley crops make up less than 1% of the total ley produced in Uppsala County. Since a small amount of ley crops will be used for biogas production and also having considered three different land use scenarios, it is justifiable to state that the use of 5000 tonnes of ley crops for the production of biogas will not displace feed or food production.

Moreover, since other substrates (organic household waste and grease separator sludge) will also be required for the proposed candidate biogas plant, the assumption in this study is that the quantity of organic waste collected in Uppsala will increase in the future in order to have adequate organic waste substrates for the biogas plant. Each truck can be loaded with 3 containers of ley crops for transport at once from the field to the plant area. A maximum load of 40 tonnes of ley crops can be loaded to a truck and transported at once. The best location is the location proposed for candidate biogas plant-2. The location of candidate biogas plant-2 is where the existing biogas plant in Uppsala municipality is situated. It is hereby recommended that the existing biogas plant in Uppsala municipality can be upgraded to use the quantity of ley crops proposed in this study.

Furthermore, a candidate biogas plant with multiple substrates is recommended for use in Uppsala because the yield of the biogas produced is higher as the variety of substrates increase. This means that the more the variety of substrates used, the higher the amount of biogas produced. Therefore, the criteria (feedstock ratio and digester volume) of the biogas plant in Västerås are adopted in this study. The biogas plant in Västerås is fed with a mix of food wastes, silage ley crops, and sludge from grease separators. The high diversity of the substrates improves the yield of the biogas plant, which is better than biogas plants with a lesser variety of substrates. "Not only the substrate and retention time affect the amount of gas produced, but also the mix of substrates, and mechanical factors such as stirring" (Behrens, 2014, p. 20). A mix of ley crops with other substrates is beneficial for the reason that the life cycle of ley crops indicate that the crop can significantly reduce greenhouse gas emissions. Moreover, the use of organic waste in biogas vehicle fuel systems result in a greenhouse gas emission savings of about 70%-80% (Börjesson et al., 2015 in EU, 2009).

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Appendix

I.

The total quantity of ley crops produced in Uppsala County in 2014 is calculated at 65% water content (see calculation in appendix I).

Total production with the reported water content of 16.5% in 2014 = 244900 tonnes

Reported water content = 16.5%

Required water content (for biogas production) = 65%

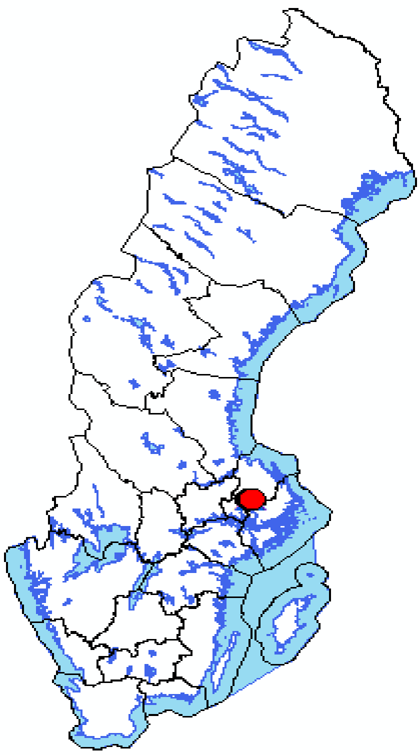
Therefore, the total production with the required water content is calculated as:

$$\frac{244900 \text{ tonnes} * (100 - 16.5)}{(100 - 65)} = 584261.4 \text{ tonnes}$$

Appendix (I)

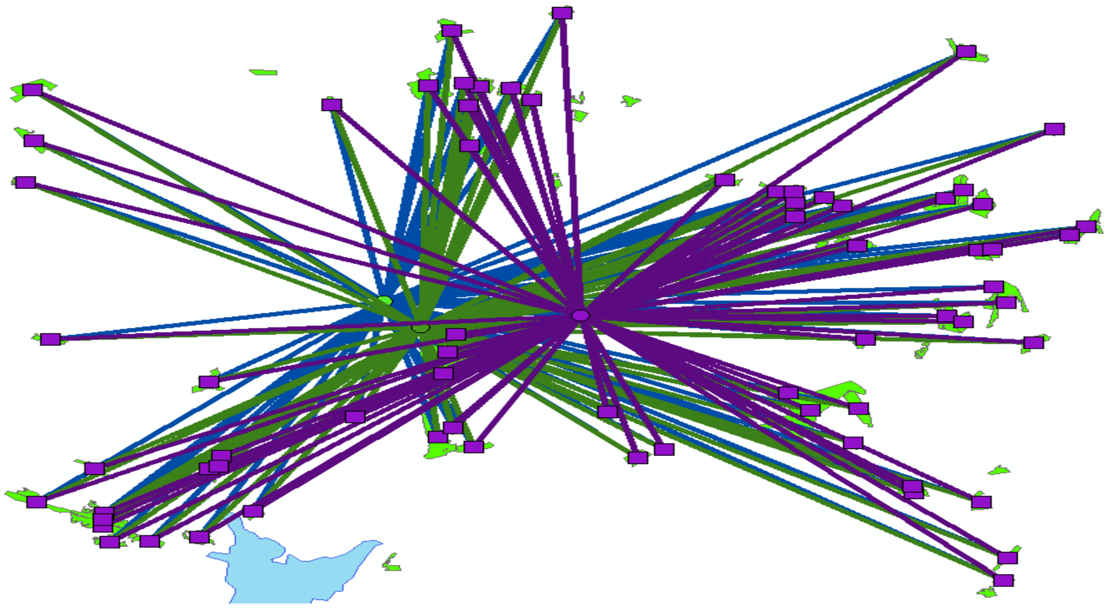
The total productivity of ley crops with 65% water content = 584261.4 tonnes

II.



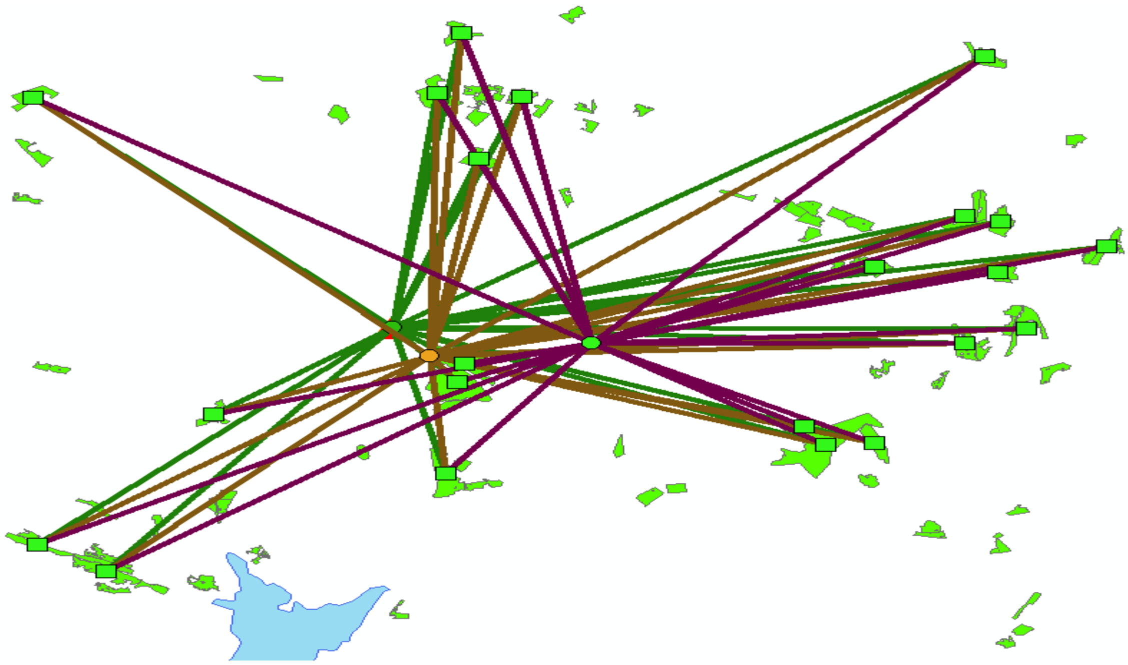
Appendix II. Map of Sweden in GIS space (© Lantmäteriet). The Red dot indicates Uppsala municipality.

III.



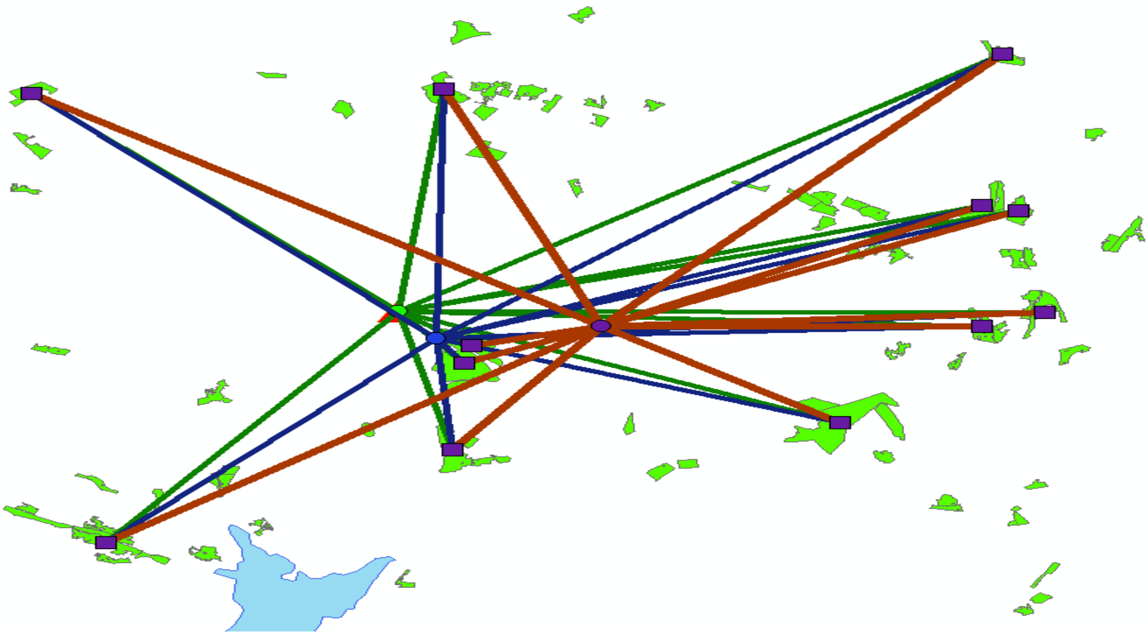
Appendix III. Description of field to biogas plant-1, 2, and 3 with straight lines in scenario 1 (30% ley crop collection and transport).

IV.



Appendix IV. Description of field to biogas plant-1, 2, and 3 with straight lines in scenario 2 (50% ley crop collection and transport).

V.



Appendix V. Description of field to biogas plant-1, 2, and 3 with straight lines in scenario 3 (70% ley crop collection and transport).

The result of LD is shown below (see appendix VI, VII, & VIII).

VI. LD values in scenario 1 (30% land use) is shown below (see appendix VI).

Quantity[t]	**Distance[km]**			**Load-Distance[t-km]**		
	Plant-1	Plant-2	Plant-3	Plant-1	Plant-2	Plant-3
L	D	D	D	LD	LD	LD
106.03	17.27	18.13	17.14	1830.89	1922.38	1817.08
349.12	1.91	0.96	3.90	667.36	333.97	1362.87
105.3	10.37	11.49	14.09	1092.29	1209.80	1483.52
201.08	6.11	5.16	6.68	1228.65	1036.63	1342.52
103.78	15.57	14.62	12.44	1616.02	1516.92	1291.44
104.17	18.27	19.14	17.75	1903.55	1993.43	1849.06
104.61	18.42	19.54	19.16	1926.94	2043.68	2004.69
135.98	9.75	10.21	12.33	1326.29	1387.96	1676.87
92.94	6.64	7.76	7.39	617.45	721.17	686.52
92.75	11.49	12.60	12.95	1065.31	1168.81	1201.08
127.35	15.14	16.00	15.01	1927.92	2037.80	1911.32
110.74	18.00	18.86	17.87	1993.02	2088.57	1978.59
515.2	12.82	11.86	9.69	6603.58	6111.60	4992.28
53.24	12.18	13.04	12.05	648.23	694.17	641.29
213.14	1.66	0.70	4.16	353.11	149.57	886.36

163.29	9.29	10.40	10.75	1516.70	1698.92	1755.74
71.37	5.91	6.42	8.54	421.99	457.97	609.60
77.11	11.12	11.57	13.70	857.22	892.19	1056.02
60.74	19.72	20.18	18.01	1197.92	1225.64	1093.68
62.99	13.30	14.16	13.17	837.73	892.08	829.53
63.43	8.61	9.72	12.32	545.88	616.66	781.54
64.27	8.86	9.97	9.60	569.35	641.07	617.12
61.96	9.90	10.36	12.48	613.56	641.67	773.31
62.06	9.41	10.52	10.15	583.76	653.01	629.88
76.37	12.69	11.74	9.57	969.35	896.42	730.50
60.49	9.86	10.31	12.44	596.31	623.74	752.26
76.67	19.37	20.24	19.24	1485.45	1551.60	1475.46
63.82	10.65	11.10	13.23	679.55	708.49	844.09
72.7	16.15	17.01	15.88	1174.20	1236.93	1154.13
66.62	16.64	17.51	16.51	1108.88	1166.36	1100.20
37.3	19.01	19.87	18.88	709.08	741.26	704.22
42.5	12.95	13.81	12.82	550.24	586.91	544.70
44.66	13.22	14.08	13.09	590.43	628.96	584.61
40.29	13.98	13.02	10.85	563.21	524.73	437.20
36.23	21.37	22.48	22.11	774.12	814.55	801.05
38.53	13.41	14.27	13.28	516.62	549.86	511.60
36.77	9.30	9.75	11.88	341.89	358.57	436.69
37.84	9.72	10.17	12.30	367.82	384.98	465.38
37.01	11.50	11.95	14.08	425.60	442.39	521.02
40.39	18.17	19.03	18.04	733.77	768.61	728.50
38.33	15.44	14.48	12.31	591.80	555.19	471.92
43.43	10.65	11.77	11.39	462.51	510.98	494.79
45.15	15.25	16.12	15.12	688.64	727.60	682.76
31.27	7.89	8.35	10.47	246.84	261.02	327.46
29.61	9.41	10.52	10.15	278.52	311.56	300.53
45.88	7.78	8.90	11.64	357.09	408.29	533.91
48.38	5.36	4.41	5.93	259.39	213.19	286.78
50.93	7.50	8.61	8.78	381.77	438.60	447.29
30.83	18.13	18.99	18.00	558.94	585.54	554.92
29.66	13.91	12.95	10.78	412.55	384.23	319.79
50.25	12.30	13.16	12.17	618.06	661.42	611.52
47.01	3.55	2.59	4.12	166.84	121.94	193.46
33.48	6.03	6.48	8.61	201.85	217.04	288.17
30.69	16.10	15.14	12.97	494.09	464.78	398.11

	32.79	6.16	5.20	6.72	201.84	170.53	220.41
	34.36	7.68	6.72	5.45	263.86	231.04	187.29
	29.85	6.43	5.47	4.18	191.82	163.31	124.80
	30.49	6.42	6.87	9.00	195.71	209.54	274.32
	30.49	15.38	14.42	12.25	468.86	439.74	373.50
	31.72	7.90	9.02	11.61	250.56	285.96	368.41
	25.8	16.64	17.51	16.51	429.43	451.69	426.07
	36.42	7.81	8.92	8.55	284.33	324.98	311.40
	33.92	6.31	6.76	8.88	213.91	229.29	301.36
	32.89	9.79	10.65	9.66	321.98	350.35	317.69
	29.41	13.92	12.96	10.79	409.37	381.28	317.39
	39.31	8.39	9.50	9.13	329.65	373.52	358.86
	50.39	15.15	14.19	12.02	763.16	715.04	605.57
	39.46	7.04	6.08	5.74	277.72	240.03	226.48
	56.96	4.95	5.06	7.52	281.77	288.18	428.62
SUM	5000	788.93	811.55	815.96	**54134.06**	**54835.94**	**55817.08**

Appendix VI. The results of LD in scenario 1 (30% land use).

The lowest value of LD is 54134.06tkm. Therefore, in scenario 1, Plant-1 is the best option (see figure 19).

VII.

LD values in scenario 2 (50% land use) is shown below (see appendix VII).

Quantity[t]	**Distance[km]**			**Load-Distance[t-km]**		
	Plant-1	Plant-2	Plant-3	Plant-1	Plant-2	Plant-3
L	D	D	D	LD	LD	LD
176.72	17.27	18.13	17.14	3051.54	3204.02	3028.52
581.87	1.91	0.96	3.90	1112.27	556.62	2271.47
175.49	10.37	11.49	14.09	1820.39	2016.23	2472.39
335.13	6.11	5.16	6.68	2047.73	1727.70	2237.51
172.96	15.57	14.62	12.44	2693.26	2528.10	2152.33
173.61	18.27	19.14	17.75	3172.46	3322.26	3081.64
174.35	18.42	19.54	19.16	3211.57	3406.13	3341.14
226.64	9.75	10.21	12.33	2210.55	2313.34	2794.87
154.9	6.64	7.76	7.39	1029.08	1201.94	1144.20
154.58	11.49	12.60	12.95	1775.48	1947.98	2001.76
212.26	15.14	16.00	15.01	3213.35	3396.49	3185.69
184.56	18.00	18.86	17.87	3321.57	3480.82	3297.53
858.67	12.82	11.86	9.69	11006.02	10186.04	8320.50

	355.23	1.66	0.70	4.16	588.51	249.28	1477.25
	272.14	9.29	10.40	10.75	2527.74	2831.43	2926.12
	118.96	5.91	6.42	8.54	703.38	763.34	1016.09
	128.51	11.12	11.57	13.70	1428.62	1486.91	1759.95
	56.16	12.69	11.74	9.57	712.83	659.20	537.18
	127.29	19.37	20.24	19.24	2466.20	2576.02	2449.61
	127.78	16.15	17.01	15.88	2063.81	2174.07	2028.53
	121.16	16.64	17.51	16.51	2016.69	2121.23	2000.90
	111.03	8.86	9.97	9.60	983.59	1107.49	1066.10
SUM	5000	263.46	271.88	274.35	**53156.62**	**53256.64**	**54591.30**

Appendix VII. The results of LD in scenario 2 (50% land use).

The lowest value of LD is 53156.62tkm. Therefore, in scenario 2, Plant-1 is the best option (see figure 22).

VIII. LD values in scenario 3 (70% land use) is shown below (see appendix VIII).

	Quantity[t]	**Distance[km]**			**Load-Distance[t-km]**		
		Plant-1	Plant-2	Plant-3	Plant-1	Plant-2	Plant-3
	L	D	D	D	LD	LD	LD
	247.4	17.27	18.13	17.14	4272.02	4485.49	4239.79
	814.61	1.91	0.96	3.90	1557.16	779.26	3180.02
	245.69	10.37	11.49	14.09	2548.58	2822.76	3461.41
	469.19	6.11	5.16	6.68	2866.86	2418.82	3132.57
	25.74	18.42	19.54	19.16	474.14	502.86	493.27
	244.09	9.75	10.21	12.33	2380.75	2491.45	3010.06
	317.29	15.14	16.00	15.01	4803.37	5077.14	4762.03
	297.16	18.00	18.86	17.87	5348.07	5604.46	5309.34
	258.38	12.82	11.86	9.69	3311.79	3065.05	2503.70
	1202.13	1.66	0.70	4.16	1991.56	843.60	4999.16
	497.32	9.29	10.40	10.75	4619.29	5174.28	5347.32
	381	18.27	19.14	17.75	6962.20	7290.94	6762.89
SUM	5000	139.01	142.44	148.53	**41135.79**	**40556.11**	**47201.55**

Appendix VIII. The results of LD in scenario 3 (70% land use).

The lowest value of LD is 40556.11tkm. Therefore, in scenario 3, Plant-2 is the best option (see figure 26).

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