Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Jennie Marieke Spruit

Potential of livestock manure processing to close the phosphorus loop in Norway

A material flow analysis approach

Master's thesis in Industrial Ecology
Supervisor: Daniel Müller
July 2019

Source: (Havro, 2019)

NTNU
Norwegian University of
Science and Technology

Industrial Ecology Programme

Jennie Marieke Spruit

Potential of livestock manure processing to close the phosphorus loop in Norway

A material flow analysis approach

Master's thesis in Industrial Ecology
Supervisor: Daniel Müller
July 2019

Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

NTNU
Norwegian University of
Science and Technology

Abstract

Norway is dependent on imports of mineral fertiliser in the form of phosphate rock, which is a scarce and non-renewable resource, but has sufficient phosphorus (P) available in the form of manure to cover the national demands for food production. The use of this secondary source of P requires its transport between regions, due to the spatial heterogeneity in animal and crop farming, which is made difficult by the heavy weight of manure. A new technology termed CowPower™ aims to address this issue through the processing of livestock manure, creating a lightweight P-rich product which can be exported to P deficient regions. A material flow analysis (MFA) of this technology was conducted, along with an MFA of a Norwegian organic farm. Subsequently, these were combined in an upscaling scenario to assess the potential quantity of cattle manure available for processing on a national scale, while accounting for current reuse of manure to produce forage feed, and the unavailability of manure excreted during grazing. CowPower was found to produce a final exportable product containing 70% of the manure P and merely 2.5% of the wet weight, along with a liquid N-rich fertiliser for use on-farm. The organic farm was found not to have a surplus of P, due to its strong reliance on homegrown feed. Out of a total manure P production of 9 kt per year from cattle, 1.3 kt P remained after deduction of losses to pasture and fertilisation of forage crops. After CowPower treatment this would yield 0.8 kt P (weighing 53 kt) in the dry fraction for transport, the plant fertilisation potential of which is unknown. We conclude that the manure share requiring interregional transport is less than anticipated, as efficient recycling into forage crops should be prioritised. Barriers to efficient local recycling should be further analysed to assess CowPower's role in overcoming these.

Acknowledgements

I would like to extend my gratitude to my supervisor professor Daniel Müller and co-supervisor Simona Sharma, for their guidance and advice throughout the past year. Also, to my co-supervisors Knut Vasdal and Marina Bleken, for sharing their expertise with me. A big thanks to Jon Kristian Sommerseth for repeatedly taking the time to answer my many questions. I would further like to thank Knut Vasdal at Foss Biolab and Finn Aakre Haugen at USN for granting permission to use their data from the analyses in 2012-2014. Finally, I can't thank my friends enough for their support and for making Trondheim even better than Edinburgh.

“Growth of the soil was something different,
a thing to be procured at any cost;
the only source, the origin of all.”
~ Knut Hamsun, Growth of the soil

Table of Contents

List of tables

List of figures

List of abbreviations

AD:	Anaerobic digestion
DC:	Dairy cattle
DM:	Dry matter
ECM:	Energy-corrected milk
MBI:	Mass balance inconsistency
MFA:	Material flow analysis
NH_4-N:	Nitrogen in ammonium
NO_3-N:	Nitrogen in nitrate
NR:	Nitrification reactor
SFA:	Substance flow analysis
WW:	Wet weight
YC:	Young cattle

1 Introduction

1.1.1 Motivation

Phosphorus (P) is a nutrient essential to food production. Modern agriculture relies on imports of mineral fertiliser from phosphate rock to sustain its production. However, phosphate rock is a non-renewable resource with currently known reserves potentially depleted in 50 to 100 years (Cordell, Drangert, & White, 2009). In addition, the remaining reserves are primarily in hands of a few countries: China, which has been limiting exports to secure their domestic supply; Morocco, which occupies the reserves in Western Sahara in violation of international laws; and the US, whose resources were forecasted to be depleted within the next thirty years (Cordell et al., 2009). In addition, reserves are located in Russia and the Middle East (Van Vuuren, Bouwman, & Beusen, 2010). For Europe, which is completely dependent on imports, it is thus desirable to decrease their demand for mineral P fertiliser, in anticipation of (geopolitical) scarcity.

In addition, overapplication of P to soils causes eutrophication of water bodies through erosion and runoff, causing widespread environmental issues both in- and outside Europe (Smith, 2003). Increasing resource efficiency by effectively utilizing secondary P resources is therefore vital to both food security and environmental management (Ashley, Cordell, & Mavinic, 2011).

1.1.2 Secondary P sources

Norway is a net importer of phosphorus, with a net import of 30 kt P per year in 2009-2011, but has the potential to significantly reduce this dependence by recycling waste P flows, mainly from agriculture and aquaculture (Hamilton et al., 2016). These potential secondary sources have been estimated at 12 kt of manure and 9 kt of fish excrements and feed losses per year (Hamilton et al., 2016). With regards to the aquaculture waste flows, the main obstacle is the difficulty in retrieving P once it is dissolved in large water bodies. Post-consumer waste forms another albeit smaller source, but comes with concerns related to contaminants due to chemical treatment used in Norway (Hamilton et al., 2016).

Agricultural wastes, such as manure, are easier to collect and are organic. In addition, manure has a high plant-availability (Hamilton et al., 2017). This is of importance to prevent a build-up of P in the soil in compounds that are unavailable to plants. The amount of manure in Norway was found to be 10.9 kt plant-available P per year (Hamilton et al., 2017). Theoretically, this source of secondary P from manure would be sufficient to cover the total national fertilisation demand, which was estimated at 10.5 kt P per year (Hanserud, Brod, Øgaard, Müller, & Brattebø, 2016).

Furthermore, the current Norwegian fertilisation regime is characterized by an over-application of P, and a transition phase with lower P fertilisation is required to lower soil P levels. Total fertiliser requirements for Norway were reduced by 48% when taking into account the existing plant-available soil P (Hanserud et al., 2016). Thus, if the fertilisation regime would be adjusted to account for existing soil P, the national demand P could be as low as 5.8 kt plant-available P (Hamilton et al., 2017), at which point the supply from manure could be more than enough to make Norway independent from mineral fertiliser imports in the short term.

1.1.3 Spatial differences and transport

In practice, the distribution of the P supply and demand is highly spatially heterogeneous, which forms an obstacle to the reuse of P as a secondary resource. Regional differentiation into either crop farming or intensive livestock production is an issue in many European countries (e.g. Hanserud et al. (2016), Bateman, van der Horst, Boardman, Kansal, and Carliell-Marquet (2011), Senthilkumar, Nesme, Mollier, and Pellerin (2012)). Even on a global scale such a differentiation can be observed (MacDonald, Bennett, Potter, & Ramankutty, 2011). Figure 1 shows the relationship between livestock density and soil P status in Norway (Brod, 2018), with high concentrations in the southwestern counties while crop farming is most intensive in the southeast (Hanserud et al., 2016). Although the vast majority of Norwegian dairy farmers uses their manure resources to produce their own forage feed (Bleken, 2019; Sommerseth, 2019), oftentimes they are still faced with a surplus.

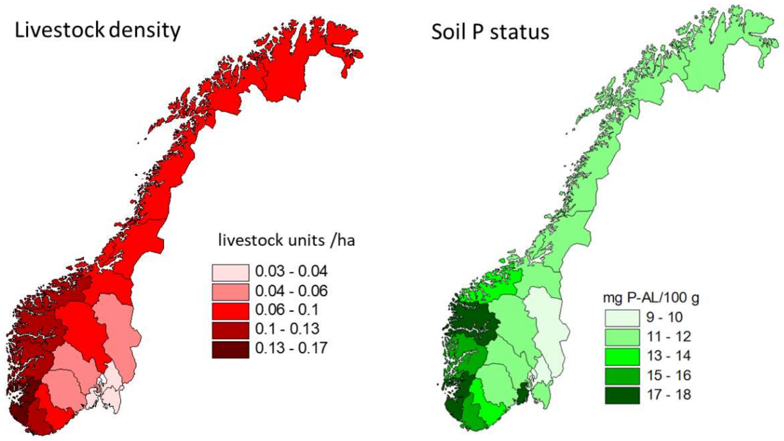

Figure 1. Livestock density and soil P status in Norway per county. With mg P-AL/100 g the unit of the Norwegian standard soil P test. Reproduced from: (Brod, 2018).

Historic farming systems where crops and livestock are co-produced are unlikely to be efficient enough to sustain modern-day food production, let alone the requirements from future population growth (Ashley et al., 2011; MacDonald et al., 2011). Therefore, solutions need to be found to optimise the existing spatially heterogeneous systems. It is currently unattractive for farmers to transport their manure over large distances, resulting in application mainly on neighbouring farms or on the fields closest to the manure storage facilities (Hanserud et al., 2016). The bulky nature of manure that makes it hard to transport is thus a major obstacle to closing phosphorus loops (Bateman et al., 2011; Cordell et al., 2009; Hamilton et al., 2017).

A solution to this could be to process the manure in such a way that most of the water is removed, thus concentrating the dry matter and nutrients inside to allow for convenient transportation. There are a range of methods by which manure can be processed; a literature review on these different techniques, their benefits, and tradeoffs is given in Chapter 2.1 'State-of-the-art'. This thesis presents a case study of one such technique, as described in the next section.

1.2 Case study of CowPower

A processing technique termed CowPower™ was developed by Knut Vasdal at the Foss Gård farm. CowPower processes dairy cattle manure using a centrifugation method, followed by anaerobic digestion producing biogas, nitrification to stabilise the nitrogen compounds, gravitational filtering, granulation, and drying (Vasdal, 2019) (see Chapter 2.1). The process has three end-products: a composted fibre fraction, a liquid fertiliser, and a granulated fibre fraction, each with different characteristics of dry matter and nutrient contents.

The aim of CowPower is to help bridge the gap that exists in Norway between areas with high animal density and hence a surplus of P, and areas where P is in demand. To this end, the granulated fibre fraction is designed to be a very dry product with a high P content, such that it can easily be transported between these regions.

For this thesis, a material flow analysis (MFA) of the CowPower method was made, tracking the total mass to obtain insight into the weight reductions achieved, as well as the contents of dry matter (DM), phosphorus (P), and nitrogen (N). The results can inform discussion on the optimisation of the technology, the application of the different end-products, and the potential that can be achieved through upscaling.

Furthermore, the case of CowPower is interesting as it involves processing of manure beyond solid-liquid separation and composting, which is a level of processing that is rarely applied in the EU (Foged et al., 2011) and scarcely covered by scientific literature (Brod, 2018). It thus not only addresses the real-life challenge of phosphorus redistribution, but also contributes to filling this research gap. See Chapter 2 'State-of-the-art', which presents a literature review of current practices.

1.3 Case study of Foss Gård and Upscaling Scenario

In addition to the MFA of CowPower, an MFA was conducted of Foss Gård, the dairy farm where CowPower is being developed. This served the dual purpose of gaining insight into the potential for CowPower to be applied here, as well as into the variables that affect the surplus of P in the manure that is available for processing.

The case of Foss Gård can serve as a typical example of a Norwegian organic dairy farm, characterised by a relatively high self-sufficiency in feed production, using its available manure without additional mineral fertiliser. The MFA covered dry matter and phosphorus flows.

Furthermore, this case was expanded upon by a simplified model, capturing the most important flows, in which the farm-specific variables were substituted by Norwegian national (average) values. Scaling this model up to a national level, a conservative estimate was obtained of the quantity of P available for CowPower, i.e. under the assumption of complete forage feed self-sufficiency and manure reuse characteristic of organic farms.

A literature review of dairy-farm phosphorus MFAs, presented in Chapter 2 'State-of-the-art', revealed a shift in problem focus from P as a cause of eutrophication to P as a resource that requires redistribution, in the past decade. This was accompanied by a shift from farm-level analyses that included a high process detail to national-level analyses and scenarios, with more simplified systems.

This thesis aims to fill a gap in literature by combining the detail of internal farm flow dynamics with estimates for secondary manure availability on a national level (see section 2.3.3 'Synthesis'). In doing so, it aims to refine the existing estimate of Norwegian secondary manure availability by Hamilton et al. (2017) by accounting for grazing practices and existing recycling practices, to more accurately reflect the reality of the Norwegian agricultural system.

1.4 Research questions

To summarise, the goals of this thesis are to (i) assess the material flows of CowPower, (ii) investigate how CowPower may be implemented at the farm level, (iii) to estimate the potential for saving primary P resources, (iv) to identify relevant barriers that need to be addressed in an attempt to upscale this technology to a national level. This will be done through a material flow analysis of the CowPower process and of the P flows on a farm level, and subsequent combination and extrapolation of these results in an upscaling scenario model.

The research questions central to this thesis are:

(i) How are the flows and end-products of CowPower characterised with regards to mass and nutrients, and to what extent is on-farm processing preferable over decentralised manure processing?

(ii) How do the P flows on Foss Gård affect the manure P surplus available for CowPower?

(iii) What is the potential of CowPower to process livestock manure for transport on a national scale?

1.5 Paper outline

The rest of this thesis is structured as follows. Chapter 2 provides an overview from literature of the state-of-the-art of manure processing techniques related to those used in CowPower, as well as an analysis of the research that has been done on MFAs of farm systems. The subsequent chapters of methodology, results, and discussion and conclusions are each split in three parts to discuss respectively the MFA of CowPower, the MFA of Foss Gård, and the upscaling scenario.

2 State-of-the-art

2.1 Processing of animal manure

Different treatment options are available to process manure. Their main goal is to decrease the water content and to concentrate the nutrients. In this section, an overview of the state-of-the art of several manure processing methods is provided, for those processes that were found to be relevant to the case of CowPower. Appendix A provides some additional information on different processing methods, i.e. struvite precipitation, reverse osmosis, and use in algae cultivation.

2.1.1 Solid-Liquid Separation

To decrease the water content, manure is often first separated into a solid and a liquid fraction. This can be done through a number of mechanical methods. Centrifugation makes use of gravitational forces to quickly separate the dry matter from the liquid fraction, removing also small particles and producing a liquid fraction with near-ideal N/P/K ratios. Sedimentation is similar but uses only gravity and is a cheaper and simpler option, at the cost of a longer settling time. Filtration can be applied using gravity only, or with additional external pressure. The latter case produces a very dry solid fraction, but results in small dry matter particles and phosphorus being forced into the liquid fraction, and thus low efficiencies. (Christensen, Christensen, & Sommer, 2013)

Centrifugation generally has the highest efficiency in terms of dry matter and P separation, producing a solid fraction with respectively 60-63% and 69-73% of the dry matter and P originally present in the manure (Christensen et al., 2013). The treatment options outlined above result in dry matter contents that are still quite low, with a water content of 70-80% (Bateman et al., 2011; Brod, 2018). Further treatment steps such as drying and pelletising of the obtained dry fraction are therefore required in order to decrease transport costs and environmental impacts to the point where it becomes cost-effective (Bateman et al., 2011).

2.1.2 Anaerobic digestion and chemical pre-treatment

Prior to mechanical treatment, the manure can be treated through anaerobic digestion. This reduces its greenhouse gas emissions (CH_4 and N_2O) during application, through a controlled fermentation process producing mainly CO_2 and CH_4 directly in the form of biogas, which can be used to replace fossil fuels (Brod, 2018). Additional positive effects include reductions of pathogens, denaturisation of weed seeds, and reduction of odours (Scholz, Roy, Brand, Hellums, & Ulrich, 2014). Although Norway aims to increase the share of manure that is treated with anaerobic digestion, to date this share is only 1%. (Brod, 2018; Sandberg, 2018)

In addition, chemical pre-treatment with flocculants or coagulants increases the settling rate of small particles, leading to increased efficiencies of up to 86% of the original phosphorus retained in the solid fraction (Popovic, Hjorth, & Stoumann Jensen, 2012).

2.1.3 Plant-availability of nutrients

The chosen processing method may affect the plant-availability of the nutrients in the final product, and thus the fertilisation potential.

Anaerobic digestion has been found not to affect the absolute nutrient concentrations in the manure (Scholz et al., 2014). However, studies on the effect of anaerobic digestion on the plant-availability of P are few and inconclusive, with some reporting a negative effect and others reporting no effect (Brod, 2018). Hypotheses differ on whether it could lead to precipitation of the phosphates as salts and thus decreased solubility, or if the specific phosphate compounds in manure are not affected in this manner (Brod, 2018). Similarly, there have been indications that composting could reduce the P fertilisation effect of manure (ibid.).

Results from experimental studies indicate that separation of solid and liquid fractions has no adverse effect on the fertilisation effect of (swine or cattle) manure. Neither did the use of flocculants and coagulants. However, filtration with external pressure may reduce the phosphorus fertilisation effect of the solid fraction, due to the loss of small particles to which phosphorus is bound. (Brod, 2018)

2.1.4 Thermal treatment

The solid fraction obtained from solid-liquid separation still has a high water content, which can be strongly reduced through thermal treatment. This can be done through combustion or gasification to produce an ash-based fertiliser, or through pyrolysis (no oxygen) to produce a biochar. Such thermal treatment can be combined with energy recovery, and removes pathogens and odour. However, it is known to lead to losses of most of the nitrogen. In addition, the plant-availability of P has been shown to reduce clearly through thermal treatment. This loss in availability was indicated to be higher at higher temperatures used, and lower for pyrolysis. (Brod, 2018)

In addition, the dried product can be pelleted or granulated, to improve the structural characteristics. However, scientific studies focusing on these processes were found to be scarce.

Mazeika, Staugaitis, and Baltrusaitis (2016) assessed a pilot system in which poultry manure was dried to a DM content of at least 90% and subsequently granulated via extrusion both with and without mineral additives. The process could be achieved with equipment commonly found on farms, and N-P-K contents could be tuned. However, high energy consumption (100 kWh/t) of the drying process indicated that the desired DM content may not be economically optimal (Mazeika et al., 2016).

A study by Kuligowski, Poulsen, Rubæk, and Sørensen (2010) on the fertiliser value of different manure-based products included pelletised pig manure biogas residue (PEL) and incinerated PEL (IA). The dry matter content of the products was not provided. Compared to a mineral fertiliser reference, application of PEL yielded 95% of the barley DM yield and 155% of the barley total P uptake, while IA yielded 79% and 123% respectively.

CowPower makes use of a drying process in combination with granulation. However, the specific method used for drying was not publicly available.

2.1.5 Environmental costs and benefits of manure processing

The large volume and weight of unprocessed manure make its inter-regional transport economically not feasible. Processing steps to dewater the manure can overcome this issue, but may come at the cost of increased environmental impacts due to e.g. energy requirements of processing and transport or emissions during storage.

In a case study on transport between two regions in Norway, Hanserud, Lyng, Vries, Øgaard, and Brattebø (2017) found that scenarios of solid-liquid separation with anaerobic digestion resulted in similar or lower environmental impacts than a reference scenario without transport. Similarly, ten Hoeve et al. (2014) concluded for Denmark that transport over 100 km after solid-liquid separation was preferable in terms of environmental impacts. Aguirre-Villegas, Larson, and Reinemann (2014) also found anaerobic digestion and solid-liquid separation to significantly reduce global warming potential and depletion of fossil fuels when compared to direct application on land. However, according to their results anaerobic digestion also led to a significant increase in ammonia emissions through volatilisation, which may be reduced by injecting the manure into the soil.

In contrast, De Vries, Groenestein, and De Boer (2012) found a 19% increase in fossil fuel depletion when processing cattle manure through anaerobic digestion. To explain the difference between their results and that of De Vries et al. (2012), Hanserud et al. (2017) pointed out the significance of their use of the Norwegian electricity mix, and their optimistic assumption of the generated biofuel replacing diesel fuel.

2.1.6 Manure treatment in the EU

An inventory of different manure processing techniques applied in the EU member states was made by Foged et al. (2011). It showed that mechanical separation of manure into a solid and liquid fraction is relatively common practice in EU countries (11,062 instances) and is almost exclusively (98%) performed on farm size installations, with drum filters, screw pressing, and sieves being the most commonly used methods.

Anaerobic treatment is somewhat less common (5,256 instances) and has a lower share of farm processing (89%), with the rest occurring in larger size installations.

Of the mere 1,486 cases where the solid fraction was processed further, this consisted of composting in 86% of the cases. Biodrying (predominantly farm-scale) and thermal drying (larger scale) together accounted for another 10% of the solid fraction processing. With regards to pelletising, only 21 cases were known in the EU, of which 5 applied on the farm-scale. Granulation was not listed in the inventory.

This shows that while primary processing steps such as solid-liquid separation and anaerobic digestion are not entirely uncommon in the EU, further processing is as of yet rarely applied. In addition, there are large differences in practice between the member states. Processing of manure is most common in Greece, where 35% of the available manure is processed, followed by Germany (15%) and Italy (7%). Not being a member state, Norway was not included in the inventory; however, the share in total manure processing was found to be low in neighbouring countries Denmark (4%) and Sweden (0.8%) (Foged et al., 2011).

2.2 Farm MFAs

2.2.1 National-level SFAs of P in agriculture

Substance flow analyses (SFA) of phosphorus in agricultural systems are common. These can be conducted at different scales. A national scale is often used, at which the scope is often extended to include not only the system of food production but the entire food chain, including waste management and flows to surface water.

Some examples include analyses of Norway (Hamilton et al., 2017; Hamilton et al., 2016), the UK (Bateman et al., 2011), the Netherlands (Smit, van Middelkoop, van Dijk, & van Reuler, 2015), Finland (Antikainen et al., 2005), Sweden (Linderholm, Mattsson, & Tillman, 2012), Denmark (Klinglmair et al., 2015), China (Chen, Chen, & Sun, 2008), and New Zealand (Li, Boiarkina, Young, & Yu, 2015), as well as the islands of Miyakoyima (Tamura & Fujie, 2014), and St Eustatius (Firmansyah, Spiller, de Ruijter, Carsjens, & Zeeman, 2017). These national balances are highly relevant as a basis for informing national policies on phosphorus.

In such analyses, the process resolution of the agricultural part of the system is often low. For example, in Li et al. (2015) this was limited to the four processes ‘fertiliser’, ‘agricultural land’, ‘animals’, and ‘food & feed’. A similar approach was taken by Hamilton et al. (2016), Linderholm et al. (2012) and Antikainen et al. (2005). In these SFAs, the flows related to manure are not made explicit, and the fate of the manure is limited to application on agricultural land.

Other SFAs include a higher process detail. For example, Chen et al. (2008) distinguish between arable land and grassland, and make the collection of livestock manure explicit. Similarly, Smit et al. (2015) include a high resolution agricultural subsystem, making different livestock practices explicit, and providing more detail on the fate of mineral fertiliser and animal manure, incl. the differentiation between manure deposited on pastureland and manure available for collection. In their system, 19% of the manure from grazing animals ends up on the pasture where it is unavailable for collection. In addition, different land use types are distinguished. Tamura and Fujie (2014) included the highest detail of the reviewed studies, but considered all manure available for collection.

Hamilton et al. (2017) kept a low resolution of the agricultural system (Fertilizer market, plant production, and animal husbandry), but integrated this with further processing and the aquaculture sector in a way that made the waste products’ value as secondary P resources explicit. Such results are highly interesting with regards to the challenge of P recycling. The study does not, however, make explicit the share of manure that is unavailable for collection due to grazing practices, nor the extent to which manure is currently already being effectively recycled as fertiliser.

Another study that focused on the challenge of manure distribution was a multi-regional P balance for the UK by Bateman et al. (2011) that showed its spatial heterogeneity and temporal variability. No formal SFA system was presented, but a simple system was used in which regional crop P requirements were set against P in animal manure after correcting for the share lost while grazing.

The most appropriate process resolution depends on the characteristics of the system under study, as well as the purpose of the study. Higher process resolutions could provide more detailed insights but require higher data availability. Nevertheless, with regards to the transportation issue arising from the challenge to improve national reuse of manure as a fertiliser, assessments like those by Hamilton et al. (2017) and Bateman et al. (2011) could be significantly improved in accuracy by including more detail.

2.2.2 Farm-level SFAs of P

In addition, there is an abundance of scientific articles on farm-level SFAs of P and other nutrients. For example, there have been case studies of dairy farms in Norway (Steinshamn et al., 2004), Sweden (Gustafson, Salomon, Jonsson, & Steineck, 2003; Modin-Edman, Öborn, & Sverdrup, 2007), Australia (Gourley et al., 2012), the US (Hutson, Pitt, Koelsch, Houser, & Wagenet, 1998; Powell, Jackson-Smith, Satter, & Bundy, 2002). Not all of these articles applied a formal substance flow analysis methodology.

Their focus generally lies on modelling the nutrient flows within the farm in order to quantify the build-up or loss of nutrients in the soil and its environmental implications. Optimising the nutrient management to prevent eutrophication and comply with regulations without leading to long-term soil P deficits is often a focus point.

From this point of view, organic farms are of particular interest. Both Gustafson et al. (2003) and Modin-Edman et al. (2007) studied Swedish dairy farms where conventional and organic farming practices were applied alongside each other, in order to compare them.

Also Steinshamn et al. (2004) conducted an SFA of internal P and N flows on an organic dairy farm in Norway. Their system included different types of animal feed, the fate of manure, and a separation between the production of crops and of grass for grazing. The study spanned a three year period, during which samples were taken for chemical analysis, and variables such as feed intake, milk production, and animal weight were recorded automatically. Their results highlighted the interdependence of the flows and the importance of including these internal farm flows.

The effects of grazing were not taken into account in any of the other farm balances reviewed here, except for the case of Australia (Gourley et al., 2012) where year-round grazing practices play an important role.

2.2.3 Synthesis

Interestingly, although no formal methodology lay behind the choice of articles for this review, a tendency was found for the farm level analyses to have been published in earlier years (mainly ‘00s) than those with a regional or national focus (mainly ‘10s). It can be hypothesised that this reflects a shift in thinking of P and other nutrients as a source of eutrophication, an issue which mainly concerns farm practices, to that of P as a scarce resource requiring relocation - which needs to be managed at a larger scale.

The larger scale analyses often had a much lower process resolution with regards to the farming system as they included different sectors, while the farm-level analyses included more process detail that showed the complexity and variability of intra-farm flows.

Although some of the reviewed articles integrated this complexity of farm flows with a national-scale analysis, this was not applied in the articles that focused on manure P (re)distribution. This while in the context of using manure as a secondary fertiliser resource, it is crucial to not only establish the total surplus or deficit of P on a regional level. Indeed, it would be important to also assess to what extent this is available for collection and transport, and to what extent the manure is already used as a fertiliser to grow forage feed.

Therefore, for the MFA conducted here (see 2.4: Case study of Foss Gård and Upscaling scenario), a high accuracy farm-level approach was combined with a national-level analysis.

3 Methodology

In this chapter, the methodology regarding the MFA system definition and the sources and assumptions underlying the system quantification are described in detail, for each of the three case studies conducted in this project: a multi-layered MFA of the CowPower system, an MFA of the Foss Gård farm, and a national level scenario for Norwegian livestock farming.

3.1 CowPower

3.1.1 System definition

A material flow analysis (MFA) (see e.g. Brunner and Rechberger (2004)) was conducted of the CowPower method for livestock manure processing. The method consists of eight processes: centrifuging, composting, anaerobic digestion, nitrification, filtering, evaporation, granulation, and drying. Figure 2 is a schematic of the processes and flows in the CowPower system; processes are visualised as boxes and flows as arrows, the orange numbers refer to samples taken at Foss Gård (see section 3.1.2 'Data sources'), and the dashed line designates the system boundaries.

The system includes all processes relevant for the CowPower method starting from the input of livestock manure and producing the three main end products: a composted fibre fraction, a liquid fertiliser (concentrate), and a fine particle granulate. The only other in- and outflows consist of gas or water. The system boundaries do not coincide with a geographical location; the pilot scale plant includes all processing steps at Foss Gård with the exception of Evaporation, which was nonetheless included here.

The MFA consists of four layers: wet weight (WW), dry matter (DM), phosphorus (P), and nitrogen (N). In addition, values for NO_3-N and NH_4-N were calculated as an aid to quantify the N layer.

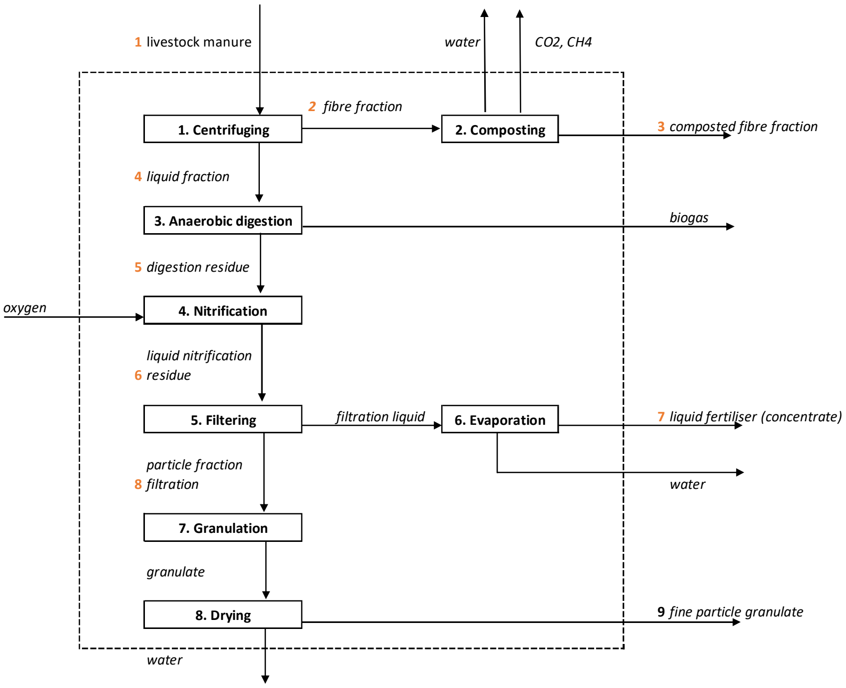

Figure 2. CowPower system. Processes are denoted as boxes, flows as arrows, orange numbers indicate samples taken from the pilot plant, and dashed lines show the system boundaries.

3.1.2 Data sources

Chemical analysis of samples by Eurofins

Nine samples were taken at the Foss Gård farm corresponding with nine different flows in the CowPower system (see fig. 2): from the livestock manure slurry (sample 1), the fibre fraction leaving the centrifuge (2), the composted fibre fraction (3), the liquid fraction leaving the centrifuge (4), the digestion residue (5), the liquid nitrification residue (6), the filtration liquid (7), the particle fraction from filtration (8), and the fine particle granulate after drying (9). The filtration liquid is further processed through evaporation to obtain a concentrate liquid fertiliser; however, no sample could be obtained of this output product.

The chemical analysis was performed by Eurofins Environment Testing Norway AS (Moss) [Eurofins] (2019); the full analysis report can be found in Appendix B. The samples were tested for DM, total P, and total N among other variables. In addition, samples 1, 2, 3, 4, 8, 9 were tested for NO_3-N and NH_4-N, and samples 1, 3, and 9 were tested for heavy metals.

The laboratory results for DM, P, N, NH_4-N, NO_3-N and volume weight are listed in table 1 below. For samples 5, 6, and 7, total dry matter was given in mg per L, which could not be converted to a percentual dry matter content, as their volume weight was unknown. Table 2 shows the results for heavy metal analysis.

Sample	Flow name	Volume weight	DM	P	N	NH_4-N	NO_3-N
1	Livestock manure	1,000 kg/m^3	7.6%	0.71%	3.9%	1.4%	<0.013 %
2	Fiber fraction	490 kg/m^3	25%	0.55%	1.4%	0.14%	0.054%
3	Composted fiber fraction	440 kg/m^3	24.3%	0.7%	2%	0.010%	0.024%
4	Liquid fraction	1,000 kg/m^3	5.1%	0.85%	5.4%	2.6%	<0.022%
5	Digestion residue	-	38,000 mg/L	350 mg/L	2,000 mg/L	-	-
6	Liquid nitrification residue	-	40,000 mg/L	330 mg/L	2,000 mg/L	-	-
7	Filtration liquid	-	22,000 mg/L	48 mg/L	2,400 mg/L	-	-
8	Particle fraction filtration	850 kg/m^3	22.8%	1.3%	4.3%	0.027%	0.13%
9	Fine particle granulate	970 kg/m^3	88.7%	1.5%	3.9%	0.0098%	0.055%

Table 1. Results from chemical analysis by (Eurofins, 2019). All concentrations are given in dry matter, with the exception of the dry matter content.

Flow	Sample	Cadmium (Cd)	Mercury (Hg)	Lead (Pb)	Nickel (Ni)	Chromium (Cr)	Zinc (Zn)	Copper (Cu)	Arsenic (As)
Manure slurry input	1	0.24	<0.001	1.6	5.8	2	150	29	1.6
Composted fibre fraction	3	0.076	0.015	1.1	3.9	2.7	110	21	4.0
Fine particle granulate	9	0.47	0.021	3.8	12	6.3	350	73	0.85

Table 2. Results on heavy metal contents from chemical analysis by Eurofins. All values in mg/kg DM.

Results from analysis of 2012-2014 samples by Foss Biolab and USN

In addition to the samples taken this year (2019), analysis data from previous sampling in the period 2012-2014 was provided by Foss Biolab and USN (2012-2014) (cf. acknowledgements section). During this period a total of 122 samples were taken from the CowPower pilot plant at Foss Gård, from the in- and outflow to the anaerobic digester and the outflow from the nitrification reactor. However, the variables that were tested for differ from those in this study: neither total P nor total N were included. The data does allow for comparison of the DM and NH_4-N values in the aforementioned flows found in this study and by Foss Biolab and USN (2012-2014) (see Chapter 4.1 ‘Uncertainty analysis’).

3.1.3 Quantification

This section describes the quantification method for WW, DM, P, and N in all CowPower flows. An overview of calculation methods can be found in table 3, and of the parameters used in table 4. The rest of this section provides a more detailed description of the calculations and their underlying assumptions.

The flows are denoted in the format A0-1 with 0 representing the originating process and 1 the destination process. All concentrations (e.g. %P) are given in dry matter, with the exception of %DM which is given in wet weight. Any numbers provided are relative to an inflow of 100 kg of livestock manure.

Code	Flow name	WW	DM	P	N
A0-1	Livestock manure	Variable input	%DM * WW	%P * DM	%N * DM
A1-2	Fiber fraction	WW_{0-1} * Kff	%DM * WW	%P * DM	%N * DM
A1-3	Liquid fraction	$WW_{0-1} – WW_{1-2}$	$DM_{0-1} – DM_{1-2}$	$P_{0-1} – P_{1-2}$	$N_{0-1} – N_{1-2}$
A2-0a	Composted fiber fraction	DM / %DM	P / %P	P_{1-2}	%N * DM
A2-0c	Biogas (CO_2 and CH_4)	DM	$DM_{1-2} – DM_{2-0a}$	-	-
A2-0b	Water (composting)	$WW_{1-2} – WW_{2-0a} – WW_{2-0c}$	-	-	-
A3-4	Digestion residue	$WW_{1-3} – WW_{3-0}$	P / %P	P_{1-3}	%N * DM
A3-0	Biogas	DM	$DM_{2-3} – DM_{3-4}$	-	-
A0-4	Oxygen	(2 * mol NH_4 reacted) / MM_{O2}	WW	-	-
A4-5	Liquid nitrification residue	$WW_{3-4} + WW_{0-4}$	P / %P	P_{3-4}	%N * DM
A5-7	Particle fraction filtration	WW_{4-5} * Kpf	%DM * WW	%P * DM	%N * DM
A5-6	Filtration liquid	$WW_{4-5} – WW_{5-7}$	$DM_{4-5} – DM_{5-7}$	%P * DM	%N * DM
A6-0a	Liquid fertiliser (concentrate)	DM / Kdm	DM_{5-6}	P_{5-6}	N_{5-6}
A6-0b	Water (evaporation)	$WW_{5-6} – WW_{6-0a}$	-	-	-
A7-8	Granulate	WW_{5-7}	DM_{5-7}	P_{5-7}	N_{5-7}
A8-0a	Fine particle granulate	DM / %DM	DM_{7-8}	P_{7-8}	N_{7-8}
A8-0b	Water (drying)	$WW_{7-8} – WW_{8-0a}$	-	-	-

Table 3. Calculation of flows of WW, DM, P, and N in the CowPower system. Concentrations of P and N are given in DM%.

Parameter	Symbol	Value	Unit	Notes
Share of centrifuge input to fiber fraction	Kff	12.5	%	
Share of particle fraction in filtration output	Kpf, P-based	12.5	%	See equation 3
Share of NH_4 reacted during nitrification		99	%	Average in Foss Biolab and USN (2012-2014)
Molar mass N		14	g/mol	
Molar mass NH_4		18	g/mol	
Molar mass NO_3		62	g/mol	
Molar mass O_2	MM_{O2}	32	g/mol	
Dry matter content of liquid fertiliser	Kdm	25	%	Estimated by Vasdal (2019)

Table 4. Parameters used in the calculation of flows in the CowPower system.

Centrifugation

The livestock manure slurry entering this process consists of the cattle's faeces and urine, mixed with water and sawdust bedding. The input is split into a fibre fraction (A1-2) and a liquid fraction (A1-3). The former was calibrated to account for 12.5% of the wet weight, such that for the latter output a mass balance approach yielded P, N and DM values that conformed the concentrations known from chemical analysis as close as possible (table 1). This resulted in an increase in DM content from 5.10% to 5.11%, a decrease in P content from 0.85% to 0.82%, and an increase in N content from 5.4% to 5.7%.

Composting

The fibre fraction (A1-2) is subjected to a composting process, in which gases (CO_2 and CH_4) and water leave the system, resulting in a composted fibre fraction (A2-0a) – one of CowPower's three end products.

As the magnitude of the gas and water removal were unknown, WW and DM in the output product were calculated from P, which was assumed to be unaltered from the input.

The difference in dry matter was then allocated to the gas outflow, and assuming the gas flow had a DM content of 100% and the water flow 0%, a mass balance approach yielded the WW of the water outflow.

The nitrogen outflow was calculated based the nitrogen content found by Eurofins Environment Testing Norway AS (Moss) [Eurofins] (2019); this resulted in an increase in total N, while NO_3-N and NH_4-N decreased by 65% and 94% respectively. This outcome is unlikely, but this approach is transparent about the uncertainties involved here.

Anaerobic digestion

The fibre fraction resulting from the centrifuge is subsequently led into an anaerobic digester, where organic material is decomposed under anaerobic circumstances to produce CO_2 and CH_4, which are then captured for use as biogas.

The DM content of the digestion residue was unknown, as the volume weight had not been measured and the results from chemical analysis were given in mg DM per litre. Therefore, a mass balance approach to P was used to derive the DM in the residue, after which the difference in DM was allocated to the biogas outflow. The DM content of this gas was assumed to be 100% to obtain a mass balanced WW value for the digestion residue.

Assuming the biogas produced consisted of CO_2 and CH_4 in a ratio of 35:65, this would correspond to 4.8 litres of gas per litre of wet weight input to the anaerobic digester (Equation 1). This is in accordance with Vasdal's estimate of 4-5L (2019, personal communication).

Equation 1. Biogas produced per litre of input.

$$\frac{biogas\ (L)}{input\ (L)} = \frac{22.4\ L}{mol\ STP} * \frac{DM_{3\text{-}0}\ (g)}{\left(\%CH_4 * \frac{16.04\ g}{mol} + \%CO_2 * \frac{44.01\ g}{mol}\right)} * \frac{\rho_{1\text{-}3}}{WW_{1\text{-}3} * \frac{1000\ L}{m^3}}$$

Finally, nitrogen was derived from its content in dry matter, which resulted in a 17% decrease indicating an unknown outflow of N. However, this may also be due to uncertainties in the measurements. NH_4-N was assumed to increase by 17% based on the average of 101 samples taken in the period 2012-2014 (Foss Biolab & USN, 2012-2014). NO_3-N was assumed to be unchanged, for lack of information.

Nitrification

The residue from the anaerobic digestion process is subsequently subjected to a nitrification process, in which NH_4^+ is oxidised to form NO_2^- and further to NO_3^-, which should in theory correspond with equation 2:

Equation 2: nitrification through biological oxidation of ammonium to nitrite followed by nitrate.

$$\left.\begin{array}{l} NH_4{}^+ + 1.5\ O_2 \rightarrow NO_2{}^- + H_2O + 2\ H^+ \\ NO_2{}^- + 0.5\ O_2 \rightarrow NO_3{}^- \end{array}\right\} \quad NH_4{}^+ + 2\ O_2 \rightarrow H_2O + 2\ H^+ + NO_3{}^-$$

The total nitrogen content in DM was known for the in- and outflow of the nitrification reactor. However, analysis of NO_3-N and NH_4-N had not been done for either of these flows. For the inflow, these were calculated as described above (section: anaerobic digestion).

We then assumed that 99% of the NH_4 was reacted, which was the average found in the 2012-2014 study (Foss Biolab & USN, 2012-2014). Based on the molar relations shown in Equation 2, and given the molar masses of N (14 g/mol), NH_4 (18 g/mol), NO_3 (62 g/mol), and O_2 (32 g/mol), the outflowing quantities of NH_4-N and NO_3-N were calculated, as well as the inflow of O_2. It was assumed that the reaction to NO_3 was complete, and that there were no losses of N in gaseous form.

Filtration

The liquid nitrification residue is filtered using gravity without external pressure, thus removing a filtration liquid (A5-6) from the remaining particle fraction (A5-7).

The DM content of the filtration liquid being unknown, a transfer coefficient was used to determine the ratio of wet weight attributed to the two fractions. Based on the known quantities in the input (A4-5), the shares of DM and P in the particle fraction, and the P content in the filtration liquid, the share of wet weight allocated to the particle fraction (Kpf) was calculated (see Appendix C for derivation):

$$K_{pf} = \frac{P_{in} - \%P_{fl} * DM_{in}}{W_{in} * \%DM_{pf} * (\%P_{pf} - \%P_{fl})}$$

Equation 3. Transfer coefficient for filtering process; share of wet weight allocated to particle fraction. ***With in=A4-5, fl=A5-6, pf=A5-7.***

Thus, for the particle fraction (A5-7) the WW was calculated using this transfer coefficient, and DM, P and N were derived based on their known concentrations. For the filtration liquid (A5-6), the DM content was unknown. Therefore, DM was calculated via mass balance, and P and N derived from that.

As Kpf was derived based on DM and P, no mass balance inconsistencies (MBIs) resulted for these layers. On the other hand, the described approach yielded a large MBI for N, with the outputs together being 44% larger than the input N. If Kpf were to be derived based on N instead of P, this would lead to a larger share of DM being retained in the particle fraction and a significant MBI for P. Finally the P-based calculation was favoured, given the large uncertainties regarding unknown outflows of N (Vasdal, 2019).

Granulation and drying

The filtered particle fraction is granulated to make the output more user-friendly and convenient to spread on the land, but which should not affect the DM or P (Vasdal, 2019, personal communication); the granulate (A7-8) therefore equals the input A5-7) for the purpose of our model.

Subsequently, the granulate is dried to remove excess water. The flows of the outgoing fine particle granulate (A8-0a) were once more calculated based on the conservation of phosphorus, such that the water removed (A8-0b) could be mass balanced on the wet weight layer.

Evaporation

The filtration liquid (A5-6) is subjected to an evaporation process, further concentrating the liquid to produce a liquid fertiliser. No sample was taken from this final product, as the on-farm pilot scale CowPower plant did not include this process. Based on previous testing at a laboratory facility, the process was estimated to produce an output product with a DM content of 25%, removing around 95% of the ingoing water (Vasdal, 2019, personal communication).

The output flows were estimated assuming no changes in P, N or DM, and assuming an outflow of water such that 25% DM was achieved, which was 92% of the water.

It should be noted that, as no data was available, these flows are subject to a high uncertainty. However, this applies to other flows as well, since data availability was low for many flows and merely one sample was taken.

3.2 Foss Gård

3.2.1 System definition

Farm geography

A material flow analysis (MFA) was conducted of the flows of dry matter and phosphorus on the Foss Gård farm, the development location of the CowPower. The farm was located in Skien in Norway's Telemark county and comprised 98 ha, of which 24 ha were owned by the farm owner Knut Gustav Vasdal with the rest being rented land area. Of the total land area, 15 ha were cropland, 69 ha were used for forage production, and 13 ha were used as pastures on which the cattle grazed. The farm was an organic dairy farm, and as such did not make use of mineral fertiliser or pesticides, and applied the livestock manure as a fertiliser.

Herd

The farm housed a herd of around 110 cattle: 53.8 dairy year-cows (TINE, 2017) and 57 'other cattle' (Landbruksdirektoratet, 2017c), which were animals of pre-lactating age (Kukontrollen, 2017) and are henceforth referred to as 'young cattle'. A year-cow (from Norwegian: Årsku) is here defined as 365 feeding days, such that stock changes within a year are accounted for. We assume that the 57 young cattle also refers to year-cows, although no unit was provided.

MFA System

Figure 3 shows a schematic of the processes and flows included in the MFA system, and table 5 provides a description of each flow. The system boundaries coincide with the total land area affiliated with Foss Gård (98 ha), i.e. the cropland, forage area, and pasture, in addition to the barn where the animals were kept indoors and the storage facilities for feed, manure, and milk.

In the system, the distinction is made between young cattle, i.e. those animals that were too young to produce milk (calves and heifers), and dairy cows, including all animals from their first lactation onwards, either currently lactating or in between lactation periods. For simplicity, processes 6 and 7 encompass all flows directly related to the cattle, i.e. feed intake and manure excretion both in the barn and on the pasture, milk production, and flows of cattle between the two age groups and out of the system boundaries.

Some processes that were not included in the system are runoff and leaching from the soils, and losses of feed, manure and milk during storage and collection.

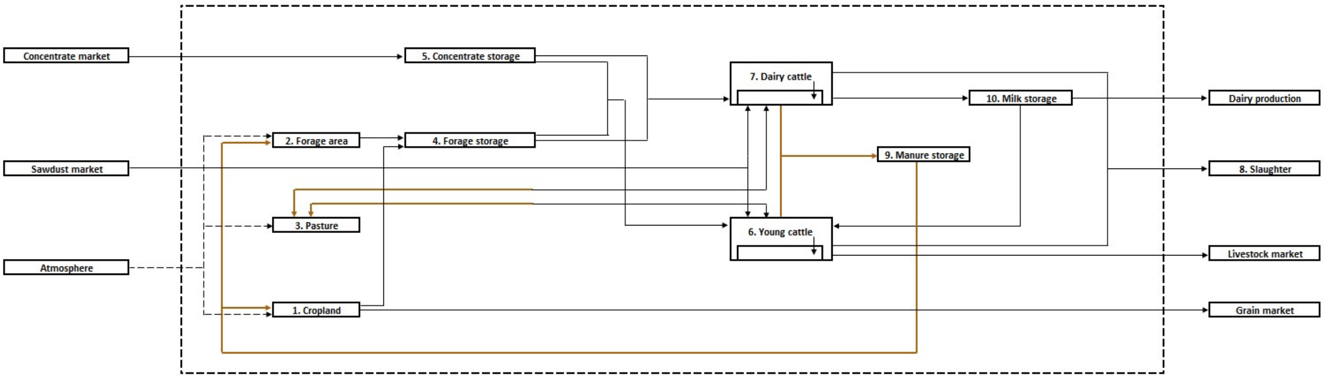

Figure 3. Foss Gård system. Processes are denoted as boxes, flows as arrows, and dashed lines show the system boundaries. Flows of manure are highlighted in brown.

Code	Flow name	Flow description
B0-5	Concentrate purchased	Quantity of concentrate feed purchased (imported) by the farm owner.
B5-7, B5-6	Concentrate consumed	Quantity of concentrate feed consumed by the herd.
B3-7, B4-6	Forage consumed	Quantity of harvested grass, hay, and straw consumed by the herd in the barn.
B4-7, B4-6	Grazing, dairy cows	Quantity of grass from the pasture consumed by the herd through grazing, during the 16 week grazing period.
B1-0a	Barley grain harvested	Quantity of barley grain harvested from the cropland of Foss Gård, excl. straw and plant residues remaining on the field.
B1-4	Straw harvested	Quantity of barley straw harvested from the cropland of Foss Gård, excl. grain and plant residues remaining on the field.
B2-4	Forage harvested	Quantity of grass and hay harvested from the forage area of Foss Gård for indoor feeding, excl. plant residues remaining on the field.
B7-0a, B6-0a	Respiration – CO_2-C	Quantity of carbon exhaled by the herd through carbon dioxide, i.e. the net outflow after accounting for oxygen intake.
B7-0b, B6-0b	Enteric CH_4 emission	Quantity of methane emitted by the adult cows from their digestion system.
B7-8, B6-8	Slaughter	Live weight (as opposed to carcass weight) quantity of calves, young and adult cows sent to slaughter facilities.
B6-0	Live sale calves	Live weight of calves sold on the market for other purposes than slaughter.
B7-10	Milk production	Quantity of raw milk produced by the dairy cows, incl. milk fed to calves.
B10-0	Milk delivered to dairy	Quantity of raw milk delivered to dairy production.
B10-6	Milk consumed by calves	Quantity of raw milk fed to the calves on the farm.
B7-3, B6-3	Manure on pasture	Quantity of manure (faeces and urine) excreted by the herd on the pasture, assumed to be remaining there.
B7-9, B6-9	Manure collected	Quantity of manure (faeces and urine) excreted by the herd in the barn, all of which is assumed to be collected and returned to the fields as fertiliser.
B9-1	Manure to fertilise cropland	Quantity of collected manure that is applied to the cropland area of Foss Gård to serve as fertiliser.
B9-2	Manure to fertilise forage area	Quantity of collected manure that is applied to the forage production area of Foss Gård to serve as fertiliser.
B7, B6	Stock growth	Increase in weight of the total herd through calving and growth of young cattle outweighing slaughter and live sales.
B7-6	Calving	Live weight of calves born throughout the year and added to the young cattle stock.
B3-7	Young cattle to adulthood	Live weight of young cows that had their first calf and started lactating (around 2 years of age), thus moving to the stock of dairy cows.

Table 5. Description of flows in Foss Gård system. Flow codes refer to the originating and destination process of each flow, e.g. B1-2 for a flow from process 1 to 2. Quantities represent the entire year 2017 for all cattle on Foss Gård, and are calculated for dry matter and phosphorus. The term 'herd' here refers to both the adult dairy cows and the young cattle, which are separated into two separate flows in the system.

3.2.2 Quantification

In this section, the sources and calculation methods used to quantify the flows are described. The methods and sources are summarised in table 7, with the related parameters in table 8, followed by a more detailed description in text. All flows in the system refer to the total production and consumption throughout the year 2017, for the entire herd.

The quantification was done on two layers: dry matter and phosphorus. Unless otherwise specified, all P contents are given as their concentration in DM.

Average Norwegian cow diet

In this chapter and the next, references are made to 'average Norwegian cows', a description of which is provided here.

Profiles of an average Norwegian dairy cow and of young cattle in 2017 were based on data from the Nordic Feed Evaluation System [NorFor] (n.d.) and TINE (2017). For the purpose of our model the average dairy cow consumed 6.0 kg DM concentrate (Formel Elite 80 FKA) per day, while the young cattle consumed 0.25 kg DM per day respectively (table 6). For the young cattle, the daily feed rations were taken to be the average of a 24 month rearing period from birth until the first calving. The age distribution of the young cattle was thus not considered. In addition, the average Norwegian dairy cow and young cattle consumed respectively 13 and 5.8 kg DM of forage per day (NorFor, n.d.), from which a share was deducted and allocated to grazing (see 'Forage feed and grazing' in this section).

Table 6 provides an overview of the dietary composition of the Norwegian average cattle compared to that at Foss Gård used in our system, which is described in the subsequent sections.

Feed type	DM content	P content	kg DM/day			
			Average Dairy Cow	Average Young cattle	Foss Gård Dairy cow	Foss Gård Young cattle
Concentrate – Blend of 70% Natura Drøv 19 and 30% Natura Drøv 16	88%	0.57%	-	-	2.8	0.12
Concentrate – Formel Elite 80 FKA	88%	0.51%	6.0	0.25	-	-
Forage – Grass silage of 64/36 blend low/medium digestibility	32%	0.29%	12	5.2	11	4.7
Grazing	15%	0.38%	0.99	0.58	2.0	1.2

Table 6. Average feed rations. Consumption of different feed types on average in Norway and at Foss Gård, along with DM and P contents of the feed types.

Code	Flow name	Calculation method		Sources		
		DM	P	Material quantity	%DM	%P
B0-5	Concentrate purchased	Purchase of concentrate in 2017 * %DM	DM * %P/DM	S1	S2	S2, S22
B5-7	Concentrate consumed, dairy cows	DM0-13 * Share of concentrate to dairy cows	DM * %P/DM	-	-	S2, S22
B5-6	Concentrate consumed, young cattle	DM0-13 - DM13-12	DM * %P/DM	-	-	S2, S22
B3-7	Forage consumed, dairy cows	Ncow * MJ apart from concentrate / energy content forage * (36/52 weeks + 16/52 weeks * 0.5 day indoors)	DM * %P/DM	S7, S8	-	S2, S22
B4-6	Forage consumed, young cattle	Nyc * Average forage ration YC * (36/52 weeks + 16/52 weeks * Share YC > 6 months)	DM * %P/DM	S2, S7	-	S2, S22
B4-7	Grazing, dairy cows	Ncow * MJ apart from concentrate / average energy content DM forage * 16/52 weeks * 0.5 day grazing	DM * %P/DM	S8	-	S4
B4-6	Grazing, young cattle	Nyc * Average forage ration YC * 16/52 weeks * Share YC > 6 months	DM * %P/DM	S2, S7	-	S4
B1-0a	Barley grain harvested	Sale of barley grain * %DM	DM * %P/DM	S10	S4	S4
B1-4	Straw harvested	Sale of barley grain * Straw:Grain ratio * %DM	DM * %P/DM	S10, S11	S26, S3	S26
B2-4	Forage harvested	Total forage consumption – straw harvested	Forage consumption – straw harvested	-	-	-
B7-0a	Respiration – CO_2-C, dairy cows	Mass share of C in CO_2 * Respiration rate CO_2 * Ncow	-	S12, S13	-	-
B6-0a	Respiration – CO_2-C, young cattle	Share YC in CH_4 emissions * CO_2-C emission dairy cows	-	-	-	-
B7-0b	Enteric CH_4 emission, dairy cows	CH_4 emission rate cows * Ncow	-	S12-S14	-	-
B6-0b	Enteric CH_4 emission, young cattle	CH_4 emission rate young cattle * Nyc	-	S15	-	-
B7-8	Slaughter, dairy cows	Live weight-to-carcass-ratio * Sale cow carcasses * %DM	WW * %P/WW	S17, S18	S16	S4, S5
B6-8	Slaughter, young cattle	Live weight-to-carcass-ratio * Sale calf + young cow carcasses * %DM	WW * %P/WW	S17, S18	S16	S4, S5
B6-0	Live sale calves	Sale live calves * %DM	WW * %P/WW	S17, S18	S16	S4, S5
B7-10	Milk production	Production ECM * conversion factor ECM * Ncow * %DM	WW * %P/WW	S8	S19	S19
B10-0	Milk delivered to dairy	Delivered ECM * conversion factor ECM * Ncow * %DM	WW * %P/WW	S7, S21	S19	S19
B10-6	Milk consumed by calves	Total milk production – Milk delivered to dairy	WW * %P/WW	-	-	S19
B0-7a	Sawdust bedding, dairy cows	0.5 * Sawdust used * kg/m3 * %DM	WW * %P/WW	S23	S24	S25
B0-6a	Sawdust bedding, young cattle	0.5 * Sawdust used * kg/m3 * %DM	WW * %P/WW	S23	S24	S25
-	Total manure dairy cows	Mass balance	Mass balance	-	-	P/DM =Pmd
-	Total manure young cattle	Mass balance	Mass balance	-	-	P/DM = Pmy
B7-3	Manure dairy cows on pasture	Total manure dairy cows * 16/52 weeks * 50% of time outside	DM * %P/DM	S18	-	Pmd
B6-3	Manure young cattle on pasture	Total manure young cattle * 16/52 weeks * share of YC >6 months	DM * %P/DM	S18, S9	-	Pmy
B7-9	Manure collected, dairy cows	Total manure dairy cows – Manure dairy cows on pasture	DM * %P/DM	-	-	Pmd
B6-9	Manure collected, young cattle	Total manure young cattle – Manure young cattle on pasture	DM * %P/DM	-	-	Pmy

Continues on next page

(Table 7, continued)

B9-1	Manure to fertilise cropland	P / %P	barley grain + straw	-	-	P/DM total manure collected
B9-2	Manure to fertilise forage area	P / %P	manure collected – manure to cropland	-	-	P/DM total manure collected
B7	Stock growth cows	Adult stock increase between 10/04 and 31/12 * average weight	DM * %P/DM	S20, S2	S16	S4, S5
B6	Stock growth young cattle	Young stock increase between 10/04 and 31/12 * average weight	DM * %P/DM	S20, S6	S16	S4, S5
B7-6	Calving	(Young stock increase + calves to adulthood + slaughtered + sold) * average birth weight	DM * %P/DM	S20, S2, S17	S16	S4, S5
B3-7	Young cattle to adulthood	(Adult stock increase + adults slaughtered) * average weight at start of lactation	DM * %P/DM	S20, S6, S17	S16	S4, S5

Table 7. Calculation methods and sources of the flows in the Foss Gård system. List of parameters in table 8. YC=Young Cattle. Sources: S1: (Felleskjøpet, 2017); S2: (Nordic Feed Evaluation System [NorFor], n.d.); S3: (CCOF, 2015); S4: (Antikainen et al., 2005); S5: (Cooper & Carliell-Marquet, 2013); S6: (TINE, 2015); S7: (Sommerseth, 2019); S8: (TINE, 2017); S9: (Landbruksdirektoratet, 2017c) ; S10: (Data Norge, 2017); S11: (Schiere et al., 2004); S12: (Leytem, Dungan, Bjorneberg, & Koehn, 2011); S13: (Aguerre, Wattiaux, Powell, Broderick, & Arndt, 2011); S14: (Grainger & Beauchemin, 2011); S15: (Morrison, McBride, Gordon, Wylie, & Yan, 2017); S16: (National Research Council, 2001); S17: (Jens Eide AS, 2017); S18: (Vasdal, 2019); S19: (Mattilsynet, 2018); S20: (Kukontrollen, 2017); S21: (Landbruksdirektoratet, 2017a); S22: (Karlengen, Svihus, Kjos, & Harstad, 2012); S23: (Western Dairy Digest, 2005); S24: (Oudot, Pain, & Martinez, 2003); S25: (Penhallegon, 2003); S26: (Redden, 2012).

Parameter	Value	Unit	Notes
Number of dairy cows in 2017 (Ncow)	53.8	year-cows	
Number of young cattle in 2017 (Nyc)	57	year-cows	Assumed to be year-cows.
Grazing period	16	weeks/year	
Share of concentrate to dairy cows	96	% of DM total	Ratio for Norwegian average dairy cow : young cattle
MJ apart from concentrate, Foss Gård 2017	78	MJ/cow/day	
Energy content of forage	6	MJ/kg DM	
Straw : Grain ratio	1.3	-	
CH_4 emission rate dairy cows	0.5	kg CH_4/cow/day	
CH_4 emission rate young cattle	0.13	kg CH_4/young cow/day	
Mass share of C in CO_2	27	%	12 g/mol divided by 44 g/mol.
Respiration rate CO_2 dairy cows	28	kg CO_2/cow/day	
Share young cattle in CH_4 emissions	0.3	%	Ratio of young : adult of CH_4 applied to CO_2.
Live weight to carcass weight ratio	2	-	
Conversion factor ECM to kg milk	0.99	kg ECM/kg milk	
Sawdust density	192	kg/m^3	
Average weight cows	607	kg ww	
Average weight young cattle	260	kg ww	Calculated with average weight per 3-month age category and number of animals per category.
Average birth weight	40	kg ww	
Average weight at start of lactation	560	kg ww	

Table 8. Parameter values used in calculation of flows. Sources listed in table 7 and in detailed explanation below.

Concentrate feed

The amount of concentrate feed consumed by the herd in 2017 was assumed to equal the 66 tons purchased that year (Felleskjøpet, 2017). Of this, 68% was of the brand Natura Drøv 19 Bulk (ND19), 23% of Natura Drøv 16 Bulk (ND16), 6% of Natura Drøv Start 800kg, and 2% of Natura Drøv 16 25kg. The contents of these feed types were obtained through NorFor, using a blend of 70% ND19 and 30% ND16 as a proxy as the latter two were lacking in the database (NorFor, n.d.). The DM and P contents of this blend were 88.2% and 0.57% respectively (see table 6).

The shares of this concentrate feed that were consumed by respectively the dairy cows and young cattle were assumed to be the same as under average feed consumption (table 6), i.e. 96% of the concentrate consumption was allocated to the dairy cows. The decrease in concentrate consumption in calves was assumed to have been corrected for by a higher consumption of milk. This resulted in a consumption of 2.9 kg DM concentrate per day for dairy cows, and 0.12 kg for young cattle.

At 17 kg concentrate per 100 kg energy-corrected milk (ECM), Vasdal's herd was known to have consumed far less concentrate in 2017 than the Norwegian average (30 kg per 100 kg ECM) (TINE, 2017). This corresponded well with the calculated flow: 16.9 kg concentrate per 100 kg ECM.

Forage feed and grazing

In addition to concentrate feed, the cattle were fed forage (hay and silage produced locally) and grazed on the pasture for 16 weeks of the year.

On a daily basis, the dairy cows consumed 78 MJ of feed other than concentrate in 2017 (Sommerseth, 2019). At an estimated energy content of 6 MJ per kg DM (Sommerseth, 2019) this translated to 11 kg DM per day.

During the weeks of grazing, the dairy cows spent half of their time on the pasture and half indoors for milking (Vasdal, 2019). The assumption was made that grazing accounted for half of this daily dry matter intake for those 16 weeks.

With regards to the young stock, these were kept indoors until they reached the age of 6 months, above which they spent the entire grazing period outside (Vasdal, 2019). Per April 10th 2017, 65% of the young stock was over 6 months of age (Kukontrollen, 2017). We assumed the average forage consumption for young cattle (table 6), and that 65% of the young cattle's dry matter intake was covered by grazing during the grazing period.

The P content of the grass was estimated from literature to be 0.38% (Antikainen et al., 2005).

Crop and forage production

Crop production at Foss Gård in 2017 consisted of barley, the total yield of which was sold, while the straw by-product was fed to the cattle (Vasdal, 2019). Sales numbers (Data Norge, 2017) were used to quantify the grain harvest, and a straw to barley grain ratio 1.33 (Schiere et al., 2004) was used to estimate the straw harvest.

The yield and dry matter content of forage is highly variable, and direct harvesting statistics were unavailable. Therefore, a mass balance approach was used to calculate the forage harvest flow, assuming that production equalled consumption.

The forage was produced on an area of 63.8 ha of cultivated meadow; given a DM content of 32.2% this gives a yield of 15 tons/ha. In contrast, the average Norwegian hay yield was 6.21 ton/ha (Statistics Norway, 2017b). This means that if our assumptions are correct, the yield at Foss Gård should have been 2.4 times the average yield. Accounting for a likely lower DM content in fresh hay would further increase this discrepancy.

The DM and P contents of the barley grain were estimated with literature values to be 86% and 0.38% respectively (Antikainen et al., 2005), and 90% and 0.10% for the straw (CCOF, 2015; Redden, 2012).

CO_2 and CH_4

The net carbon outflow, i.e. the quantity of CO_2 exhaled minus the O_2 inhaled, was calculated with a daily respiration rate of 28 kg CO_2 per cow for the dairy cows (Aguerre et al., 2011; Leytem et al., 2011).

As CH_4 emissions are influenced by many dietary variables, estimates varied more, from 0.3-0.65 kg CH_4 per cow per day (Aguerre et al., 2011; Grainger & Beauchemin, 2011; Leytem et al., 2011), but given the small size of this flow this variation was deemed negligible. In the model, 0.5 kg CH_4 per cow per day was used for dairy cows.

For the young cattle, an estimate of 0.13 kg CH_4 per cow per day was used, following the prediction equation based on dry matter intake from Morrison et al. (2017). No data could be found on respiration rates of young cows; therefore, the Young cattle:Dairy cow ratio of CH_4 (26%) was applied to CO_2, obtaining an estimate of 7.3 kg CO_2 per young cattle day.

Cattle stock dynamics

The year 2017 was characterised by a strong growth in livestock at Foss Gård: the dairy stock saw an increase from 35.6 year-cows in 2015, to 48.3 in 2016, and 53.8 in 2017 (TINE, 2017), with a year-cow being defined as 365 feeding-days, e.g. a cow that is slaughtered after six months of feeding constitutes 0.5 year-cow.

Between spring and autumn 2017, the number of dairy cows increased by 10%, and the young cattle stock by 28% (Landbruksdirektoratet, 2017c). By spring 2018, the dairy cow stock had increased by another 10% (Landbruksdirektoratet, 2017c).

In order to accurately capture the dynamics of this growing stock, and the flows between the adult and young stocks through birth and maturing, a cow population model that accounts for age distribution would be required. This was beyond the scope of this project. The large differences in feed demand between lactating cows and calves or heifers were the reason to distinguish between these two categories. However, the young cattle process is subject to high uncertainties due to a lack of information on its age distribution, as well as a lack of scientific studies on the metabolism of calves and heifers. With regards to the feeding requirements, an evenly spread age distribution was assumed, by taking the average daily consumption over a 24 month rearing period.

The number of dairy cows was set to be 53.8 year-cows (TINE, 2017). This was approximately equal to the 53.5 average of the spring and autumn reported values, for which no unit (year-cow or otherwise) was provided (Landbruksdirektoratet, 2017c). Lacking further data, the number of young cattle was set to be the average of spring and autumn reports as well, i.e. 57, assuming this to be in year-cows.

The number of dairy cows and young cattle in the herd changed through the live sale of calves, and sale of calves, young cows, and adult cows for slaughter. These outflows were quantified using the annual statement of sale to slaughter, assuming a live weight:carcass weight ratio of 2:1 (Jens Eide AS, 2017; Vasdal, 2019). To convert to dry matter, an estimated 35% DM in live cattle was used (National Research Council, 2001)

There was no purchase of cows in 2017, but between April 10th and December 31st the number of dairy cows increased by 8, and the number of young cattle by 17 (Kukontrollen, 2017). Estimating the dairy cow weight to be 607 kg (NorFor, n.d.), and using average weights for different age groups of the young cattle (TINE, 2015), these stock increases were estimated to have been 4.9 tons for the dairy cows, and 1.3 tons for the young cattle.

A flow of young cattle entering the dairy cow stock was estimated to be 13 by summing the increase in individuals with the number of adults slaughtered, and assuming a weight of 560 kg for newly lactating cows (NorFor, n.d.). In addition, the number of calves born in 2017 was estimated to be 46, as the sum of the young stock increase, the young cattle slaughtered or sold, and the young cattle entering adulthood. A flow from dairy cow to the young cattle stock was then estimated assuming a birth weight of 40 kg (TINE, 2015).

The stock growth, calving, and entering adulthood flows are all based on stock changes between April and December, since no data was available for earlier in 2017. Therefore, the assumption is made that there were no stock changes earlier in the year, and that the timing of the slaughter and live sale was after April that year.

Milk

The cattle at Foss Gård produced 6106 kg energy-corrected milk (ECM) per year-cow in 2017, which was 25% lower than the national average of 8116 kg ECM (TINE, 2017). At 4.07% fat and 3.39% protein in the milk, and assuming 4.7% lactose, this was converted to 6150 kg milk per year-cow. The DM and P contents of the milk were based on the 4.1% fat organic whole milk entry in Matvaretabellen (Mattilsynet, 2018), assuming that these are also representative for raw milk.

This gave a total production of 43.01 tons of milk in 2017. However, only 243 thousand litres (Landbruksdirektoratet, 2017a) of milk were delivered to dairy, corresponding to 4515 kg per year-cow (Sommerseth, 2019).

The remaining 25% of the milk production was fed to the calves (Vasdal, 2019), i.e. around 200 kg of milk per unit of young cattle. In comparison, the average calf consumes around 430 L milk (520 L for organic calves), spread over its first 8 life weeks (TINE, 2015). Thus, under an evenly spread age distribution of the young cattle over a 24 month rearing period, the milk consumption per individual would be on average 215-260 L per year. This indicates that in Vasdal's case the milk consumption was either somewhat below the average for organic calves, or the age distribution of the young cattle was skewed towards older individuals.

Sawdust bedding

The bedding for the cattle consisted of sawdust and was around 40 m^3 (Vasdal, 2019). Conversion factors used were a density of 192 kg/m3 (Western Dairy Digest, 2005), DM content of 50% (Oudot et al., 2003), and a P content of 0.08% P in WW (Penhallegon, 2003). For simplicity, the quantity was divided evenly between the dairy cows and the young cattle.

Manure

The manure from both dairy cows and young cattle was split into two fractions, one that could be collected from the housing units, and one that was deposited on the pasture while grazing. The collected fraction was then applied to the cultivated land areas for crop and forage production.

Dairy cow P excretion via manure is subject to strong variation, depending for example on the concentration of P in the diet, the excretion via milk production, and the age and breed of the cow (Morse et al., 1992; Powell et al., 2002). Therefore, a mass-balance approach was taken to calculate the total manure P excretion, assuming that the animals excreted all P taken up via the feed, either through milk or manure outflows, after accounting for the known stock increase (see 'Cattle stock dynamics').

The livestock manure slurry sample taken from Foss Gård for the CowPower system analysis (Eurofins, 2019) had a P content of 0.71%. If the DM manure excretion were to be calculated based on this concentration, this would be fairly accurate for the dairy cows, but result in a large mass balance inconsistency for the young cattle (inflows larger than outflows). Given the difference in diet between 2017 and 2019, as well as between the dairy cows and the young stock, different P contents of the manure can be expected.

Therefore, it was decided to apply a mass-balance approach to the DM layer as well. This resulted in P contents of respectively 0.68% and 0.43% for the dairy cow and young cattle manure, or 0.57% for the combined total.

Of the total dairy cows' total manure production, we assumed that half of 16/52nd was excreted on the pasture, according to the number of weeks in the grazing period during which the cows spent half of the day outdoors. For the young cattle, the grazing period was multiplied with the share of the young that were old enough to be outdoors (i.e. 6 months), which was estimated using the age distribution in April (Kukontrollen, 2017).

The remainder of the manure production was then allocated to the collected manure flows (B7-9 and B6-9). Subsequently, the collected manure was assumed to be applied to the fields according to P uptake for the cropland, with the remainder applied to the forage production area.

3.3 Upscaling scenario

3.3.1 System definition

In addition to the MFA of a single farm (Foss Gård), an upscaling scenario was made, in which the totality of Norwegian cattle farms (dairy and meat production) was modelled for 2017. This scenario was a hypothetical situation, designed to provide insight into the quantity of livestock manure P that can be expected to need relocation, and thereby the potential market for CowPower processing.

The scenario is based on the assumption of all farms resembling the case of Foss Gård. Firstly, it is assumed that all dairy farms meet their forage feed demand through local production, using only their available manure P sources as fertiliser (no mineral fertiliser). Although no formal statistics on this could be found, this is thought to be the case for the vast majority of Norwegian dairy farmers (Sommerseth, 2019).

Secondly, the source of the concentrate feed is left unspecified, since statistics on its homegrown share and the related use of mineral fertiliser were lacking. Thus, if the first assumption is correct, the scenario gives a high estimate of the quantity of livestock manure that requires export from the farm, as in reality a share of the concentrate feed will be produced using manure as a fertiliser.

Furthermore, while the system was based on that of Foss Gård, it was simplified in order to allow quantification on a national level. Based on the results from the MFA of Foss Gård an assessment was made of which flows were the most significant (see section 6.2.6 'Significance of flows'), and the conclusion was made that the following flows could be excluded from the farm system without significantly changing the results: crop production (harvest of barley grain and straw), bedding material, stock growth, and movement between the adult and young stock (calving and reaching adulthood). In addition, the live sale of calves was excluded since it represents a relocation between farms and thus is not relevant for an assessment of the totality of Norwegian dairy farms. Stock growth was also excluded, as Norway's dairy cow population has been very stable in recent years (Statistics Norway, 2017c).

The system did include slaughter, milk production, and grazing, as well as the distinction between adult dairy cows and young cattle. Figure 4 shows a schematic of the system.

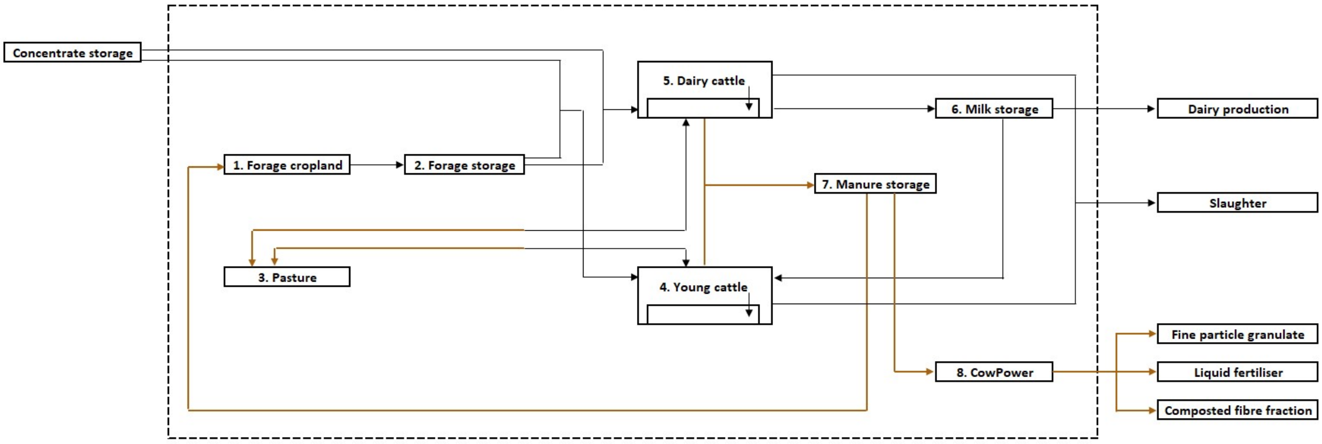

Figure 4. Upscaling scenario system. Processes are denoted as boxes, flows as arrows, and dashed lines show the system boundaries. Flows of manure are highlighted in brown.

3.3.2 Quantification

The flows in this upscaling scenario were quantified according to the methodology described in this section, and as summarised in tables 9 and 10. The quantification was done for P only, on a national scale, and for the year 2017.

Code	Flow name	Calculation method P flows	Material quantity sources	%P sources
C0-5	Concentrate consumed, dairy cows	Ncow * Average concentrate ration DC * %P	-	S1
C0-4	Concentrate consumed, young cattle	Nyc * Average concentrate ration YC * %P	-	S1
C2-5	Forage consumed, dairy cows	Ncow * Average forage ration DC * (44/52 weeks + 8/52 weeks * 50% of time on pasture during grazing) * %P	-	S1
C2-4	Forage consumed, young cattle	Nyc * Average forage ration YC * (44/52 weeks + 8/52 weeks * Share YC on pasture) * %P	-	S1
C1-2	Forage harvested	Forage consumed DC + Forage consumed YC	-	-
C3-5	Grazing, dairy cows	Ncow * Average forage ration DC * 8/52 weeks * 0.5 day grazing *%P		S2
C3-4	Grazing, young cattle	Nyc * Average forage ration YC * 8/52 weeks * Share YC > 6 months *%P		S2
C5-0	Slaughter, dairy cows	Live weight-to-carcass-ratio * (Cows + Bulls to slaughter) * %P/WW	S3	S2, S7
C4-0	Slaughter, young cattle	Live weight-to-carcass-ratio * (Heifers + Male and Female calves to slaughter) * %P/WW	S3	S2, S7
C5-6	Milk production	Ncow * Milk Production per year-cow (ECM) * conversion factor ECM * %P/WW	S4	S5
C6-0	Milk delivered to dairy	Milk production – Milk consumed by calves	-	-
C6-4	Milk consumed by calves	Nyc * Average milk consumption YC * %P/WW	S6	S5
-	Total manure dairy cows	Mass balance	-	-
-	Total manure other cattle	Mass balance	-	-
C5-3	Manure dairy cows on pasture	Total manure dairy cows * 8/52 weeks * 50% of time outside	-	-
C4-3	Manure young cattle on pasture	Total manure young cattle * 8/52 weeks * share of YC on pasture	-	-
C5-7	Manure collected, dairy cows	Total manure dairy cows – Manure dairy cows on pasture	-	-
C4-7	Manure collected, young cattle	Total manure young cattle – Manure young cattle on pasture	-	-
C7-8	Manure to CowPower	(Total manure DC + Total manure YC) – Manure for fertilising	-	-
C7-1	Manure for fertilising	Forage harvested	-	-

Table 9. Calculation methods and sources for the upscaling scenario. Sources: S1: (Nordic Feed Evaluation System [NorFor], n.d.); S2: (Antikainen et al., 2005); S3:(Landbruksdirektoratet, 2017b); S4: (Landbruksdirektoratet, 2017a); S5: (Mattilsynet, 2018), S6: (TINE, 2015); S7: (Cooper & Carliell-Marquet, 2013). In addition, see parameter sources (table 10).

Parameter	Value	Unit	Notes
Number of dairy cows in 2017 (Ncow)	304,459	animals	Assumed to be year-cows. Source: (Statistics Norway, 2017c)
Number of young cattle in 2017 (Nyc)	560,640	animals	Assumed to be year-cows. Source: (Statistics Norway, 2017c)
Grazing period	8	weeks/year	Source: (Hind, 2016)
Time spent on pasture during grazing period, dairy cows	50	%	Assumption based on Foss Gård
Time spent on pasture during grazing period, young cattle	100	%	Assumption based on Foss Gård
Share of young cattle older than 6 months	20	%	Source: (Data Norge, 2019)
Live weight to carcass weight ratio	2	-	Estimate: (Vasdal, 2019)
Conversion factor ECM to kg milk	1.02	kg ECM/kg milk	Source: see section 3.2.2 'Milk'
Average milk consumption young cattle	200	kg/year	Source: see section 3.2.2 'Milk'

Table 10. Parameters used in the upscaling scenario.

Herd size

Per March 2017, Norway's livestock count was around 865 thousand, including both dairy and meat production, of which 304 thousand were classified as cows and 561 thousand as 'other cattle' (Statistics Norway, 2017c). The latter category thus accounted for 65%, which approximated the share of Norwegian livestock individuals that never calved in the Livestock

Register of May 2019 (Data Norge, 2019). Therefore, it was assumed this category matched the definition of young cattle used here for the MFA of Foss Gård, i.e. cattle of pre-lactation age.

The data represented the number of heads on March 1st 2017, without information on changes within the year. Therefore, changes in number of cattle during the year were not taken into account, and young cattle were assumed to all reach adulthood in the calculations of feed consumption, thus disregarding a skewed age distribution due to slaughter at a young age.

Feed

The concentrate and forage consumption of the cows and young cattle were assumed to equal the average Norwegian cow per 2017 (NorFor, n.d.), as described in section 3.2.2 'Average Norwegian cow diet'. That is, respectively 6.0 and 0.25 kg DM concentrate per day, and 13 and 5.8 kg DM forage per day, for dairy cows and young cattle (see table 6). Of this forage ration, a share was assumed to be met through grazing. This share was calculated as for Foss Gård (see section 3.2.2 'Forage feed and grazing'), except with an 8 week grazing period (Hind, 2016) instead of 16 weeks. The time spent on the pasture during the grazing period was assumed to be the same as on Foss Gård, for lack of data. Similarly, the assumption that young cattle were let onto the pasture from the age of 6 months was kept, a share that was estimated based on the June 2019 Livestock Register (Data Norge, 2019) to be 20%.

However, it is important to note that these average feed rations by NorFor (n.d.) were designed for dairy cattle, while we applied this to all Norwegian cattle, including those raised for meat consumption.

Milk

The total quantity of milk produced was based on the Norwegian national average milk production per year-cow, i.e. 8116 kg energy-corrected milk (ECM) per year-cow (TINE, 2017). Containing on average 4.27% fat and 3.44% protein (TINE, 2017), and assuming 4.7% lactose, this was converted to 7950 kg milk, according to the equation:

$$\frac{kg\ ECM}{kg\ milk} = 0.01 + 0.122 * \%fat + 0.07 * \%protein + 0.053 * \%lactose$$ (Sommerseth, 2019)

The milk consumption by the calves was estimated based on the average of the three example feeding milk feeding strategies for non-organic farms in TINE (2015), i.e. 400 L milk per calf over the course of its first 8 weeks of life. Assuming a 2-year 'lifetime' of the young cattle until their first lactation period, this corresponded with 200 L of milk per year per young animal, which was assumed to be equal to 200 kg of milk.

Slaughter

Statistics on livestock slaughter for 2017 were obtained from Landbruksdirektoratet (2017b). From this, cows and bulls to slaughter were allocated to the outflow of dairy cows, and heifers and calves (male and female) to slaughter to young cattle. As in the MFA for Foss Gård, we assumed that live weight was two times the slaughter weight.

Manure and processing

As for the Foss Gård MFA, the total excretion of manure was calculated via mass balance, for the dairy cow and young cattle processes. The allocation method between manure excreted on the pasture and manure collected was also unchanged from that described in section 3.2.2 'Manure', except for the change in parameters regarding grazing (see above).

In this model, the collected manure was used to meet the P fertilisation requirements for forage production based on the consumption thereof by the total Norwegian herd. The surplus was subsequently sent to processing through CowPower.

This CowPower process was assigned three output flows: composted fibre fraction, liquid fertiliser, and fine particle granulate (see section 3.1.1 'CowPower: system definition'). The transfer coefficients used were based on the results from the CowPower MFA, see Chapter 5.1 'CowPower results', according to which the aforementioned output products contained 32%, 8% and 70% of the ingoing P. These coefficients were scaled down to total 100%, such that the composted fibre fraction contained 29% of the ingoing P, the liquid fertiliser 7%, and the fine particle granulate 64%.

4 Uncertainty analysis

Uncertainty analyses are provided in this chapter for the CowPower MFA, discussing the robustness of the system and comparing our results to data from earlier sampling, as well as for the Foss Gård MFA, discussing the uncertainty level of each flow. In addition, further detail on uncertainties is given in the next chapter, 'Discussion and conclusions'. As the Upscaling Scenario is by nature relying on assumptions, its limitations are solely discussed in this next chapter.

4.1 CowPower

Uncertainty measurements were provided for the chemical analysis of the samples: 5-10% for DM, 20-25% for P, and 10-20% for N (Eurofins, 2019).

Due to the uncertainties surrounding the pathways of nitrogen in the CowPower system (Vasdal, 2019), with potential outflows not excluded, the phosphorus results from chemical analysis were considered more robust. Therefore, where necessary due to a lack of direct measurements or unknown outflows of water or gases, the DM was calculated from the P results based on a mass balance principle, notwithstanding the higher uncertainty margin associated with the chemical analysis of P.

The N flows were subsequently calculated from the dry matter based on the concentrations obtained from chemical analysis, which resulted in mass balance inconsistencies in this layer. The choice was made to leave these inconsistencies unresolved, as it was unknown to what extent these stemmed from errors in the measurements or calculations, variation between samples, or that these indicated in- or outflows that were not accounted for in the system. For example, drying processing techniques have been associated with significant losses of N (Brod, 2018), which could explain the loss observed in our system.

Another source of uncertainty in the model is the assumption that the outflows of water in the composting process and the drying process did not contain any DM, P, or N, while in reality there may be losses.

In addition, in- and outflows of gaseous substances were assumed to have a DM content of 100%, while in reality the H and O atoms they contain may stem from water molecules or recombine to form water. However, this would only overestimate the wet weight values of these flows, on which scale they have no significant impact.

Comparison to previous sampling by Foss Biolab and USN (2012-2014)

In addition to the measuring uncertainties connected to the chemical analysis of the samples taken in 2019, one should bear in mind that merely one sample was taken for each flow analysed. This does not account for the significant variation that is known to exist between samples. Being based on one measurement, the results obtained here are therefore merely indicative. To improve these results, a large number of samples should be taken and averaged.

Such a long-term study was conducted by Foss Biolab and USN (2012-2014) (see section 3.1.2 'Data sources'). Figure 5 compares our results to the range of values found by this long-term study; the grounds for comparison were limited to these variables.

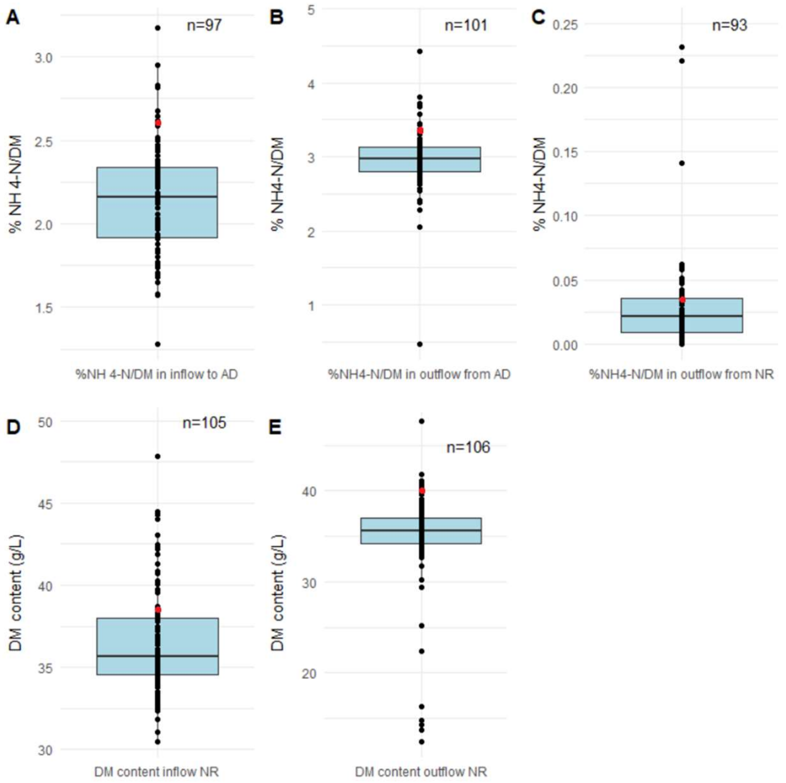

Figure 5. Comparison with previous sampling. Comparison of results from Foss Biolab and USN (2012-2014) with the current study, signified by red dots. AD = anaerobic digestion, NR = nitrification reactor.

The comparison shows that our findings fall into the range of values measured previously, with regards to the concentrations of DM and NH_4 in the in- and outflows related to anaerobic digestion and nitrification. It should be noted that our assumptions on the effects of these processes on the NH_4 content were based on the average effect found by Foss Biolab and USN (2012-2014) (see 3.1.3. ‘CowPower: Quantification’). Therefore, our results are not fully independent from this dataset.

The effect of anaerobic digestion (AD) on NH_4-N is highly variable and has been measured both to be strongly negative and strongly positive (fig. 5). We assumed an increase of 17% after the average effect found in Foss Biolab and USN (2012-2014), but these results show that the reality could be very different. Nonetheless, the results seem to fit well. In addition, the impact of this flow on the rest of the system is likely to be low.

4.2 Foss Gård

In constructing this MFA, the data availability was found to be lower than anticipated. As a result, the quantification of the system relied on a range of assumptions and simplifications.

Table 11 below lists the assumptions underlying the quantification of each flow, based on which they were assigned to one of four uncertainty levels from low to very high. This was done through a qualitative assessment according to the following criteria:

Low: Assumptions regarding unit conversion, literature values for DM and P contents, minor uncertainties regarding fit of data to flow.

Medium: Literature value or estimate for a parameter central to flow calculation.

High: Combination of multiple estimates or literature values, that together created low confidence in the flow's accuracy (qualitative assessment). Or flow equalled another flow which had been given a high level of uncertainty (B2-4, forage harvested).

Very high: Strong reliance via mass balance on multiple other flows that have been given a high level of uncertainty, in addition to assumptions on transfer coefficients. Applied to all manure-related flows: collected manure (B6-9 and B7-9), manure on pasture (B6-3 and B7-3), and manure used as fertiliser (B9-1 and B9-2).

Flow	Flow name	Level of uncertainty	Assumptions
B0-5	Concentrate purchased	Low	-
B5-7	Concentrate consumed by dairy cows	Medium	Feed purchase equals feed consumption; Ratio dairy cows:young cattle in concentrate consumption as for average
B5-6	Concentrate consumed by young cattle	Medium	Feed purchase equals feed consumption; Ratio dairy cows:young cattle in concentrate consumption as for average
B3-7	Forage feed consumed by dairy cows	High	Literature value for energy content in forage feed; Grazing accounts for half (time outdoors) of 16/52th (weeks outdoors) of forage consumption;
B4-6	Forage feed consumed by young cattle	High	Literature value for energy content in forage feed; Norwegian average value for young cattle forage consumption, of which grazing accounts for 16/52th (weeks outdoors); Estimated share of young cattle older than 6 months.
B4-7	Grazing, dairy cows	High	Literature value for energy content in forage feed; Grazing accounts for half (time outdoors) of 16/52th (weeks outdoors) of forage consumption; Literature value for %P in grass.
B4-6	Grazing, young cattle	High	Literature value for energy content in forage feed; Norwegian average value for young cattle forage consumption, of which grazing accounts for 16/52th (weeks outdoors); Estimated share of young cattle older than 6 months; Literature value for %P in grass.
B1-0a	Barley grain harvested	Low	Sale of grains equals harvest; Literature values for %P and %DM in barley grain.
B1-4	Straw harvested	High	Literature values for ratio of straw to barley grain yield, and for %P and %DM in barley straw, which are parameters that are subject to a large variation.
B2-4	Forage harvested	High	Production equals consumption; Forage feed consumption flows are correct.
B7-0a	Net flow respiration (CO_2-C) - Dairy cows	Medium	Literature value for dairy cow respiration rate.
B6-0a	Net flow respiration (CO_2-C) - Young cattle	Medium	Dairy cow to young cattle ratio of methane emissions (from literature) applied to CO_2.
B7-0b	Enteric methane emission (CH_4) - Dairy cows	Medium	Literature value for dairy cow methane production rate; DM content of CH_4 is 100%.
B6-0b	Enteric methane emission (CH_4) - Young cattle	High	Literature estimated value for young cattle methane production rate; Disregarding age distribution of young cattle; DM content of CH_4 is 100%.
B7-8	Cows to slaughter	Medium	Live weight to carcass weight ratio of 2:1. DM and P contents from literature.
B6-8	Calves/young cows to slaughter	Medium	Live weight to carcass weight ratio of 2:1. DM and P contents from literature.
B6-0	Live sale calves	Low	DM and P contents from literature.
B7-10	Milk produced total	Low	Conversion from liters of energy-corrected milk to kg of milk. DM and P contents from milk for consumption assumed equal to those in raw milk.

(Table 11, continued on next page)

(Table 11, continued)

B10-0	Milk to Dairy production	Low	Conversion from liters of energy-corrected milk to kg of milk. DM and P contents from milk for consumption assumed equal to those in raw milk.
B10-6	Milk to calves	Low	Calves' milk consumption is difference between production and delivery to dairy. Conversion from liters of energy-corrected milk to kg of milk. DM and P contents from milk for consumption assumed equal to those in raw milk.
B0-7a	Sawdust for bedding, dairy cows	Medium	Estimated by Vasdal (2019); Divided between dairy cows and young cattle equally; Literature values for density and DM and P contents.
B0-6a	Sawdust for bedding, young cattle	Medium	Estimated by Vasdal (2019); Divided between dairy cows and young cattle equally; Literature values for density and DM and P contents.
B7-9	Manure slurry collected, dairy cows	Very high	Share of manure on pasture is correct; Intake equals excretion; All flows are accounted for in the system definition and are correct (mass balance).
B6-9	Manure slurry collected, young cattle	Very high	Share of manure on pasture is correct; Intake equals excretion; All flows are accounted for in the system definition and are correct (mass balance).
B7-3	Manure cows on pasture	Very high	Manure excretion continuous throughout day and year; Cows spend 0.5*16/52nd share of year on pasture; Intake equals excretion; All flows are accounted for in the system definition and are correct (mass balance).
B6-3	Manure young cattle on pasture	Very high	Manure excretion continuous throughout day and year; Estimated share of young cows on pasture; Young cattle on pasture do not go inside for 16 weeks; Intake equals excretion; All flows are accounted for in the system definition and are correct (mass balance).
B9-1	Manure to fertilise cropland	Very high	Fertilisation according to crop P requirements; No leaching or runoff; Collected manure flow is correct.
B9-2	Manure to fertilise forage area	Very high	Application of all manure besides what is applied to cropland; No leaching or runoff; Collected manure flow is correct.
B7	Stock growth cows	High	No stock change between start of year and April 10th; All slaughter and sale occurring after April 10th; Average weight of dairy cow.
B6	Stock growth young cattle	High	No stock change between start of year and April 10th; All slaughter and sale occurring after April 10th; Average weight values for age groups.
B7-6	Calving	High	No stock change between start of year and April 10th; All slaughter and sale occurring after April 10th; Average calf birth weight.
B3-7	Young cows entering adulthood	High	No stock change between start of year and April 10th; All slaughter and sale occurring after April 10th; Average weight of dairy cow at start of lactation.

Table 11. Assumptions and uncertainty of Foss Gård flows. Qualitative assessment of flow uncertainties based on underlying parameters. Method described in text.

This qualitative assessment gives an indication of the uncertainty involved in the different flows. It indicates that the flows related to manure production and management had the lowest associated confidence level, while these were of particular interest to this project. To reduce their uncertainty, the related flows with a high uncertainty level should be targeted. When taking into account their relative flow sizes (see Chapter 5.2 'Foss Gård Results'), it follows that the feed intake through forage and grazing would have the largest impact on manure production. To best improve their quality for future studies of a similar kind, their consumed quantities should be reported or samples should be tested for their energy content as well as P and DM contents.

In addition, it should be kept in mind that biological processes related to plant and animal growth, which are fundamental to this system, are subject to a large natural variation. These are therefore particularly unsuited to quantification via literature values or national averages, as has nevertheless been done repeatedly in this project.

A sensitivity analysis would be recommended in order to gain a better understanding of the relative importance of the underlying parameters, and to estimate the likely variance in the manure production based on these uncertainties. For example, it would be interesting to gain insight into the sensitivity of the system to variation in P contents, which were mostly literature based. However, this was outside of the scope for this project.

Nonetheless it is important to take into account the significant uncertainty of the system when considering the results of this MFA.

5 Results

5.1 CowPower results

In this section the results from the CowPower MFA are discussed. Table 12 shows the obtained characteristics for the input and three end products. Table 13 lists the results for all layers in terms of concentration and values obtained for a theoretical input of 100 kg livestock manure. A description of the results is provided below, followed by Sankey diagrams of the results for wet weight and dry matter (fig. 6), phosphorus (fig. 7), and nitrogen (fig. 8). The Sankey diagrams were created using the open-source Python tool developed by Lupton and Allwood (2017).

Product	%P/DM	%N/DM	N:P ratio
Livestock manure input	0.7%	3.9%	5.5:1
Composted fibre fraction	0.7%	2.0%	3:1
Filtration liquid	0.2%	10.9%	50:1 *
Fine particle granulate fertiliser	1.3%	4.3%	2.5:1 *

Table 12. P:N ratios of end-products. *N:P ratios likely overestimated due to MBI of N in filtration process.

Code	Flow name	WW	DM		P		N		NH_4-N		NO_3-N	
		kg	%	kg	%	g	%	kg	%	kg	%	kg
A0-1	Livestock Manure	*100*	**7.6%**	7.6	**0.7%**	54	**3.9%**	0.30	**1.4%**	1.1E-01	**<0.013%**	9.9E-04
A1-2	Fiber Fraction	13	**25%**	3.1	**0.6%**	17	**1.4%**	0.04	**0.14%**	4.4E-03	**0.054%**	1.7E-03
A2-0a	Composted Fiber Fraction	10	**24%**	2.5	**0.7%**	17	**2.0%**	0.05	**0.01%**	2.5E-04	**0.024%**	5.9E-04
A2-0b	Water (Compost)	1.7	-	-	-	-	-	-	-	-	-	-
A2-0c	Biogas (CO_2, CH_4)	0.7	100%	0.7	-	-	-	-	-	-	-	-
A1-3	Liquid Fraction	88	**5.1%**	4.5	**0.8%**	37	**5.6%**	0.25	**2.6%**	1.2E-01	**<0.022%**	9.8E-04
A3-0	Biogas	0.5	100%	0.5	-	-	-	-	-	-	-	-
A3-4	Digestion Residue	87	4.6%	4.0	**0.9%**	37	**5.3%**	0.21	3.4%	1.4E-01	0.02%	9.8E-04
A0-4	Oxygen	0.6	100%	0.6	-	-	-	-	-	-	-	-
A4-5	Liquid Nitrification Residue	88	5.1%	4.5	**0.8%**	37	**5.0%**	0.22	0.03%	1.4E-03	3.0%	1.4E-01
A5-6	Filtration Liquid	77	2.6%	2.0	**0.2%**	4.3	**10.9%**	0.21	0.04%	6.9E-04	6.8%	1.3E-01
A6-0a	Liquid fertiliser (concentrate)	7.8	25%	2.0	0.2%	4.3	10.9%	0.21	0.04%	6.9E-04	6.8%	1.3E-01
A6-0b	Water (evaporation)	69	-	-	-	-	-	-	-	-	-	-
A5-7	Particle Fraction Filtration	11	**23%**	2.5	**1.3%**	33	**4.3%**	0.11	**0.03%**	6.8E-04	**0.13%**	3.3E-03
A7-8	Granulate	11	23%	2.5	1.3%	33	4.3%	0.11	0.03%	6.8E-04	0.13%	3.3E-03
A8-0b	Water (Drying)	8.1	-	-	-	-	-	-	-	-	-	-
A8-0a	Fine Particle Granulate	2.8	**89%**	2.5	**1.5%**	38	**3.9%**	0.10	**0.01%**	2.5E-04	**0.055%**	1.4E-03

Table 13. CowPower model results for an input of 100 kg livestock manure. Concentrations given in dry matter. Values in bold were obtained from chemical analysis (Eurofins, 2019).

Description of results

The results show that the centrifuge separated out 12.5% of the wet weight. Subsequent composting of the fibre fraction led to a reduction of its weight by 20% through the outflow of water and gases. The resulting composted fibre fraction contained 32% of the original DM, 32% of the P, and 17% of the N. It had a P:N ratio of 1:2.9.

The liquid fraction from the centrifuge had a lower dry matter content, containing 59% of the original DM whilst 87.5% of the WW. It had a P:N ratio of 1:6.9, which was over 2.5 times as high as that of the fibre fraction.

The anaerobic digestion was found to produce 4.8 litres of biogas per litre of WW input (A1-3). This outflow had no significant effect on the quantities of wet weight or dry matter, and did not affect the P and N layers.

Similarly, the inflow of oxygen for the subsequent nitrification process was negligible. The nitrification residue contained 0.04% NH_4-N and 6.8% NO_3-N.

The filtration process was shown to have a high efficiency. It was estimated to divide the wet weight over the liquid and particle fraction in an 88:11 ratio, with 56% of the DM input remaining in the particle fraction. In addition, 88% of the P was retained in the particle fraction. With regards to N, the concentrations found through chemical analysis yielded a summed output that was 44% larger than the input N, a mass balance inconsistency that was kept unresolved for transparency regarding the system uncertainties. The model thus predicts that nearly all N flows into the filtration liquid, and around half of the N is retained in the particle fraction from filtration.

The P:N ratio in the particle fraction was found to be 1:3.3, as opposed to a ratio of 1:50 in the filtration liquid, due to the minimal presence of P in the latter.

All layers were assumed to be unaltered by the granulation process, which was hence equal to the particle fraction of the filtration.

Through drying, the outflow of water resulted in a 74% reduction in wet weight, resulting in a fine particle granulate with an 89% DM concentration, 1.3% P, and 4.3% N. It contained 33% of the original DM, 70% of the P, and 33% of the N.

CowPower Sankey diagrams

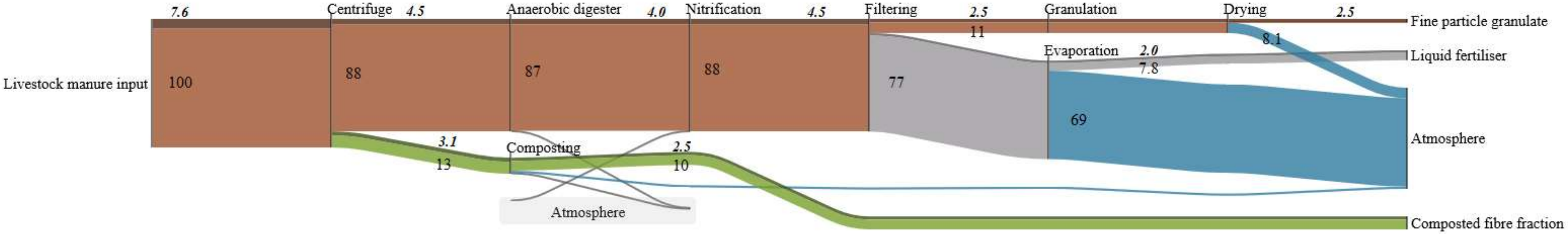

Figure 6. Total wet weight and dry matter flows in the CowPower system. Flows in kg for 100 kg wet weight input. Dry matter flows indicated by darker colours and italic flow values; flows of water in blue.

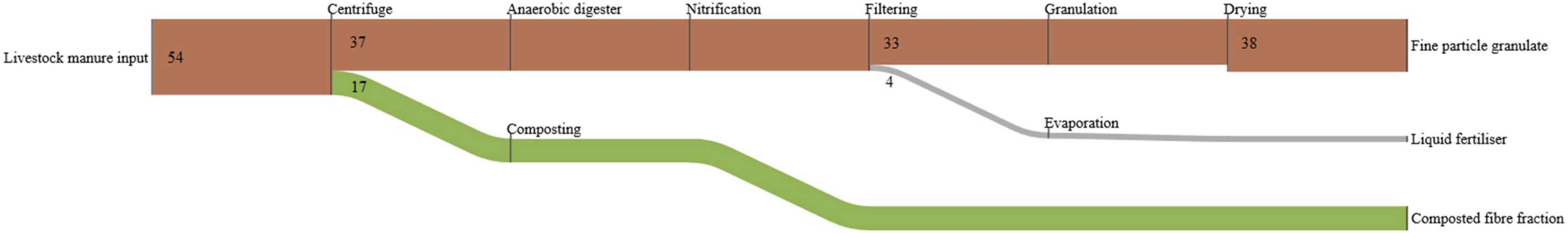

Figure 7. Phosphorus flows in the CowPower system. Flows in grams for 100 kg wet weight input.

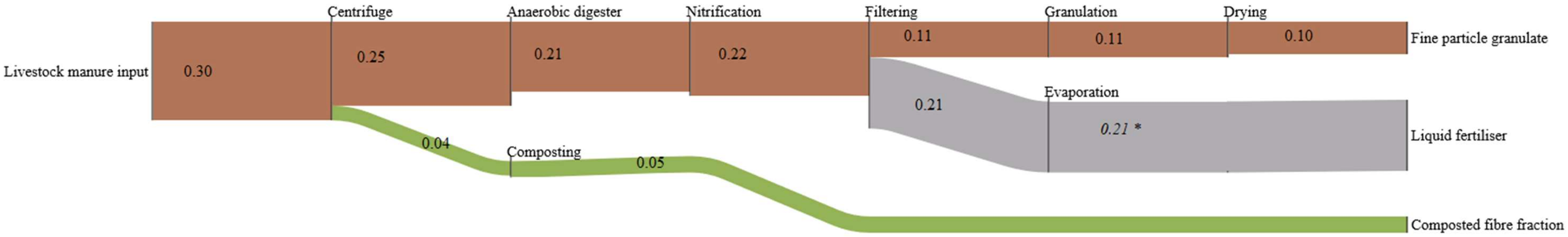

Figure 8. Nitrogen flows in the CowPower system. Flows in kg for 100 kg wet weight input. *N in liquid fertiliser assumption with high uncertainty.

5.2 Foss Gård results

In this section, the results from the MFA of Foss Gård in 2017 are presented. Table 14 shows the flow values found for DM and P along with their concentrations. In addition, the two layers are visualised in figures 9 and 10 as Sankey diagrams, created using the open-source Python tool developed by Lupton and Allwood (2017).

The livestock was found to rely mostly on homegrown feed; at 317 kg P the imported concentrate feed accounted for 30% of the dairy cows' feed P intake, while for the young cattle it merely accounted for 3%; in terms of DM the concentrate accounted for respectively 18% and 2% for the dairy cows and young cattle. Grazing fulfilled 14% and 19% of the feed P intake for the dairy cows and young cattle respectively, and 13% and 18% of their feed DM intake. And forage accounted for 57% and 59% of P intake, and 69% and 71% of the DM intake of the dairy and young cattle. Finally, at 89 kg P per year, milk supplied the young cattle with 18% of their P demand and 8% of their DM feed intake.

The total livestock stock increase was found to be 2 ton DM or 45 kg P, which was small relative to the flows of feed, milk, and manure. Thus 2% of the young cattle's P intake was invested into stock growth, or 3% for the adult dairy cows. The herd produced 43 ton DM of milk, containing 340 kg P, of which 32 ton DM (250 kg P) was delivered to dairy, with the remainder fed to calves.

In addition to milk, the farm exported barley grain, and cattle for slaughter and live sales. In total 2.2 tons of DM was sent to slaughter, containing 52 kg P. Crop exports were 16 tons DM, containing 60 kg P, while the straw that was produced as a by-product totalled 22 tons of DM of which merely 22 kg of P since it had a much lower P content. The straw thus did not play a significant role in supplying the cattle's feed P intake.

The total quantity of manure collected was 150 ton DM of which 940 kg P, while 35 ton DM, of which 190 kg P, was deposited on the pasture while grazing. All collected manure was applied to soils as fertiliser, of which 8% of P on the croplands and 92% on the forage area. After meeting the cropland's P requirements, the P demand on the forage area could not be satisfied: there was a deficit of 29 kg P, corresponding to 3% of the forage harvest. Thus, a reduction in soil P levels would be expected based on these results. Similarly, the pastures were predicted to have a larger P outflow through grazed grass than the inflow of P in manure, with a deficit of 49 kg P corresponding to 20% of the uptake.

Code	Flow name	DM (tons)	P (kg)	%DM	%P
B0-5	Concentrate purchased	58	330	88%	0.57%
B5-7	Concentrate consumed, dairy cows	56	320	-	0.57%
B5-6	Concentrate consumed, young cattle	2.5	14	-	0.57%
B3-7	Forage consumed, dairy cows	220	630	32%	0.29%
B4-6	Forage consumed, young cattle	97	280	32%	0.29%
B4-7	Grazing, dairy cows	39	150	-	0.38%
B4-6	Grazing, young cattle	24	92	-	0.38%
B1-0a	Barley grain harvested	16	60	86%	0.38%
B1-4	Straw harvested	22	22	90%	0.10%
B2-4	Forage harvested	290	890	-	0.29%
B7-0a	Respiration – CO2-C, dairy cows	150	0	-	0.00%
B6-0a	Respiration – CO2-C, young cattle	39	0	-	0.00%
B7-0b	Enteric CH4 emission, dairy cows	10	0	-	0.00%
B6-0b	Enteric CH4 emission, young cattle	2.7	0	-	0.00%
B7-8	Slaughter, dairy cows	0.9	20	32%	0.72%
B6-8	Slaughter, YC	1.4	32	32%	0.72%
B6-0	Live sale calves	0.27	6.1	32%	0.72%
B7-10	Milk production	43	340	13%	0.10%
B10-0	Milk delivered to dairy	32	250	13%	0.10%
B10-6	Milk consumed by calves	11	89	-	0.10%
B0-7a	Sawdust bedding, dairy cows	1.9	2.9	50%	0.08%
B0-6a	Sawdust bedding, young cattle	1.9	2.9	50%	0.08%
-	*Total manure dairy cows*	*110*	*740*	-	*0.68%*
-	*Total manure young cattle*	*91*	*390*	-	*0.43%*
B7-3	Manure dairy cows on pasture	17	110	-	0.68%
B6-3	Manure young cattle on pasture	18	79	-	0.43%
B7-9	Manure collected, dairy cows	93	630	-	0.68%
B6-9	Manure collected, young cattle	73	310	-	0.43%
B9-1	Manure to fertilise cropland	14	81	-	0.43%
B9-2	Manure to fertilise forage area	150	860	-	0.57%
B7	Stock growth cows	1.6	35	32%	0.72%
B6	Stock growth young cattle	0.43	9.7	32%	0.72%
B7-6	Calving	0.59	13	32%	0.72%
B3-7	Young cattle to adulthood	2.3	52	32%	0.72%

Table 14. MFA results for Foss Gård. P content in dry matter. All values rounded to two significant numbers.

Foss Gård Sankey diagrams

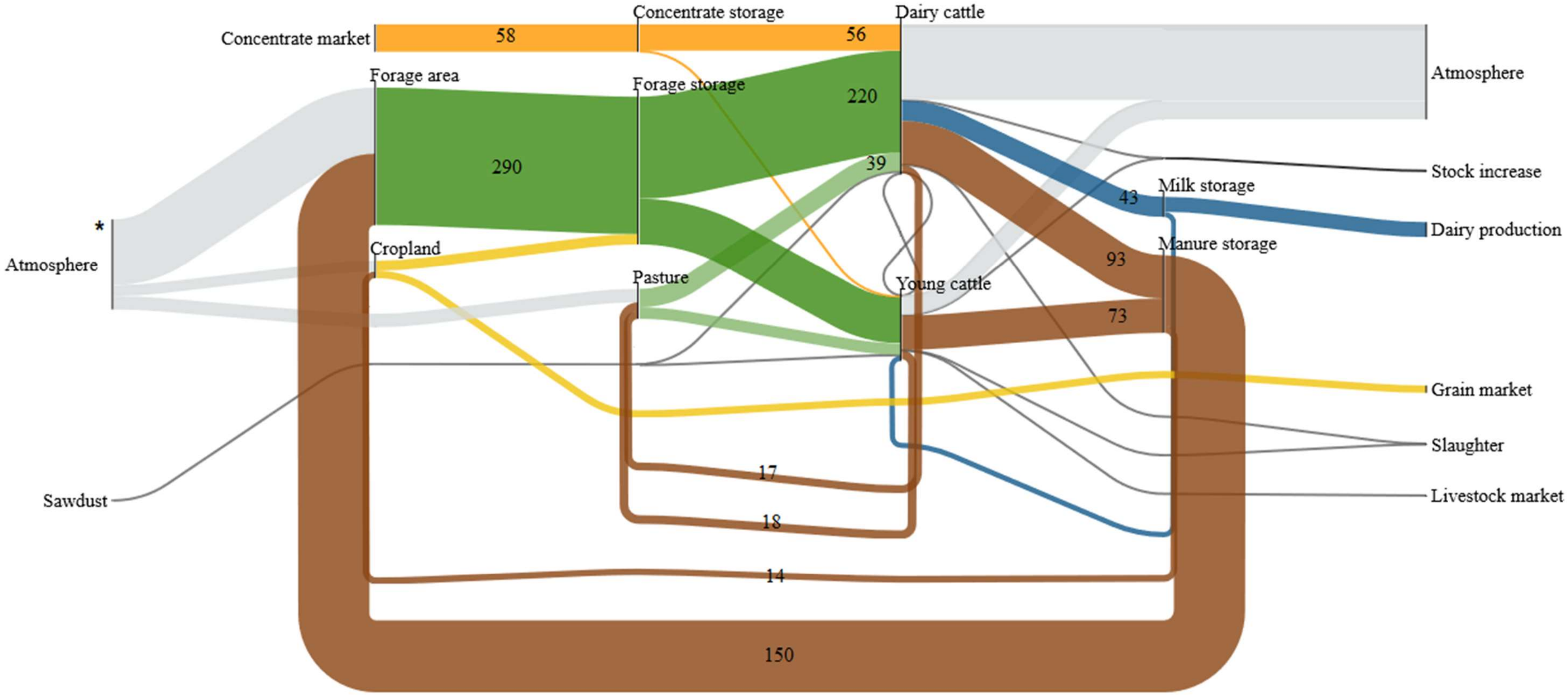

Figure 9. Dry matter flows (tons) on Foss Gård. **The difference between plant uptake and fertiliser addition is here visualised as an inflow of atmospheric carbon, which is a simplification as in reality a large share of the applied manure DM would volatilise and not enter the soil stock.*

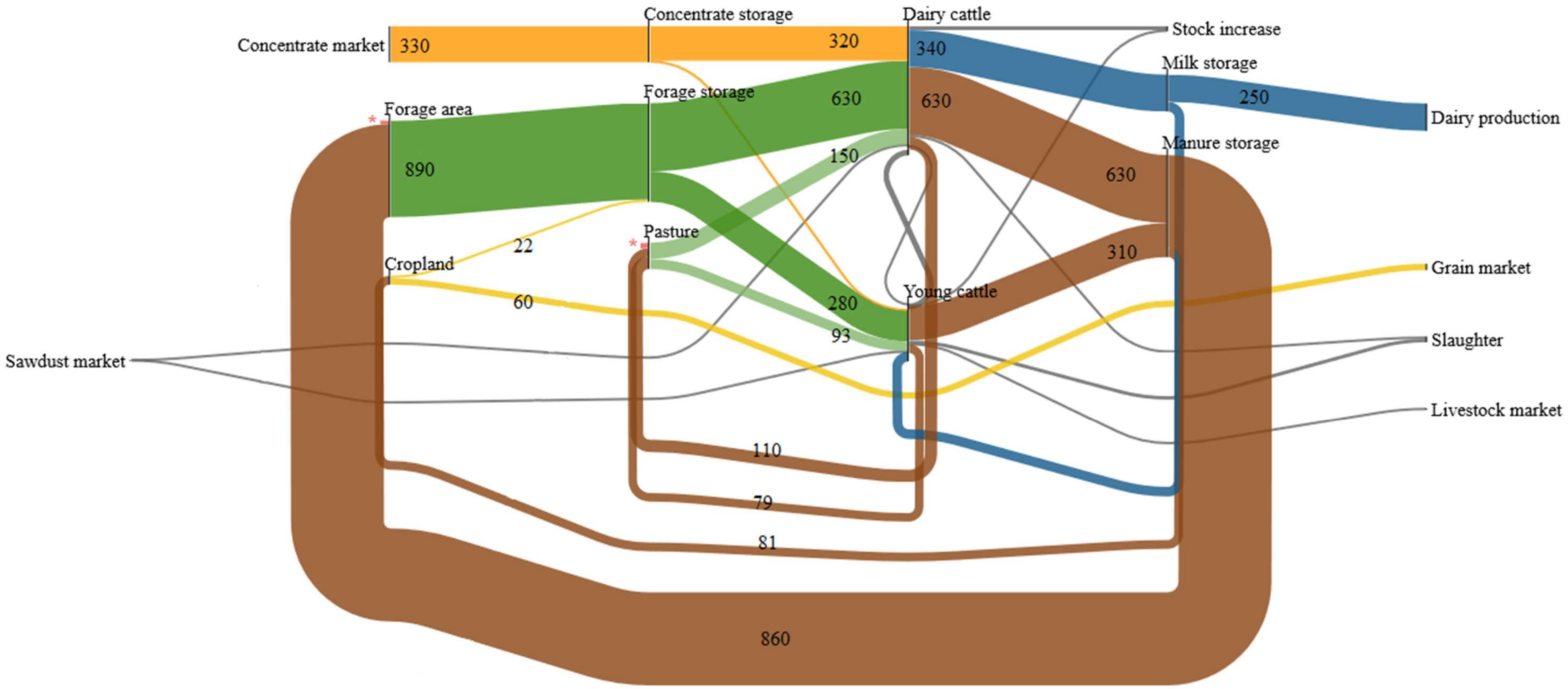

Figure 10. Phosphorus flows (kg) on Foss Gård. * denotes the difference between fertilisation and crop uptake.

5.3 Upscaling scenario results

Upscaling scenario Sankey diagram

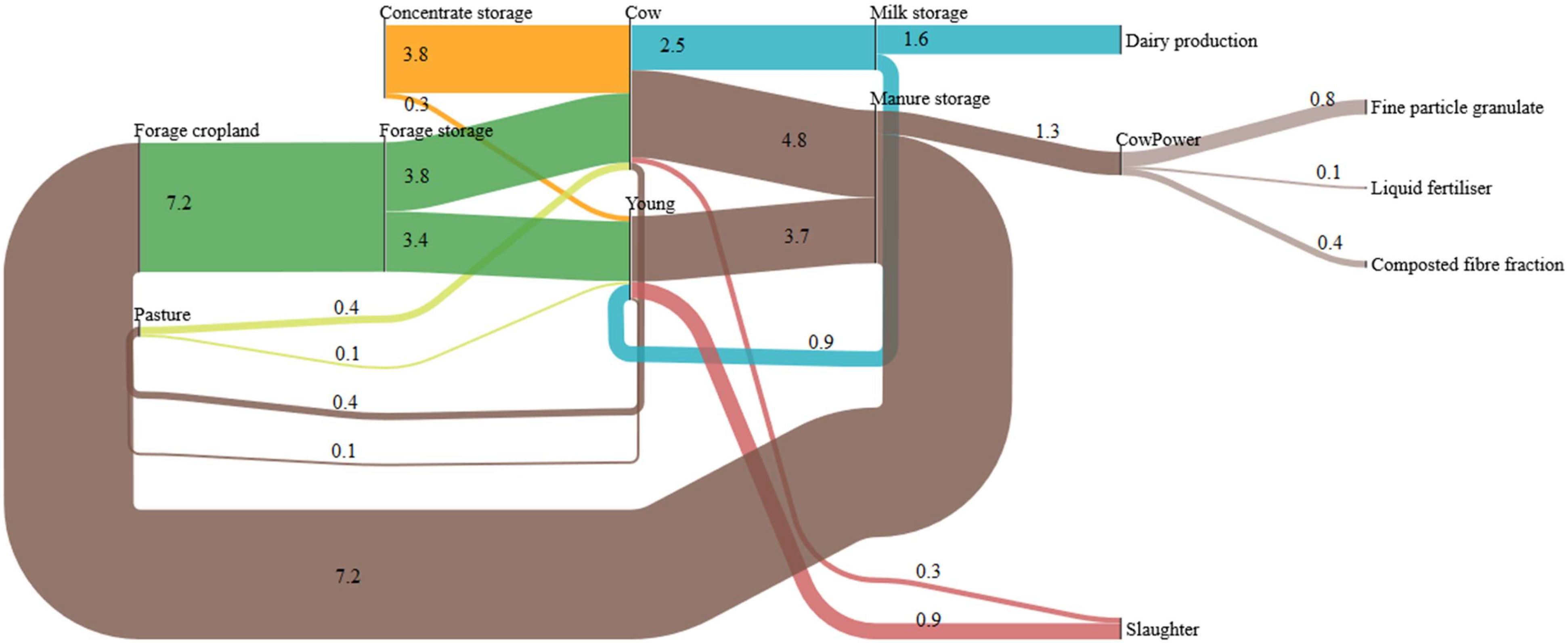

Figure 11. Phosphorus flows (kt) in the Upscaling Scenario for the Norwegian livestock system for dairy and meat production in 2017.

Figure 11 shows the results of the upscaling scenario in a Sankey diagram (tool by Lupton and Allwood (2017)). The results are given in kt P, for all dairy and meat cattle in Norway in 2017, according to the assumptions as outlined in the Chapter 3.3 ‘Methodology Upscaling scenario’.

The adult cows were found to consume equal amounts of concentrate and forage feed, both 3.8 kt P per year. The young cattle relied primarily on forage feed, consuming 3.4 kt P of this while only 0.3 kt of concentrate feed. Grazing did not account for a significant share of the diet of either adult or young cattle.

Milk production contained 2.5 kt P per year, of which 1.6 kt was delivered to dairy production. Meat production totalled 1.2 kt P, of which three quarters stemmed from the young cattle.

The total manure production of the adult cattle was 5.2 kt P, of which 0.4 kt was excreted on the pasture and the remainder collected. The quantity of manure from young cattle approached that of the adults, at 3.8 kt P, of which 0.1 kt P excreted on the pasture.

Of the total 9.0 kt P in collected manure, 7.2 was applied to the forage area, according to crop uptake. The manure excreted on the pasture (0.5 kt P) also equalled the uptake through grazing, although this was not predefined in the system design. There were thus no soil surpluses or deficits.

The origin of the 4.1 kt P in concentrate was left unspecified and may partially be met through manure P as well. After fertilising the forage area, 1.3 kt P was found to remain of the collected manure. After this quantity was processed through CowPower, the output products obtained were 0.8 kt P in fine particle granulate, 0.1 kt P in liquid fertiliser, and 0.4 kt P in composted fibre fraction.

6 Discussion and conclusions

In this chapter, the results from the MFA of CowPower, the MFA of Foss Gård, and the upscaling scenario are presented, each in their own subchapter. However, the upscaling scenario builds on the results from both the MFAs and integrates them into a national context. Thus, while the scope of the CowPower discussion in the first section is narrow, the broader implications of the upscaling scenario on the role of CowPower are discussed further on.

Given the wide array of subjects discussed in this chapter, it was deemed more meaningful for conclusions to be drawn alongside the discussion than to summarise these in a separate chapter with a lack of context and connection. This chapter therefore encompasses both discussion and conclusions.

6.1 CowPower

The results of the multi-layer CowPower MFA can inform us on its effects regarding weight reductions, which are highly relevant with regards to the transport of manure from regions with P surpluses to regions with P deficits. In addition, the results from P and N analysis can inform on the suitability of the end products for use as fertiliser. Finally, heavy metal contents are discussed to assess to what extent the end products are safe to use.

6.1.1 Transport weight and trade-offs

A key question for CowPower in terms of upscaling is to what extent its processing steps should be implemented by each farmer on-site, and to what extent these should be implemented in a small- or medium-scale facility, after collecting the (partially processed) manure from a number of farms. Such decentralised processing would require transport from each farm to the processing facility which, although the distances are shorter compared to interregional transport, would still be costly for heavy substances. On the other hand, decentralised processing could increase efficiencies and lower the threshold for farmers' participation. Therefore, in this section the wet weight in the different flows is analysed, and through that the benefits of on-site or decentralised processing for the different processing steps.

The first step, centrifugation, allocates 13% of the wet weight to the fibre fraction for compost. With regards to minimising transport weight, it would be recommended for this step to be performed on location. This appears to be relatively simple to implement, and yields a composting product for which use can easily be found on the farm.

The subsequent steps of anaerobic digestion and nitrification do not significantly affect wet weight. Therefore, if an on-farm approach is chosen for the filtration step then, from a transport weight perspective, this would be recommendable for these two processes as well. However, this would imply a prolonged storage of the manure slurry, which may for example lead to emissions of methane and carbon dioxide without their capture for use as biogas (Sommer, Petersen, Sørensen, Poulsen, & Møller, 2007). On the other hand, this may be prevented by the low temperatures (below 10°C) experienced in the winter season in Norway (Umetsu et al., 2005).

Filtration is a crucial step from a transport weight perspective, as the resulting particle fraction contains just around 11% of the ingoing weight. With a need for P exports being the driver for CowPower, the weight of this P-rich flow should be minimised. Applying filtration locally would result in a very large transport weight reduction as compared to decentralised processing. In addition, since farms on average are characterised by deficits of N which are compensated for through the use of mineral fertilisers, it would be inefficient to export a substance that is high in N and low in P, merely to re-import this N-rich liquid fertiliser after processing.

The next step for the filtration liquid is to be thickened through an evaporation process, which is likely to be a relatively energy-intensive procedure. The question is therefore whether it would be beneficial to do so, in a scenario where filtration is performed at a farm-level scale. That is, is there a need for export of this N-rich substance from the farm? Or are there any practical benefits to applying a fertiliser with a higher DM content (±25% instead of ±2.5%), and would such benefits outweigh the costs of transport and processing? For example, a higher DM content might reduce N_2O emissions, which were found to be related to soil moisture content (Luo, Ledgard, & Lindsey, 2007).

As for the final processing of the P-rich particle fraction, another weight reduction of 75% is achieved through drying, yet the ingoing flow is already just 11% of the original manure slurry. Therefore it is likely that at a dry matter content of 23%, this substance is worth transporting before further processing at a small- or medium-size installation (e.g. treating up to 50,000 tons per year (Foged et al., 2011)). However, an analysis of the energy requirements for this drying process is highly recommended; in a study on a similar processing technique, drying to 90% DM was found to require 100 kWh/t which was not economically optimal (Mazeika et al., 2016). The DM content realised by CowPower is the same, thus energy requirements could be a similar obstacle. This raises the question of what DM content is desirable from a transport point of view, and what the environmental trade-offs are with regards to energy requirements from further processing. For example, it might then prove to be optimal not to process the solid fraction beyond the filtration step at all. Hanserud et al. (2017) performed a life cycle analysis of manure processing and transport between two regions in Norway, with processing scenarios including anaerobic digestion and solid-liquid separation, and found such processing to be environmentally beneficial. A similar study on the effects of further processing through drying would be recommended.

In conclusion, the results give insight into the pathways of the bulk weight throughout the CowPower system, which is useful in the design of upscaling scenarios. For all three end-products of CowPower, the removal of water to reduce the wet weight took place in the last processing step. Therefore, in terms of minimising the transport weight to a decentralised processing facility, on-farm processing would be favoured for each step. The results indicate that when decentralisation is pushed to after centrifugation, with compost locally used, the transport weight is reduced by 13%; including processing up to filtration at the farm site, and using the liquid nitrogen fertiliser locally, reduces the original weight to be transported by 89%; and if all processing would take place on-site, the reduction would be 97%.

A cost-benefit analysis should be made regarding which processing steps are to be decentralised and at what scale, taking into account both the environmental impacts associated with transportation, and the feasibility and efficiency of applying the required technologies on a small or larger scale, including the impact of scale on their energy requirements. Such analyses were beyond the scope of this thesis, and are recommended for future investigation. In addition, further evaluation is recommended of the chemical aspects associated with the different processing steps and their timing, such as CH_4 emissions from delayed anaerobic digestion or the relationship between dry matter content and N_2O emissions.

6.1.2 Efficiency of centrifugation

One of the aims of CowPower is to concentrate the existing manure P into the fine particle granulate, which is suitable for transport. In this regard, the biggest inefficiency of the processing method was found in centrifugation. This first processing step is essential to remove large particles of >1mm in order to prevent the machinery from clogging in subsequent processing steps (Vasdal, 2019). Ideally this would be achieved at minimal losses of nutrients (especially P) to the fibre fraction, given that the liquid fraction is to be converted into fertiliser products. In an analysis of existing current practices by Brod (2018), centrifugation was found to produce a fibre fraction containing 60-63% of the original DM, and 69-73% of the original phosphorus.

In comparison, CowPower was found to separate merely 41% of the DM, and 32% of the P. Thus, relative to the findings by Brod (2018) the ‘loss’ of P in this processing step was low. In addition, this indicates that the separation efficiency of DM could be increased for this step, but that this would likely result in higher P losses, as P in manure is mainly bound to small particulate matter (Brod, 2018). In addition, given the low DM content of the original slurry input (7.6%), additional DM removal would not lead to significant benefits in terms of wet weight.

Nonetheless, centrifugation is the least efficient step with regards to overall P flows, and if measures could be taken to reduce the P loss here this would immediately translate into significant gains for the fine particle granulate end-product. This would have to be achieved through adaptation of the machinery further down the processing chain, such that these are equipped to handle larger fibre contents. From this standpoint, processing at a larger scale may be advocated. However, centrifugation as a solid-liquid separation technique is almost exclusively applied at the farm-level scale (Foged et al., 2011), which may be due to weight-related barriers.

6.1.3 N:P ratios in CowPower end-products

The ratio of N:P in the CowPower output products is important to assess. Application of manure as a fertiliser according to crop N requirements, which is common practice, results in an accumulation of P in the soils (Edmeades, 2003; Szögi, Vanotti, & Hunt, 2015). This is due to the low N:P ratio of animal manure (<4:1) compared to that of most crops' requirements (around 8:1) (Szögi et al., 2015). The resulting P accumulation increases risks of eutrophication through leaching and runoff.

The results show the N:P ratios of the input and the three end-products: 5.5:1 for the livestock manure input, 3:1 for the composted fibre fraction, 50:1 for the liquid fertiliser, and 2.5:1 for the fine particle granulate.

However, it should be noted that these ratios are heavily influenced by the uncertainties regarding the N flows. Especially for the filtration process, as the results for N were not mass balance consistent, this means that one or both of its outflows (A5-6, A5-7) should have a significantly lower N:P ratio. Applying a mass balance approach to N in A5-6 instead would result in an N:P ratio of the liquid fertiliser of 27:1 instead of 50:1. In the case of A5-7, this would result in an N:P ratio of the fine particle granulate of 0.3:1 instead of 2.5:1. This shows that the variation in N:P ratio of these output products is very large, and will likely lie somewhere in between these values.

The composted fibre fraction and the fine particle granulate both had relatively high concentrations of phosphorus compared to nitrogen, and thus should not be applied according to crop N requirements, but be supplemented with a N-rich fertiliser. The filtration liquid on the other hand was very high in N and low in P; at an N:P ratio of 27-50:1 it is much higher than the 8:1 ratio that crops typically require (Szögi et al., 2015). Therefore, this product too requires a combination with a more phosphorus rich fertiliser product, thus it lends itself well for use on animal farms where P-rich animal manure is used as a fertiliser.

Thus, the fine particle granulate and to a lesser extent the composted fibre fraction is well suited as a supplement to fertiliser use on P-deficient croplands, while the liquid fertiliser is suitable as a supplement on farms with a surplus of P.

6.1.4 Plant availability

Manure contains a combination of inorganic and organic forms of phosphorus. Typically, around 45-70% is inorganic P, of which most is present in the form of orthophosphate which has a high plant availability (Zhang, 2012). The organic P on the other hand, is easily transformed to inorganic P through microbial activity in the soil (Zhang, 2012).

However, little is known on the effects of manure processing on the plant availability of the present phosphorus compounds. Although studies indicated that solid-liquid separation does not reduce the phosphorus fertilisation effect, there are indications that reductions in plant availability occur during anaerobic digestion through the precipitation of phosphates, as well as during filtration with external pressure, due to the loss of small particles to which P is bound (Brod, 2018; He, Pagliari, & Waldrip, 2016). In addition, composting has repeatedly been found to significantly decrease the P availability of organic materials such as manure (He et al., 2016).

Thermal processing, through pyrolysis or incineration, was found to clearly reduce the P availability of the processed manure, with a relationship between higher temperatures and greater losses (Brod, 2018). The details of CowPower's drying step were not made public, thus complicating any comparisons with other studies.

Although fertilisation experiments with plants are recommended to determine the plant-availability of the three output products of CowPower, it would also have been interesting to analyse the molecular state of their P compounds in this study. However, this was not included in the chemical analysis of the samples. The presence of inorganic phosphate would also be interesting because of the positive side-effects found in manure of immobilising heavy metals such as lead in contaminated soils, and restoring their microbial activity (He et al., 2016).

Orthophosphate was however analysed in earlier CowPower sampling of the outflow from the anaerobic digestion (Foss Biolab & USN, 2012-2014); in the 10 samples taken, the orthophosphate varied from 9-25 mg/L with an average of 14 mg/L. In comparison, the total P in the corresponding outflow measured for this study was 350 mg/L (Eurofins, 2019). This suggests that only a small share of the P present in this flow, and thus in the fine particle granulate, consists of the highly plant-available orthophosphate.

With regards to nitrogen, the sharp contrast in N:P ratio between the input (6:1) and outputs (resp. 50:1 and 3.3:1) for the filtration process indicates a high solubility of the present N compounds. This fits well with the results: the input N consisted of 61% NO_3^--N and negligible NH_4^+-N, such that the remaining 39% of the total N should consist of N in organic compounds, which typically have a low solubility (Bleken, 2019). Indeed, the N in the particle fraction output consisted of merely 3.6% NO_3^--N and NH_4^+-N, as compared to 62% for the liquid fraction.

Thus, the particle fraction and subsequent fine particle granulate is indicated to contain mainly organic N with a low solubility, and little orthophosphate. Further research regarding the consequences of these results for its fertilisation potential are highly recommended.

6.1.5 Inorganic pollutants

Animal manure can contain heavy metals in relatively high concentrations, for example due to their use as dietary supplements, which can lead to adverse environmental effects in areas with intensive livestock production (Møller, Jensen, Tobiasen, & Hansen, 2007). The application of manure rich in heavy metals can lead to a build-up of their soil concentration. The concentration at which negative effects are observed differ per substance. For example, crops require copper and zinc as nutrients but these substances are harmful in higher concentrations, while lead and zinc are already harmful in small dosages. (Møller et al., 2007)

Accordingly, limit concentrations have been established for the use of organic fertiliser in Norway (Ministry of Agriculture and Food, 2003), on the basis of which a quality class is assigned which determines the quantity that is legal to apply on soils: at Quality Class 0 application up to the crop fertilisation demand is allowed, while at Quality Classes 1 and 2 one can apply respectively 40 and 20 tons of organic fertiliser per hectare (Ministry of Agriculture and Food, 2003).

Figure 12 shows these limits, along with the concentrations of heavy metals found in the manure slurry input (sample 1), the composted fibre fraction (sample 3), and the fine particle granulate (sample 9). The concentration limits were under reconsideration (Haraldsen, Brod, & Øgaard, 2018); for those substances where measured concentrations exceeded the limit for Quality Class 0 and a higher new limit had been proposed, the latter was indicated as well.

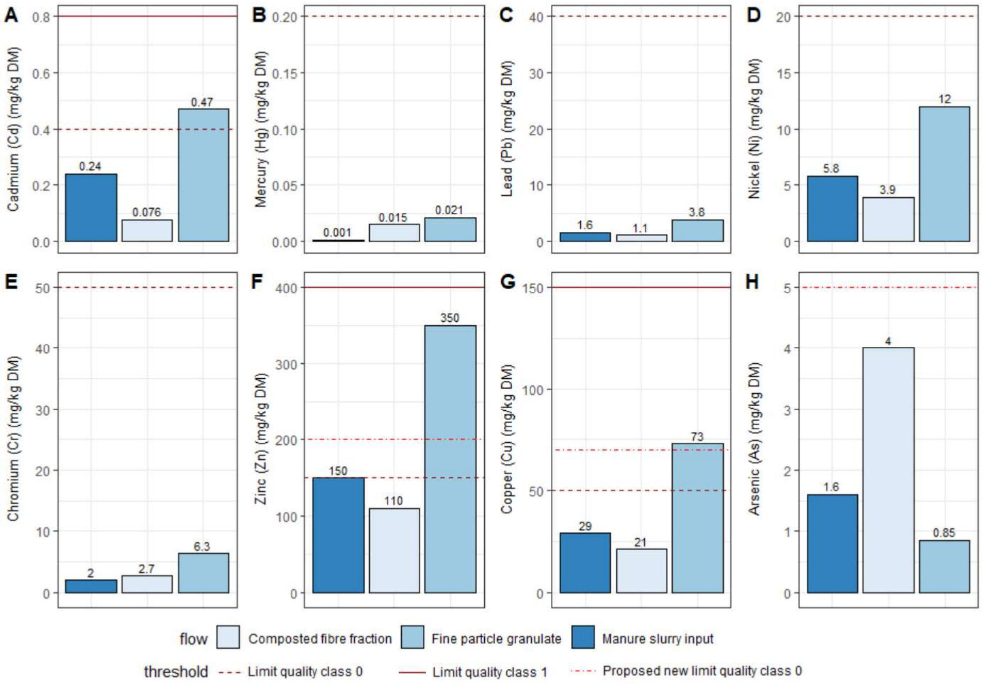

Figure 12. Heavy metal contents and Norwegian limit concentrations for organic fertilisers. Heavy metal contents (mg/kg DM) of the manure slurry input (sample 1), composted fibre fraction (sample 3), and fine particle granulate (sample 9). Limit concentrations for quality classes 0 and 1. Sources: (Ministry of Agriculture and Food, 2003), (Haraldsen et al., 2018).

The results in figure 12 show that the concentrations of Hg, Pb, Ni, and Cr are well below the limits of Quality Class 0, and As, for which no current limit exists, was below the proposed limit. However, the fine particle granulate contained Cd, Zn, and Cu exceeding the limits of Quality Class 0, which has the implication that the product would only be legal to use up to 40 tons/ha. The heavy metal contents in the composted fibre fraction were significantly lower, except for arsenic.

However, such results may appear misleading as the P and N contents of the three flows compared here are very different. Quality Class 0 allows application of the substance up to the crop nutrient requirements. The restriction of 40 tons/ha in Quality Class 1 then implies a reduction in the quantity applied, while the very high P content of the fine particle granulate may mean that significantly less than 40 tons/ha would be required to meet the crop nutrient needs. It can therefore be concluded that the existing framework of limit concentrations are not well suited for highly processed manure products.

The fate of heavy metals through different manure processing techniques is highly variable and has been little studied. Møller et al. (2007) studied the transfer coefficients of DM, P, N, Mg, Cd, Cu, and Zn to the solid fraction via a decanting centrifuge. However, this process does not seem to be comparable to that employed at Foss Gård, with respectively 73% and 32% of P, and 25% and 15% of N being transferred to the solid fraction in Møller et al. (2007) and Foss Gård. The transfer coefficients for the CowPower centrifuging and filtering processes were calculated, i.e. the share of each element being allocated to the solid fraction, and listed in table 15.

Process	Cd	Hg	Pb	Ni	Cr	Zn	Cu	As
Centrifuge	90%	-385%*	78%	78%	56%	76%	77%	19%
Filtering	72%	-180%*	100%	87%	184%*	101%	108%	91%

Table 15. Shares of heavy metal contents assigned to the solid fraction in the centrifuge and filtering process. (*) inconsistencies in values are expected to be due to faulty measurements.

Although the mercury content in the manure slurry input (sample 1) was measured to be merely <0.001 mg/kg DM, both the composted fibre fraction and the fine particle granulate contained concentrations that were an order of magnitude higher. At the calculated DM flows, this would mean that the composted fibre fraction contained >385% of the Hg in the inflow. Thus, this measurement is expected to be faulty. Such outliers emphasise the importance of taking a larger set of samples. Similarly, calculating the transfer coefficients through centrifuging and filtering yielded values over 100% for Cr, Zn, and Cu, but unlike the case of Hg these inconsistencies were small enough to be explained by the uncertainty range of the laboratory analysis (25%).

The concentrations found in the manure slurry (sample 1) are of the same order of magnitude as those found for cattle slurry by Møller et al. (2007), for Zn, Ni, Pb, Cd, As, and Cr. For Hg they found 0.4 mg/kg DM, i.e. two orders of magnitude higher than found in this study, which is another indication that our measurement is off.

In addition, they found a copper concentration of 100 mg/kg DM as opposed to 29 mg/kg DM found in this study (Møller et al., 2007). Copper is commonly used as an additive in hoof baths for dairy cows (Møller et al., 2007); the lower concentration found in our study could indicate alternative practices at Foss Gård perhaps related to its status as organic farm. If that were the case, higher concentrations could be expected on conventional farms, while that in the fine particle granulate was currently already found to exceed the limit of quality class 0. Therefore, we particularly recommend additional analysis of Cu and considerations of its origins.

Finally, although no sample was analysed of the liquid fraction from filtering, which would be further processed into a liquid fertiliser, filtering led to most heavy metals being retained in the solid fraction. Thus, heavy metals are not expected to be an issue for this end product.

In conclusion, the results show that the presence of inorganic pollutants is generally below the thresholds of what is considered safe to apply to crops. The fine particle granulate is an exception to this rule with regards to cadmium, zinc, and copper; however, restricted use of up to 40 tons/ha is not expected to be an issue considering its high concentration of P. The substance should either be applied in low quantities, or combined with another more liquid fertiliser.

Besides inorganic pollutants, it would be important to address the presence of organic pollutants. Pollutants such as pathogens, veterinary medicine, biocides, and antibiotics are possible points of concern (Scholz et al., 2014), and should be examined in further studies.

6.1.6 Further research

Firstly, further research is recommended to fill the knowledge gaps highlighted in the preceding discussion. For example, regarding the energy requirements of CowPower, the plant fertilisation potential of the end-products, in particular the plant-availability of the P compounds, and the presence of organic pollutants.

Secondly, some specific recommendations arise from the scarcity of data points that were available for this study. The mass balance inconsistencies in the results, especially in the nitrogen layer, highlight a need for more than one sample. In addition, analysis of NH_4^+ and NO_3^- should conducted for the relevant flows, in particular in the flows entering and exiting the nitrification reactor. Furthermore, several measurements of dry matter were only available in a g/L format without knowledge of the flow's volume weight, as a result of which the dry matter was calculated based on phosphorus. Improving data availability in these areas would thus greatly improve the accuracy of our findings.

Finally, we recommend the extension of this MFA with a layer on potassium (K), which was not included in this thesis as its laboratory results were delayed.

6.2 Foss Gård

The material flow analysis of the Foss Gård farm was conducted with a high level of process detail, notwithstanding the scarcity of available data. The uncertainties resulting from the inevitable assumptions that have been discussed in Chapter 4 'Uncertainty analysis' are expanded upon in higher detail in this chapter. In addition, the significance of the flows for the overall farm P balance are discussed, with a view to simplifying the system for the upscaling scenario. In particular, we discuss those aspects that set this MFA apart from most literature reviewed, i.e. the distinction between manure excreted indoor and while grazing, dietary composition, and the separate analysis of the young cattle.

6.2.1 Uncertainties

As discussed in Chapter 4.2 'Uncertainty Analysis', the results from the MFA of Foss Gård have a low confidence level. A lack of data through on-site measurements meant that literature values, estimates, and Norwegian average statistics had to be resorted to. Therefore, the specific result quantities presented here should not be regarded as a scientific basis for policy-making.

Nonetheless, it is clear that some flows do not have a large impact on the system as a whole due to their small size, regardless of the uncertainties involved in their calculation. For example, those surrounding crop production, use of sawdust, concentrate consumption by the young cattle, slaughter, and livestock stock increases. Therefore, the main uncertainty with regards to the amount of manure collected is to be found in the feed composition and quantities, together with the outflow of milk and the share of manure that is excreted during grazing. Of these, the flow of milk production has a low uncertainty level, while the others are characterised by a high to a very high uncertainty.

The most important factors to verify or measure in order to improve the reliability of the results are therefore: the P contents of the forage and pasture grass, daily forage consumption rates or its energy content, the share of grazing in the cows' energy requirements met through forage feed, and the forage intake of the young cattle.

In general, the flows related to the young cattle's metabolism are subject to a very high uncertainty. Consumption patterns change rapidly as a young cow grows from a calf into a heifer, such that aggregating these age categories into one process without regarding the age distribution is a significant simplification. It was assumed that each animal reaches adulthood, while in reality calves are often sold or slaughtered at a young age. However, of the studies reviewed for this project, to our knowledge none distinguished between young and adult cattle (see Chapter 2.2 'State-of-the-art: Farm MFAs'). The consumption of forage and concentrate are thus most likely overestimated, but including this distinction may produce more realistic results than ignoring it altogether.

Overestimation of the feed P consumed would be translated to an overestimation of manure P produced in a 1:1 relationship, since the latter was calculated via mass balance. This result is therefore highly uncertain.

The quantity of manure P excreted by a cow is subject to a high variation depending on e.g. diet, milk production, age, and breed (Morse et al., 1992; Nennich et al., 2005; Powell et al., 2002). Comparison of the results with values found in other studies is therefore not very meaningful, especially given the adjusted dietary composition of the dairy cows at Foss Gård in 2017 to lower their milk production.

High variability is characteristic of biological processes, e.g. concerning crop growth and animal metabolism, and thus at the core of any MFA on farms. Variation between individual animals, between breeds, in climatic and geographical (e.g. soil type) conditions, farming practices, and temporal variation in weather conditions are some of the variables that complicate the prediction of internal farms flows, and comparison between cases. For example, Theobald, Schipper, and Kern (2016) found that in their study weather variations caused a 46% change in crop P removal.

To get accurate results despite this variability, primary data from on-site measurements should be used as much as possible, and the study should span multiple years. On the other hand, this requires substantial monetary and time resources and produces results that are not easy to translate to other cases.

Finally, another source of variation is found in the system definition. There are some known processes that have been omitted from the system, i.e. the loss of P to surface- or groundwater through runoff and leaching, and losses of feed during storage and feeding, as these were expected to be small and an estimation of their size would likely be inaccurate. In addition, there could be processes that were unknowingly omitted from the system. Especially the manure P excretion flow would be vulnerable to flaws in the system definition, as since it was calculated via mass balance it could be directly affected.

6.2.2 Soil P balances

The results show that there is a small soil P reduction when subtracting the plant P uptake from the total manure returned to the soils. However, given the uncertainty around the quantity of collected manure P, no conclusions can be drawn from this – in reality there could well be a surplus. Nevertheless, the results indicate that a use can be found for all manure on the farm, such that there seems to be no incentive for export of phosphorus with or without the use of CowPower.

However, the spatial aspect of the farm has not been taken into account, and it is still possible that a share of the cultivated land is at a prohibitive distance from the area where the livestock is held. If this is the case, CowPower could still be of benefit.

In addition, even when distance is not an obstacle, processing through anaerobic digestion and nitrification may still be beneficial from an environmental point of view, e.g. by reducing emissions and producing biogas.

6.2.3 Manure on the pastures

The amount of manure that is deposited on the pasture while grazing was estimated and the underlying assumptions caused it to have a very high uncertainty level (see table 11). In particular, the time spent indoors for milking and additional feeding during the weeks where the cows are grazing is uncertain. In addition, the manure P content was low at 0.57% (adult and young combined), as compared to 0.71% at Foss Gård in 2019 (Eurofins, 2019). This may be explained by the low share of concentrate in the feed in 2017, which had nearly double the P concentration of forage feed, as lower dietary P concentrations have been found to result in lower absolute P excretions (Morse et al., 1992; Powell et al., 2002).

According to our results, 190 kg of P is deposited on the pastures through manure excreted while grazing, which is 17% of the herd's total manure production. This concurs with the 19% share found by Smit et al. (2015). The results also indicate that the resulting fertilisation of the pasture could be resulting in a depletion of soil P stocks. However, this is likely due to the low P content of the manure in 2017.

Interestingly, as Foss Gård is an organic farm, the cattle spent 16 weeks on the pasture, while the general requirement for Norwegian cows is merely 8 weeks of grazing. As this is a 50% reduction, one could still expect a need for additional fertilisation of pastureland for conventional farms. In any case, we can conclude that the P thus deposited should not be considered for export from the farms as its fertilisation effects are likely necessary.

6.2.4 Diet and milk

The variables of dietary composition, milk production, and manure P excretion are strongly related. In our results, the composition of the feed was found to have a strong impact on the manure P excreted. The P content of the feed sources differed, with concentrate feed being much more nutrient-rich than the forage feed. Therefore, the share of concentrate feed in a cow's diet is a major driver for P excretion. In the case of Foss Gård in 2017, this share was very low; the adult cows were fed 2.8 kg DM concentrate per day, as compared to 6.0 kg DM for the average Norwegian cow.

Powell et al. (2002) found an increase in the quantity of P excreted through faeces with increasing P in the diet, from 52 g per day at 0.35% dietary P to 96 g per day at 0.55% dietary P. In our model, the dietary P was low at 0.35%, yet the adult cattle was found to excrete merely 38 g P in manure per day. Morse et al. (1992) found a similar relationship between diet and P excretion; in this study the manure of cows on a low 0.3% P diet contained 32-52 g P per day, thus corresponding better with the results for Foss Gård. However, the total excretion of P, through both milk and manure, was found to vary from 83-100% of the dietary intake; this suggested that the cows on a low P diet were lacking P to an extent where they conserved it to build up a stock (Morse et al., 1992). In contrast, our assumption was that the P excretion equalled the P intake, which thus may not have been accurate in the case of Foss Gård because of the remarkably low dietary P levels. In reality, the manure P flow may therefore have been smaller, as well as the concentration of P in the milk.

Indeed, the milk production at Foss Gård was below average, at 6.1 ton energy-corrected milk (ECM) per year-cow as compared to 8.1 ton ECM per year-cow on average in Norway in 2017. This was intentional: the stock at Foss Gård was grown in 2017 to have a larger milk-producing capacity by the next year, and given a limited quota on milk delivery to dairy it was desirable to suppress milk production, hence the small quantities of concentrate (Sommerseth, 2019).

On the other hand, the quantity of forage feed consumed is relatively stable compared to the concentrate, as the former is related to the needs and capacity of the cows' digestive system (Sommerseth, 2019). This variable is therefore of lesser importance in predicting the manure production at a specific farm.

To conclude, in a case like Foss Gård where manure is the only source of fertiliser, all forage is homegrown, and the production of other crops is small, the P surplus on a farm seems to be largely determined by the two factors concentrate P consumption and milk P production. However, these factors mutually influence each other, with e.g. concentrate feed affecting both the total P output of manure and milk, as well as their concentrations.

6.2.5 Population dynamics

Another aspect in which the MFA of Foss Gård distinguished itself from the established literature, was the consideration of a separate young cattle stock, along with flow interactions between the adult and young.

The herd of Foss Gård grew in size in 2017, with an increase in dairy cows of 16% and in young cattle of 33% between April and December. Although this stock growth was significant, these flows are nearly insignificant when compared to the cumulative in- and outflows of the cows' daily metabolism. It follows that for any farm not experiencing a strong stock change, this flow may be considered insignificant for the purpose of estimating P flows.

More complex is the differentiation between the adult dairy cows and the young cattle stock, and the interactions between them. Our model estimated the flows between these stocks through calving or heifers starting their first lactation period. However, once more these flows were found to be small compared to the flows related to cow's daily metabolism, notwithstanding the fact that they were larger than usual due to the stock growth.

The distinction between dairy cows and young stock was of importance. The two groups were fed significantly different diets, with the young stock receiving very little concentrate, and a significant amount of milk. In addition, milk production accounted for a large share of the dairy cows' P excretion, and slaughter of young cattle was more substantial.

The assumption of an average age distribution for the young cattle is an oversimplification that likely resulted in an overestimation of their feed consumption and manure production. The short lifetime of many calves would skew the age distribution towards a younger age, and thus decrease the consumption of concentrate and forage. Thus, the distinction between the two groups of cattle is likely to be even more significant than shown by our results.

Interestingly, this distinction was not made in the other dairy farm SFAs we reviewed (see Chapter 2.2 'State-of-the-art: Farm MFAs'). It was unclear in what manner this distinction was then managed. Possibly, the flows were based on total consumption and production data through measurements on-site. If all cattle were considered adults, those studies may have made significant overestimations of the manure excretion and feed consumption (concentrate in particular). On the other hand, it is possible that the young were neglected altogether (underestimation). In any case, our results stress the importance of distinguishing between the age groups, albeit through estimates based on average feed consumption data.

6.2.6 Significance of flows

This MFA included a high process detail, which was made possible by personal interaction with actors directly involved in the farm management. However, this is more difficult in cases where the study subject comprises a large number of farms. While certain data was found to be publicly available, such as slaughter and milk data, some flows would have to rely on many assumptions in order to be quantified on such a scale. It is therefore worth assessing whether these flows have a significant impact on the system.

The results showed that for the case of Foss Gård the flows of sawdust for bedding, stock changes, and the population dynamics between the adult and young stock did not have a significantly affect the manure flows on the farm. There is no reason to expect these flows to be much larger for an average farm; especially considering the relatively strong stock change that Foss Gård experienced in 2017, while total stocks are likely to be more stable when a large number of farms is assessed. Therefore, unless robust data is available to quantify these flows, we conclude that they are not relevant to include.

Crop production did not have a large impact on the system either, but could carry much more importance on other farms. For our upscaling scenario an approach was taken where crop production was excluded from the system, and the source of concentrate feed left unspecified under the assumption that the vast majority of crops in Norway is consumed by animals in the form of concentrate feed.

Finally, from what has been discussed in previous sections, we concluded that the distinction between young and adult cattle, dietary composition, and the effects of grazing on manure collection, are important parameters with regards to manure flows. The inclusion of these flows, albeit based on uncertain assumptions, would improve manure collection estimates more than leaving them out altogether.

6.3 Upscaling scenario

The results from the upscaling scenario give insight into the quantity of manure that may be available for processing through CowPower. To recapitulate, the system covers all livestock, i.e. for dairy and meat production, in Norway in 2017, as well as all forage production, which is fertilised using manure according to P uptake. Production of other crops, and the use of mineral fertiliser, were not explicitly included in the system, but are implicit in the consumption of concentrate feed, the origins of which were left unspecified. All manure P that was not required for forage production was processed through CowPower (see Chapter 5.1 'CowPower results').

In this section, the results from the scenario are discussed, starting with an assessment of the uncertainties concerning the assumptions. Subsequently, the results are compared with those of two highly relevant articles with regards to Norway's phosphorus management challenges: the national assessment of phosphorus flows in Norway by Hamilton et al. (2017), followed by the multi-regional assessment of soil phosphorus balances in Norway by Hanserud et al. (2016). Finally, conclusions are drawn on the implications of our findings for the potential role of CowPower in closing the phosphorus loop in Norway.

6.3.1 Uncertainties

The upscaling scenario was based on a number of assumptions (see Chapter 3.3 'Methodology Upscaling Scenario'), which affect the resulting estimate of the manure available for processing through CowPower.

Firstly, the total number of cows and young cattle in Norway in 2017 were obtained from statistics and were both regarded as year-cows, which is to say that they lived the full year; in reality, the data represented the number of heads as per March 1st. For the adult cattle this should not have major consequences, since no significant stock variation within the year is expected. However, for the young cattle this may result in an overestimation, because many calves are slaughtered at a young age and seasonal variations in stock are therefore well possible. In addition, as the feed consumption of the young increases with their age, the daily feed rations per unit of young cattle would be lower when not all animals reach adulthood, thus contributing to any overestimation. On the other hand, because young cattle consume very little concentrate feed, their overestimation would result in lower forage consumption and lower manure production in somewhat equal proportions. Thus, this would only affect the total manure P production by livestock, but not the surplus.

Secondly, the diet of the cattle was based on the rations recommended by the Nordic feed evaluation tool (n.d.) for 'average' cattle. However, this does not necessarily coincide with the real average of Norwegian cows, and the reality could be significantly different. The case of Foss Gård can serve as an example, with its dairy cattle obtaining less than a third of their P intake through concentrate, as opposed to our assumed average cattle, for which it accounts for nearly half of the intake. Furthermore, the 'average' diet rations used were designed for dairy cattle, while cattle for meat production is also included in this scenario. Their feeding regime may be different, as well as their grazing patterns.

Finally, there are uncertainties related to our assumptions on forage production. Multiple experts confirmed that it is common practice for farmers in Norway to produce sufficient forage feed to sustain their cattle (Bleken, 2019; Sommerseth, 2019; Vasdal, 2019), and that deviations from this rule are rare. However, we are less confident in our assumption that manure is effectively used as a fertiliser for this production, without the use of mineral fertiliser. This assumption would be intuitive, as farmers are required to own land areas proportional to their number of cattle in order to limit the concentrations with which manure is applied. However, in reality it is possible that factors such as transport distance between forage plots discourage manure application, so that mineral fertiliser is used in addition.

6.3.2 Comparison with Hamilton et al. (2017)

Hamilton et al. (2017) analysed the P flows in Norway for 2009-2011, including those surrounding plant production and animal husbandry, and concluded that animal manure was the most promising source of secondary P fertiliser. In this section, our scenario results for the national P flows within dairy production are compared to this study.

The estimated total manure production by all livestock in Norway was 9 kt P based on our upscaling scenario. In comparison, Hamilton et al. (2017) estimated the total manure production of all husbandry in Norway in 2009-2011 to be 11.4 kt P, i.e. including other animals than cattle. Between the two time periods, the number of cattle remained fairly constant, with a 0.3% decrease in total livestock between 2009-2011 and 2017 (Statistics Norway, 2017c), thus not explaining the higher estimate by Hamilton et al. (2017). However, besides 865 thousand cattle, in 2017 Norway housed 27 thousand horses, 1.1 million sheep, 34 thousand goats, 1.7 million pigs, and 70 million chickens (Statistics Norway, 2017c).

A rough estimation of the share of cattle in the total manure production was made using data on average P excretion for different animals in the Netherlands in 2008 by Statistics Netherlands (2012). This resulted in an estimated total production of 22 kt P, of which cattle contributed 43% (figure 13; for method see Appendix D). Thus, while our results for cattle manure resembled the value obtained by Hamilton et al. (2017) for all husbandry, this rough estimate indicates that in reality there should be a large difference between the two. Therefore, based on our results we expect the total husbandry P excretion through manure to be significantly higher than 11.4 kt P, although it could also be explained in part by an overestimation of the livestock's excretion.

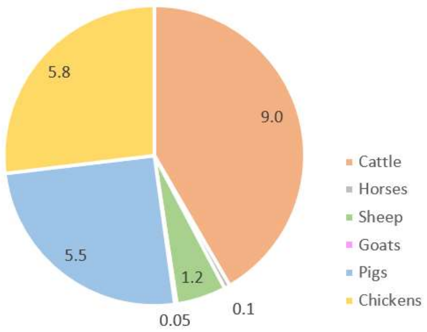

Figure 13. Estimate for manure production (kt P) per type of husbandry in Norway in 2017. Sources: (Statistics Netherlands, 2012; Statistics Norway, 2017c)

Of the total manure production, we estimated that 5% (0.5 kt P) is excreted on the pasture, thus leaving 8.5 kt collectable P. Of this, 7.2 kt P was modelled to be used as fertiliser for forage production, which was assumed to be homegrown. Hamilton et al. (2017) found a total plant uptake of 10.1 kt P for all husbandry, encompassing both the national production of forage and of concentrate crops. In addition, they found that Norway imported 4.4 kt P of imported husbandry feedstuff. Thus, the animals consumed 15.5 kt P, while our scenario predicted a consumption by cattle of 11.3 kt P, of which 4.1 kt P from concentrate feed. Finally, we predicted a total output of meat and dairy products of 2.8 kt P, as compared to 4.8 kt P of total husbandry products by Hamilton et al. (2017).

Thus, our model for the Norwegian dairy farms predicted flows for feed consumption and manure production that were 70-90% of those predicted by Hamilton et al. (2017) for all Norwegian husbandry types. It seems unlikely that cattle accounted for such a large share of these flows, when taking into account the large numbers of pigs and chickens in Norway. Thus, this either indicates that our results overestimate the manure P produced by dairy cattle, or that the total manure P production is higher than previously estimated, or a combination of the two.

6.3.3 Comparison with Hanserud et al. (2016)

Hanserud et al. (2016) performed a multiregional soil P balance for Norway in 2009-2011, and found a surplus of annual P application for each of its counties. In total, they found a surplus of 8.5 kt P applied to agricultural soils, of which 1.5 kt remained after subtracting the use of mineral fertiliser.

In comparison, our scenario (for cattle only) showed that after accounting for the P requirements of the forage feed and grazing, only a small share of the manure P (1.3 kt) is left which is not sufficient to meet the demands of concentrate feed (4.1 kt P). A balance without mineral fertiliser would thus come up negative, at -2.8 kt P. This is an intuitive result when considering the outputs of dairy and meat production, such that the phosphorus in the manure production cannot exceed that in the feed intake.

The difference in total P balances can be explained in part by the fact that Hanserud et al. (2016) included inputs of sewage sludge, the deduction of which also results in a negative balance at -0.4 kt P. Thus, our results indicate a larger P deficit without mineral fertiliser from the livestock industry alone, than Hanserud et al. (2016) when including other husbandry and crop production. This indicates that a significant share of the cattle's concentrate feed consumption was imported from abroad, thus lowering the national fertilisation requirements.

In addition, Hanserud et al. (2016) analysed the P balances for each of Norway's counties, which (without mineral fertiliser) ranged from -0.5 to +0.2 kt P, with the exception of Rogaland, where a surplus of 1.1 kt P was found. While our scenario was conducted under the premise of a high forage self-sufficiency, these results indicate that this may not be the case in reality.

To gain insight into the possible causes of these regional differences, we compared for each county the number of cattle, forage production, and grain production (Statistics Norway, 2017a), and P-balance (without mineral fertiliser and sewage sludge) following Hanserud et al. (2016), shown in figure 14. For forage, statistics on hay yields and green fodder and silage were summed, while grains here refer to the sum of wheat, barley, oats, rye and triticale.

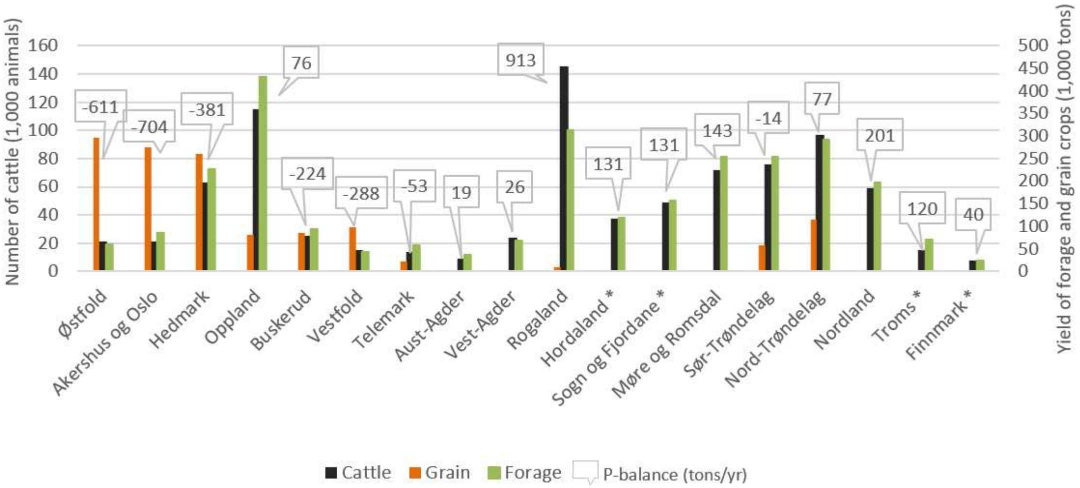

Figure 14. Forage, grain, and cattle in Norwegian counties (2017), and P-balances. Phosphorus balances adapted from Hanserud et al. (2016), excl. mineral fertiliser and sewage sludge. For counties marked with *, data on grain yields was not publicly available. Sources: (Statistics Norway, 2017a), (Hanserud et al., 2016).

Some generalisations can be drawn from this comparison. Firstly, 7 out of the 9 counties with the highest grain production have a negative P-balance, while all other countries have a positive balance. This indicates that the production of grains has a significantly stronger reliance on mineral fertiliser and sewage sludge than the production of forage crops. Secondly, forage production was generally proportional to the number of cattle in a county, with the clear exception of Rogaland which also had a remarkably high surplus of P. Thirdly, the positive P-balances in could be related to the use of fertiliser in spite of available manure P resources. However, as our scenario results show, there may be a surplus due to imports of concentrate feed even when all forage crops are manure-fertilised. Finally, the use of mineral fertiliser was still substantial (5.8-8.2 kg/ha (Hanserud et al., 2016)) in Nordland, Aust- and Vest-Agder, and Møre and Romsdal – counties with negligible crop production besides forage.

This could be a sign of inefficient use of the manure resources available, or of low shares of the P-rich concentrate in the cattle's diet which could lead to a P deficit as in the case of Foss Gård. However, one should keep in mind the modest share of cattle in Norway's total husbandry count; an analysis that includes the manure production from other husbandry types as well as their feed regimen could prove insightful here.

6.3.4 Implications for CowPower

The original motivation for this thesis was to find solutions to the spatial heterogeneity of phosphorus in Norway, in order to utilise the available 11.4 kt P of manure, as found by Hamilton et al. (2017), as a secondary fertiliser. In light of our findings, our understanding of the problem has to some extent shifted the focus toward the need to quantify and optimise local reuse instead of interregional transport. This has implications for the role of CowPower in addressing these issues, which are discussed in this section.

Our results show that on a national basis there was no large surplus of cattle manure P (of which dairy is a share) after accounting for the demands from forage production, i.e. 1.3 kt P surplus from a total production of 9 kt manure P. After processing, this would correspond with 0.8 kt P (53 kt wet weight) in the form of the phosphorus-rich and dry fine particle granulate, suitable for transport to P-deficient regions where it could substitute mineral fertiliser.

The scenario instead emphasises the importance of accounting for possible local recycling of the manure through self-sufficiency in forage feed production; according to our scenario, the production of forage feed requires 80% of the total manure P. This self-sufficiency is most likely the case to a large extent already, but reaching the full potential in this regard should be prioritised over interregional transport. It is therefore important to investigate what the barriers to efficient recycling are on a local basis.

The question to what extent distance prevents efficient manure reuse for forage production is important, in order to assess whether this is an issue that CowPower could help overcome. In a survey about forage production among Norwegian farmers, the average number of forage production plots was found to be 14, sometimes with large distances in between (Thuen & Tufte, 2017). Nevertheless, only 18% stated that long driving distances were an obstacle to high yields and quality of the forage, while 61% said this was not an obstacle. However, many of the farmers answered that the distances between the plots had a negative economic effect (Thuen & Tufte, 2017).

In addition, CowPower may be of use in improving the user-friendliness of manure as a fertiliser and increase awareness of its fertilisation potential among farmers. A further investigation into the current barriers would be beneficial so that CowPower can be developed to tailor to such needs.

However, besides exploring the potential for application in short distance use, long distance transport still appears to have a large potential. Firstly, the 1.3 kt P surplus identified in our scenario only represents cattle; substantial manure P quantities should also be available from other husbandry types, in particular from pigs and poultry. The suitability of the CowPower method for these types of manure would therefore be interesting to explore.

In addition, our national estimate for cattle manure production disregards spatial differences and thus severely underestimates the need for interregional transport of phosphorus, since regions with surpluses and deficits cancel each other out. A spatial analysis is therefore recommended, in particular one that takes farm-specific parameters into account. To move from a multiregional analysis to a realistic assessment of the potential for CowPower, inter- but also intra-regionally, it is important to assess surpluses and deficits on a farm-level. For this to be meaningful, knowledge of farm-specific feed rations would be especially important. While data on milk and slaughter production are publicly available, this was found not to be the case for feed data.

7 References

Aguerre, M. J., Wattiaux, M. A., Powell, J. M., Broderick, G. A., & Arndt, C. (2011). Effect of forage-to-concentrate ratio in dairy cow diets on emission of methane, carbon dioxide, and ammonia, lactation performance, and manure excretion. *Journal of Dairy Science, 94*(6), 3081-3093. doi:https://doi.org/10.3168/jds.2010-4011

Aguirre-Villegas, H. A., Larson, R., & Reinemann, D. J. (2014). From waste-to-worth: energy, emissions, and nutrient implications of manure processing pathways. *Biofuels, Bioproducts and Biorefining, 8*(6), 770-793. doi:10.1002/bbb.1496

Antikainen, R., Lemola, R., Nousiainen, J. I., Sokka, L., Esala, M., Huhtanen, P., & Rekolainen, S. (2005). Stocks and flows of nitrogen and phosphorus in the Finnish food production and consumption system. *Agriculture, Ecosystems & Environment, 107*(2), 287-305. doi:https://doi.org/10.1016/j.agee.2004.10.025

Ashley, K., Cordell, D., & Mavinic, D. (2011). A brief history of phosphorus: From the philosopher’s stone to nutrient recovery and reuse. *Chemosphere, 84*(6), 737-746. doi:https://doi.org/10.1016/j.chemosphere.2011.03.001

Bateman, A., van der Horst, D., Boardman, D., Kansal, A., & Carliell-Marquet, C. (2011). Closing the phosphorus loop in England: The spatio-temporal balance of phosphorus capture from manure versus crop demand for fertiliser. *Resources, Conservation and Recycling, 55*(12), 1146-1153. doi:https://doi.org/10.1016/j.resconrec.2011.07.004

Bilstad, T., Madland, M., Espedal, E., & Hanssen, P. H. (1992). Membrane Separation of Raw and Anaerobically Digested Pig Manure. *Water Science and Technology, 25*(10), 19-26. doi:10.2166/wst.1992.0234

Bleken, M. (2019). [Personal communication].

Brod, E. (2018). *Manure-based recycling fertilisers: A literature review of treatment technologies and their effect on phosphorus fertilisation effects* (NIBIO, 4/91/2018). Retrieved from http://hdl.handle.net/11250/2503440

Brunner, P. H., & Rechberger, H. (2004). Practical handbook of material flow analysis. *The International Journal of Life Cycle Assessment, 9*(5), 337-338. doi:10.1007/BF02979426

California Certified Organic Farmers [CCOF]. (2015). *Average Dry Matter Percentages for Various Livestock Feeds*. Retrieved from: https://www.ccof.org/

Chen, M., Chen, J., & Sun, F. (2008). Agricultural phosphorus flow and its environmental impacts in China. *Science of the Total Environment, 405*(1), 140-152. doi:https://doi.org/10.1016/j.scitotenv.2008.06.031

Christensen, M. L., Christensen, K. V., & Sommer, S. G. (2013). Solid–liquid separation of animal slurry *Animal manure recycling* (pp. 105-130): Wiley Online Library.

Cooper, J., & Carliell-Marquet, C. (2013). A substance flow analysis of phosphorus in the UK food production and consumption system. *Resources, Conservation and Recycling, 74*, 82-100. doi:https://doi.org/10.1016/j.resconrec.2013.03.001

Cordell, D., Drangert, J.-O., & White, S. (2009). The story of phosphorus: Global food security and food for thought. *Global Environmental Change, 19*(2), 292-305. doi:https://doi.org/10.1016/j.gloenvcha.2008.10.009

Data Norge. (2017). Leveranser til kornkjøper eller såvareforretning i landbruket i kornåret juli 2017 til juni 2018. [Deliveries to grain purchaser or sawmill in agriculture in the grain year July 2017 to June 2018.]. https://data.norge.no/data/landbruksdirektoratet/

Data Norge. (2019). Husdyrregisteret - data om registrerte storfeindivider [Livestock register - data on registered cattle individuals]. https://data.norge.no/data/mattilsynet/

De Vries, J. W., Groenestein, C. M., & De Boer, I. J. M. (2012). Environmental consequences of processing manure to produce mineral fertilizer and bio-energy. *Journal of Environmental Management, 102*, 173-183. doi:https://doi.org/10.1016/j.jenvman.2012.02.032

Edmeades, D. C. (2003). The long-term effects of manures and fertilisers on soil productivity and quality: a review. *Nutrient Cycling in Agroecosystems, 66*(2), 165-180. doi:10.1023/a:1023999816690

Eurofins Environment Testing Norway AS (Moss) [Eurofins]. (2019). *Analyserapport MIND-P, p.nr. 10632. Analysis by Eurofins.*

Felleskjøpet. (2017). Kjøpshistorikk Kraftfôr K. G. Vasdal.

Firmansyah, I., Spiller, M., de Ruijter, F. J., Carsjens, G. J., & Zeeman, G. (2017). Assessment of nitrogen and phosphorus flows in agricultural and urban systems in a small island under limited data availability. *Science of the Total Environment, 574*, 1521-1532. doi:https://doi.org/10.1016/j.scitotenv.2016.08.159

Foged, H. L., Flotats, X., Blasi, A. B., Palatsi, J., Magri, A., & Schelde, K. M. (2011). *Inventory of manure processing activities in Europe. Technical Report No. I concerning "Manure Processing Activities in Europe" to the European Commission, Directorate-General Environment. Project reference: ENV.B.1/ETU/2010/0007.* Retrieved from https://upcommons.upc.edu/handle/2117/18943

Foss Biolab, & USN. (2012-2014). *Analyses for Foss Biolab. Anaerobic digestion reactor ADR2 and nitrification reactor NR.*

Gourley, C. J. P., Dougherty, W. J., Weaver, D. M., Aarons, S. R., Awty, I. M., Gibson, D. M., . . . Peverill, K. I. (2012). Farm-scale nitrogen, phosphorus, potassium and sulfur balances and use efficiencies on Australian dairy farms. *Animal Production Science, 52*(10), 929-944. doi:https://doi.org/10.1071/AN11337

Grainger, C., & Beauchemin, K. A. (2011). Can enteric methane emissions from ruminants be lowered without lowering their production? *Animal Feed Science and Technology, 166-167*, 308-320. doi:https://doi.org/10.1016/j.anifeedsci.2011.04.021

Gustafson, G. M., Salomon, E., Jonsson, S., & Steineck, S. (2003). Fluxes of K, P, and Zn in a conventional and an organic dairy farming system through feed, animals, manure, and urine—a case study at Öjebyn, Sweden. *European Journal of Agronomy, 20*(1), 89-99. doi:https://doi.org/10.1016/S1161-0301(03)00077-7

Hamilton, H. A., Brod, E., Hanserud, O., Müller, D. B., Brattebø, H., & Haraldsen, T. K. (2017). Recycling potential of secondary phosphorus resources as assessed by integrating substance flow analysis and plant-availability. *Science of the Total Environment, 575*, 1546-1555. doi:https://doi.org/10.1016/j.scitotenv.2016.10.056

Hamilton, H. A., Brod, E., Hanserud, O. S., Gracey, E. O., Vestrum, M. I., Bøen, A., . . . Brattebø, H. (2016). Investigating Cross-Sectoral Synergies through Integrated Aquaculture, Fisheries, and Agriculture Phosphorus Assessments: A Case Study of Norway. *Journal of Industrial Ecology, 20*(4), 867-881. doi:10.1111/jiec.12324

Hanserud, O. S., Brod, E., Øgaard, A. F., Müller, D. B., & Brattebø, H. (2016). A multi-regional soil phosphorus balance for exploring secondary fertilizer potential: the case of Norway. *Nutrient Cycling in Agroecosystems, 104*(3), 307-320. doi:10.1007/s10705-015-9721-6

Hanserud, O. S., Lyng, K.-A., Vries, J. W. D., Øgaard, A. F., & Brattebø, H. (2017). Redistributing Phosphorus in Animal Manure from a Livestock-Intensive Region to an Arable Region: Exploration of Environmental Consequences. *Sustainability, 9*(4). doi:10.3390/su9040595

Haraldsen, T. K., Brod, E., & Øgaard, A. F. (2018). *Kvalitetskriterier og merkekrav for organiske avfallsmaterialer. Forslag til endringer i forskrift om gjødselvarer mv. av organisk opphav.* Retrieved from Norsk Institutt for Bioøkomi (NIBIO): http://hdl.handle.net/11250/2575688

Havro, H. L. (2019). Det vanskelege kjøttkuttet. *Nationen.* Retrieved from https://www.nationen.no/motkultur/kommentar/det-vanskelege-kjottkuttet/

He, Z., Pagliari, P. H., & Waldrip, H. M. (2016). Applied and Environmental Chemistry of Animal Manure: A Review. *Pedosphere, 26*(6), 779-816. doi:https://doi.org/10.1016/S1002-0160(15)60087-X

Hind, L. J. (2016). Nå skal norske melkekyr mosjonere Retrieved from https://www.nibio.no/nyheter/norske-melkekyr-skal-ut-p-beite

Hutson, J. L., Pitt, R. E., Koelsch, R. K., Houser, J. B., & Wagenet, R. J. (1998). Improving Dairy Farm Sustainability II: Environmental Losses and Nutrient Flows. *Journal of Production Agriculture, 11*, 233-239. doi:10.2134/jpa1998.0233

Jens Eide AS. (2017). *Annual statement of sales for slaughter by K.G. Vasdal.*

Karlengen, I. J., Svihus, B., Kjos, N. P., & Harstad, O. M. (2012). *Husdyrgjødsel; oppdatering av mengder gjødsel og utskillelse av nitrogen, fosfor og kalium*. Retrieved from Landbruksdirektoratet: https://www.landbruksdirektoratet.no/no/dokumenter/

Kataki, S., West, H., Clarke, M., & Baruah, D. C. (2016). Phosphorus recovery as struvite from farm, municipal and industrial waste: Feedstock suitability, methods and pre-treatments. *Waste Management, 49*, 437-454. doi:https://doi.org/10.1016/j.wasman.2016.01.003

Klinglmair, M., Lemming, C., Jensen, L. S., Rechberger, H., Astrup, T. F., & Scheutz, C. (2015). Phosphorus in Denmark: National and regional anthropogenic flows. *Resources, Conservation and Recycling, 105*, 311-324. doi:https://doi.org/10.1016/j.resconrec.2015.09.019

Kukontrollen. (2017). *Fordeling av dyr i buskapen pr. 10.04.2017 og 31.12.2017 [Cow control: Distribution of animals in the livestock per 10.04.2017 and 31.12.2017]*. .

Kuligowski, K., Poulsen, T. G., Rubæk, G. H., & Sørensen, P. (2010). Plant-availability to barley of phosphorus in ash from thermally treated animal manure in comparison to other manure based materials and commercial fertilizer. *European Journal of Agronomy, 33*(4), 293-303. doi:https://doi.org/10.1016/j.eja.2010.08.003

Landbruksdirektoratet. (2017a). *Leveranser til meieri i landbruket i 2017 [Deliveries to dairy in agriculture in 2017].* Retrieved from: https://data.norge.no/data/landbruksdirektoratet

Landbruksdirektoratet. (2017b). *Leveranser til slakteri i landbruket i 2017 [Deliveries to slaughter in agriculture in 2017].* Retrieved from: https://data.norge.no/data/landbruksdirektoratet

Landbruksdirektoratet. (2017c). *Produksjons- og avløsertilskudd til jordbruksforetak – søknadsomgang 2017 [Production and replacement subsidies for agricultural enterprises - application round 2017].* Retrieved from: https://data.norge.no/data/landbruksdirektoratet

Leytem, A. B., Dungan, R. S., Bjorneberg, D. L., & Koehn, A. C. (2011). Emissions of Ammonia, Methane, Carbon Dioxide, and Nitrous Oxide from Dairy Cattle Housing and Manure Management Systems. *Journal of Environmental Quality, 40*, 1383-1394. doi:10.2134/jeq2009.0515

Li, B., Boiarkina, I., Young, B., & Yu, W. (2015). Substance flow analysis of phosphorus within New Zealand and comparison with other countries. *Science of the Total Environment, 527-528*, 483-492. doi:https://doi.org/10.1016/j.scitotenv.2015.04.060

Linderholm, K., Mattsson, J. E., & Tillman, A.-M. (2012). Phosphorus Flows to and from Swedish Agriculture and Food Chain. *Ambio, 41*(8), 883-893. doi:10.1007/s13280-012-0294-1

Luo, J., Ledgard, S. F., & Lindsey, S. B. (2007). Nitrous oxide emissions from application of urea on New Zealand pasture. *New Zealand Journal of Agricultural Research, 50*(1), 1-11. doi:10.1080/00288230709510277

Lupton, R. C., & Allwood, J. M. (2017). Hybrid Sankey diagrams: Visual analysis of multidimensional data for understanding resource use. *Resources, Conservation and Recycling, 124*, 141-151. doi:https://doi.org/10.1016/j.resconrec.2017.05.002

MacDonald, G. K., Bennett, E. M., Potter, P. A., & Ramankutty, N. (2011). Agronomic phosphorus imbalances across the world's croplands. *Proceedings of the National Academy of Sciences, 108*(7), 3086-3091. doi:10.1073/pnas.1010808108

Masse, L., Massé, D. I., & Pellerin, Y. (2007). The use of membranes for the treatment of manure: a critical literature review. *Biosystems Engineering, 98*(4), 371-380. doi:https://doi.org/10.1016/j.biosystemseng.2007.09.003

Mattilsynet. (2018). *Matvaretabellen.* Retrieved from: https://data.norge.no/data/mattilsynet

Mazeika, R., Staugaitis, G., & Baltrusaitis, J. (2016). Engineered Pelletized Organo-Mineral Fertilizers (OMF) from Poultry Manure, Diammonium Phosphate and Potassium Chloride. *ACS Sustainable Chemistry & Engineering, 4*(4), 2279-2285. doi:10.1021/acssuschemeng.5b01748

Forskrift om gjødselvarer mv. av organisk opphav. [Regulations on fertiliser products etc. of organic origin], FOR-2003-07-04-951-§10 C.F.R. (2003).

Modin-Edman, A.-K., Öborn, I., & Sverdrup, H. (2007). FARMFLOW—A dynamic model for phosphorus mass flow, simulating conventional and organic management of a Swedish dairy farm. *Agricultural Systems, 94*(2), 431-444. doi:https://doi.org/10.1016/j.agsy.2006.11.007

Møller, H. B., Jensen, H. S., Tobiasen, L., & Hansen, M. N. (2007). Heavy Metal and Phosphorus Content of Fractions from Manure Treatment and Incineration. *Environmental Technology, 28*(12), 1403-1418. doi:10.1080/09593332808618900

Mondor, M., Masse, L., Ippersiel, D., Lamarche, F., & Massé, D. I. (2008). Use of electrodialysis and reverse osmosis for the recovery and concentration of ammonia from swine manure. *Bioresource Technology, 99*(15), 7363-7368. doi:https://doi.org/10.1016/j.biortech.2006.12.039

Morrison, S. J., McBride, J., Gordon, A. W., Wylie, A. R. G., & Yan, T. (2017). Methane Emissions from Grazing Holstein-Friesian Heifers at Different Ages Estimated Using the Sulfur Hexafluoride Tracer Technique. *Engineering, 3*(5), 753-759. doi:https://doi.org/10.1016/J.ENG.2017.03.018

Morse, D., Head, H. H., Wilcox, C. J., Van Horn, H. H., Hissem, C. D., & Harris, B. (1992). Effects of Concentration of Dietary Phosphorus on Amount and Route of Excretion1. *Journal of Dairy Science, 75*(11), 3039-3049. doi:https://doi.org/10.3168/jds.S0022-0302(92)78067-9

Mulbry, W., Kondrad, S., Pizarro, C., & Kebede-Westhead, E. (2008). Treatment of dairy manure effluent using freshwater algae: Algal productivity and recovery of manure nutrients using pilot-scale algal turf scrubbers. *Bioresource Technology, 99*(17), 8137-8142. doi:https://doi.org/10.1016/j.biortech.2008.03.073

National Research Council. (2001). *Nutrient Requirements of Dairy Cattle: Seventh Revised Edition*. Retrieved from The National Academies Press: https://doi.org/10.17226/9825

Nennich, T. D., Harrison, J. H., VanWieringen, L. M., Meyer, D., Heinrichs, A. J., Weiss, W. P., . . . Block, E. (2005). Prediction of Manure and Nutrient Excretion from Dairy Cattle. *Journal of Dairy Science, 88*(10), 3721-3733. doi:https://doi.org/10.3168/jds.S0022-0302(05)73058-7

Nordic Feed Evaluation System [NorFor]. (n.d.). Feed contents and rations. Data provided by J.K. Sommerseth.

Oudot, C., Pain, B., & Martinez, J. (2003). *Elements for devising a policy for abating agricultural ammonia emissions in France*.

Penhallegon, R. (2003). *Nitrogen-phosphorus-potassium values of organic fertilizers*. Retrieved from https://extension.oregonstate.edu/

Popovic, O., Hjorth, M., & Stoumann Jensen, L. (2012). Phosphorus, copper and zinc in solid and liquid fractions from full-scale and laboratory-separated pig slurry. *Environmental Technology, 33*(18), 2119-2131. doi:10.1080/09593330.2012.660649

Powell, J. M., Jackson-Smith, D., Satter, L., & Bundy, L. (2002). *Whole-farm phosphorus management on dairy farms.* Paper presented at the Proceedings of the Wisconsin fertilizer aglime and pest management conference'.(Eds KA Kelling, JL Wedberg) pp.

Prabhu, M., & Mutnuri, S. (2014). Cow urine as a potential source for struvite production. *International Journal of Recycling of Organic Waste in Agriculture, 3*(1), 49. doi:10.1007/s40093-014-0049-z

Redden, R. R. (2012). Forages and grazing: Feeding Straw. *North Dakota State University.* Retrieved from https://www.ag.ndsu.edu/drought/forages-and-grazing/feeding-straw

Sandberg, T. (2018, 13th of February). Regjeringen satser på møkk. *Dagsavisen.* Retrieved from https://www.dagsavisen.no/innenriks/regjeringen-satser-pa-mokk-1.1100789

Schiere, J. B., Joshi, A. L., Seetharam, A., Oosting, S. J., Goodchild, A. V., Deinum, B., & Van Keulen, H. (2004). Grain and straw for whole plant value: implications for crop management and genetic improvement strategies. *Experimental Agriculture, 40*(3), 277-294. doi:10.1017/S0014479704001814

Scholz, R. W., Roy, A. H., Brand, F. S., Hellums, D. T., & Ulrich, A. E. (2014). *Sustainable Phosphorus Management - A global transdisciplinary roadmap.* (pp. 299). doi:10.1007/978-94-007-7250-2

Senthilkumar, K., Nesme, T., Mollier, A., & Pellerin, S. (2012). Regional-scale phosphorus flows and budgets within France: The importance of agricultural production systems. *Nutrient Cycling in Agroecosystems, 92*(2), 145-159. doi:10.1007/s10705-011-9478-5

Shen, Y., Ogejo, J. A., & Bowers, K. E. (2011). Abating the Effects of Calcium on Struvite Precipitation in Liquid Dairy Manure. *Transactions of the ASABE, 2011 v.54 no.1*(no. 1), pp. 325-336.

Smit, A. L., van Middelkoop, J. C., van Dijk, W., & van Reuler, H. (2015). A substance flow analysis of phosphorus in the food production, processing and consumption system of the Netherlands. *Nutrient Cycling in Agroecosystems, 103*(1), 1-13. doi:10.1007/s10705-015-9709-2

Smith, V. H. (2003). Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environmental Science and Pollution Research, 10*(2), 126-139. doi:10.1065/espr2002.12.142

Sommer, S. G., Petersen, S. O., Sørensen, P., Poulsen, H. D., & Møller, H. B. (2007). Methane and carbon dioxide emissions and nitrogen turnover during liquid manure storage. *Nutrient Cycling in Agroecosystems, 78*(1), 27-36. doi:10.1007/s10705-006-9072-4

Sommerseth (2019). [Personal communication].

Statistics Netherlands. (2012). *Standardised calculation methods for animal manure and nutrients. Standard data 1990-2008.* Retrieved from: https://www.cbs.nl/-/media/imported/documents/2012/26/2012-c173-pub.pdf

Statistics Norway. (2017a). *04609: Kornavling (1 000 tonn) (F) 2001 – 2017; 05772: Avling i jordbruket, etter ymse jordbruksvekstar (1 000 tonn) (F) 2000 – 2018; 03791: Husdyr per 1. januar, etter husdyrslag (F) 1998 - 2019.* Retrieved from: https://www.ssb.no/en/jord-skog-jakt-og-fiskeri

Statistics Norway. (2017b). *05776: Avling per dekar, etter ymse jordbruksvekstar (kg) 2000 - 2018.*

Statistics Norway. (2017c). *Husdyrhald - Talet på storfe og sau per 1. mars, etter fylke*. Retrieved from: https://www.ssb.no/jord-skog-jakt-og-fiskeri/statistikker/jordhus

Steinshamn, H., Thuen, E., Bleken, M. A., Brenøe, U. T., Ekerholt, G., & Yri, C. (2004). Utilization of nitrogen (N) and phosphorus (P) in an organic dairy farming system in Norway. *Agriculture, Ecosystems & Environment, 104*(3), 509-522. doi:https://doi.org/10.1016/j.agee.2004.01.022

Szögi, A. A., Vanotti, M. B., & Hunt, P. G. (2015). Phosphorus recovery from pig manure solids prior to land application. *Journal of Environmental Management, 157*, 1-7. doi:https://doi.org/10.1016/j.jenvman.2015.04.010

Tamura, S., & Fujie, K. (2014). Material Cycle of Agriculture on Miyakojima Island: Material Flow Analysis for Sugar Cane, Pasturage and Beef Cattle. *Sustainability, 6*(2), 812-835.

ten Hoeve, M., Hutchings, N. J., Peters, G. M., Svanström, M., Jensen, L. S., & Bruun, S. (2014). Life cycle assessment of pig slurry treatment technologies for nutrient redistribution in Denmark. *Journal of Environmental Management, 132*, 60-70. doi:https://doi.org/10.1016/j.jenvman.2013.10.023

Theobald, T. F. H., Schipper, M., & Kern, J. (2016). Phosphorus flows in Berlin-Brandenburg, a regional flow analysis. *Resources, Conservation and Recycling, 112*, 1-14. doi:https://doi.org/10.1016/j.resconrec.2016.04.008

Thörneby, L., Persson, K., & Trägårdh, G. (1999). Treatment of Liquid Effluents from Dairy Cattle and Pigs using Reverse Osmosis. *Journal of Agricultural Engineering Research, 73*(2), 159-170. doi:https://doi.org/10.1006/jaer.1998.0405

Thuen, A. E., & Tufte, T. (2017). Hva mener melkebondene om å dyrke mer og bedre grovfôr? [What do milk farmers think of growing more and better forage?]. *Buskap, 7*.

TINE. (2015). *Kalvebrosjyre*. Retrieved from https://medlem.tine.no/fagprat/oppdrett/kalv/se-den-nye-kalvebrosjyren

TINE. (2017). *Mjølkeproduksjon og laktasjonsopplysninger [Milk production and lactation information]. Access to 2017 data for K.G. Vasdal provided in 2019 by Jon Kristian Sommerseth.*

Uludag-Demirer, S., Demirer, G. N., & Chen, S. (2005). Ammonia removal from anaerobically digested dairy manure by struvite precipitation. *Process Biochemistry, 40*(12), 3667-3674. doi:https://doi.org/10.1016/j.procbio.2005.02.028

Umetsu, K., Kimura, Y., Takahashi, J., Kishimoto, T., Kojima, T., & Young, B. (2005). Methane emission from stored dairy manure slurry and slurry after digestion by methane digester. *Animal Science Journal, 76*(1), 73-79. doi:10.1111/j.1740-0929.2005.00240.x

Van Vuuren, D. P., Bouwman, A. F., & Beusen, A. H. W. (2010). Phosphorus demand for the 1970–2100 period: A scenario analysis of resource depletion. *Global Environmental Change, 20*(3), 428-439. doi:https://doi.org/10.1016/j.gloenvcha.2010.04.004

Vasdal, K. G. (2019). [Personal communication].

Western Dairy Digest. (2005). Manure production estimates.

Wilkie, A. C., & Mulbry, W. W. (2002). Recovery of dairy manure nutrients by benthic freshwater algae. *Bioresource Technology, 84*(1), 81-91. doi:https://doi.org/10.1016/S0960-8524(02)00003-2

Zhang, H. (2012). *Managing phosphorus from animal manure*. Retrieved from Oklahoma Cooperative Extension Service: http://dasnr22.dasnr.okstate.edu/docushare/dsweb/Get/Document-2641/PSS-2249web.pdf

Zhao, Q., Zhang, T., Frear, C., Bowers, K., Harrison, J., & Chen, S. (2010). *Phosphorus recovery technology in conjunction with dairy anaerobic digestion. Washington State University Centre for Sustaining Agriculture and Natural Resources.*

8 Appendices

Appendix A – State-of-the-art: additional information

8.1.1 Struvite precipitation

The removal of P and N from farm wastes, but also industrial and municipal waste, through forced precipitation as struvite ($MgNH_4PO_4 \cdot 6H_2O$) has been studied extensively (Kataki, West, Clarke, & Baruah, 2016). It is technically feasible and besides laboratory and field studies it is being applied on a pilot or commercial scale in a handful of cases around the globe (Kataki et al., 2016).

An overview of studies P recovery through struvite removal was made by Kataki et al. (2016), including several successful cases of struvite recovery from dairy manure (Shen, Ogejo, & Bowers, 2011; Uludag-Demirer, Demirer, & Chen, 2005; Zhao et al., 2010) and cow urine (Prabhu & Mutnuri, 2014). Although the P content of dairy manure is high, only around 63% is available for recovery due to the presence of P in particulate form (Kataki et al., 2016). Pre-treatment to reduce the particulate P is therefore needed, e.g. anaerobic digestion, acid leaching, chelating agents, or microwave treatment (Kataki et al., 2016). An average P recovery efficiency of 75% was found for dairy manure. This was lower than for swine waste (90%), potentially due to the high Ca content of dairy manure.

The P fertilisation effect was found to vary strongly depending on the mineral composition of the output product (Brod, 2018).

8.1.2 Reverse osmosis

Reverse osmosis is a process that can separate nutrients from a liquid fraction. While microfiltration is able to separate P, as it is associated with particles, through reverse osmosis the soluble N and K can also be retained (Masse, Massé, & Pellerin, 2007). The associated ammonia volatilisation and quality of the concentrate output are impacted by the characteristics of the animal feed, a lack of data on which complicates comparisons of studies.

Case studies (e.g. Bilstad, Madland, Espedal, & Hanssen, 1992; De Vries et al., 2012; Mondor, Masse, Ippersiel, Lamarche, & Massé, 2008) typically focused on N recovery, as the technology lends itself well for the production of separate solid P and concentrate N/K output products. These studies highlighted the need to control ammonia volatilisation. Nonetheless, Thörneby, Persson, and Trägårdh (1999) found recovery rates of 98% for P and 93-97% for NH_3, with volume reductions of 60-80%.

8.1.3 Cultivation of algae

Cultivation of freshwater algae on manure effluent has been proposed as a treatment option that recovers nutrients and provides an alternative feed source (Mulbry, Kondrad, Pizarro, & Kebede-Westhead, 2008; Wilkie & Mulbry, 2002). This method could recycle P at 23%

lower land use than through crop uptake (Wilkie & Mulbry, 2002) but was projected to have very high operational costs (Mulbry et al., 2008).

Appendix B – Eurofins chemical analysis report

See subsequent pages.

Eurofins Environment Testing Norway AS (Moss)
F. reg. 965 141 618 MVA
Møllebakken 50
NO-1538 Moss

Tlf: +47 69 00 52 00
miljo@eurofins.no

Norsk Institutt for Bioøkonomi
Frederik A. Dahls vei 20
1432 ÅS
Attn: Anne Falk Øgaard

AR-19-MM-030921-01

EUNOMO-00223821

Prøvemottak: 28.03.2019
Temperatur:
Analyseperiode: 28.03.2019-30.04.2019
Referanse: MIND-P, p.nr. 10632

ANALYSERAPPORT

Merknader prøveserie:

AL-analyser utgår på flere av prøvene da prøvematerialet var for flytende.

Prøvenr.:	**439-2019-03290105**	Prøvetakingsdato:	27.03.2019
Prøvetype:	Slam Flytende gjødsel	Prøvetaker:	Anne Falk Ødegaard
Prøvemerking:	1	Analysestartdato:	28.03.2019

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	**Tørrstoff**					
a)	Total tørrstoff	7.6	%	0.1	10%	EN 12880: 2001-02
a)	Total tørrstoff glødetap	78.8	% TS	0.1	10%	EN 12879 (S3a): 2001-02
	pH målt ved 23 +/- 2°C	8.7		1		Intern metode
*	**Konduktivitet/ledningsevne ved 25°C**					
*	Konduktivitet ved 25°C (målt ved 23 +/- 2°C)	180	mS/m	1	25%	NS-EN ISO 7888
a)	Fosfor (P)	0.71	g/100 g tørrstoff	0.015	25%	EN ISO 11885:2009 / SS 028150 ed. 2
b)	Total nitrogen (mod. Kjeldahl)	39	g/kg tv		20%	EN 13654-1 (mod.), EN 13342
b)	Total nitrogen (mod. Kjeldahl)	3.9	g/100 g tørrstoff	0.1	20%	EN 13654-1 (mod.), EN 13342
b)	Total nitrogen (mod. Kjeldahl)	2.9	kg/m³		20%	EN 13654-1 (mod.), EN 13342
a)	Jern (Fe)	0.16	g/100 g tørrstoff	0.015	25%	ICP-OES
a)	Aluminium (Al)	0.096	g/100 g tørrstoff	0.005	25%	EN ISO 11885:2009 / SS 028150 ed. 2
a)	Kalsium (Ca)	2.0	g/100 g tørrstoff	0.015	25%	EN ISO 11885:2009 / SS 028150 ed. 2
a)	Bor (B)	27	mg/kg TS	5	25%	EN ISO 11885:2009/SS 028311 ed. 1
a)	Mangan (Mn)	240	mg/kg TS	0.3	30%	EN ISO 11885:2009/SS 028311 ed. 1
b)*	**Nitrogen (NO3-N og NH4-N), KCl-løselig**					
b)*	Ammonium-N (NH4-N), KCl-løselig	1.4	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Nitrat-N (NO3-N), KCl-løselig	<0.013	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Nitrogen (NO3-N og NH4-N), KCl-løselig	1.4	g/100 g tørrstoff			Spektroskopi (FIA)
a)	Svovel (S)	0.50	g/100 g tørrstoff	0.002	25%	EN ISO 11885:2009 / SS 028150 ed. 2

Tegnforklaring:

* Ikke omfattet av akkrediteringen LOQ: Kvantifiseringsgrense MU: Måleusikkerhet

<: Mindre enn >: Større enn nd: Ikke påvist. Bakteriologiske resultater angitt som <1,<50 e.l. betyr 'ikke påvist'.

Måleusikkerhet er ikke tatt hensyn til ved vurdering av om resultatet er utenfor grenseverdi/ -området og er angitt med dekningsfaktor k=2.

For mikrobiologiske analyser oppgis konfidensintervallet. Ytterligere opplysninger om måleusikkerhet fås ved henvendelse til laboratoriet.

Rapporten må ikke gjengis, unntatt i sin helhet, uten laboratoriets skriftlige godkjennelse. Resultatene gjelder kun for de(n) undersøkte prøven(e).

a)	**Kadmium (Cd) Premium LOQ**					
a)	Kadmium (Cd)	0.24	mg/kg TS	0.01	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	**Kvikksølv (Hg) Premium LOQ**					
a)	Kvikksølv (Hg)	< 0.001	mg/kg TS	0.001		EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	**Bly (Pb) Premium LOQ**					
a)	Bly (Pb)	1.6	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	Nikkel (Ni)	5.8	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	Krom (Cr)	2.0	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	Sink (Zn)	150	mg/kg TS	2	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	Kobber (Cu)	29	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	**Arsen (As) Premium LOQ**					
a)	Arsen (As)	1.6	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
b)*	Volumvekt	1000	kg/m³	100		Gravimetri

Prøvenr.:	**439-2019-03290106**	Prøvetakingsdato:	27.03.2019
Prøvetype:	Slam Gjødsel	Prøvetaker:	Anne Falk Ødegaard
Prøvemerking:	2	Analysestartdato:	28.03.2019

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Tørrstoff	25.0	%	0.1	5%	EN 12880: 2001-02
a)	Fosfor (P)	5500	mg/kg TS	30	25%	EN ISO 11885:2009/SS 028311 ed. 1
	Total tørrstoff glødetap	88	% TS	0.02		NS 4764
	pH målt ved 23 +/- 2°C	9.3		1		Intern metode
*****	**Konduktivitet/ledningsevne ved 25°C**					
*	Konduktivitet ved 25°C (målt ved 23 +/- 2°C)	120	mS/m	1	25%	NS-EN ISO 7888
b)	Total nitrogen (mod. Kjeldahl)	14	g/kg tv		20%	EN 13654-1 (mod.), EN 13342
b)	Total nitrogen (mod. Kjeldahl)	1.4	g/100 g tørrstoff	0.1	20%	EN 13654-1 (mod.), EN 13342
b)	Total nitrogen (mod. Kjeldahl)	1.8	kg/m³		20%	EN 13654-1 (mod.), EN 13342
b)*	**Nitrogen (NO3-N og NH4-N), KCl-løselig**					
b)*	Ammonium-N (NH4-N), KCl-løselig	0.14	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Nitrat-N (NO3-N), KCl-løselig	0.054	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Nitrogen (NO3-N og NH4-N), KCl-løselig	0.20	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Volumvekt	490	kg/m³	100		Gravimetri

Prøvenr.:	**439-2019-03290107**	Prøvetakingsdato:	27.03.2019
Prøvetype:	Slam Gjødsel	Prøvetaker:	Anne Falk Ødegaard
Prøvemerking:	3	Analysestartdato:	28.03.2019

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	**Tørrstoff**					
a)	Total tørrstoff	24.3	%	0.1	10%	EN 12880: 2001-02
a)	Total tørrstoff glødetap	82.9	% TS	0.1	10%	EN 12879 (S3a): 2001-02
	pH målt ved 23 +/- 2°C	9.0		1		Intern metode
*	**Konduktivitet/ledningsevne ved 25°C**					
*	Konduktivitet ved 25°C (målt ved 23 +/- 2°C)	120	mS/m	1	25%	NS-EN ISO 7888
a)	Fosfor (P)	0.70	g/100 g tørrstoff	0.015	25%	EN ISO 11885:2009 / SS 028150 ed. 2
b)	Total nitrogen (mod. Kjeldahl)	20	g/kg tv		20%	EN 13654-1 (mod.), EN 13342
b)	Total nitrogen (mod. Kjeldahl)	2.0	g/100 g tørrstoff	0.1	20%	EN 13654-1 (mod.), EN 13342
b)	Total nitrogen (mod. Kjeldahl)	2.2	kg/m³		20%	EN 13654-1 (mod.), EN 13342
a)	Jern (Fe)	0.15	g/100 g tørrstoff	0.015	25%	ICP-OES
a)	Aluminium (Al)	0.062	g/100 g tørrstoff	0.005	25%	EN ISO 11885:2009 / SS 028150 ed. 2
a)	Kalsium (Ca)	1.6	g/100 g tørrstoff	0.015	25%	EN ISO 11885:2009 / SS 028150 ed. 2
a)	Bor (B)	26	mg/kg TS	5	25%	EN ISO 11885:2009/SS 028311 ed. 1
a)	Mangan (Mn)	190	mg/kg TS	0.3	30%	EN ISO 11885:2009/SS 028311 ed. 1
b)*	**Nitrogen (NO3-N og NH4-N), KCl-løselig**					
b)*	Ammonium-N (NH4-N), KCl-løselig	0.010	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Nitrat-N (NO3-N), KCl-løselig	0.024	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Nitrogen (NO3-N og NH4-N), KCl-løselig	0.034	g/100 g tørrstoff			Spektroskopi (FIA)
a)	Svovel (S)	0.53	g/100 g tørrstoff	0.002	25%	EN ISO 11885:2009 / SS 028150 ed. 2
a)	**Kadmium (Cd) Premium LOQ**					
a)	Kadmium (Cd)	0.076	mg/kg TS	0.01	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	**Kvikksølv (Hg) Premium LOQ**					
a)	Kvikksølv (Hg)	0.015	mg/kg TS	0.001	20%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	**Bly (Pb) Premium LOQ**					
a)	Bly (Pb)	1.1	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	Nikkel (Ni)	3.9	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	Krom (Cr)	2.7	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	Sink (Zn)	110	mg/kg TS	2	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1

Tegnforklaring:

* Ikke omfattet av akkrediteringen LOQ: Kvantifiseringsgrense MU: Måleusikkerhet

<: Mindre enn >: Større enn nd: Ikke påvist. Bakteriologiske resultater angitt som <1,<50 e.l. betyr 'ikke påvist'.

Måleusikkerhet er ikke tatt hensyn til ved vurdering av om resultatet er utenfor grenseverdi/ -området og er angitt med dekningsfaktor k=2.

For mikrobiologiske analyser oppgis konfidensintervallet. Ytterligere opplysninger om måleusikkerhet fås ved henvendelse til laboratoriet.

Rapporten må ikke gjengis, unntatt i sin helhet, uten laboratoriets skriftlige godkjennelse. Resultatene gjelder kun for de(n) undersøkte prøven(e).

a)	Kobber (Cu)	21	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	**Arsen (As) Premium LOQ**					
a)	Arsen (As)	4.0	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
b)*	Volumvekt	440	kg/m³	100		Gravimetri

Prøvenr.: **439-2019-03290108**
Prøvetype: Slam Flytende gjødsel
Prøvemerking: 4
Prøvetakingsdato: 27.03.2019
Prøvetaker: Anne Falk Ødegaard
Analysestartdato: 28.03.2019

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Tørrstoff	5.1	%	0.1	10%	EN 12880: 2001-02
a)	Fosfor (P)	8500	mg/kg TS	30	25%	EN ISO 11885:2009/SS 028311 ed. 1
	Total tørrstoff glødetap	68	% TS	0.02		NS 4764
	pH målt ved 23 +/- 2°C	8.7		1		Intern metode
*****	**Konduktivitet/ledningsevne ved 25°C**					
*	Konduktivitet ved 25°C (målt ved 23 +/- 2°C)	190	mS/m	1	25%	NS-EN ISO 7888
b)	Total nitrogen (mod. Kjeldahl)	54	g/kg tv		20%	EN 13654-1 (mod.), EN 13342
b)	Total nitrogen (mod. Kjeldahl)	5.4	g/100 g tørrstoff	0.1	20%	EN 13654-1 (mod.), EN 13342
b)	Total nitrogen (mod. Kjeldahl)	2.5	kg/m³		20%	EN 13654-1 (mod.), EN 13342
b)*	**Nitrogen (NO3-N og NH4-N), KCl-løselig**					
b)*	Ammonium-N (NH4-N), KCl-løselig	2.6	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Nitrat-N (NO3-N), KCl-løselig	<0.022	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Nitrogen (NO3-N og NH4-N), KCl-løselig	2.6	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Volumvekt	1000	kg/m³	100		Gravimetri

Tegnforklaring:

* Ikke omfattet av akkrediteringen LOQ: Kvantifiseringsgrense MU: Måleusikkerhet

<: Mindre enn >: Større enn nd: Ikke påvist. Bakteriologiske resultater angitt som <1,<50 e.l. betyr 'ikke påvist'.

Måleusikkerhet er ikke tatt hensyn til ved vurdering av om resultatet er utenfor grenseverdi/ -området og er angitt med dekningsfaktor k=2.

For mikrobiologiske analyser oppgis konfidensintervallet. Ytterligere opplysninger om måleusikkerhet fås ved henvendelse til laboratoriet.

Rapporten må ikke gjengis, unntatt i sin helhet, uten laboratoriets skriftlige godkjennelse. Resultatene gjelder kun for de(n) undersøkte prøven(e).

Prøvenr.:	**439-2019-03290109**	Prøvetakingsdato:	27.03.2019
Prøvetype:	Avløpsvann Flytende gjødsel	Prøvetaker:	Anne Falk Ødegaard
Prøvemerking:	5	Analysestartdato:	28.03.2019

	Analyse	Resultat	Enhet	LOQ	MU	Metode
	Suspendert stoff glødetap	21000	mg/l	1.5		Intern metode
	pH målt ved 23 +/- 2°C	7.7		1		NS-EN ISO 10523
	Suspendert stoff	27000	mg/l	2	20%	Intern metode
*	Total tørrstoff	38000	mg/l	20		NS 4764
	Total Fosfor	350	mg/l	0.003	20%	NS-EN ISO 15681-2
	Total Nitrogen	2000	mg/l	0.01	10%	NS 4743
a)	Aluminium (Al), oppsluttet	51000	µg/l	5	15%	EN ISO 17294-2
a)	Bor (B), oppsluttet	1900	µg/l	5	20%	EN ISO 17294-2
a)	**Jern (Fe), oppsluttet**					
a)	Jern (Fe), oppsluttet ICP-MS	87000	µg/l	2	25%	EN ISO 17294-2
a)	**Mangan (Mn), oppsluttet**					
a)	Mangan (Mn), oppsluttet ICP-MS	17000	µg/l	0.2	15%	EN ISO 17294-2
a)	Svovel (S), oppsluttet	220	mg/l	0.1	20%	EN ISO 11885
a)	Kalium (K), oppsluttet	4900	mg/l	0.1	15%	According NEN EN ISO 17294-2
a)	Kalsium (Ca), oppsluttet	1100	mg/l	0.05	15%	According NEN EN ISO 17294-2

Prøvenr.:	**439-2019-03290110**	Prøvetakingsdato:	27.03.2019
Prøvetype:	Avløpsvann Flytende gjødsel	Prøvetaker:	Anne Falk Ødegaard
Prøvemerking:	6	Analysestartdato:	28.03.2019

	Analyse	Resultat	Enhet	LOQ	MU	Metode
	Suspendert stoff glødetap	21000	mg/l	1.5		Intern metode
	pH målt ved 23 +/- 2°C	7.4		1		NS-EN ISO 10523
	Konduktivitet ved 25°C (målt ved 23 +/- 2°C)	1470	mS/m	0.1	10%	NS-EN ISO 7888
	Suspendert stoff	30000	mg/l	2	20%	Intern metode
*	Total tørrstoff	40000	mg/l	20		NS 4764
	Total Fosfor	330	mg/l	0.003	20%	NS-EN ISO 15681-2
	Total Nitrogen	2000	mg/l	0.01	10%	NS 4743
a)	Aluminium (Al), oppsluttet	54000	µg/l	5	15%	EN ISO 17294-2
a)	Bor (B), oppsluttet	1700	µg/l	5	20%	EN ISO 17294-2
a)	**Jern (Fe), oppsluttet**					
a)	Jern (Fe), oppsluttet ICP-MS	93000	µg/l	2	25%	EN ISO 17294-2
a)	**Mangan (Mn), oppsluttet**					
a)	Mangan (Mn), oppsluttet ICP-MS	14000	µg/l	0.2	15%	EN ISO 17294-2
a)	Svovel (S), oppsluttet	260	mg/l	0.1	20%	EN ISO 11885
a)	Kalium (K), oppsluttet	4500	mg/l	0.1	15%	According NEN EN ISO 17294-2
a)	Kalsium (Ca), oppsluttet	1000	mg/l	0.05	15%	According NEN EN ISO 17294-2

Tegnforklaring:

* Ikke omfattet av akkrediteringen LOQ: Kvantifiseringsgrense MU: Måleusikkerhet

<: Mindre enn >: Større enn nd: Ikke påvist. Bakteriologiske resultater angitt som <1,<50 e.l. betyr 'ikke påvist'.

Måleusikkerhet er ikke tatt hensyn til ved vurdering av om resultatet er utenfor grenseverdi/ -området og er angitt med dekningsfaktor k=2.

For mikrobiologiske analyser oppgis konfidensintervallet. Ytterligere opplysninger om måleusikkerhet fås ved henvendelse til laboratoriet.

Rapporten må ikke gjengis, unntatt i sin helhet, uten laboratoriets skriftlige godkjennelse. Resultatene gjelder kun for de(n) undersøkte prøven(e).

Prøvenr.:	**439-2019-03290111**	Prøvetakingsdato:	27.03.2019
Prøvetype:	Avløpsvann Flytende gjødsel	Prøvetaker:	Anne Falk Ødegaard
Prøvemerking:	7	Analysestartdato:	28.03.2019

	Analyse	Resultat	Enhet	LOQ	MU	Metode
	Suspendert stoff glødetap	300	mg/l	1.5		Intern metode
	pH målt ved 23 +/- 2°C	7.9		1		NS-EN ISO 10523
	Konduktivitet ved 25°C (målt ved 23 +/- 2°C)	2450	mS/m	0.1	10%	NS-EN ISO 7888
	Suspendert stoff	420	mg/l	2	20%	Intern metode
*	Total tørrstoff	22000	mg/l	20		NS 4764
	Total Fosfor	48	mg/l	0.003	20%	NS-EN ISO 15681-2
	Total Nitrogen	2400	mg/l	0.01	10%	NS 4743
a)	Aluminium (Al), oppsluttet	21	µg/l	5	25%	EN ISO 17294-2
a)	Bor (B), oppsluttet	330	µg/l	5	20%	EN ISO 17294-2
a)	**Jern (Fe), oppsluttet**					
a)	Jern (Fe), oppsluttet ICP-MS	250	µg/l	2	25%	EN ISO 17294-2
a)	**Mangan (Mn), oppsluttet**					
a)	Mangan (Mn), oppsluttet ICP-MS	420	µg/l	0.2	15%	EN ISO 17294-2
a)	Svovel (S), oppsluttet	78	mg/l	0.1	20%	EN ISO 11885
a)	Kalium (K), oppsluttet	6100	mg/l	0.1	15%	According NEN EN ISO 17294-2
a)	Kalsium (Ca), oppsluttet	370	mg/l	0.05	15%	According NEN EN ISO 17294-2

Prøvenr.:	**439-2019-03290112**	Prøvetakingsdato:	27.03.2019
Prøvetype:	Slam Gjødsel	Prøvetaker:	Anne Falk Ødegaard
Prøvemerking:	8	Analysestartdato:	28.03.2019

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	Tørrstoff	22.8	%	0.1	5%	EN 12880: 2001-02
a)	Fosfor (P)	13000	mg/kg TS	30	25%	EN ISO 11885:2009/SS 028311 ed. 1
	Total tørrstoff glødetap	76	% TS	0.02		NS 4764
	pH målt ved 23 +/- 2°C	8.5		1		Intern metode
*****	**Konduktivitet/ledningsevne ved 25°C**					
*	Konduktivitet ved 25°C (målt ved 23 +/- 2°C)	86	mS/m	1	25%	NS-EN ISO 7888
b)	Total nitrogen (mod. Kjeldahl)	43	g/kg tv		20%	EN 13654-1 (mod.), EN 13342
b)	Total nitrogen (mod. Kjeldahl)	4.3	g/100 g tørrstoff	0.1	20%	EN 13654-1 (mod.), EN 13342
b)	Total nitrogen (mod. Kjeldahl)	8.5	kg/m³		20%	EN 13654-1 (mod.), EN 13342
b)*	**Nitrogen (NO3-N og NH4-N), KCl-løselig**					
b)*	Ammonium-N (NH4-N), KCl-løselig	0.027	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Nitrat-N (NO3-N), KCl-løselig	0.13	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Nitrogen (NO3-N og NH4-N), KCl-løselig	0.16	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Volumvekt	850	kg/m³	100		Gravimetri

Prøvenr.:	**439-2019-03290113**	Prøvetakingsdato:	27.03.2019
Prøvetype:	Slam Gjødsel	Prøvetaker:	Anne Falk Ødegaard
Prøvemerking:	9	Analysestartdato:	28.03.2019

	Analyse	Resultat	Enhet	LOQ	MU	Metode
a)	**Tørrstoff**					
a)	Total tørrstoff	88.7	%	0.1	10%	EN 12880: 2001-02
a)	Total tørrstoff glødetap	62.6	% TS	0.1	10%	EN 12879 (S3a): 2001-02
	pH målt ved 23 +/- 2°C	9.2		1		Intern metode
*	**Konduktivitet/ledningsevne ved 25°C**					
*	Konduktivitet ved 25°C (målt ved 23 +/- 2°C)	200	mS/m	1	25%	NS-EN ISO 7888
a)	Fosfor (P)	1.5	g/100 g tørrstoff	0.015	25%	EN ISO 11885:2009 / SS 028150 ed. 2
b)	Total nitrogen (mod. Kjeldahl)	39	g/kg tv		20%	EN 13654-1 (mod.), EN 13342
b)	Total nitrogen (mod. Kjeldahl)	3.9	g/100 g tørrstoff	0.1	20%	EN 13654-1 (mod.), EN 13342
b)	Total nitrogen (mod. Kjeldahl)	34	kg/m³		20%	EN 13654-1 (mod.), EN 13342
a)	Jern (Fe)	0.30	g/100 g tørrstoff	0.015	25%	ICP-OES
a)	Aluminium (Al)	0.20	g/100 g tørrstoff	0.005	25%	EN ISO 11885:2009 / SS 028150 ed. 2
a)	Kalsium (Ca)	3.9	g/100 g tørrstoff	0.015	25%	EN ISO 11885:2009 / SS 028150 ed. 2
a)	Bor (B)	65	mg/kg TS	5	25%	EN ISO 11885:2009/SS 028311 ed. 1
a)	Mangan (Mn)	630	mg/kg TS	0.3	30%	EN ISO 11885:2009/SS 028311 ed. 1
b)*	**Nitrogen (NO3-N og NH4-N), KCl-løselig**					
b)*	Ammonium-N (NH4-N), KCl-løselig	0.0098	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Nitrat-N (NO3-N), KCl-løselig	0.055	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Nitrogen (NO3-N og NH4-N), KCl-løselig	0.064	g/100 g tørrstoff			Spektroskopi (FIA)
b)*	Fosfor (P-AL)	0.55	g/100 g tørrstoff	1		SS 028310 + T1
b)*	Kalium (K-AL)	1.5	g/100 g tørrstoff	1		SS 028310 + T1
b)*	Kalsium (Ca-AL)	1.7	g/100 g tørrstoff	2.5		SS 028310 + T1
b)*	Magnesium (Mg-AL)	0.44	g/100 g tørrstoff	1		SS 028310 + T1
b)*	Natrium (Na-AL)	0.13	g/100 g tørrstoff	1		SS 028310 + T1
a)	Svovel (S)	0.85	g/100 g tørrstoff	0.002	25%	EN ISO 11885:2009 / SS 028150 ed. 2
a)	**Kadmium (Cd) Premium LOQ**					
a)	Kadmium (Cd)	0.47	mg/kg TS	0.01	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	**Kvikksølv (Hg) Premium LOQ**					
a)	Kvikksølv (Hg)	0.021	mg/kg TS	0.001	20%	EN ISO 17294-2:2016

						/ SS 028311, ed. 1
a)	**Bly (Pb) Premium LOQ**					
a)	Bly (Pb)	3.8	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	Nikkel (Ni)	12	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	Krom (Cr)	6.3	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	Sink (Zn)	350	mg/kg TS	2	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	Kobber (Cu)	73	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
a)	**Arsen (As) Premium LOQ**					
a)	Arsen (As)	0.85	mg/kg TS	0.5	25%	EN ISO 17294-2:2016 / SS 028311, ed. 1
b)*	Volumvekt	970	kg/m³	100		Gravimetri

Utførende laboratorium/ Underleverandør:

a) Eurofins Environment Sweden AB (Lidköping), Box 887, Sjöhagsg. 3, SE-53119, Lidköping ISO/IEC 17025:2005 SWEDAC 1125,
b)* Eurofins Viljavuuspalvelu (Mikkeli), PL 500, FI-50101, Mikkeli
b) Eurofins Viljavuuspalvelu (Mikkeli), PL 500, FI-50101, Mikkeli SFS EN ISO/IEC 17025:2005 FINAS T096,

Moss 30.04.2019

Kjetil Sjaastad

Kjetil Sjaastad
Kjemitekniker

Appendix C – Derivation of transfer coefficient for CowPower filtering process

Given:
Pin = Pfl + Ppf
Ppf = Kpf * Win * %DMpf * %Ppf
Pfl = %Pfl * DMfl
DMfl = DMin - DMpf
DMpf = Kpf * Win * %DMpf

We can derive:
Pin = %Pfl * (DMin – Kpf * Win * %DMpf) + Kpf * Win * %DMpf * %Ppf
Pin = %Pfl*DMin – %Pfl*Kpf*Win*%DMpf + Kpf*Win*%DMpf*%Ppf
Pin / Kpf = %Pfl*DMin/Kpf – %Pfl*Win*%DMpf + Win*%DMpf*%Ppf
(Pin – %Pfl*DMin) / Kpf = Win*%DMpf*%Ppf – %Pfl*Win*%DMpf
(Pin – %Pfl*DMin) = Kpf * (Win*%DMpf*%Ppf – %Pfl*Win*%DMpf)
Kpf = (Pin – %Pfl*DMin) / (Win*%DMpf*%Ppf – %Pfl*Win*%DMpf)

Thus: $K_{pf} = \frac{P_{in} - \%P_{fl} * DM_{in}}{W_{in} * \%DM_{pf} * (\%P_{pf} - \%P_{fl})} = 0.125$

Appendix D – Estimating manure P production per animal type

Husbandry type	kg P_2O_5 /animal/year	kg P /animal/year	Number of animals Norway 2017	Manure production 2017 (kt P)	Share in manure production
Cattle	47.6 *	10.4 *	865,000	9.0	42%
Horses	22.6	4.9	27,000	0.1	1%
Sheep	4.8	1.0	1,100,000	1.2	5%
Goat	6.4	1.4	34,000	0.0	0%
Pig	14.7	3.2	1,700,000	5.5	25%
Laying hen	0.38	0.1	70,000,000	5.8	27%

Table 16. Estimate for manure P production per animal type in Norway in 2017. Average P excretion values taken from Statistics Netherlands, except for cattle, for which our results (Chapter 5.3 'Upscaling scenario results') were used, i.e. 48 instead of 43 kg P_2O_5. Sources: (Statistics Netherlands, 2012; Statistics Norway, 2017c)

Jennie Marieke Spruit

Potential of livestock manure processing to close the phosphorus loop in Norway: An MFA approach.

NTNU
Norwegian University of
Science and Technology

Industrial Ecology Programme