Sveriges lantbruksuniversitet
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Department of Soil and Environment

Analysis of the distribution of plant nutrients in a biogas production system

– A look at VH Biogas, co-digesting manure from several farms

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Analysis of the distribution of plant nutrients in a biogas production system
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Analys av omfördelningen av växtnäring i ett biogasproduktionssystem
– En titt på VH Biogas, samrötning av gödsel från flera olika gårdar

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Abstract
This study examined nutrient flows in a system where 20 farms deliver manure to a biogas plant for digestion, and then receive digestate back. Some other substrates were also anaerobically digested at the plant e.g. slaughter residues. The farms had different types of production: Organic and conventional dairy and conventional pig. The aim was to analyse the re-distribution of plant nutrients this creates. Biogas production is of interest since it has the potential to reduce the use of fossil fuels and potentially also greenhouse gas emission. The use of digestate as fertilizer has the potential for a more even distribution of plant nutrients across the landscape.

Data was taken from the biogas production plant and then analysed and organized to be able to see what the different types of farms contributed with in terms of plant nutrients. The results showed that there is a redistribution of plant nutrients between the farms and one type of farm can lose or gain nutrients compared to the other types of farms. The "winner" of the different types of farms seemed to be the organic dairy farms as they gained mineral nitrogen, whereas the others lost mineral N. The organic dairy farms lost phosphorous and potassium however, so it is dependent on each individual farm what plant nutrient is valued the most. Conventional pig farms gained K whereas the dairy farms lost K. All types of farms lost P which was probably due to the solid fraction of the digestate being separated and not included in the digestate going back to the farms. The study also showed that the substrates other than manure had an influence on the plant nutrient content of the digestate. Slaughter residues stood for a lot of the total ingoing organic nitrogen to the biogas plant.

Keywords: Biogas, digestate, manure, nutrients

Sammanfattning

Denna uppsats undersökte flödet av växtnäring i ett biogasproduktionssystem där 20 gårdar levererar gödsel för rötning och tar tillbaka rötrest. En del andra substrat användes också i rötningen, exempelvis slaktrester. Gårdarna hade olika produktionsinriktningar: Ekologisk och konventionell mjölkproduktion samt konventionell svinuppfödning. Målet med uppsatsen var att analysera omfördelningen av växtnäring som skapas mellan gårdarna i detta system. Biogasproduktion är av intresse på grund av dess möjlighet att minska användandet av fossila bränslen och potentiellt även utsläpp av växthusgaser. Att använda rötrest som gödselmedel skapar förutsättningar för en jämnare fördelning av växtnäring i landskapet.

Data som togs från biogasanläggningen analyserades och organiserades för att skapa en bild av vad de olika produktionsinriktningarna bidrog med till systemet, i form av växtnäring. Resultatet visade att växtnäring omfördelas mellan gårdarna och att en typ av gård kan förlora eller tjäna växtnäring jämfört med en annan typ av gård. ”Vinnaren” bland de olika produktionsinriktningarna verkade vara de ekologiska mjölkgårdarna eftersom de tjänade mineralkväve medan de andra typerna förlorade mineralkväve. Gårdarna med ekologisk mjölkproduktion förlorade dock fosfor och kalium, och vilken typ av gård som kan anses tjäna på systemet var därmed subjektivt. De konventionella grisgårdarna tjänade kalium medan både ekologiska och konventionella mjölkgårdar förlorade kalium. Alla typer av gårdar förlorade fosfor vilket troligtvis berodde på att den fasta fraktionen i rötresten separerades och var inte inkluderad i den rötrest som transporterades tillbaka till gårdarna. Dessutom såldes en del rötrest till växtodlingsgårdar. Studien visade också att substraten utöver gödseln påverkade växtnäringsinnehållet i rötresten. Slaktrester stod för en stor del av den totala mängden organiskt kväve som inkom till biogasanläggningen.

Nyckelord: Biogas, rötrest, gödsel, växtnäring

Popular scientific summary

Who's the winner and who's the loser when co-digesting manure to produce biogas?

Conventional dairy and pig farms are giving valuable plant nutrients to organic dairy farms in a biogas production system where animal manure is the main substrate. The plant nutrients studied were nitrogen, phosphorus and potassium, N, P and K. The biogas plant, situated in south-west Sweden, used a system where different types of farms delivered manure to the plant and then received digestate back. The study showed that organic dairy farms were the biggest winners and conventional dairy farms were the biggest losers.

Biogas production is a hot topic in Sweden, and Europe overall, due to the climate change crisis we stand before. The question of how to replace fossil fuels with renewable energy sources has therefore rightly been in focus, and the production of biogas is no doubt an interesting alternative. What has been overlooked in public debate and research when it comes to biogas, is what's in the leftovers – the digestate – and what to do with it. A common substrate in biogas production is manure. Manure contains plant nutrients, including N, P and K but the concentrations of these may vary between animal species and production systems. So, in a system where you mix manure (and nutrients) from different types of farms and then send that blend back, you'll end up with some farms gaining nutrients and some farms losing nutrients. That is exactly what a student at SLU decided to take closer look at in a thesis.

The study showed that organic dairy farms were winners of N, conventional dairy farmers were losers of all plant nutrients and the conventional pig farms lost N and P but gained K. This could pour fuel into the fire of the debate around the question if organic farming is dependent on conventional farming for its supply of plant nutrients, but it shines light upon a greater issue as well. Plant nutrients are

valuable, and most farmers wouldn’t happily give them away for free to others, which is why it is important to try and find out what nutrients are going where in a biogas production system using co-digestion of manure. The study made may possibly lay the groundwork for a compensation system between the involved farms to make sure everyone is getting a fair deal.

One surprising find was that all farms were losers of P, and that was attributed to the fact that the biogas plant separated a solid fraction from the liquid one in the digestate. No analyses were made on the solid fraction as it was not sent back to farms delivering manure, but it seems likely that a lot of the P were bound to the organic matter contained within that fraction.

The results in the thesis was created by taking analyses of manure and digestate that was available via the biogas plant and running them with all the data of incoming and outgoing deliveries to see what the nutrient flows between the farms looked like.

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1 Introduction

1.1 Objectives

This study examined nutrient flows in a system where 20 farms deliver manure to a biogas plant for digestion, and then receive digestate back. The specific purpose was to analyse how the distribution of plant nutrients (organic and mineral nitrogen, phosphorus and potassium), as well as fresh weight and dry matter weight of the substrates and digestate to and from the different farms is affected. The overall aim was to assess the potential for resource-efficient utilization of plant nutrients in small to large-scale biogas plants.

Questions:

- Can digesting manure help to more evenly distribute plant nutrients?
- Is there a risk of farmers losing plant nutrients that they would like to keep?
- Do different kinds of farms (dairy, pigs, organic, conventional) deliver/receive different ratios and/or amounts of plant nutrients?
- Is there a seasonal difference in plant nutrient delivery (e.g. grazing period for dairy) to the biogas plant?
- How much do the added substrates (eg food waste etc) influence the plant nutrient content of the digestate?

1.2 Biogas production reduces the need of fossil fuels

Biogas is a renewable source of energy and in a world of increasing energy demands it is necessary to find valid alternatives to fossil-based fuels to reduce the anthropogenic greenhouse gas emissions. The Paris agreement that has been signed by 195 countries states that the increase of the mean global temperature must be kept under 2°C (unfccc.int, 2017) and the emissions of greenhouse gases must be lowered in order to reach that goal. One way of decreasing the use of fossil fuels is to increase biogas production. That would also create an opportunity to decrease the negative impact that management of waste and agricultural practices have on the environment as of today (Börjesson & Berglund, 2007).

1.3 The microbiology of biogas production

Biogas is a mixture of gases, consisting mainly of carbon dioxide and methane, which is produced through anaerobic digestion of a substrate (Morgan & Pain, 2008). The microbial processes that together produce biogas is generally divided into four different steps (Fig. 1). These names vary depending on the literature but in this thesis, they will be called hydrolysis, fermentation, acetogenesis and methanogenesis after Angenent *et al.,* (2004), Weiland (2010) and Zhang *et al.,* (2014). A different group of microorganisms are responsible for each step and they are all somewhat dependent on each other (Weiland, 2010).

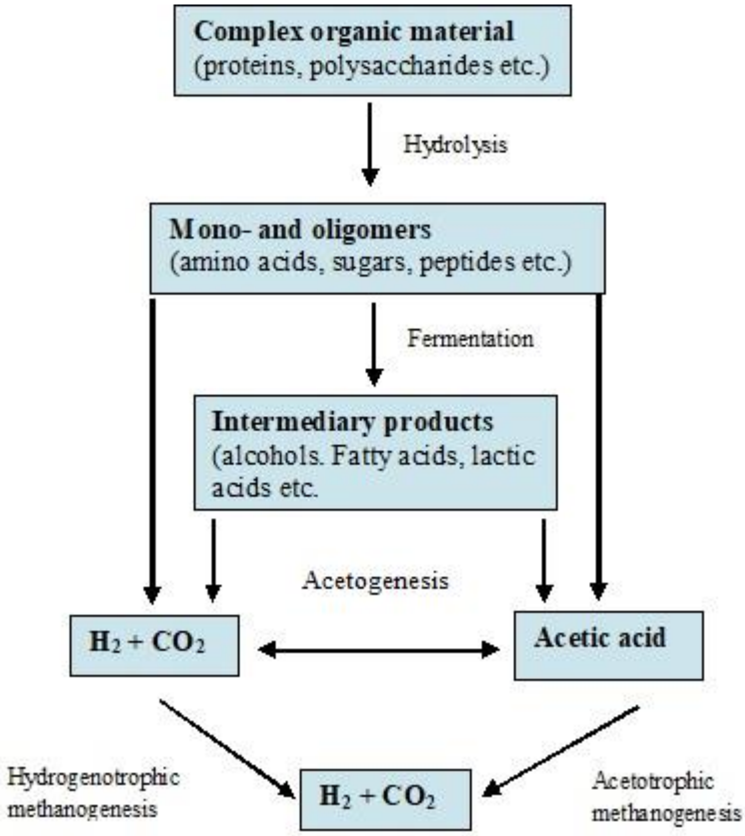

Figure 1. Illustration of the chemical processes involved in biogas production. From Schnürer & Jarvis (2009).

The first step, hydrolysis, consists of the degradation of organic substances like lipids, proteins and carbohydrates (Weiland, 2010; Morgan & Pain, 2008). These substances are broken down to monomers and oligomers such as long chain fatty acids, amino acids, sugars and some alcohols by enzymes produced by different types of microorganisms (Weiland, 2010; Schnürer & Jarvis, 2009; Morgan & Pain, 2008). This step enables microorganisms to directly absorb the nutrients and use as substrate. Different substrates take different amount of time for the microbes to hydrolyse, proteins are for example broken down more rapidly than cellulose and hemicellulose (Schnürer & Jarvis, 2009)

The second step, fermentation, produces mostly organic acids, alcohols, CO_2, H_2 as well as ammonia. The amounts and ratios of these substances that are produced depends on both the substrate and what microorganisms are present in the digestion chamber (Schnürer & Jarvis, 2009). All of the products of the second step may be used as substrate for other groups of microorganisms in the third step: acetogenesis. In that step they are further oxidized to H_2 and acetic acid. The other pathway in acetogenesis is the formation of acetate from H_2 and CO_2 (Angenent *et al.*, 2004)

The fourth and last step, methanogenesis, is heavily dependent on the third step. Biogas is produced from acetate and from H_2 and CO_2 by Archea as opposed to the first three steps where bacteria are responsible for the decomposition of the substrates. The methanogenesis is dependent on the acetogenesis and vice versa because the acetogenetic bacteria will stop producing H_2 whenever the concentration of it gets too high. The process of methanogenesis consumes H_2 at a steady rate which creates the possibility of a steady production of it by the bacteria involved in the third step. If both the third and fourth step are in line with each other, an equilibrium may be reached where biogas is produced while the concentration of H_2 is kept low. (Schnürer & Jarvis, 2009).

In conclusion, it can be said that the production of biogas is a complex process with several organisms involved that all need adequate living conditions. The process is also heavily dependent on the substrates used in the anaerobic digestion chamber.

1.4 Anaerobic digestion of manure could lead to less eutrophication

Aside from the potential reduction of fossil fuel use when producing biogas, eutrophication is an acknowledged issue in waters, as in for example the Baltic sea (Andersen *et al.*, 2015) and the phenomenon is due to increased influx of nitrogen and phosphorus into the sea (Gustafsson *et al.*, 2012). Eutrophication leads to hypoxic conditions in the water and it has been proven that the influx of nutrients to the Baltic sea is caused by anthropogenic activities (Carstensen *et al.*, 2014). It has been seen that a significant portion of the leached nutrients stem from agriculture. (Humborg, 2016; Bonsdorff *et al.*, 1997) point out that aqua- and agriculture are the two activities that first and foremost cause oxygen-deficient sea bottoms as a result of eutrophication. The Baltic Sea Action Plan states that changed agricultural practices to reduce the flow of nutrients into the Baltic sea, are an objective towards the goal of striving for a healthy sea (HELCOM, 2007). All the countries around the Baltic sea are responsible for the influx of nutrients into it, but some countries, such as Denmark have shown a decrease in anthropogenic inputs from 1990-2010. Meanwhile, other countries, such as Poland have instead shown an increase in nutrient inputs during the same time span (Humborg, 2016). Humborg (2016) also states that nutrient imbalances are usually connected to high densities of livestock. This is likely due to the fact that the manure is spread on a relatively small area. This thesis will focus on the possible environmental advantages of anaerobically digesting manure from several farms, where digestate is redistributed to farmland after digestion as a valuable fertilizer. This might enable efficient use of plant nutrients due to, in theory, a lower N-org/NH_4-N quota and the difference in physical properties between manure and digestate. Moreover digestion of manure from different farms at one biogas plant may enable logistic networks for strategic spreading of digestate that might reduce leaching and nutrient load on the Baltic Sea. In order to be able to distribute the nutrients on an even larger scale, more regionally, some sort of concentration of the digestate would be needed to make it economically sound to transport it further. This could perhaps be done through drying or filtering the nutrients from the water.

In both countries mentioned earlier, Denmark and Poland, agricultural practises are bound to have changed in some way during 1990-2010 and that may act as an indicator that change can both be positive and negative in regard to leaching of nutrients. It is therefore of interest to investigate how the anaerobic digestion of manure from several farms affects the distribution of plant nutrients and if it may increase or decrease the leaching of them. Pig manure contains more phosphorus than dairy manure (Brown, 2008), so from a plant nutrient distribution perspective it should be positive to co-digest manure from different farms to get a better distribution of phosphorus in the landscape.

1.5 Manure as a biogas production substrate

When constructing a biogas production plant there are many things to consider, not the least what to use as the primary digestion substrate. Using manure as a substrate comes with many advantages including its steady supply, in terms of that there is little variance in the volumes produced throughout the year, it being a waste product and that it contains many of the micronutrients that the anaerobic digestion microbes demands. If manure is not used as substrate, many of the micronutrients need to be added in order to achieve satisfactory production of biogas e.g. cobalt and iron (Weiland, 2010; Jarvis *et al.*, 1997) There is also no shortage of substrate as 1578 million tonnes of manure is produced in the EU as of 2003 (Nielsen *et al.*, 2007). It is also a substrate that requires little handling or pre-treatment before it can be put through the digestion chamber compared to for example a ley crop or municipal organic waste (Börjesson & Berglund, 2006). Thereby, little energy would be needed to make it a suitable substrate, which increases the net energy output. Furthermore, manure is produced regardless of it being used in biogas production or not which is not the case if for example ley would be produced for the purpose of biogas production. However, a biogas plant is generally a facility were wastes of different kinds are used and may act as a valuable step towards closing the circulation of nutrients between agricultural production and the consumption in cities. It is also possible that if a greater deal of the manure available were to be put through an anaerobic digestion chamber, it would be possible to prevent methane from leaking to the atmosphere due to spontaneous anaerobic digestion taking place at the liquid manure storage. If the energy stored in the manure could instead be gathered and utilized, a clean source of renewable energy has been found as well as a way to reduce greenhouse gas emissions. Anaerobic digestion also changes the properties of the manure. A review by Möller and Müller (2012) states that digestion of manure leads to higher NH_4-N content and pH as well as lower content of organic matter, carbon and viscosity(Möller & Müller, 2012)

1.6 Biogas yield potential

The energy and nutrient contents of manure can vary greatly between different kinds of manure. Factors that influence are the species of animal, or rather more specifically on how the digestive system of the animal is formed (Omnivore, ruminant, colon digester etc.) (Lukehurst *et al.*, 2010), as well as the sex, age and diet of the animal (Lukehurst *et al.*, 2010). The potential methane yield from manure is relatively low compared to other substrates (see table 1) but it has other advantages.

With a dry matter content typically around 5-9 % (Angelidaki & Ellegaard, 2003) it has a high content of water and may therefore act as a solvent for other substrates with a higher dry matter content. That facilitates practical issues on the plant regarding pumping and treatment of the more solid substrates. Manure has also got a high buffering capacity, providing stability to the anaerobic digestion process which is sensitive to changes in pH (Angelidaki & Ellegaard, 2003).

Table 1. Potential methane yields in m^3 per m^3 of different kinds of substrates. From (Angelidaki & Ellegaard, 2003) and (Lehtomäki et al., 2008)

Substrate	**Methane yield (m^3/m^3)**
Manure-pig	13,9
Manure-dairy	13,4
Manure-mixed with straw	28,5
Industrial waste-conc. sludge	50-70
Industrial waste-molasse	190
Industrial waste-meat and bone fluor	325
Household waste	100-150

1.7 Separation of digestate

If the digestate is separated into a solid and a liquid fraction after going through the digestion chamber, it will affect the plant nutrients it contains. The solid fraction usually has high content of N and most of the total P will be allocated to the solid fraction (Möller & Müller, 2012). There are increased risks of N losses in the solid fraction due to ammonia volatilization, leaching and denitrification if it is not stored anaerobically. The same review by Möller & Müller (2012) states that the liquid fraction usually has a low dry matter and P content, but high N and K levels. They also state other advantages in terms of nutrient use efficiency of separating anaerobically digested manure. These are for example:

- Practical improvements due to changed physical properties, e.g. more homogenous, easier to spread, faster infiltration in soil for the liquid fraction
- The liquid fraction will contain less P and heavy metals
- Increased plant uptake of N because of higher NH_4-N/N-tot quotas and lower content of C in the liquid fraction, leading to less immobilization in the ground when applied.

1.8 The effect of anaerobic digestion on weed seeds, chemicals and pathogens

When putting manure through anaerobic digestion it also seems to stimulate microbial activity and thus helping dissipating farm chemicals for example. It has been shown that digestate from manure increases dissipation of the herbicide atrazine (Kadian *et al.*, 2008) and increases the microbial activity in soil contaminated with the insecticide chlorpyrifos compared to fresh manure (Kadian *et al.*, 2012).

Weed seed viability is another important factor to consider when anaerobically digesting manure, especially where manure from different farms are being co-digested. The digestion process itself does substantially reduce the viability of weed seeds according to (Šarapatka *et al.*, 1993) but (Allan *et al.*, 2003) found no significant differences before or after digestion. It seems there is no scientific consensus on the matter. However, the hygienization routines of substrate are likely to decrease weed seed germination.

Another concern when spreading manure and/or digestate on your fields are that the pathogens therein are also being spread, if there is no hygienization step. This is of special concern where manure from several different farms are being co-digested, and the digestate then being used on all of those farms. It is especially sensitive when spreading on fields where forage is grown, so as to not have the animals become infected through feeding. Studies show, however, that anaerobic digestion dramatically decreases the pathogenic bacteria present in manure faster than if the manure is being stored as is (Côté *et al.*, 2006; Kearney *et al.*, 1993). It could therefore be seen as an advantage to each farm to anaerobically digest the manure, even if it means risking exposure to pathogens on other farms because they are likely to be eliminated in the digestion process anyway. All substrate going into the digestion chamber at VH Biogas plant, which was studied in this work, is hygienized which should reduce pathogen presence anyway.

1.9 Greenhouse gas emissions

Producing biogas from manure to reduce fossil fuel use seems like a step towards reducing greenhouse gas emissions, but it is important to take into account the difference in emissions from manure and digestate. It has been shown that digestate have three times higher emissions of CH_4 during storage than manure during summer (Rodhe *et al.*, 2015). The authors of that article recommends cooling or acidifying the digestate as an alternative to limiting storage during summer months and utilizing gas tight covers to collect CH4 during the warm months. They also point out that digestate cause more NH3 emissions during spreading than manure does, due to higher pH. Rodhe (2018) lists in a more recent article several measures that can be taken to reduce greenhouse gas emissions from both manure and digestate derived from manure. These include: acidification, reducing temperature through installing white cover on storage or making the storage is shaded, having a long retention time for the substrate in the biogas production process and finally to make sure there is some form of crust on the manure/digestate (Rodhe *et al.*, 2018)

1.10 VH Biogas – a biogas production plant in Vårgårda, Västergötland

The biogas production plant from which the data used in this study was taken is situated in Sweden. The plant has many owners and none of them own more than 8 % of the company. Biogas production was started in October 2013. The main substrate is animal manure which stands for about 85 % of the total mass of the substrates used. The other 15 % are mainly slaughter residues, industrial residues (grease trap grease, frying oil, iron filter sludge), ley and some food waste. The manure that is delivered to the plant is produced on farms that receive digestate in return, without any payment in-between. Both farms with organic and conventional production deliver manure to and receive digestate from the biogas plant. The farms that deliver manure have dairy, pork, and poultry production. The poultry manure is bought in and the poultry farmers do not receive digestate in return. Of the manure that is used for the biogas production, 80 % is produced in a 15km radius from the plant and the farm furthest away is located 30km away. The size of the farms and therefore the amount of substrate delivered from them, varied during the study period (Tables 2-7 in Appendix). The other substrates are purchased and are considered valuable due to their higher biogas potential (Table 1.). In order to handle variation in influx of substrate and outflux of digestate (Fig. 3) the storage capacity at the plant was dimensioned for this. On top of the previous mentioned substrates, about 300-400 tonnes of iron filter sludge is added to the digestion chambers every year. This is not documented in the plants web-based data handling tool (DVTime), according to the manager, and added that it contains a lot of P which is seen as an advantage for the plant nutrient content in the digestate.

The biogas production plant is of the continuous stirred tank reactor type. The stirring system today is not adequate, according to the manager, and it is believed it impairs the biogas production. There is three propeller-stirrers in each chamber with a combined effect of 48kW. There are currently ideas of implementing a gas-bubble stirring system in the future to make digestion more efficient.

The end product at the plant is vehicle gas, a purified version of biogas containing at least 97 % methane. The biogas collected in the anaerobic digestion chambers have a methane content of about 65 %. The production of biogas in this facility starts with all of the substrates (around 250 m^3 per day) getting mixed and then pumped through a hygienization chamber where the mixed substrate is heated to 70°C for one hour. From there, the substrate is pumped into the bottom of the digestion chambers where the temperature is kept around 39-40 °C. Solid substrates, like silage, are added from the top of the digestion chambers. The volume of the two chambers is 2500 m^3 and 4500 m^3 respectively. The plant is heated by a boiler fuelled by wood-chips and the heating system is automatic. The retention time in the digestion chambers is 34 days and then an additional three to four days in the unloading chamber. The unloading chamber as of today does not have a working gas collecting system but there are plans to build a new digestion chamber and use one of the old ones as a post-digestion gas collection chamber to maximize biogas output of the substrate. It is estimated that there is about 4 m^3 of biogas left per wet tonne of digestate after going through the digestion chamber, a number that is figured to drop to about half when the post-digestion gas collection chamber is in place.

The digestate is also put through an auger press that separates a dry faction of about 30 % dry matter from the digestate. The dry faction contains mostly fibres and is sold as animal bedding to farmers.

Every day, 4700kg of purified vehicle gas is produced at the plant and delivered and sold to the company Svensk Fordonsgas via a 4km long pipeline. In the end, the gas is primarily used for fuel in public transport such as buses and municipality owned vehicles. No gas is stored at the plant leading to some of it being burned when Svensk Fordonsgas cannot receive and store any more. The total amount of gas burned adds up to only a few parts per mille. The purification is made through a dry-filtration followed by a process called membrane filtration which reduces CO_2, H_2, condense water, sulphuric gases and other unwanted substances.

The total methane emissions from the plant is about 0,2 – 0,3 %, which can be compared with the regulations stating that it must be under 0,5 %. The whole plant consumes about 200 000kW of electricity every month. No electricity is produced from the biogas produced at the site. The digestate is organically certified (biogodsel.se, 2018) and can be used as fertilizer in both conventional and organic crop production.

Many of the farmers that deliver manure and receives digestate do so in the belief that they receive a better fertilizer. Better in this case may be from a plant nutrient perspective, but also because of practical reasons. This will be discussed later in the thesis. The manager of the plant, and some of the stakeholders that do not deliver manure are solely focused on the production of biogas however and that is the main interest for them. Many of the farmers are also owners of the plant, aside from delivering manure.

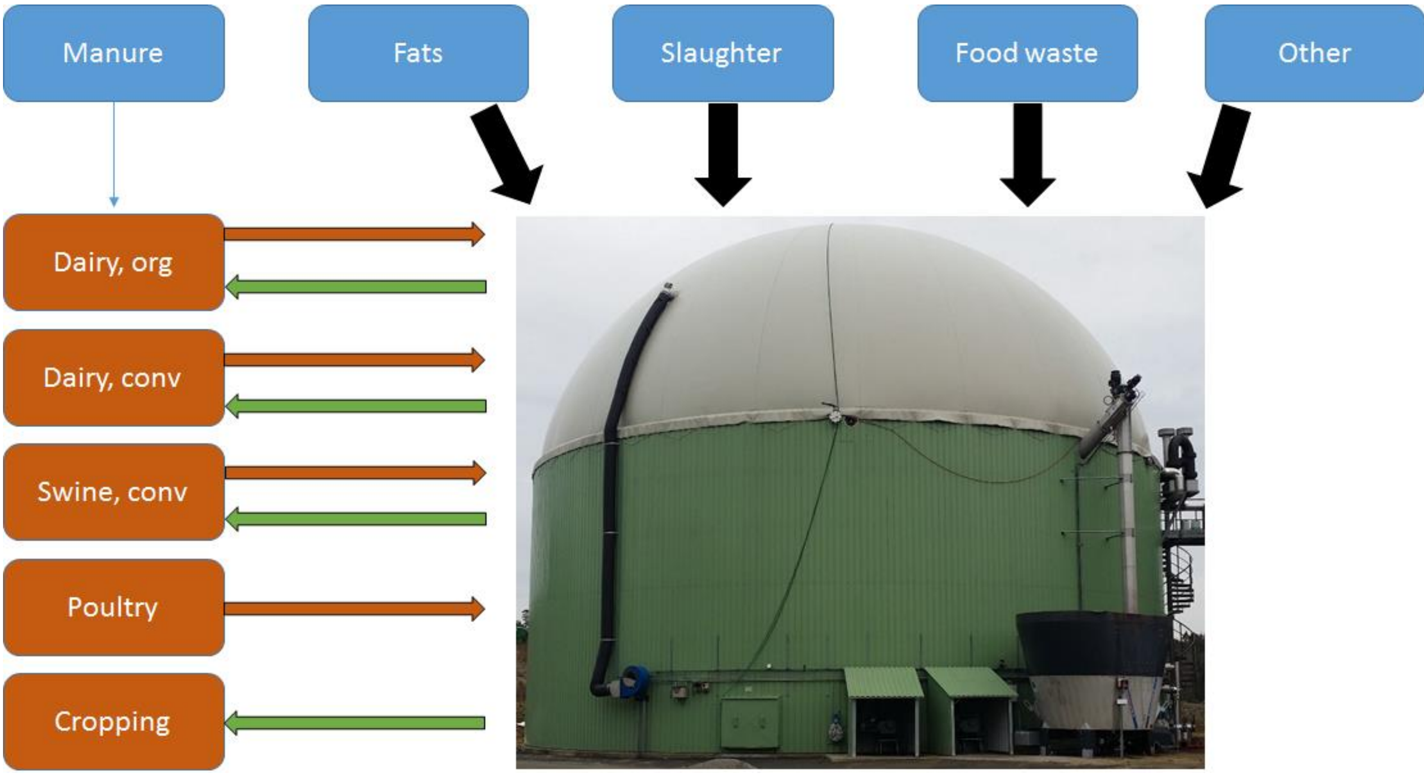

Figure 2. Illustration of the different flows of substrates (arrows pointing towards the digestion chamber) to and digestate (arrows pointing away from the digestion chamber) from VH Biogas plant.

2 Method

In order to investigate flows of materials and nutrients from farms and other sources to the biogas plant and back to farms (Fig. 2), existing data from VH Biogas was used. This included collecting and analysing data available from VH Biogas, interviewing the manager of the plant as well as one of the farmers delivering manure to the plant. A literature review was also made in order to examine how manure as a biogas substrate might affect the nutrient balances on farms as well as balances on a more regional or national level.

2.1 Collection of data

The raw data were collected from a web-based tool called DVTime (Developed by Dataväxt) which is used to store data at VH biogas plant. All inbound deliveries of substrates, mainly manure, and all outbound deliveries of digestate are registered. In DVTime, the digestate was sometimes registered under the name bioslurry but in this report digestate will be the term used. Data from 2015 and 2016 were used in this study. The data stored in the tool consisted of, for example, net weight and analysis of plant nutrient content. Analyses of the manure was taken twice every year at every farm that delivered manure and the digestate produced in the plant was analysed four times every year. This means that every in- and outbound delivery was not individually analysed but rather the latest available analysis was applied for the substrate/digestate and therefore the values for plant nutrients and dry matter are based on the net weight of the delivery and calculated by DVTime. All the values that are present in DVTime have been manually typed in by the staff at the biogas plant or calculated by the tool from values manually typed in. All analyses had been made from samples that the staff at the plant sent in to Eurofins lab. One demarcation that was made for this study was to not include any micronutrients or heavy metals, so it is not known to what extent the distribution of those are affected.

The data that was available through DVTime was downloaded and pasted in Microsoft Excel where it was arranged in such a way that it was suitable for statistical analysis. The statistical analyses were then made in JMP. Most of the work done in JMP consisted of sorting and organizing data as well as constructing tables. The data was sorted and grouped by different parameters which will be further explained. They were:

- Grazing/non-grazing period
- Category
- Type of product
- Substrate/digestate
- Type of deliverer/receiver
- Farm/customer

2.2 Processing of data

Grazing/non-grazing period: The data was divided in six different groupings according to year and whether the delivery had been made before, during or after the grazing period for a given year (2015 or 2016). The grazing period was set as June, July and August. The intention of dividing the data by grazing/non-grazing period was to see if there were any differences between how much the dairy farms and the pig farms delivered to the biogas plant in terms of plant nutrients during the summer months compared to the rest of the year. The idea was to see if the dairy farms delivered less nutrients since the dairy were out on pasture and spread a portion of the nutrients on the pastures through urination and defecation.

Category: The categories concern how the biogas plant classified the different substrates taken into the facility as well as the digestate taken out of it. The different categories were digestate, manure, food waste, slaughter residues category 1 and 2 and other. The reason VH Biogas had for dividing the data into these groups was to see how much the different substrates contributed towards the plant nutrient content in the digestate. There were some inconsequence's in how the plant had divided the different deliverers and therefore I chose to rename the categories according to Type of product in order to better explain what was included.

Type of product: This grouping was made by me and was intended to divide the different substrates into different categories so that it would be possible to trace from where the nutrients in the digestate came and what type of substrate was most valuable from a plant nutrient perspective. I identified four different kinds of substrates that would be interesting to analyse, and they were: manure, fats, slaughter residues and wheat processing residues (Lantmännen Reppe).

Substrate/digestate: A simple grouping based on whether the data concerned substrate or digestate.

Type of deliverer/receiver: This grouping was based on what type of farm or industry the substrates were delivered to the biogas plant from. They were divided into nine different categories. Conventional or organic dairy, conventional pig, conventional poultry, ley producer, circulation, food waste, other and receiver of digestate. The group called other is a collection of miscellaneous deliverers consisting of a ley producer, a cider brewery and two companies that process grains and deliver the rest product of that process.

Farm/customer: This category divided the data in 50 different groups. Each group was one farm/customer that either delivered substrate, received digestate or both delivered substrate and received digestate. By doing this, it was possible to analyse the flow of nutrients in and out from each farm.

2.3 Study visit to Västergötland

A study visit to the biogas plant was made where the manager showed me around and talked about some of the technical specifications and how the plant was run from a practical perspective. An interview with the manager was also conducted to get more information on how the staff uploaded the data to DVTime, possible errors and faulty data in the tool and other general information about the plant.

A visit was also paid to one of the organic dairy farmers that delivers manure and receives digestate were a short interview was made as well as a general discussion on his experiences about being involved in the project. The guide used in the interviews with the farmer and the plant manager can be found in the appendix. The interviews were made casually and through dialogue rather than question-answer, so the guides were not followed strictly.

2.4 Statistics

The data that was collected from DVTime was pasted into excel where it was coded according to the different categories named under the headline "collection of data". The data was then pasted into JMP, where all histograms and statistical analyses have been made. In total, 7802 rows of data have been processed and 8246 rows of data was extracted from DVTime. Thus, 444 rows of data or 5.4 % of the total data have been excluded from statistical analysis. The unprocessed data is due to no nutrient analysis being available or it being otherwise untrustworthy.

3 Results

In general, the results sought to describe the different flows of substrates and digestate to and from VH Biogas plant according to figure 1. The cropland area of all of the farms receiving digestate are unknown, which is important to note when reading the results. All numbers are totals for each farm or company and it is not known what the average net gain, or loss, of plant nutrients is per hectare. However, the numbers in the tables in the appendix give an indication of the size of each farm as the amount of substrate delivered is likely related to the arable area of the farm. The farms described are all specialized in one type of production (organic or conventional dairy or conventional pig) except farm 25 which has both organic dairy and conventional pig production. Data for the different farms are available in Tables 3-7 in appendix. There were seven conventional dairy farms, ten organic dairy farms and four conventional pig farms (farm 25 is counted for both of the latter). The poultry farms only deliver substrate without receiving any digestate while all cropping farms only receive digestate without delivering substrate. The types of deliverers that are named “Fats”, “Slaughter residues”, “Food waste” and “Other” only deliver substrate. All the diagrams in the results are based on the combined data from 2015 and 2016 (unless stated otherwise). This is warranted due to the different years being very similar in terms of substrate delivered and digestate received by the farms.

3.1 Time periods

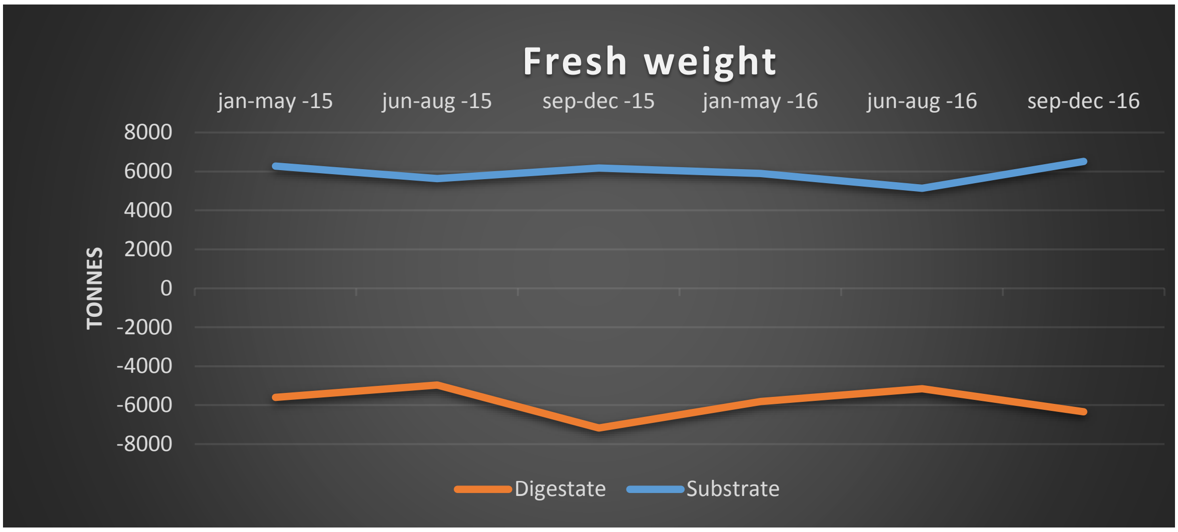

Figure 3. Monthly average fresh weight of outgoing digestate and incoming substrate to VH Biogas plant. The average is calculated from the total amounts of outgoing digestate and incoming substrate during the time periods stated on the x axle. Positive values indicate influx to and negative values indicate outflux from VH Biogas plant.

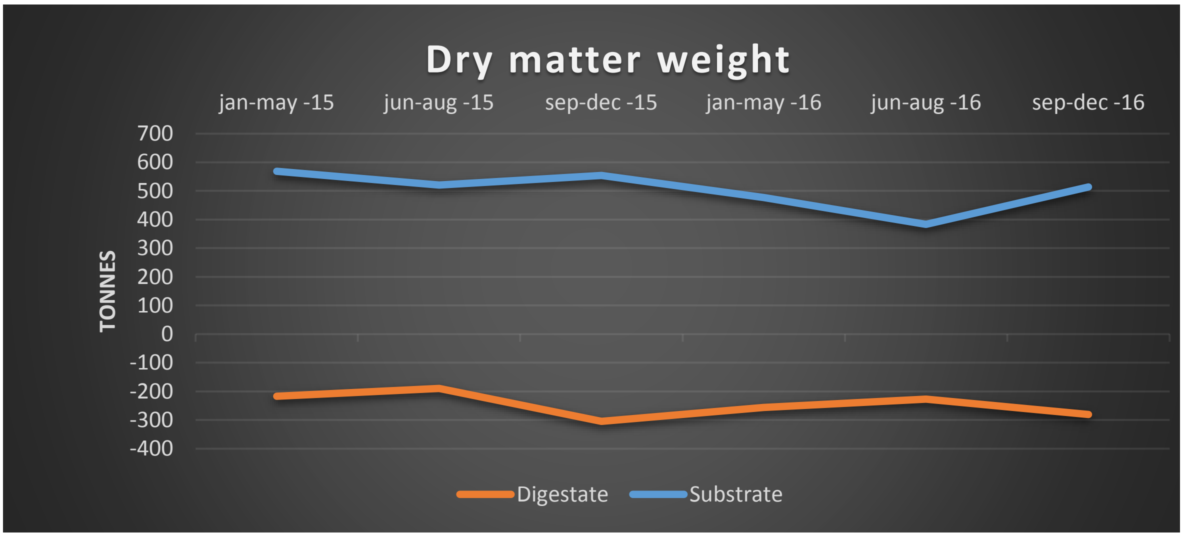

Figure 4. Monthly average dry matter weight of outgoing digestate and incoming substrate to VH Biogas plant. The average is calculated from the total amounts of outgoing digestate and incoming substrate during the time periods stated on the x axle. Positive values indicate influx to and negative values indicate outflux from VH Biogas plant.

The fresh weight of substrates coming in to VH Biogas plant did not differ greatly between the selected time periods (Fig. 3) or between years (Fig. 5). More variation could be found in the outgoing digestate which had peaks in Sep-Dec in both 2015 and 2016 (Fig. 3). Regarding incoming dry matter weight of substrates, there were more variation between the selected time periods compared to the fresh weight of incoming substrates (Fig. 4). The dry matter weight of substrates going in were considerably lower in 2016 compared to 2015 (Fig. 7). Taking that into account, together with the fact that the fresh weight of incoming substrates was only slightly lower in 2016 than in 2015 (Fig. 5), it gives an indication that the substrates going in in 2016 had a lower dry matter percentage than in 2015.

Both the fresh and dry matter weight of digestate going out showed similar variations between time periods and they seemed to follow the ups and downs of the incoming substrates (Fig. 3 and 4). The total fresh weight of digestate going out from VH Biogas was slightly higher in 2015 than in 2016 (Fig. 7) whereas the dry matter weight was lower (Fig. 8). This indicates a lower dry matter percentage in the digestate that was produced in 2015.

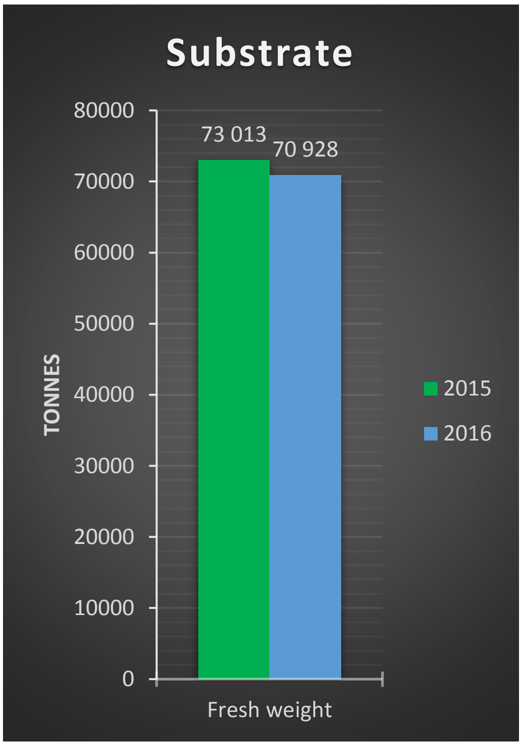

Figure 5. The total fresh weight of all substrates delivered to VH Biogas plant per year.

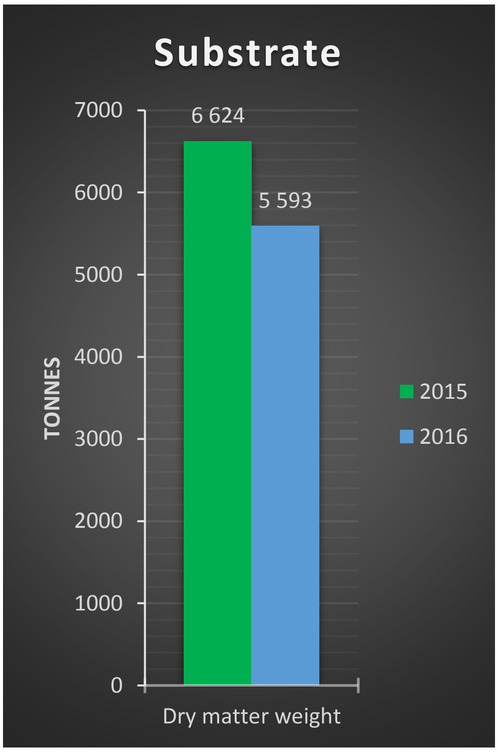

Figure 6. The total dry matter weight of all substrates delivered to VH Biogas plant per year.

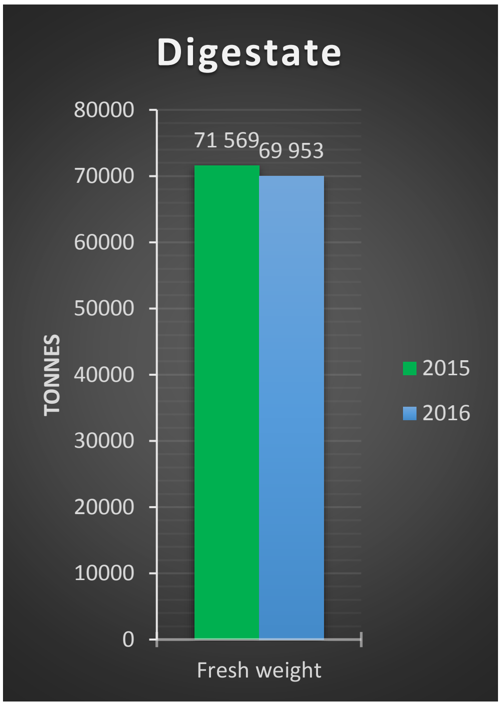

Figure 8. *The total fresh weight of all digestate going out from VH Biogas plant per year.*

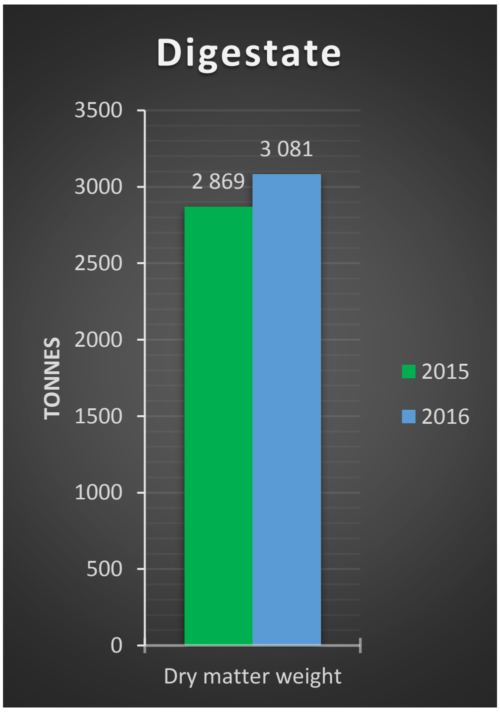

Figure 7 The total dry matter weight of all digestate going out from VH Biogas plant per year.

3.2 Type of farm/company

3.2.1 Substrate

The different types of farms/companies were divided into groups as described in the methods. The types that stood for the greatest part of the fresh- and dry matter weights as well as most of the plant nutrients were the conventional and organic dairy farms, the conventional pig farms and slaughter residues (Fig. 9-15).

The organic dairy farms were the biggest contributor in all of the categories that was studied, except for phosphorous (Fig. 13) where both slaughter residues and conventional dairy farms delivered more to VH Biogas plant. Organic dairy farms delivered relatively little nitrogen (Fig. 10-12) compared to the fresh weight delivered by them. Contrarily, they contributed with a huge amount of potassium (Fig. 14).

The conventional dairy farms were the second largest deliverer of fresh weight to the plant (Fig. 9), and they delivered a relatively larger share of the nitrogen compared to the organic dairy farms when compared with the fresh weight (Fig. 10-12), indicating that the manure from the conventional dairy farms have got a higher concentration of N in it compared to the organic dairy farms. In terms of weight, they were the second largest deliverer of NH_4-N (Fig. 12) and the third largest deliverer of organic N (Fig. 11). The conventional dairy farms also delivered the second most P, after slaughter residues, (Fig. 13) and K, after organic dairy farms, (Fig.14). The amount of P delivered by the organic and conventional dairy farms respectively was fairly similar whereas the K delivered from the conventional dairy farms was lower than the organic dairy farms, indicating that the manure from the organic dairy contained more K than the manure from conventional dairy. The conventional dairy farms deliver the second most dry matter to VH Biogas (Fig. 15)

The pig farms delivered the third most fresh weight of substrate to VH Biogas, but it was significantly less than both types of dairy farms (Fig. 9). The pig farms stood out since they delivered almost 18 % of the total NH_4-N (Fig. 12) even though the total N they delivered only represented 11.63 % of the N delivered to VH Biogas (Fig. 10). The pig farms delivered only 6.8 % of the organic N and thus, the pig manure has a higher NH_4-N/N-tot quota and contributed to an increased amount of NH_4-N in the digestate. The pig farms' deliverance of P (Fig. 13) and K (Fig. 14) was relatively low compared to the dairy farms. The dry matter weight delivered from the pig farms was under 7 % (Fig. 15)

Amongst the types of farms and companies that delivered substrate without receiving digestate, the biggest ones in terms of fresh weight were slaughter residues and other. The other category seems to contribute with a miniscule amount of plant nutrients (Fig. 10-14). However, this was due to the fact that most of the nutrient analyses were missing from the raw data used in this study and the share that the other category contributed with is therefore unknown. Though it was likely a little bit higher than what is shown in figures 10-13 because the unknown data was set to 0.

Slaughter residues were only 9 % of the total fresh weight (Fig. 9) but stood for 20 % of the total N (Fig. 10). However, the overwhelming part of the N was organic (Fig. 11-12). Seemingly, the slaughter residues greatly boosted the total N-content of the digestate. Slaughter residues was also the biggest contributor of P out of all types of farms/companies (Fig. 13) whereas the contribution of K was minimal (Fig. 14). The slaughter residues were also a major contributor of dry matter weight at almost 15 % of the total (Fig. 15).

The poultry farms delivered only approximately 1% of the fresh weight (Fig. 9) but stood for over 4 % of the total NH_4-N in the substrates (Fig. 12) and 3.6 % of the total N (Fig. 10) which indicates its value for the plant nutrient content of the digestate. It was also a significant contributor of P at almost 5 % of the total in the substrates (Fig. 13). The contribution of K was not as great at just over 2 % of the total (Fig. 14) and the dry matter weight from the poultry manure stood for 5.4 % of the total (Fig. 15).

The total weight in substrates of N-tot (Fig. 10) is 649.1 tonnes and the total weight in substrates of N-org (Fig. 11) plus NH_4-N (Fig. 12) was

336.0 + 249.5 = 585.5 tonnes. The discrepancy was due to some analyses not specifying in what form the N was present. Thus, the pie charts shown in Fig. 11 and Fig. 12 might be slightly skewed.

3.2.2 Digestate

The share was very similar between each plant nutrient as well as the fresh and dry matter weight that was delivered to the receivers (Fig. 16-22). This was because the digestate was relatively homogenous and that the receivers got digestate in relation to how much substrate they delivered.

The different receivers got approximately the following percentages of the weight and nutrients in the digestate (Fig. 16-22):

- Organic dairy – 43 %
- Conventional dairy – 32 %
- Pig – 16 %
- Cropping – 6 %
- Other – 2 %

Substrate

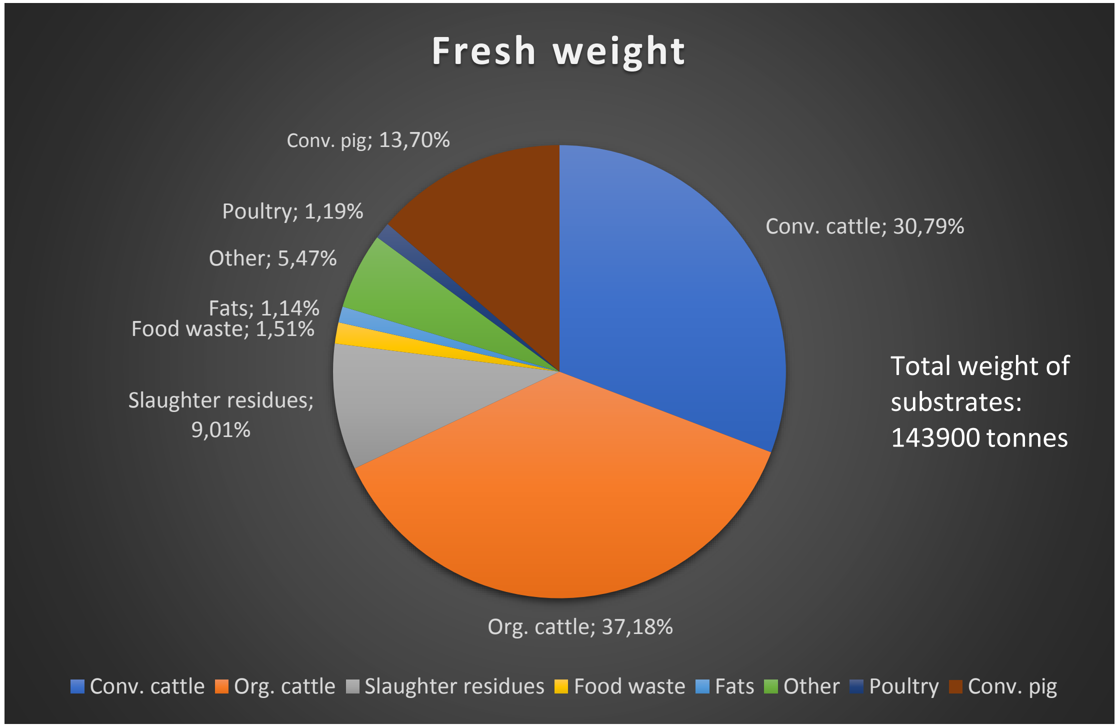

Figure 9. Pie chart showing the share of the total fresh weight of substrate delivered to VH Biogas by each type of deliverer. The data is taken from 2015 and 2016.

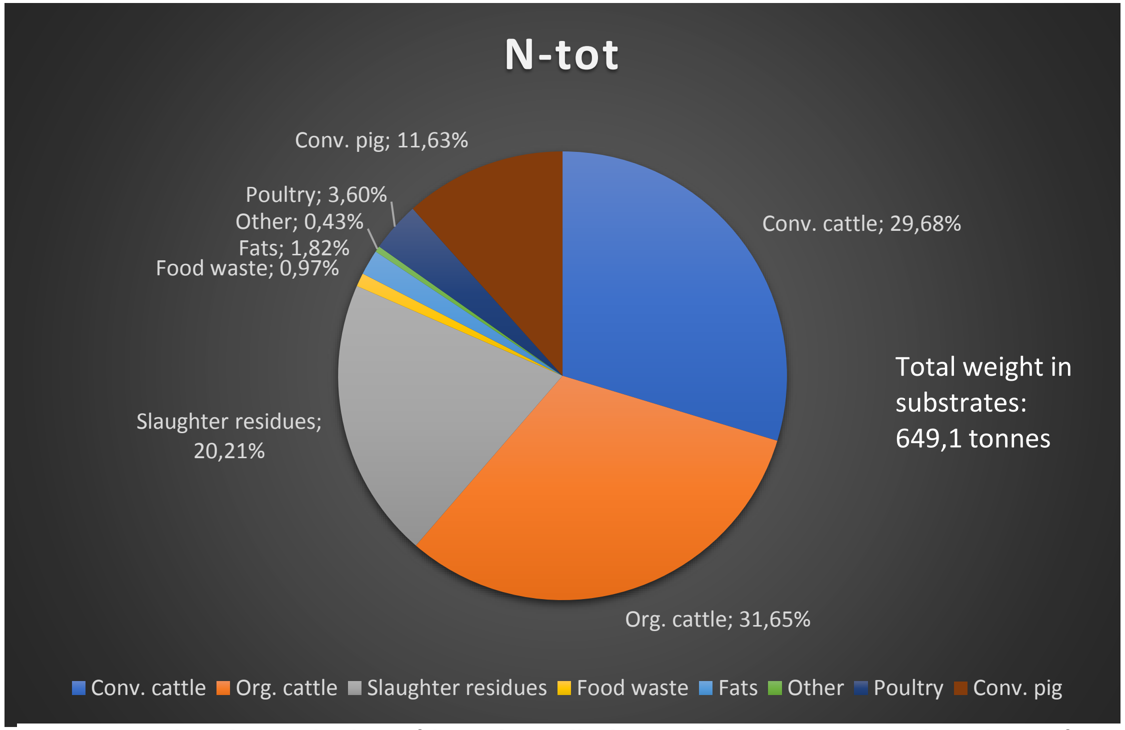

Figure 10. Pie chart showing the share of the total N in all substrates delivered to VH Biogas by each type of deliverer. The data is taken from 2015 and 2016.

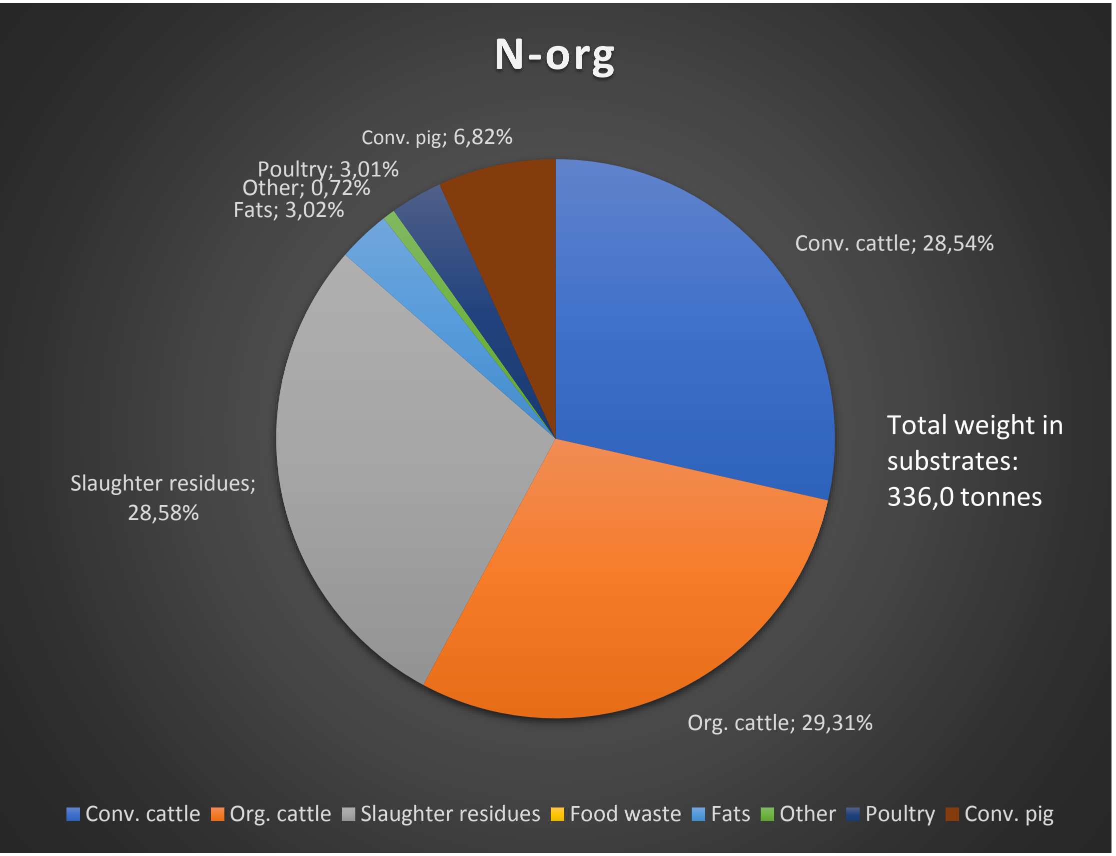

Figure 11. Pie chart showing the share of total amount of N-org in all substrates delivered to VH Biogas by each type of deliverer. The data is taken from 2015 and 2016.

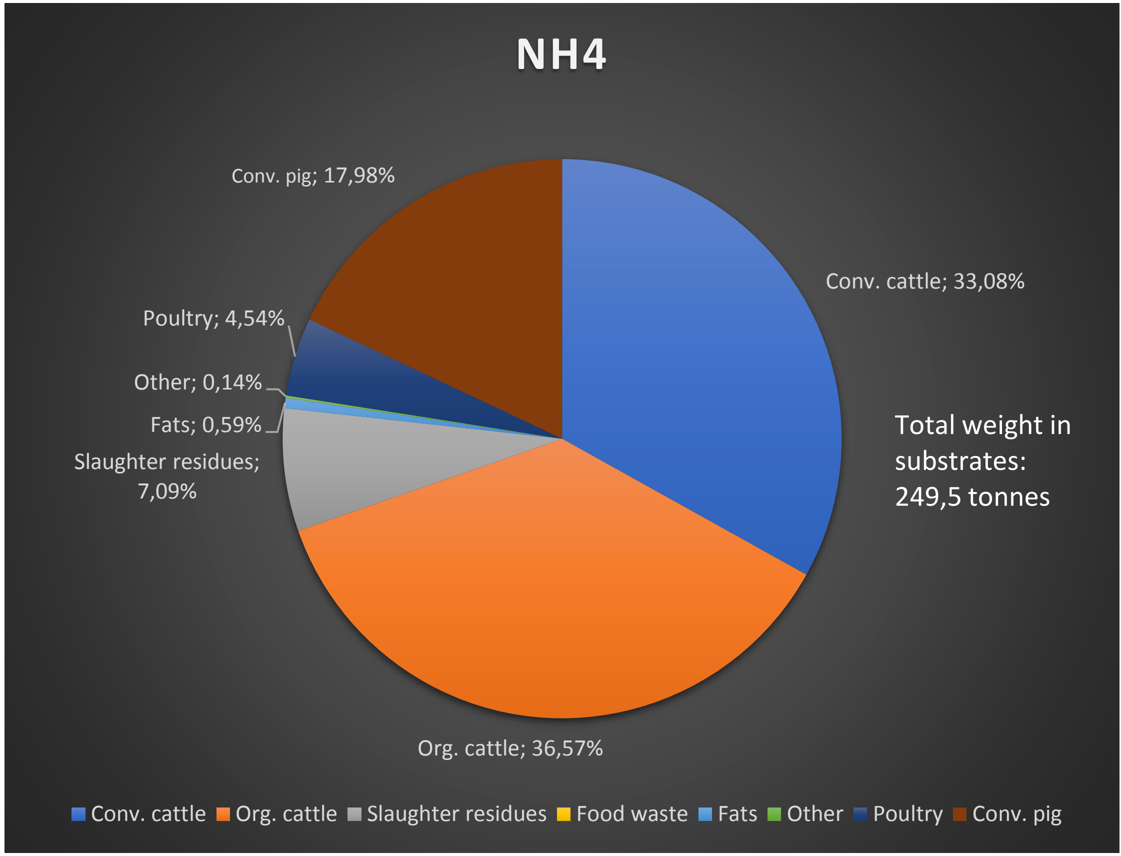

Figure 12. Pie chart showing the share of total amount of NH_4 in all substrates delivered to VH Biogas by each type of deliverer. The data is taken from 2015 and 2016.

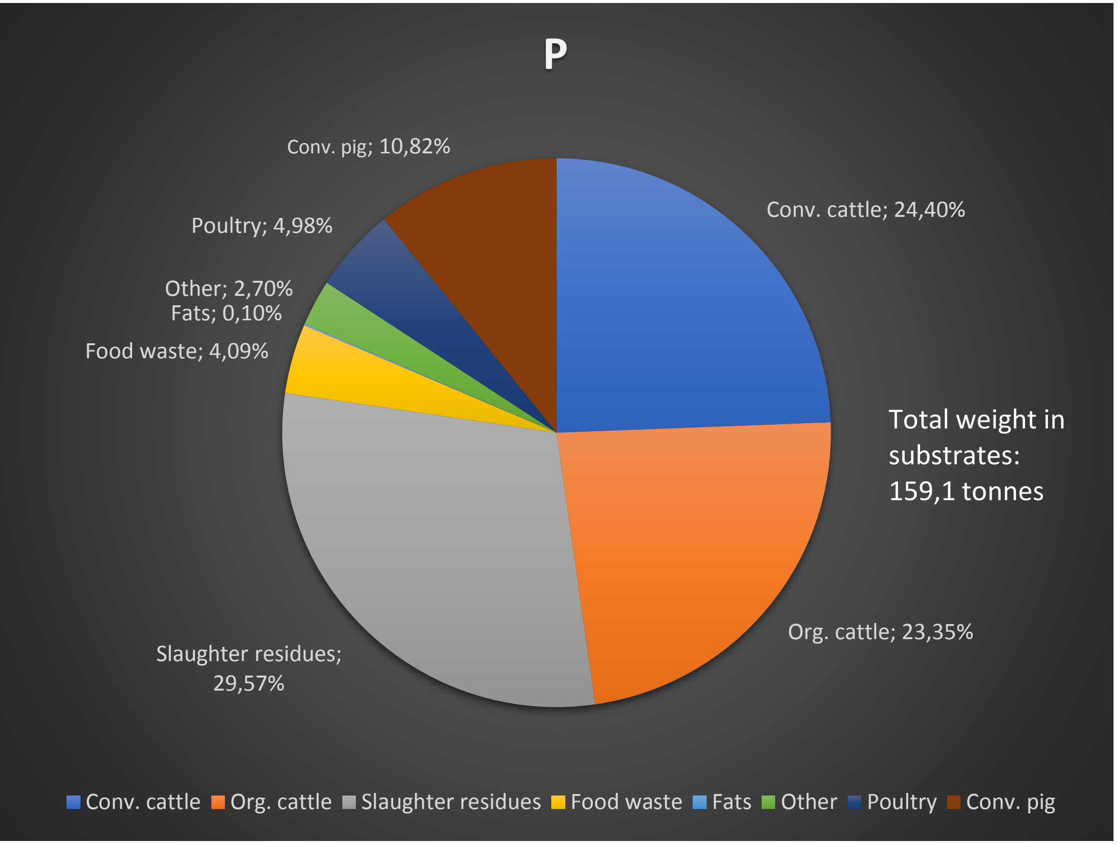

Figure 13. Pie chart showing the share of total amount of P in all substrates delivered to VH Biogas by each type of deliverer. The data is taken from 2015 and 2016.

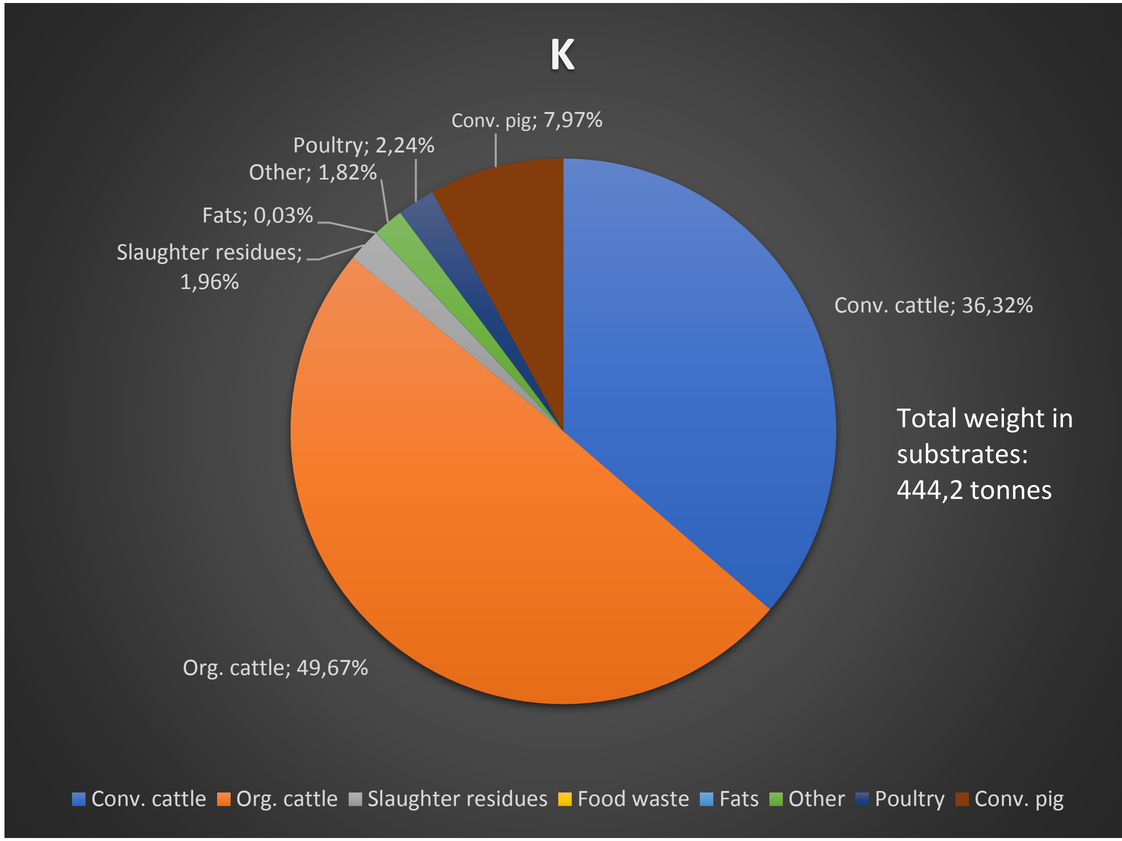

Figure 14. Pie chart showing the share of total amount of K in all substrates delivered to VH Biogas by each type of deliverer. The data is taken from 2015 and 2016.

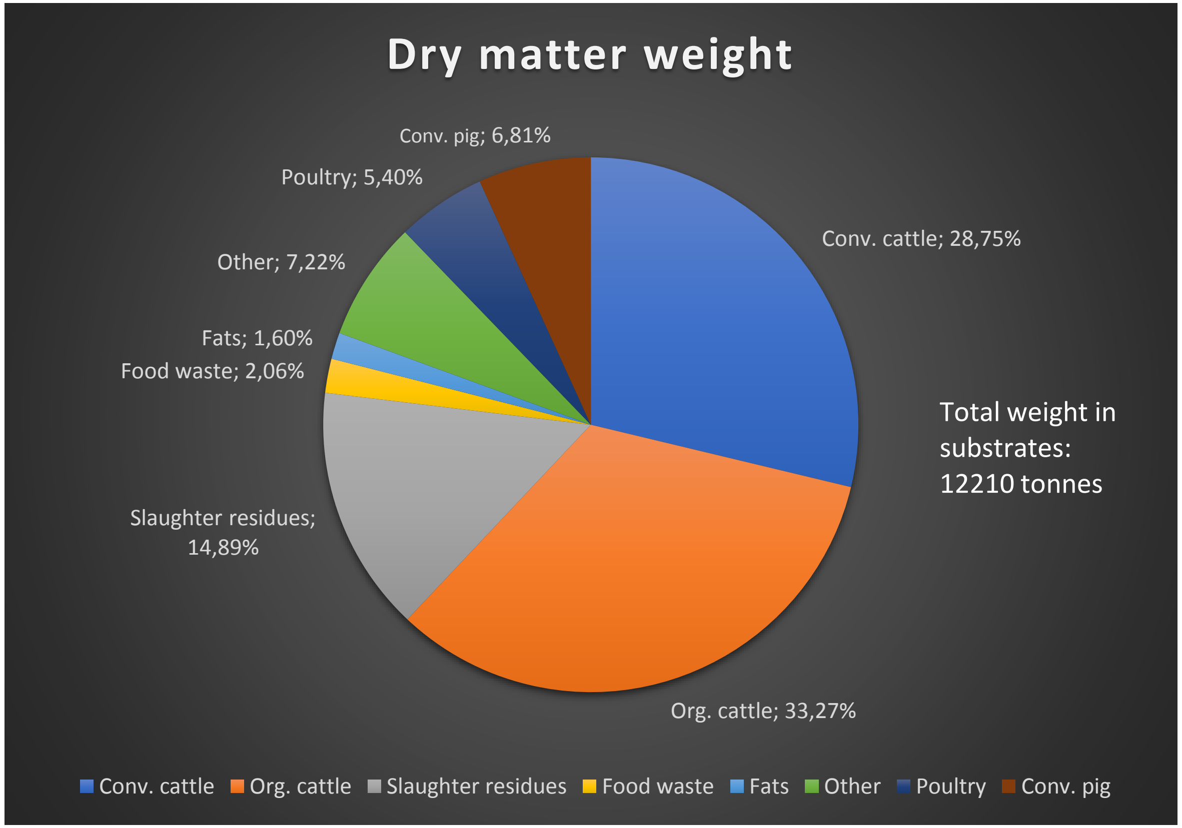

Figure 15. Pie chart showing the share of total dry matter weight of all substrates delivered to VH Biogas by each type of deliverer. The data is taken from 2015 and 2016.

Digestate

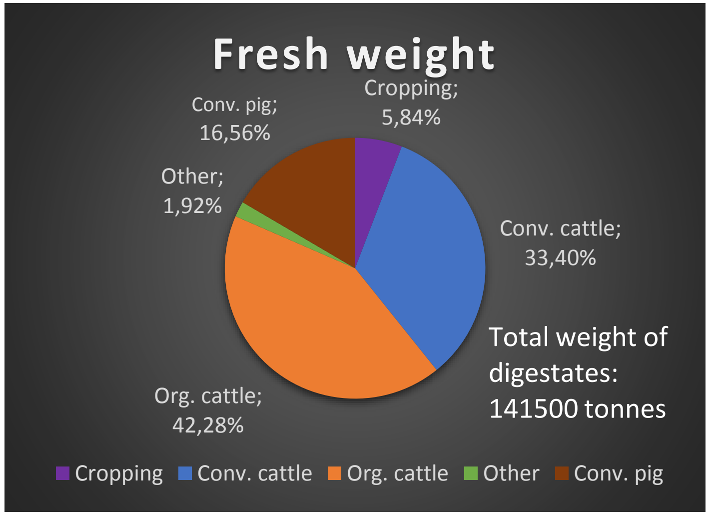

Figure 16. Pie chart showing the share of the total fresh weight of digestate produced by VH Biogas, by each type of receiver. The data is taken from 2015 and 2016.

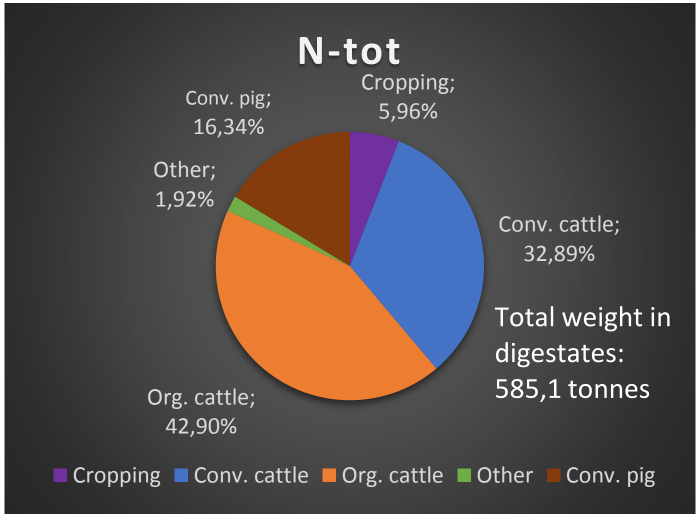

Figure 17. Pie chart showing the share of the total N in all digestate produced by VH Biogas, by each type of receiver. The data is taken from 2015 and 2016.

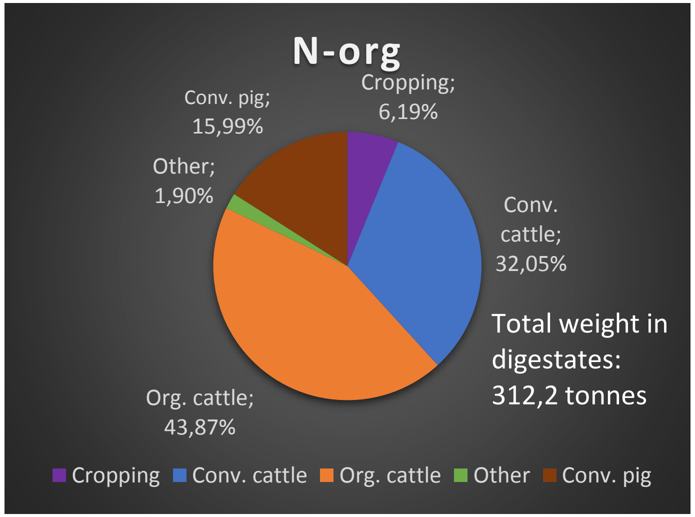

Figure 18. Pie chart showing the share of the total amount of N-org in all digestate produced by VH Biogas, by each type of receiver. The data is taken from 2015 and 2016.

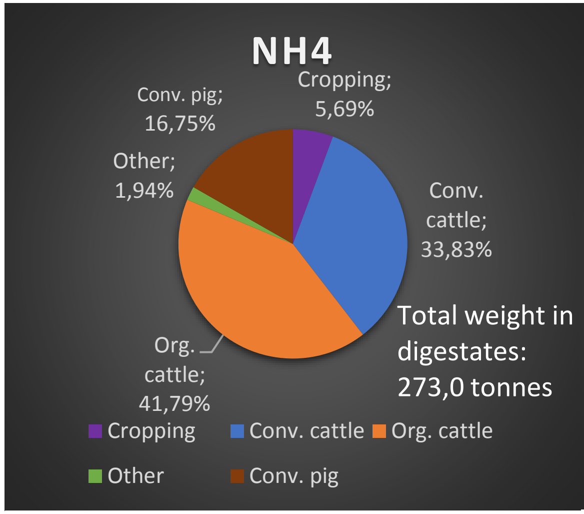

Figure 19. Pie chart showing the share of the total amount of NH4 in all digestate produced by VH Biogas, by each type of receiver. The data is taken from 2015 and 2016.

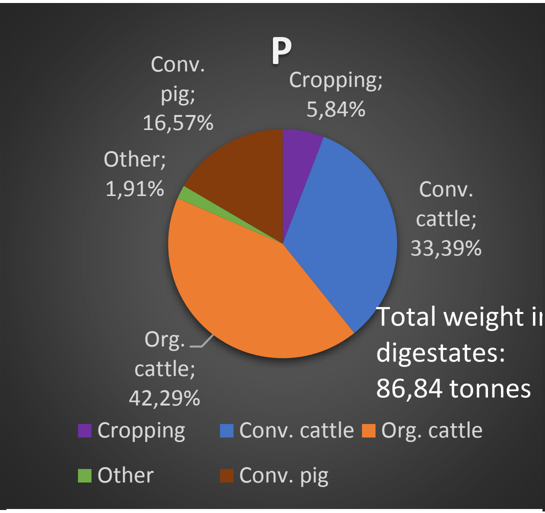

Figure 20. Pie chart showing the share of the total amount of P in all digestate produced by VH Biogas, by each type of receiver. The data is taken from 2015 and 2016.

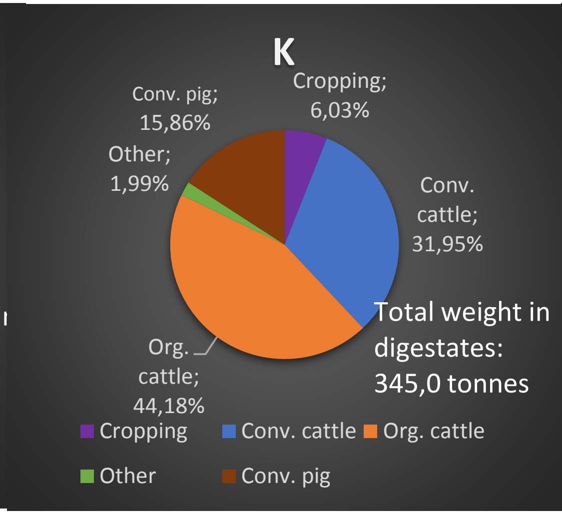

Figure 21. Pie chart showing the share of the total amount of K in all digestate produced by VH Biogas, by each type of receiver. The data is taken from 2015 and 2016.

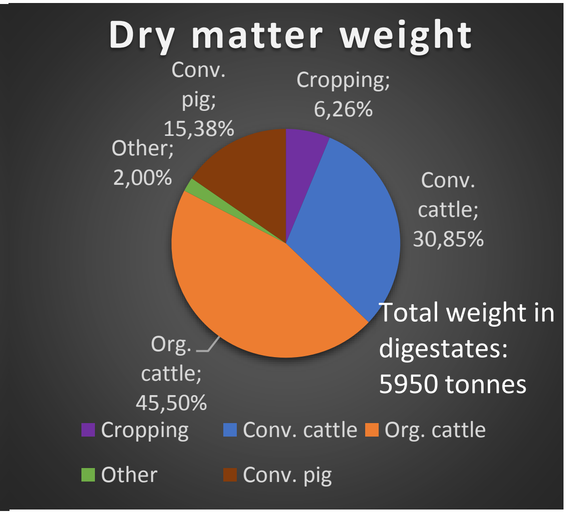

Figure 22. Pie chart showing the share of total dry matter weight of all digestate produced by VH Biogas, by each type of receiver. The data is taken from 2015 and 2016.

3.3 Digestate-substrate difference for type of deliverer/receiver

Diagrams with only the dairy and pig farms can be found in appendix. According to Fig. 28, there was a net loss of K when considering all types of deliverers and receivers.

Cropping: The cropping farms that only received digestate without delivering substrate had a net gain of all plant nutrients, fresh and dry matter weight (Fig. 23-29).

Conventional dairy: The conventional dairy farms received more fresh weight than they delivered, as did the other types of farms that both delivered substrate and received digestate (Fig. 23). This was due to that the total fresh weight of the digestate was higher than the total fresh weight of the substrates and that there were more groups delivering substrates than there were groups receiving digestate. Conventional dairy farms as a group had a slight net loss of total N (Fig. 24), which was caused by the net loss of NH_4-N that was found (Fig. 26) but offset a bit by the net gain of N-org (Fig. 25). Conventional dairy farms also had a net loss of P (Fig. 27), K (Fig. 28) and dry matter weight (Fig. 29).

Organic dairy: The organic dairy farms as a whole had a significant net gain of fresh weight (Fig. 23), N-tot (Fig. 24), N-org (Fig. 25) and NH_4-N (Fig. 26). They had an obvious net loss of K (Fig. 28) and dry matter weight (Fig. 29), and a slight net loss of P (Fig.27). This supported what the interviewed farmer said, as he described the digestate positively in terms of plant nutrients (mainly for the high content of mineral N) but expressed some worries about feeling like he was losing P and K. He also commented that he thinks the dairy farms needed the K, whereas the pig farms did not.

Pig: The pig farms had a net gain of fresh weight (Fig. 23), N-tot (Fig. 24), N-org (Fig. 25), K (Fig. 28) and dry matter weight (Fig. 29). They were the only type of farm that both delivered substrate and received digestate that had a net gain of K. The pig farms had a net loss of NH_4-N (Fig. 26) and P (Fig. 27). It was worth noting the big difference between the gain of N-org and the loss of NH_4-N, which indicates a high NH_4-N/N-tot quota in the substrate delivered from the pig farms. Another interesting result is that the pig farms gained dry matter weight, and thus the dry matter percentage in the substrate delivered ought to have been lower than the dairy farms.

Other: The figures were not accurate for the “other” group except for fresh weight (Fig. 23), since many analyses were missing for plant nutrients. It is likely that the slight net gains in N-tot (Fig. 24), N-org (Fig. 25) and NH_4-N (Fig. 26) were in reality slight net losses because the missing values from the analyses were set to 0. Within the same argument, the net losses in P (Fig. 27), K (Fig. 28) and dry matter weight (Fig. 29) were likely higher in reality than what was showed in these results.

Deliverers of substrate only: The types of farms/companies that delivered substrate without receiving digestate (slaughter residues, food waste, fats and poultry), all displayed net losses of all plant nutrients, fresh weight and dry matter weight (Fig. 23-29). Out of these types, slaughter residues had the greatest net loss of fresh weight, dry matter weight and all nutrients (Fig. 23-27 and 29) except K where they were second behind poultry (Fig. 28). In regard to plant nutrients, the other types apart from slaughter residues were not very large contributors except for poultry, which displayed a marked net loss of NH_4-N (Fig. 26) and dry matter weight (Fig. 29) as well as some P (Fig. 27) and K (Fig. 28).

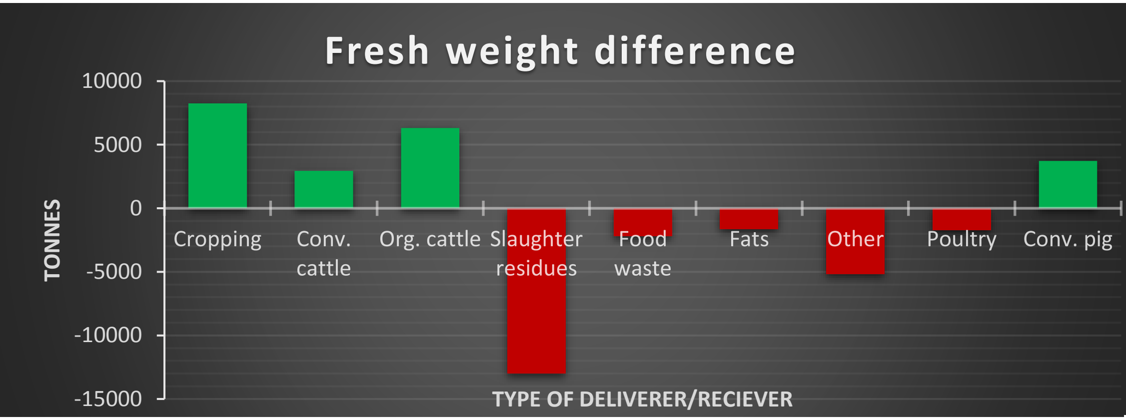

Figure 23. Diagram showing, for each type of deliverer/reciever, the difference between the amount of digestate (in fresh weight) received from VH Biogas minus the amount of substrate (in fresh weight) delivered to VH Biogas. The data is taken from 2015 and 2016.

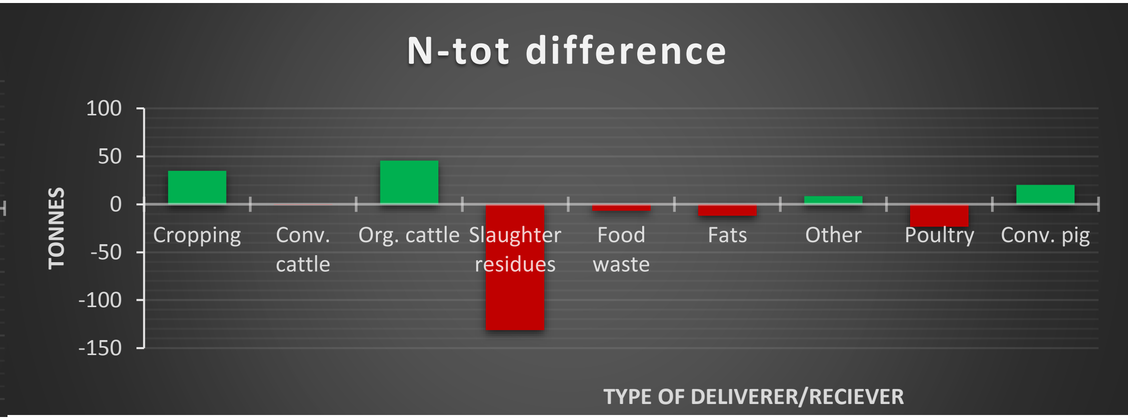

Figure 26. Diagram showing, for each type of deliverer/receiver, the difference between the total amount of N received from VH Biogas minus the total amount of N delivered to VH Biogas. The data is taken from 2015 and 2016.

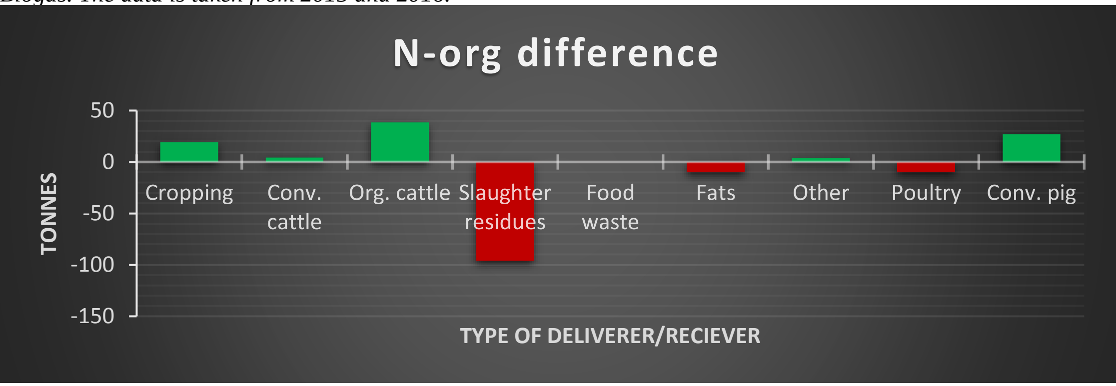

Figure 25. Diagram showing, for each type of deliverer/receiver, the difference between the amount of N-org received from VH Biogas minus the amount of N-org delivered to VH Biogas. The data is taken from 2015 and 2016.

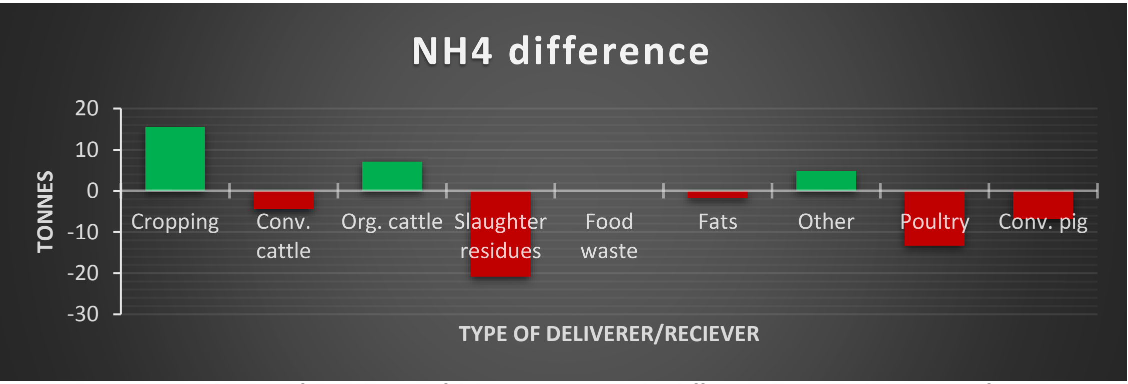

Figure 24. Diagram showing, for each type of deliverer/receiver, the difference between the amount of NH4 received from VH Biogas minus the amount of NH4 delivered to VH Biogas. The data is taken from 2015 and 2016.

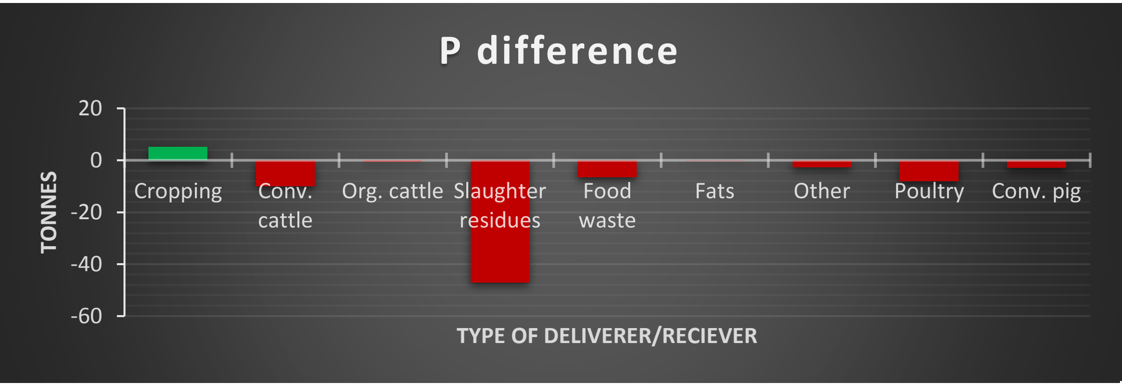

Figure 29. Diagram showing, for each type of deliverer/receiver, the difference between the amount of P received from VH Biogas minus the amount of P delivered to VH Biogas. The data is taken from 2015 and 2016.

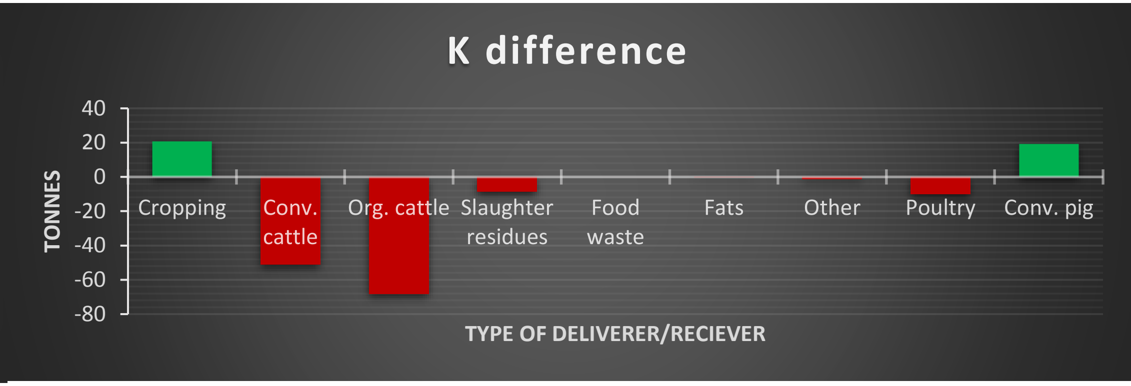

Figure 28. Diagram showing, for each type of deliverer/receiver, the difference between the amount of K received from VH Biogas minus the amount of K delivered to VH Biogas. The data is taken from 2015 and 2016.

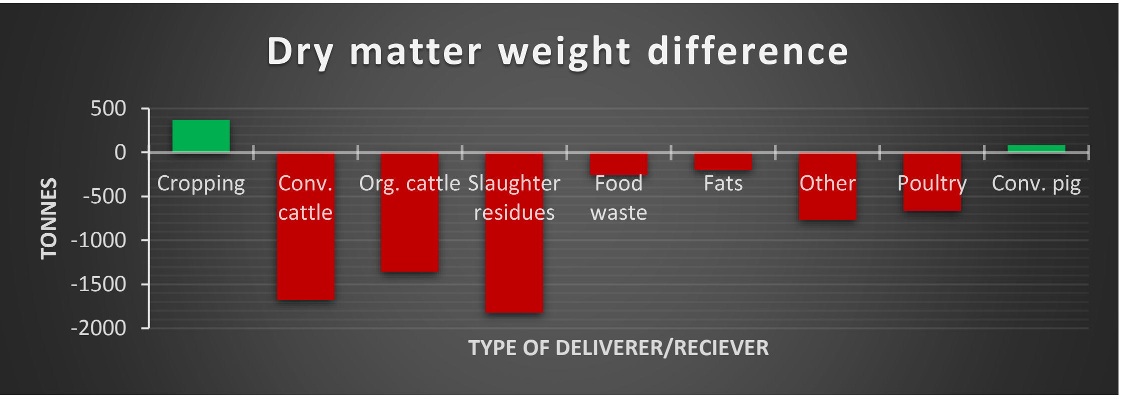

Figure 27. Diagram showing, for each type of deliverer/receiver, the difference between the amount of digestate (in dry matter weight) received from VH Biogas minus the amount of substrate (in dry matter weight) delivered to VH Biogas. The data is taken from 2015 and 2016.

3.4 Digestate – substrate differences for individual farms

The diagrams shown in Fig. 23-29 summarize the different types of farms and what their net loss or gain was of fresh weight, dry matter weight and plant nutrients. The diagrams in Fig. 30-36 show the net gain or loss of each individual farm, along with type of farm they are. Thus, a greater understanding of the variation between the farms can be achieved. However, the crop land area of the farms was unknown and thus the net gain or loss per hectare as well. It is important to keep that in mind when reading these results since what might look like a great gain or loss for a farm, might be negligible in reality because of the area it is spread out upon. The same, but opposite reasoning goes for smaller farms where what seems like a negligible gain or loss is a distinguishable gain or loss in reality because of the small area of crop land it is spread out upon. In practice, the difference per ha of crop land is more important, rather than the total difference on the farm.

Conventional dairy: All farms except 19, which had a small net loss, had a net gain of total fresh weight (Fig. 30). This is likely due to the fact that digestate usually has a lower dry matter percentage and that there are more deliverers of substrate than there are receivers of digestate. Farm 50 had the largest net gain of all the conventional dairy farms. Farm 50 was also the biggest deliverer and receiver out of all the conventional dairy farms (Tables 3-4 in appendix). The fresh weight difference for the conventional dairy farms as a whole was around +3000 tonnes (Fig. 23). For an individual farm, however, the difference in this study could range from ca +1700 tonnes to -100 tonnes (Fig. 30).

The difference in net gain or loss of N-tot varied from ca +4 tonnes for farm 11 to -6 tonnes for farm 50. Farms 6 and 24 also showed net losses whereas farms 19, 34 and 49 showed net gains (Fig. 31).

Farms 6 and 50 had a negative difference in N-org. The rest of the conventional dairy farms had a positive difference (Fig. 32). Farm 50 had the largest net loss at ca -7 tonnes and farm 34 had the largest net gain at ca 3,5 tonnes. It is interesting to note that farm 24 had an apparent gain of N-org even though it showed an evident loss of N-tot.

Conventional dairy farms as a whole had a net loss of NH_4-N (Fig. 26), but Fig. 33 shows that there are farms within the production type with net gains as well as net losses of NH_4-N. Farm 24 had the largest net loss of NH_4-N, explaining how it had a nett loss of total N (Fig. 31) even though it had net gain of N-org (Fig. 32).

All conventional dairy farms displayed a loss of P (Fig. 34), where farm 50 had the greatest loss at around 4.2 tonnes. Farm 34 stood for the smallest loss of P among the conventional dairy farms, at less than -0.1 tonnes (Fig. 34).

Only one farm displayed a net gain of K, farm 49, the rest all had a negative balance (Fig. 35). The two biggest deficits were shown on farms 24 and 11, which had a loss of 14 and 18 tonnes of K respectively (Fig. 35).

Fig. 36 shows that all conventional dairy farms had a net loss of dry matter weight, especially farms 24 and 50. They both showed a net loss of over 400 tonnes of dry matter weight. Farm 49 stood for the smallest difference, at around 20 tonnes (Fig. 36).

Organic dairy: Farm 25 had both organic dairy and conventional pig production and the results from that farm are therefore presented separately. Farm 25 displayed net gains of fresh weight (Fig. 30), N-tot (Fig. 31), N-org (Fig. 32), NH_4-N (Fig. 33) and P (Fig. 34). It showed net losses of K (Fig. 35) and dry matter weight (Fig. 36).

All organic dairy farms showed a positive fresh weight difference except for one-farm 35 (Fig. 30), which had a loss of around 150 tonnes. The biggest gainer was farm 41 at around 1500 tonnes.

As opposed to the conventional dairy farms, the organic dairy farms displayed a net gain of N-tot throughout where the former had three farms actually losing N (Fig. 31). The smallest gain was at farm 35 with under 0.5 tonnes and the greatest gains were at farms 16 and 41 with both being at around a 6 tonne gain.

All organic dairy farms also showed a net gain of N-org, ranging from around 1 tonne at farm 30 up to around 7.5 tonnes at farm 41 (Fig. 32).

The results from the differences on the farms regarding NH_4-N were more scattered (Fig. 33). Five farms displayed a net gain and the other 4 a net loss. The largest gains were at farms 2 and 43 with around 3 tonnes each and the largest loss was at farm 41 with about -1.5 tonnes.

There were four farms that had a net gain of P (Fig. 34), as opposed to the conventional dairy farms where none of them had a net gain of P. Four of the farms displayed relatively minor losses and one of them, farm 43, was fairly major at around -2 tonnes of P.

Two of the organic dairy farms had a net gain of K, both under 2 tonnes, and the rest displayed net losses of up to -15 tonnes (Fig. 35).

All the organic dairy farms had a net loss of dry matter weight (Fig. 36). Farm 8 stood for the largest loss at around -260 tonnes.

Conventional pig: There were three farms with conventional pig production that delivered substrate to and received digestate from VH Biogas (in addition from farm 25). These farms all had a net gain of fresh weight (Fig. 30), total N (Fig. 31), N.org (Fig. 32) and K (Fig. 35).

Potentially, the most intriguing result within the N differences among the conventional pig farms lies in farm 45. The total N gain was around 1 tonne (Fig. 31), but the farm had the greatest loss of NH_4-N of all farms (including the dairy farms) at over -8 tonnes (Fig. 33). Thus, it also gained around 9 tonnes of N-org (Fig. 32). Farm 34 also displayed a small loss of NH_4-N.

All the conventional pig farms showed net losses of P, with farm 45 having the largest at -2.4 tonnes (Fig. 34)

Farm 38 was the only one out of all the farms that had a net gain dry matter weight at about 120 tonnes (Fig. 36). The remaining two conventional pig farms showed fairly minor net losses.

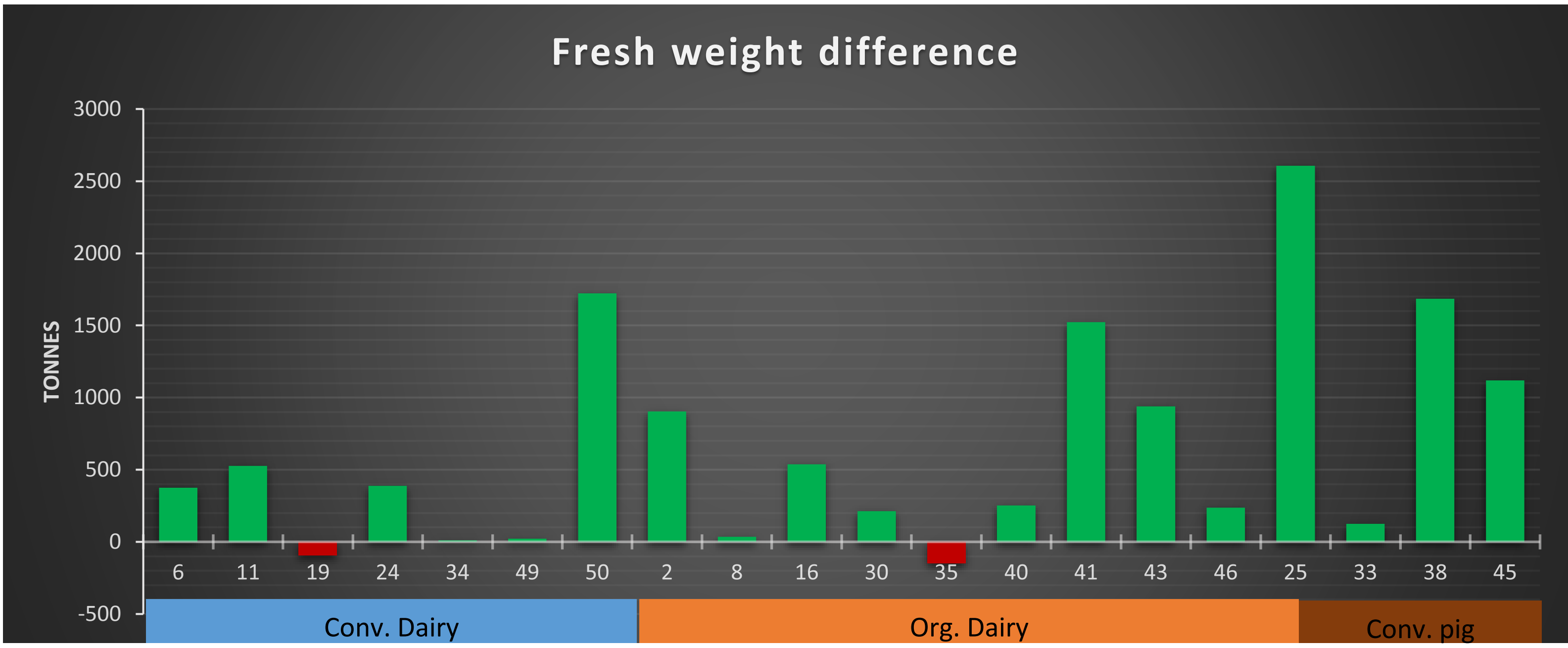

Figure 30. Diagram showing, for individual farms, the difference between digestate received from VH Biogas (in fresh weight) minus substrate delivered to VH Biogas (in fresh weight). The numbers on the x-axle anonymously indicate each individual farm and their production type is marked by the coloured bar at the bottom of the diagram. Farm 25 is both an organic dairy farm and a conventional pig farm. The data is taken from 2015 and 2016.

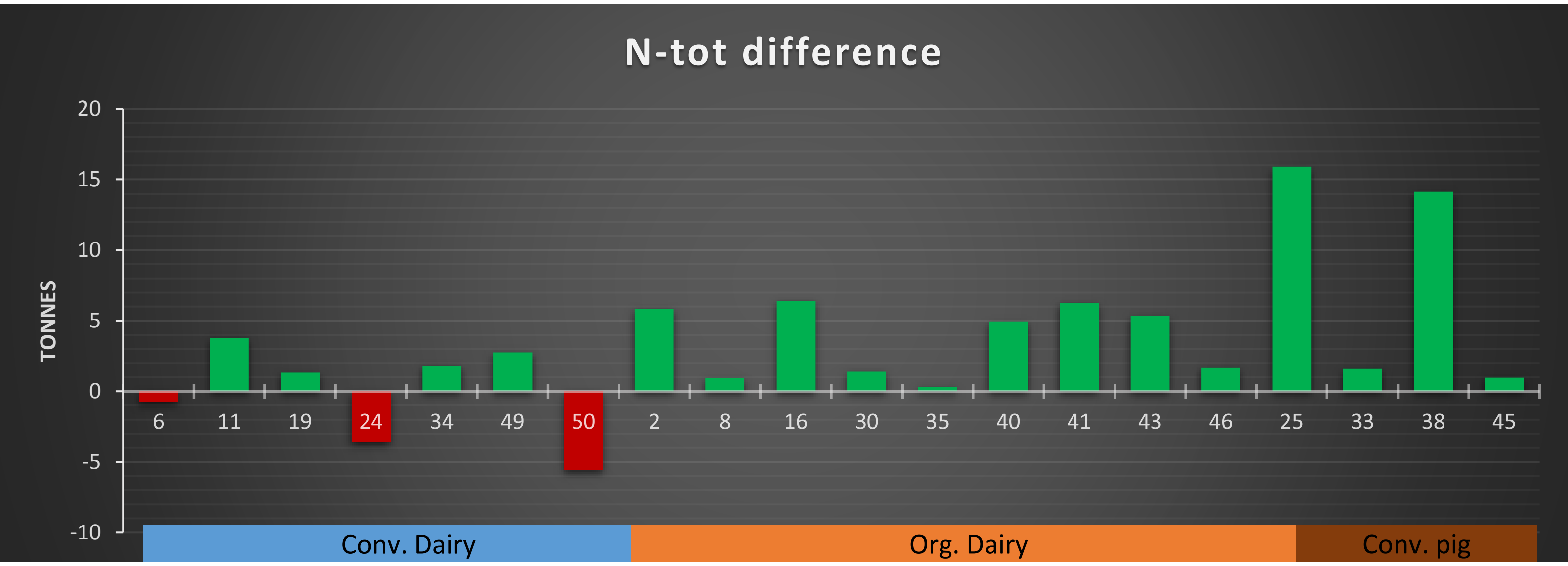

Figure 31. Diagram showing, for individual farms, the difference between total amount of N received from VH Biogas minus total amount of N delivered to VH Biogas. The numbers on the x-axle anonymously indicate each individual farm and their production type is marked by the coloured bar at the bottom of the diagram. Farm 25 is both an organic dairy farm and a conventional pig farm. The data is taken from 2015 and 2016.

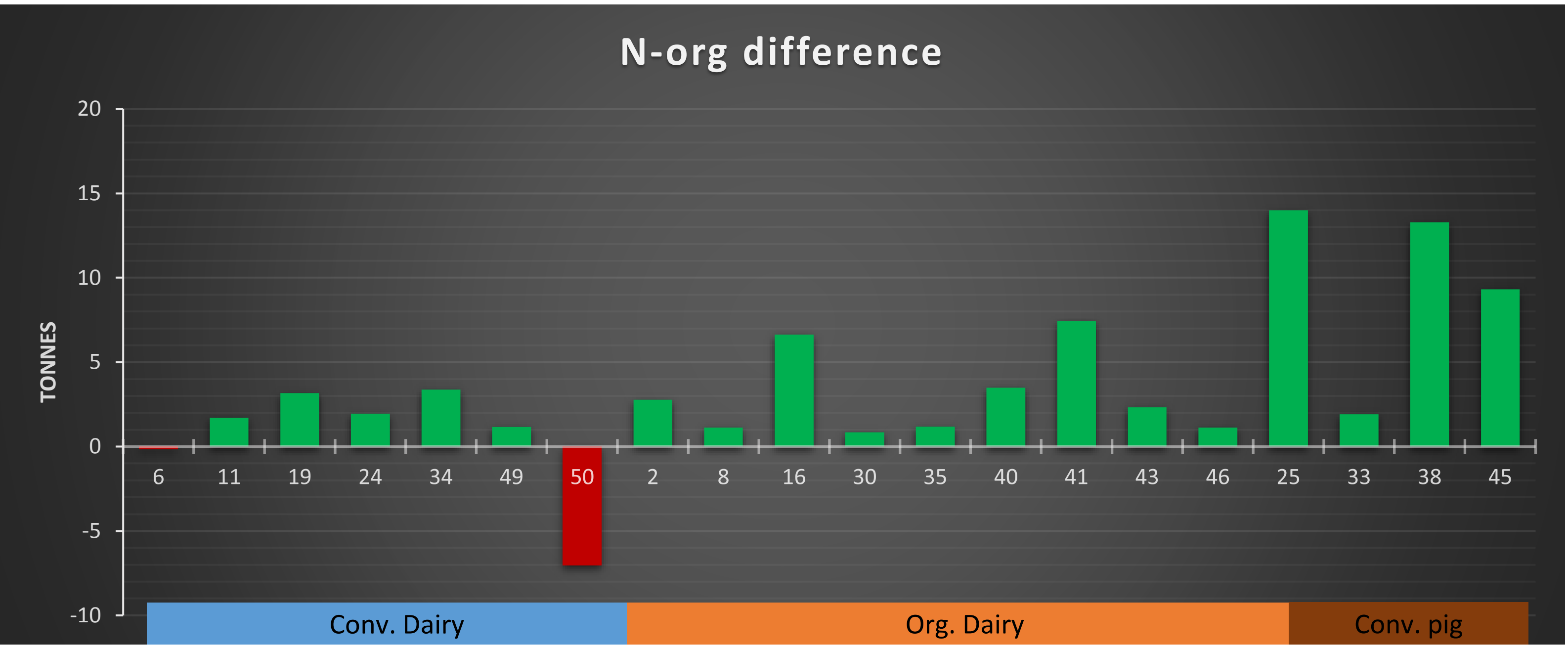

Figure 32. Diagram showing, for individual farms, the difference between the amount of N-org received from VH Biogas minus the amount of N-org delivered to VH Biogas. The numbers on the x-axle anonymously indicate each individual farm and their production type is marked by the coloured bar at the bottom of the diagram. Farm 25 is both an organic dairy farm and a conventional pig farm. The data is taken from 2015 and 2016.

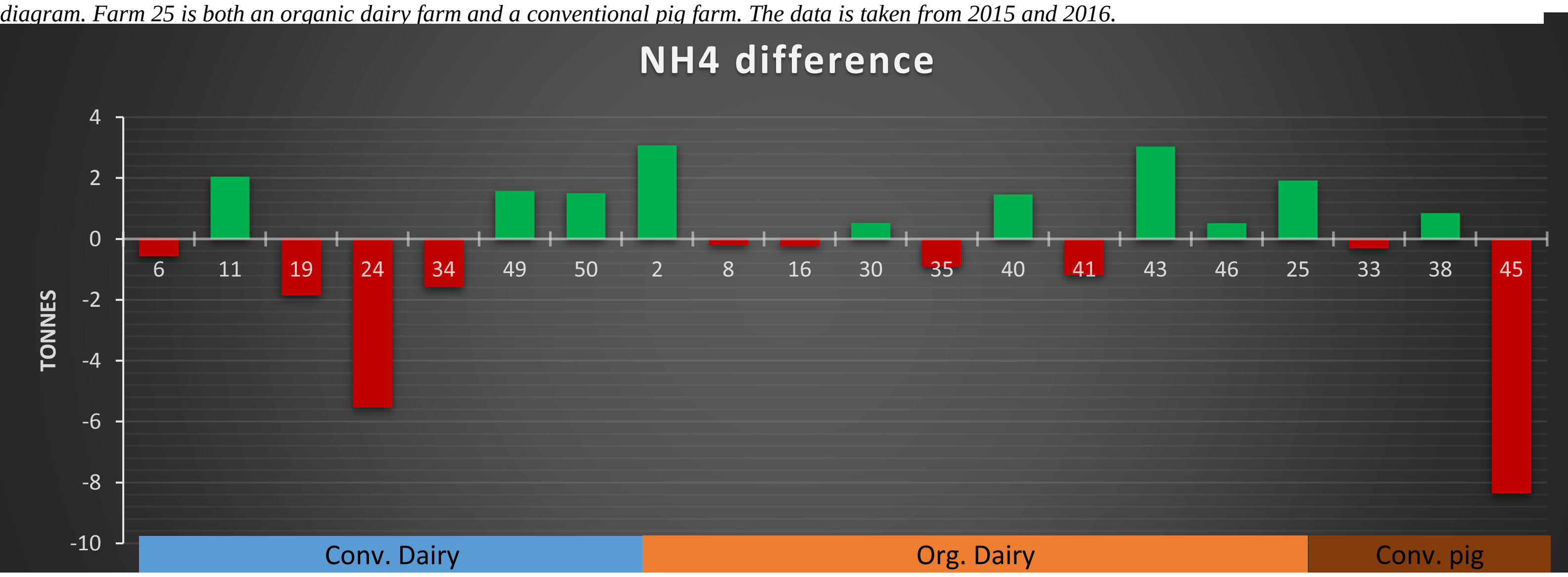

Figure 33. Diagram showing, for individual farms, the difference between the amount of NH4 received from VH Biogas minus the amount of NH4 delivered to VH Biogas. The numbers on the x-axle anonymously indicate each individual farm and their production type is marked by the coloured bar at the bottom of the diagram. Farm 25 is both an organic dairy farm and a conventional pig farm. The data is taken from 2015 and 2016.

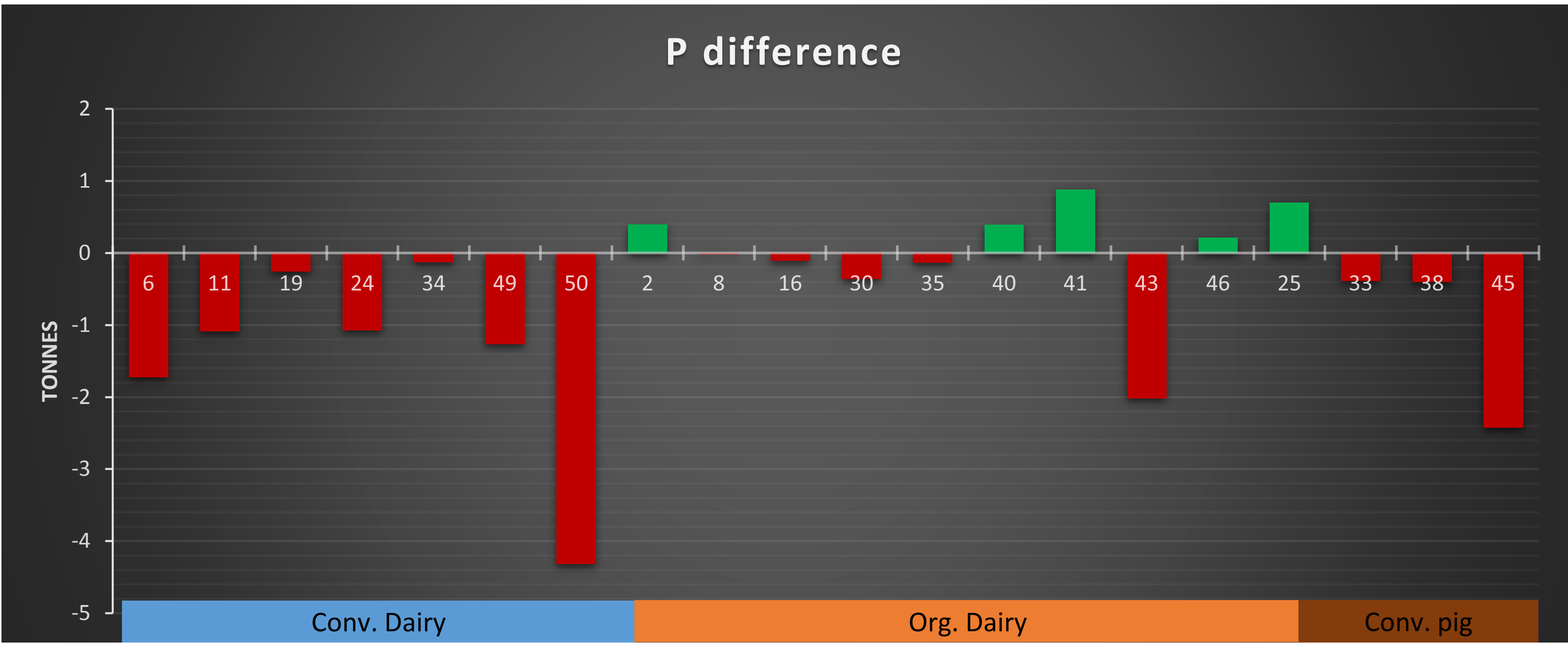

Figure 34. Diagram showing, for individual farms, the difference between the amount of P received from VH Biogas minus the amount of P delivered to VH Biogas. The numbers on the x-axle anonymously indicate each individual farm and their production type is marked by the coloured bar at the bottom of the diagram. Farm 25 is both an organic dairy farm and a conventional pig farm. The data is taken from 2015 and 2016.

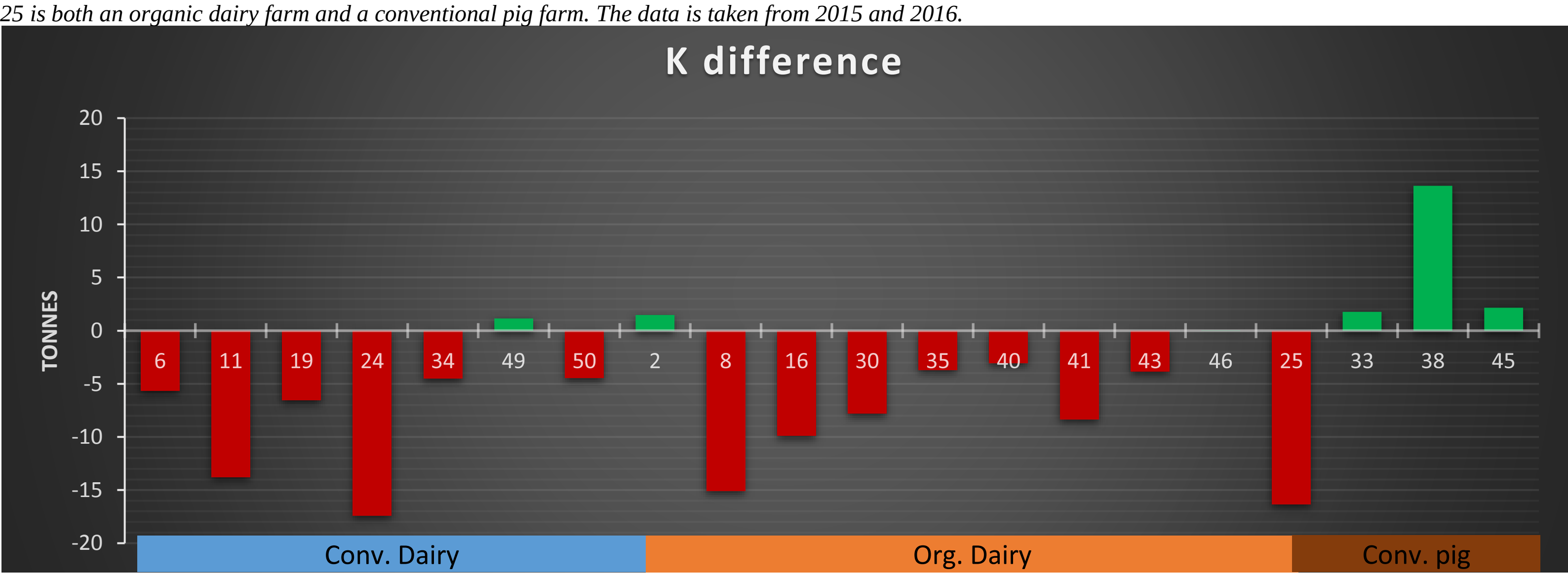

Figure 35. Diagram showing, for individual farms, the difference between the amount of K received from VH Biogas minus the amount of K delivered to VH Biogas. The numbers on the x-axle anonymously indicate each individual farm and their production type is marked by the coloured bar at the bottom of the diagram. Farm 25 is both an organic dairy farm and a conventional pig farm. The data is taken from 2015 and 2016.

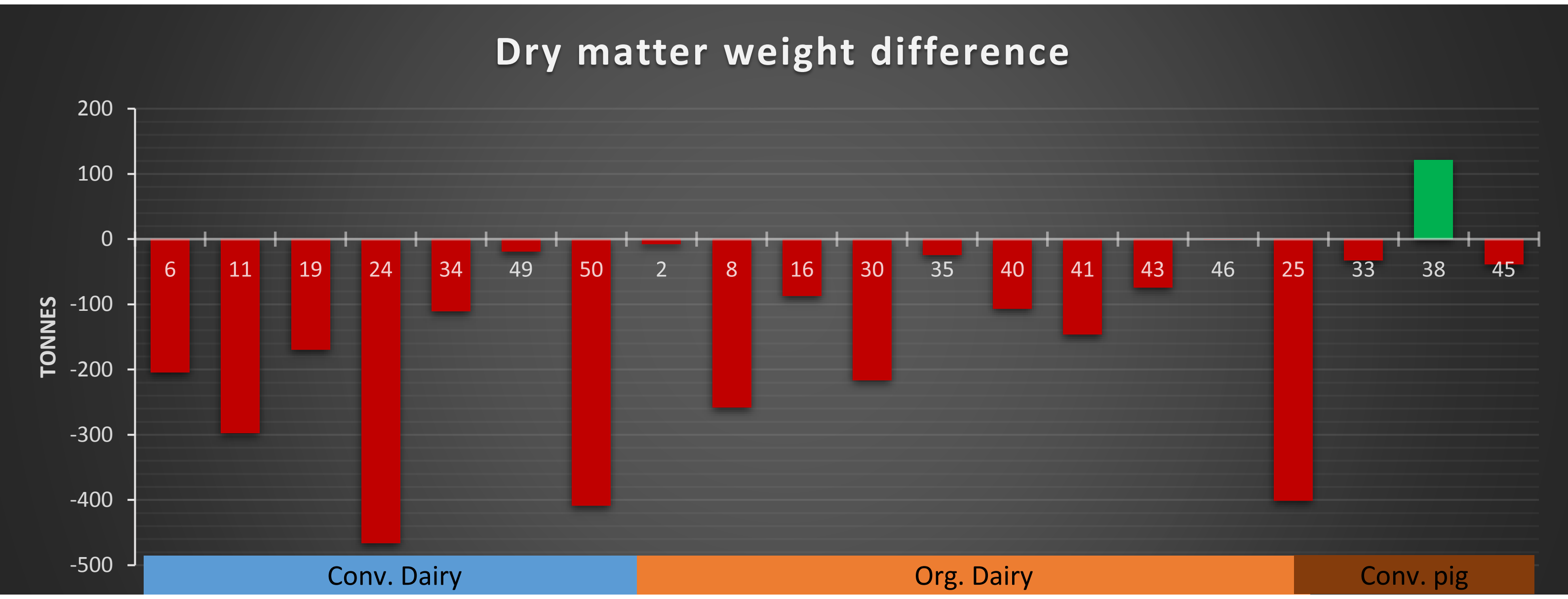

Figure 36. Diagram showing, for individual farms, the difference between digestate received from VH Biogas (in dry matter weight) minus substrate delivered to VH Biogas (in dry matter weight). The numbers on the x-axle anonymously indicate each individual farm and their production type is marked by the coloured bar at the bottom of the diagram. Farm 25 is both an organic dairy farm and a conventional pig farm. The data is taken from 2015 and 2016.

3.5 Interview with organic dairy farmer

The interviewed farmer identified some advantages of using digestate instead of manure for fertilization. He identified:

- Better hygiene in the ley feed
- Quicker loading of digestate into the manure spreader compared with manure
- Increased yields on all crops except winter canola
- Created the opportunity to build a separate storage well

The disadvantages he identified:

- Losing P and K
- Worried about the clover in the ley diminishing due to higher N application
- Seeds of *Rumex Crispus* being transported with the digestate
- More difficult than liquid dairy manure to create a crust on

4 Discussion

4.1 Method

No data were available for heavy metals or micronutrients through DVTime as VH Biogas did not analyse those in either manure or digestate, which is why these are not part of this study. Further research is needed to see how a system like VH Biogas affects the distribution of micronutrients and heavy metals. In the raw data taken from DVTime, some was incomplete. 5.4 % of the total data was taken out of this thesis and that is important to keep in mind when reading and interpreting the results.

There are some limitations and possible errors with the data used in this thesis. For one, analysis of the manure coming into the plant as substrate was analysed twice per year and the most recent analysis was used for each incoming delivery to determine its' content of N, P and K as well as dry- and fresh matter weight. Therefore, the data being put into DVTime is not going to be completely accurate. It is however reasonable to believe that two analyses per year and farm is adequate to get a good estimation of the total inflows of nutrients, even if it can be argued that the data might vary from the actual values. The same kind of reasoning holds true for the outgoing digestate but that is being sampled and tested four times a year. The data that was put into DVTime was done so manually. That leaves some room for human error that might have affected the results in this study. To try and minimize that, all data was examined and anything that looked to be out of the ordinary was double checked with the plant manager and adjusted when needed. This way the impact of these errors was minimized.

4.2 Results

As mentioned in the introduction, it is important to try and minimize environmental impact from the anaerobic digestion of manure, and part of that is to consider how the digestate is stored and what technique is used when spreading. One theoretical option would be to eliminate storage during summer but then the biogas production would suffer, making it practically impossible. The interviewed farmer said that it was tricky to form a crust on the digestate when storing it but mentioned that he solved it by putting bad silage on top of it. Practical experiences like that are key to counter any negative impact on the environment.

With the reasoning brought up in the introduction that production of biogas can help reduce the use of fossil fuels, the issue of transport and logistics which are energy consuming must be considered. The manure used in the biogas plant must be transported from the farms to the plant and the digestate must then be transported back out to the farms. It is assumable that this leads to a higher use of fossil fuels. However, in the interview made with one of the farmers involved in VH Biogas, it was brought up that he had built another storage for manure just because of the cooperation with the biogas plant. Since the plant owned and operated a lorry to transport manure and digestate, they could deliver the digestate to wherever the farmer desired. For that reason, the farmer saw the opportunity to build a storage not in immediate connection to the stables but closer to the fringes of his land. That way, there will be less transportation of digestate during spreading on the fields. The farmer himself though, could not say if he thought it led to less transport or not. Humborg (2016) brings up livestock density and how that is connected to imbalances in nutrient balances. He also mentions that storage and improving spreading techniques and timing are important to decrease nutrient leaching. Arguably, a more even distributed storage could lead to a more even spreading of manure/digestate and thus reducing nutrient leaching as well as a possible reduction in use of fossil fuels. However, calculations on the net result of fossil fuels usage has not been made in this study but it is nonetheless interesting to ponder.

It can be argued that this study is lacking since the acreage on each farm is unknown and therefore impossible to know where the digestate is actually being spread. It would have been interesting to further examine what the farm nutrient balances looked like. However, it is reasonable to assume that farmers have a spreading area corresponding to the amount manure being produced. There is no reason to believe that the farmers are below the minimum spreading acreage that they are required by law to have (corresponding to 22kg P/ha in manure) (Eskilsson, 2013). The size of the farms may also be estimated through the amount of substrate they deliver to VH Biogas, as shown in Table.1 in appendix. It is advisable to take table. 1 into account when examining figures 30-36.

4.2.1 Dry matter

Almost all farms experienced a loss of dry matter, except for farm 38 (Fig. 36). This is due to the fact that in the biogas producing process, carbon molecules are used as substrate for the microorganisms in their metabolism and the "waste products" are CO_2 and CH_4. Therefore, the weight of the solid and liquid fractions that come out of the digestion chambers will have a lower total weight than the substrates being put through it.

It could be seen as a disadvantage for farmers that the digestate they receive back has a lower dry matter content than the manure they delivered (Tables 3-7 in appendix) because there is more water in it. However, there are physical properties with the digestate that makes it preferable over manure. For example: pig manure has a tendency to form sedimentation while being stored. This increases the need for stirring and pumping the manure before it is suitable to spread on the fields. Digestate does not form sedimentation to the same degree and is therefore more desirable from the point of view that it needs less stirring, as per the interviewed farmer. Furthermore, the interview with the farmer shone light upon the fact that the digestate is more homogenous with less lumps. This likely facilitates an even distribution on the field which would be desirable. The digestate also possesses a greater ability to infiltrate the ground once spread due to its lower dry matter percentage and homogeneity and that could potentially lead to lesser losses of N to evaporation.

4.2.2 Total Nitrogen

The results show that conventional dairy farms lost a little N in total while the organic dairy farms had a net gain (Fig. 24). One explanation for this might lie in where the different farms get their feed. In Sweden, conventional farms imported more N to the farm than organic farms do (Wivstad & Salomon, 2009). In their report, conventional farms imported nearly twice the amount of N/ha through feed than the organic ones. It is reasonable to assume that due to this, manure produced by conventional cows will have a richer N-content. With the way the system at VH Biogas works, that leads to the conventional dairy farms experiencing a small net loss of total N. In the study made by Wivstad & Salomon (2009), they also showed that the total import of N from all sources were 65% higher for the conventional dairy farms than the organic ones. This further supports the results shown in Fig.

24. It is also possible that there are differences in the way the farms store their manure and therefore have different amounts of losses. This should not, however, be a structural difference between organic and conventional farms.

4.2.3 Potassium

The fact that the organic dairy farms lost more K than the conventional dairy farms could potentially be attributed to organic dairy having a larger portion of their rations based on roughage. Roughage such as grass/clover silage or hay and straw contain more K than for example grain or protein feed. This could lead to organic dairy having a higher K-content in the manure than conventional dairy. If the organic farms use more straw for bedding, that could also explain why the organic farms would lose more K than the conventional farms. It is reasonable to assume that the net loss of K (Fig. 28) might also stem from the separation of the solid fraction of the digestate. Perhaps some of the lost K is brought back to the dairy farms if they buy the solid fraction and use as bedding in their stables. However, it is not clear exactly to whom the solid fraction is being sold to.

4.2.4 Phosphorous

The different types of farms that both delivered substrate and received digestate all suffered net losses of P (Fig. 41). The explanation for this might be that a lot of P could be bound to the organic material (fibre) that is separated from the digestate after passing through the digestion chamber. That material is then sold separately and is not brought back to the farms that delivered manure to VH Biogas. This reasoning is supported by what Möller and Müller (2012) wrote in their review, as is elaborated on in the introduction. The other explanation could be that some of the analyses were not complete or that analyses of the manure and digestate were not made often enough to give an accurate description of the actual nutrient flows.

4.2.5 NH_4-N

The addition of poultry manure to the digestion chamber was viewed as very positive from both the plant manager, and the interviewed farmer. They claimed that it increased the production of biogas as well as enriched the digestate with N, which was desirable from the farmer's perspective. However, the poultry manure has a high concentration of NH_4-N and research shows that it inhibits the microorganisms involved in the anaerobic digestion if concentrations reach 3-14g/l (Schnürer & Jarvis, 2009). NH_3 is even more toxic and inhibition can be seen at 30mg/l (Schnürer & Jarvis, 2009). NH_4-N exists in an equilibrium with NH_3 which is mainly dependent on pH and temperature, and thus the more that equilibrium shifts towards NH_3 the greater the risk is of experiencing inhibition of the biogas process. It is of importance to note that the microorganisms can adapt and tolerate higher concentrations of ammonium and ammonia, as shown by (Schnürer & Nordberg, 2008). All in all, the use of poultry manure at VH Biogas is likely to be positive for the stakeholders involved.

4.2.6 Weed seeds

When co-digesting manure from different farms, there is a risk that weed seeds in the manure from one farm can end up on another farm that receive digestate, and as mentioned in the introduction, there seems to be no scientific consensus on how digestion affects the viability of weed seeds. However, at VH Biogas all substrates go through hygienization and it feasible to believe that that should dramatically reduce the risks of viable seeds being spread between farms. The interviewed farmer mentions that he believes viable seeds of *Rumex Crispus* survives the digestion process and are spread with the digestate.

4.2.7 Who is the winner?

When trying to determine what plant nutrients are being distributed where, it is of interest to see what group of farms are “winners” and which group are “losers”. All practical advantages of storing and spreading digestate aside, the results inevitably show that some farms lose plant nutrients through this kind of system. Plant nutrients that will have to be replaced somehow unless lower yield potential of their crops would be acceptable. From the conventional dairy farms perspective, they lose total N, P and K (Fig. 24, 27, 28). Essentially, they give nutrients to all the other types of receivers and may therefore collectively be seen as losers of this system. The clearest winners seem to be the organic dairy farms since they have a net gain of both N-org and NH_4-N. NH_4-N in particular is valuable for organic farmers since the options for buying fertilizers are limited and/or expensive. The organic dairy farms lose P in small quantities (Fig. 27) and a lot of K (Fig. 28) but this is not necessarily a major issue since P-AL classes generally are high on farms with animals (Eriksson *et al.*, 2010). So even if the farms end up losing P, it might still be sufficient for the crops grown on their fields. The same report by Eriksson (2010) states, however, that K-AL is not clearly connected to farms with animals, so the loss of potassium is potentially a problem. It is important to remember that the aforementioned diagrams do not show the farm nutrient balances though, only the delivered substrate and the received digestate. The conventional pig farms can be seen as both losers and winners with this system. They gain N-tot but with an increased N-org/NH_4-N quota which could be seen as a disadvantage since less N would be plant available after spreading the digestate. The loss of P might be seen as an advantage for this group due to the fact that pig farms often are at or near the limit of 22kg P/ha. They also gain some K. Something to think about when examining what farms gain nutrients and what farms lose nutrients, is that the dairy farms also have animals out on pasture where they defecate and leave some nutrients on the fields that are not accounted for in this study. How much that affects the nutrients balances on the farms can only be speculated in.

The interviewee says that he is taking higher yields on all his crops except for the winter canola since starting to spread digestate instead of manure, so it is possible that other farms are experiencing the same thing even if they are potentially losing some nutrients.

It is of importance to note, however, that within the types of deliverers and receivers, there are both winners and losers amongst the individual farms even if the type in total is either winner or loser (Fig. 30-36).

4.2.8 Further improvements

To further improve the environmental gain of biogas production and make a better dispersal of nutrients possible, it would be of interest to examine the possibilities of concentrating the nutrients in the digestate in some way to make transportation over further distances possible. Perhaps this could be done through drying, or filtering. At VH Biogas, some of the digestate is already being sold to other farms (cropping farms) but perhaps it would be possible to further develop that concept.

5 Conclusions

With the system in place at VH Biogas, plant nutrients from the contributing farms are being redistributed – between individual farms and between types of farms (organic and conventional dairy production, conventional pig production). Farms with organic dairy production are arguably the biggest winners in the system due to their net gain of NH_4-N. They do however lose P and K. Almost all farms receive back more digestate in fresh weight than they deliver in manure, but less in dry matter weight. It seems this system creates opportunities for a more even distribution of nutrients in the landscape as well as a way to reduce greenhouse gas emissions and utilizing waste products.

To answer the questions posed in the objectives:

- Can digesting manure help to more evenly distribute plant nutrients?
  - Yes, with the system at VH Biogas plant nutrients are distributed more evenly on fields on local scale with the potential to get to the regional scale if the nutrients in the digestate would be concentrated in some way.
- Is there a risk of farmers losing plant nutrients that they would like to keep?
  - Yes. The dairy farms lose K which is valuable to them. The conventional farms lose NH_4-N.
- Do different kinds of farms (dairy, pigs, organic, conventional) deliver/receive different ratios and/or amounts of plant nutrients?
  - Yes. The conventional farms deliver more N than the organic farms. The organic farms deliver more K. All receivers get nearly the same ratios of nutrients due to all substrates being mixed in the digestion chamber.
- Is there a seasonal difference in plant nutrient delivery (e.g. grazing period for dairy) to the biogas plant?
  - Possibly. This study showed a small seasonal difference in substrate delivery from all sources, but it was not done for only dairy farms.

- How much do the added substrates (e.g. food waste etc) influence the plant nutrient content of the digestate?
    - They have an influence. Slaughter residues contribute a lot of N-org and P. Poultry manure contribute relatively large amounts of NH_4-N and P. The other substrates seem to contribute in a fairly minor way.

Acknowledgements

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Appendix 1: Digestate-substrate difference, dairy and pig farms only

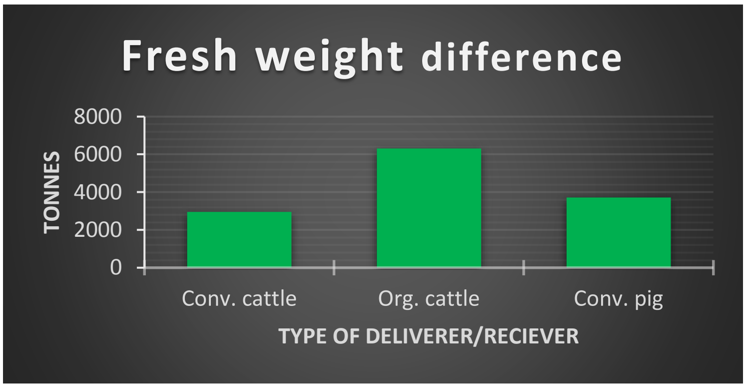

Figure 40. Diagram showing, for each type of farm, the difference between the total fresh weight of digestate received from VH Biogas minus the total fresh weight of substrate delivered to VH Biogas. The data is taken from 2015 and 2016.

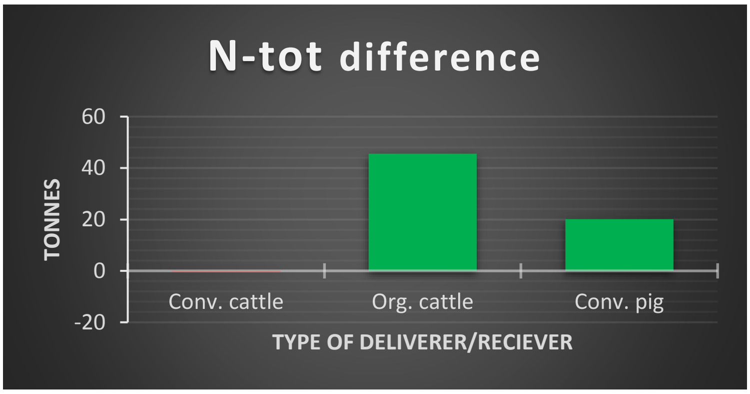

Figure 39. Diagram showing, for each type of farm, the difference between the total amount of N received from VH Biogas minus the total amount of N delivered to VH Biogas.The data is taken from 2015 and 2016.

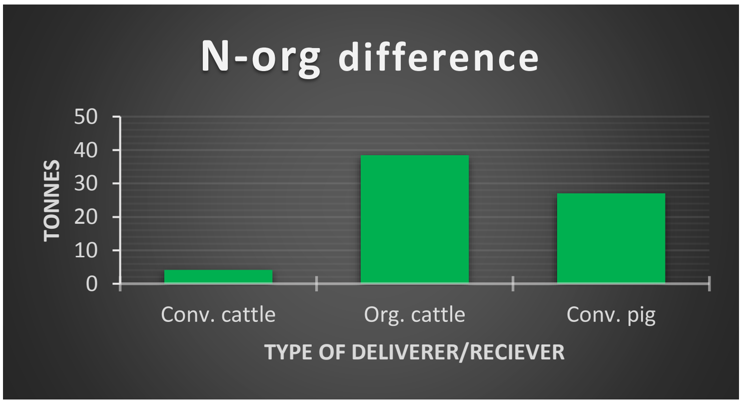

Figure 38. Diagram showing, for each type of farm, the difference between the amount of N-org received from VH Biogas minus the amount of N-org delivered to VH Biogas. The data is taken from 2015 and 2016.

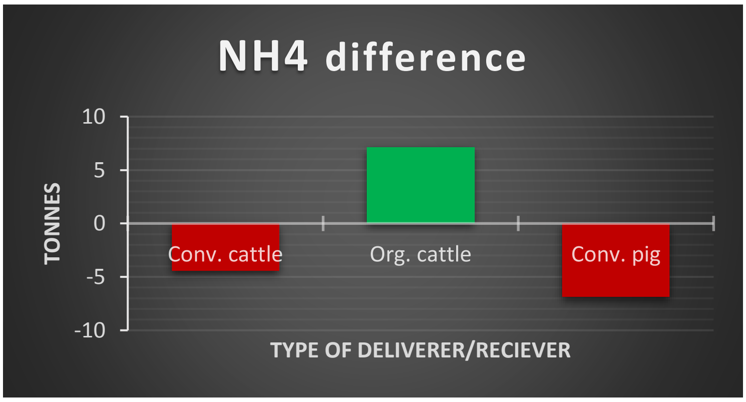

Figure 37. Diagram showing, for each type of farm, the difference between the amount of NH_4 received from VH Biogas minus the amount of NH_4 delivered to VH Biogas. The data is taken from 2015 and 2016.

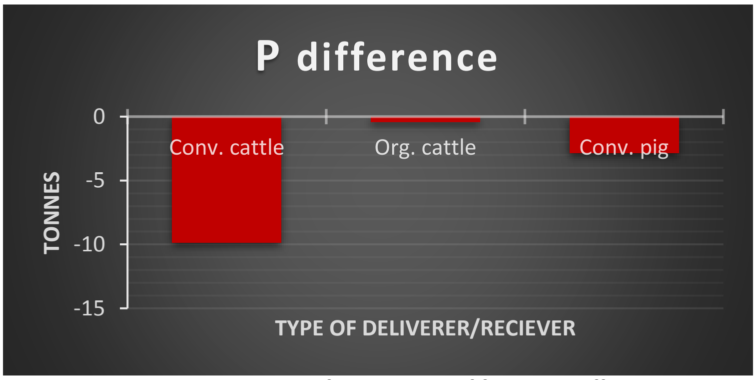

Figure 41. Diagram showing, for each type of farm, the difference between the amount of P received from VH Biogas minus the amount of P delivered to VH Biogas. The data is taken from 2015 and 2016.

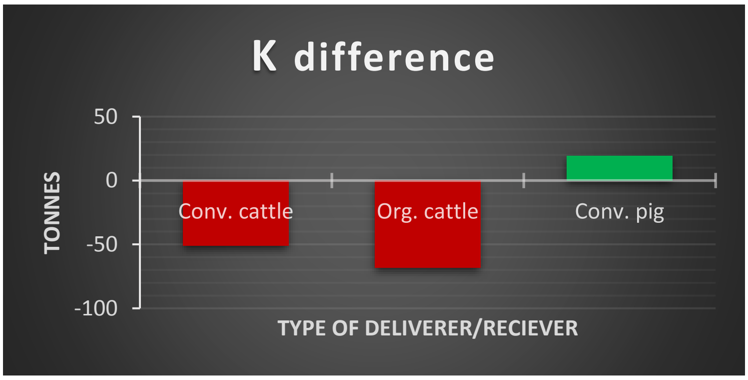

Figure 42. Diagram showing, for each type of farm, the difference between the amount of K received from VH Biogas minus the amount of K delivered to VH Biogas. The data is taken from 2015 and 2016.

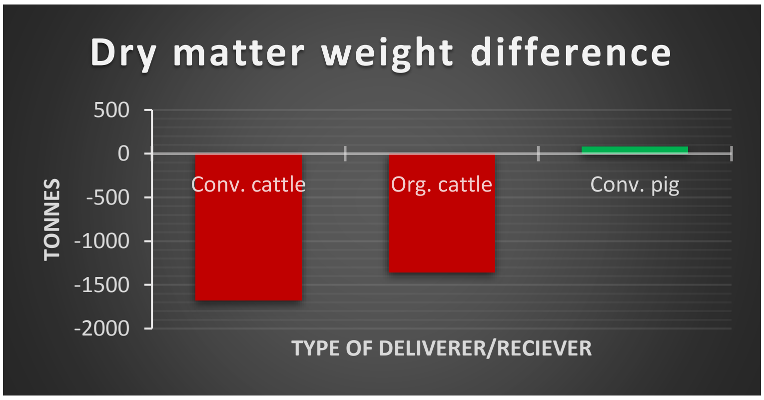

Figure 43. Diagram showing, for each type of farm, the difference between the total dry matter weight received from VH Biogas minus the total dry matter weight delivered to VH Biogas. The data is taken from 2015 and 2016.

Appendix 2: Fresh weight of substrate delivered to VH Biogas for each farm

Table 2. The total amount of substrate delivered to VH Biogas by the conventional dairy farms, organic dairy farms and conventional pig farms. The percentages stand for each farm's share of the total fresh weight of substrates coming in to VH Biogas.

Fresh weight of substrate

Farm/company	% of Total	Total delivered (Kg)
2	1,31%	1 885 910
6	2,97%	4 281 400
8	3,50%	5 036 870
11	4,58%	6 597 170
16	4,17%	6 003 950
19	3,66%	5 267 708
24	6,74%	9 705 200
25	12,82%	18 454 390
30	3,18%	4 583 650
33	1,26%	1 817 490
34	2,69%	3 873 380
35	2,67%	3 842 841
38	6,36%	9 160 840
40	3,08%	4 427 752
41	3,92%	5 641 650
43	2,32%	3 336 430
45	5,90%	8 490 780
46	0,39%	564 450
49	2,05%	2 947 860
50	8,09%	11 648 296
Sum	**81,66%**	**1,18E+08**

Appendix 3: Weight and nutrient sums for each individual farm

Conventional dairy farms

Table 3. The sums of all weights and nutrients in the substrate delievered to VH Biogas by each individual conventional dairy farm.

Substrate delivered									
	nettovikt	**N-tot**	**N-org**	**NH4**	**NH4/N-tot**	**P**	**K**	**DM (Kg)**	**DM (%)**
Farm	**Sum**	**Sum**	**Sum**	**Sum**		**Sum**	**Sum**	**Sum**	
11	6597170	25180	13269	11912	0,473	5451	30368	573019	0,087
19	5267708	19489	7372	12117	0,622	3428	18439	363472	0,069
24	9705200	44645	19405	25240	0,565	7265	40757	854064	0,088
34	3873380	14337	5427	8910	0,621	2520	13557	267269	0,069
49	2947860	9192	4860	4333	0,471	3083	5744	131498	0,045
50	11648296	60164	35622	24541	0,408	12512	35954	938081	0,081
6	4281400	19644	9938	9707	0,494	4574	16505	384784	0,090

Table 4. The sums of all weights and nutrients in the digestate received from VH Biogas by each individual conventional dairy farm.

Digestate recieved									
	nettovikt	**N-tot**	**N-org**	**NH4**	**NH4/N-tot**	**P**	**K**	**DM (Kg)**	**DM (%)**
Farm	**Sum**	**Sum**	**Sum**	**Sum**		**Sum**	**Sum**	**Sum**	
11	7124310	28939	14977	13962	0,482	4366	16590	275362	0,039
18	208470	917	564	353	0,385	130	480	9174	0,044
19	5172670	20813	10549	10261	0,493	3172	11919	193918	0,037
24	10093630	41055	21348	19707	0,480	6192	23365	388144	0,038
34	3884840	16141	8803	7334	0,454	2395	9064	156667	0,040
49	2970800	11941	6031	5911	0,495	1819	6894	112176	0,038
50	13371000	54630	28582	26044	0,477	8198	31523	529672	0,040
6	4657060	18907	9769	9134	0,483	2850	10855	179980	0,039

Organic dairy farms

Table 5. The sums of all weights and nutrients in the substrate delievered to VH Biogas by each individual organic dairy farm.

Substrate delivered									
	nettovikt	**N-tot**	**N-org**	**NH4**	**NH4/N-tot**	**P**	**K**	**DM (Kg)**	**DM (%)**
Farm	**Sum**	**Sum**	**Sum**	**Sum**		**Sum**	**Sum**	**Sum**	
16	6003950	21087	8434	12653	0,600	4128	26487	382603	0,064
2	1885910	5973	3832	2140	0,358	1315	5498	133616	0,071
25	18198650	71329	34029	37300	0,523	11955	69185	1341382	0,074
30	4583650	18579	9819	8761	0,472	3305	20194	434139	0,095
35	3842841	15054	6971	8084	0,537	2394	13232	191573	0,050
40	4427752	14611	7083	7528	0,515	2477	15056	318798	0,072
41	5641650	24106	9535	14571	0,604	3529	26337	470706	0,083
43	3336430	12800	7904	4896	0,383	4653	14455	266725	0,080
46	564450	1748	788	960	0,549	276	1975	36690	0,065
8	5036870	20150	10076	10074	0,500	3119	28202	488576	0,097

Table 6. The sums of all weights and nutrients in the digestate received from VH Biogas by each individual organic dairy farm.

Digestate recieved									
	nettovikt	**N-tot**	**N-org**	**NH4**	**NH4/N-tot**	**P**	**K**	**DM (Kg)**	**DM (%)**
Farm	**Sum**	**Sum**	**Sum**	**Sum**		**Sum**	**Sum**	**Sum**	
16	6542420	27489	15074	12422	0,452	4021	16600	295646	0,045
2	2790990	11813	6598	5215	0,441	1712	6980	125607	0,045
25	20017969	83828	45533	38304	0,457	12274	51126	906309	0,045
30	4795610	19964	10673	9291	0,465	2945	12391	217827	0,045
35	3693700	15344	8160	7183	0,468	2262	9558	167350	0,045
40	4679590	19556	10571	8989	0,460	2872	12006	212097	0,045
41	7163950	30364	16973	13387	0,441	4410	17991	324362	0,045
43	4275820	18163	10229	7931	0,437	2636	10623	192083	0,045
46	800410	3402	1919	1481	0,435	491	1986	35939	0,045
8	5072840	21075	11203	9873	0,468	3102	13140	230081	0,045

Conventional pig farms

Table 7. The sums of all weights and nutrients in the substrate delievered to VH Biogas by each individual conventional pig farm.

Substrate delivered									
	nettovikt	**N-tot**	**N-org**	**NH4**	**NH4/N-tot**	**P**	**K**	**DM (Kg)**	**DM (%)**
Farm	**Sum**	**Sum**	**Sum**	**Sum**		**Sum**	**Sum**	**Sum**	
25	255740	1179	324	855	0,725	260	657	11870	0,046
33	1817490	6177	1999	4178	0,676	1578	2724	105413	0,058
38	9160840	29941	9550	20387	0,681	7060	11633	298771	0,033
45	8490780	38207	11030	27177	0,711	8324	20374	416040	0,049

Table 8. The sums of all weights and nutrients in the digestate received from VH Biogas by each individual conventional pig farm.

Digestate recieved									
	nettovikt	**N-tot**	**N-org**	**NH4**	**NH4/N-tot**	**P**	**K**	**DM (Kg)**	**DM (%)**
Farm	**Sum**	**Sum**	**Sum**	**Sum**		**Sum**	**Sum**	**Sum**	
25	1042790	4587	2815	1772	0,386	642	2401	45884	0,044
33	1942360	7781	3906	3878	0,498	1190	4489	72547	0,037
38	8889820	36045	18582	17462	0,484	5453	20632	340992	0,038
45	9610480	39170	20340	18830	0,481	5900	22538	376927	0,039

Appendix 4: Interview guides

Interview guide – biogas plant

- Vilket substrat används i anläggningen? Bara stallgödsel? Tillsatser?
- Vilken typ av anläggning? Utformning, temp, etc.
- Blir det något restmaterial? Vad händer med restmaterialet, ex fiber?
- Hur stor är rötkammaren/kamrarna?
- Hur lagras rötresten (Tak, svämtäcke)? Hur mycket lagrar ni? Lagrings-kapacitet?
- Hur mycket biogas bildas? Per dag, per kg gödsel. Varierar det mycket?
- Anses biogasen eller rötresten vara viktigast? Ur ert och ur lantbrukarnas perspektiv
- Hur fungerar in- och utkörning rent praktiskt?

Interview guide – farmer

- Hur lagras rötresten, tak eller svämtäcke?
- Vid vilken tidpunkt sprids rötresterna och med vilken teknik? Varför?
- Uppskatta ungefär hur fulla lagren är under vinter- och sommarhalvår?
- Vad är viktigast, biogasproduktionen eller tillgången till rötrest?
- Hur kommer det sig att du är med i projektet?