Master's thesis

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

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Spatial discrepancies in the distribution of animal manure as phosphorus fertilizer in Norway

A multi-level Substance Flow Analysis approach

Master's thesis in Industrial Ecology
Supervisor: Daniel Müller

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ABSTRACT

Many countries rely today on the import of non-renewable phosphate rock as a source of phosphorus (P) for fertilizers used in food production. Secondary fertilizers in the form of organic sources, like animal manure, are at the same time available in quantities that could meet crop fertilization requirements, but spatial discrepancies in the distribution of these resources (among other challenges) makes them an unattractive alternative to primary fertilizers. This spatial segregation needs to be addressed in order to foster the re-distribution of organic P-fertilizer and alleviate the demand for mineral-P. System-based approaches can contribute to a refined understanding of the causes of those spatial discrepancies, by a quantification of the stocks and flows of nutrients at different scales. In this project, Norway was used as a case study to conduct a multi-level Substance Flow Analysis (SFA) of P in the agricultural sector. The use of production statistics from the Norwegian Agriculture Agency (Landbruksdirektoratet), combined with parameters and estimates, enabled to calculate a soil P balance for the 39,652 Norwegian farms that applied to agricultural subsidies in 2018. Integrating these farm P-balances into a Geographic Information System (GIS) enabled to upscale the analysis to municipality and county level through a spatially-explicit model. In a first fictional perspective where it was assumed no trade of fertilizers, productions based on animal husbandry as a main activity experienced a significant fertilization surplus and an accumulation of soil P, while crop-based productions or extensive mixed-farming systems were characterized by a fertilization deficit. This underlines the need for more incentives for the trade of organic resources if an independence from mineral fertilizers is to be achieved. A second perspective with more stringent regulations for the spreading of animal manure (i.e. more agricultural area required per manure animal unit in farms) resulted in a reduced soil P accumulation and more resource available for potential trade, reflecting the importance of regulatory framework for the practical implementation of P redistribution. A third and last perspective, where the fertilization planning in farms followed guidelines from the Norwegian Institute of Bioeconomy Research (NIBIO), led to the smallest soil P accumulation and the largest amount of manure available for export, thereby highlighting the important influence of local fertilization practices on global resource efficiency.

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Acronyms

DM Dry Matter.

DTU Danmarks Tekniske Universitet, the Technical University of Denmark.

FS Fertilization Strategy.

GDE Gjødselsdyrenhet, Manure Animal Unit.

IMTA Integrated Multi-Trophic Aquaculture.

NIBIO Norsk institutt for bioøkonomi, the Norwegian Institute of Bioeconomy Research.

NMBU Norges Miljø- og biovitenskapelige universitet, the Norwegian University of Life Sciences.

NTNU Norges teknisk-naturvitenskapelige universitet, the Norwegian University of Science and Technology.

SFA Substance Flow Analysis.

SSB Statistikk Sentralbyrå, the national statistics institute of Norway.

1 INTRODUCTION

1.1 IMPORTANCE OF PHOSPHORUS

Phosphorus (P) is an essential, non-substitutable ingredient for primary life development. Like nitrogen (N), P is a critical element in organic compounds like nucleic acids involved in genetic coding (DNA, RNA) , adenosine di- or triphosphate (ADP and ATP) that ensure metabolism by providing living cells with energy, and other important enzymes (Smil, 2000).

This makes phosphorus a central element for any living organism. While human beings and animals get access to nutrients through food and feed, the access to phosphorus in lower trophic levels is completely dependent on the P concentration of the soil or the water. The availability of phosphorus for plants is therefore a limiting condition for terrestrial ecosystems development, but also for agricultural activities (production of plants for food, fiber or bio-energy). Although a rapid development of the biofuel industry is expected to accelerate the current need for P in agriculture in the coming decades, it is today food production that drives 90 % of the global phosphorus demand (Cordell et al., 2009), with 80 % being used as fertilizer and 10 % to animal feed and food additives production (Syers et al., 2008).

Unlike other key elements involved in plant development, like carbon (C) or nitrogen (N), the phosphorus cycle is not looped through atmospheric gases fixation on plants (Mahowald et al., 2008), meaning that the uptake of P by plants is directly dependent on the soil's P content. Moreover, even in soils that are not P deficient, a significant fraction of P is not plant-available since chemically bound to calcium carbonate in calcareous soils or aluminium/iron oxides in acid soils (Hamilton et al., 2017; Syers et al., 2008). Phosphorus is therefore often a limiting factor for plant production, illustrating Justus Liebig's "Law of the Minimum", which states that if one of the essential plant nutrients is deficient, plant growth will be poor even when all other essential nutrients are abundant (Brunner, 2010).

1.2 CHARACTERISTICS OF THE P CYCLE

1.2.1 PRINCIPAL SOURCES, FLOWS AND SINKS OF P

The terrestrial phosphorus cycle is mostly a one-way flow, from phosphate rocks weathering as a main natural source, to the accumulation in soil through anthropogenic activities (especially agriculture) and the release in water bodies (lakes, oceans) through erosion and runoff flows (Smil, 2000).

Human activities, especially soil management through agriculture, have considerably altered this cycle (Bouwman et al., 2009; Van Vuuren et al., 2010). Qualitatively, with the progressive shift from a P-recycling society, that systematically used animal manure, human excreta and city waste as valuable fertilizing material, to a steady fade-out of those practices as a combined consequence of phenomena like urbanization, the sanitation revolution or the segregation of food consumption and production (Ashley et al., 2011). Quantitatively as well, through the industrial and chemical revolutions, that enabled both the extraction and treatment of phosphate rocks and thereby accelerated the shift towards an intensive agriculture and the use of mineral fertilizers (Schröder et al., 2011). These changes enabled obvious improvements in terms of food production through boosted yields, and therefore led to an increased human population with a globally more affluent diet. However, they also came with an exponential growth of the anthropogenic mobilization of phosphorus, that already tripled natural P flows in magnitude at the beginning of the 21th century (Smil, 2000).

1.2.2 Depletion of a non-renewable resource

Today, the agricultural sector alone depletes globally around 19 Mt/yr of P from non-renewable phosphate rock for fertilizer production (Schröder et al., 2011). While the demand for this resource is estimated to almost double by 2050 through a global food demand increase and changing diets, the current extraction rates could lead to a depletion of global commercial phosphate reserves in 50-100 years, with a peak in P production expected in 2030 (Cordell et al., 2009). In addition to this global scarcity of the resource, more and more concern is raised by its geographic distribution. Four countries represented 75 % of global phosphate rock production in 2019 – China (45 %), Morocco and Western Sahara (15 %), the United States (10 %) and Russia (5 %) – while 63 % of the current reserves are concentrated in Morocco and Western Sahara alone (USGS, 2020). Regions like Western Europe or India, characterized by a significant demand for phosphate rocks but relying mostly on imports, are facing the threat of supply shortages in case of geopolitical conflicts at medium term, and show therefore a need to reduce their dependency on mineral P fertilizers.

1.2.3 Inefficient utilization

At the same time, the utilization of P fertilizers for agronomic purposes has become very inefficient in many developed countries, that remain net importers of mineral fertilizers although they show a significant potential for the recovery of secondary P sources.

Over-application of fertilizers

The inefficiency of P fertilization regards at first the overall overestimation of the fertilization requirements of crops. Decades of generous application of chemical fertilizers to maintain or increase yields have led to a significant accumulation of phosphorus in the agricultural soils of European and North American countries, implying that current harvest yields could probably be preserved with considerably reduced fertilizer application (Cordell et al., 2009; Van Dijk et al., 2016). This is because P fertilization follows the law of diminishing returns: there is a decoupling between the level of yields and the application of plant-available P above a certain soil P level (Syers et al., 2008).

Disregard of secondary P sources

P fertilization is also inefficient because of a very limited recycling of valuable organic resources. Common secondary P fertilizers include animal manure (Schoumans et al., 2010) and sewage sludge (Krogstad et al., 2005), but Norway has also a significant reservoir of secondary P in fish sludge flows from the aquaculture industry (Hamilton et al., 2016). As illustrated in Figure 1, adapted from the combined findings of Hanserud et al. (2016) and Hamilton et al. (2016), these secondary resources could to a large extent meet the demand for phosphorus fertilizers in the Norwegian agricultural sector (in total P quantity that is).

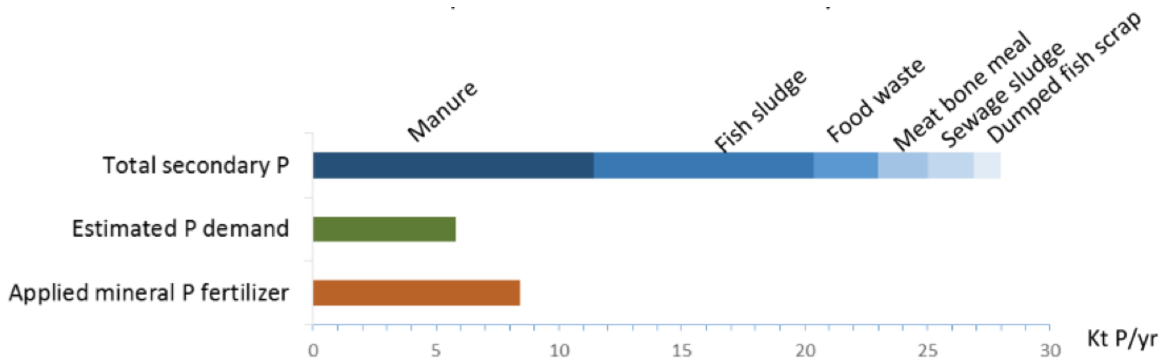


Figure 1: Total secondary P, estimated P fertilization demand and mineral P fertilizer applied in Norway for the period 2009-2011 (Source: MIND-P (2016))

However, critical barriers have been identified that hinder the use of those valuable organic fertilizers.

Quality of secondary P products

Secondary P sources used for food production need to fulfill non-toxicity requirements in order to comply with secondary fertilizer regulations (Forskrift om organisk gjødsel, 2003). Some bio-resources of P, for example collectable fish sludge from land-based fish farms or sewage sludge ash, show high heavy metals content (Cd, Pb, Zn) and therefore need prior treatment before application as fertilizers to avoid soil contamination (Wuana & Okieimen, 2011). Different sources also show different plant-availability, which directly affects the relevance of their use as fertilizers: unlike mineral fertilizers in which phosphorus is present in the form of simple phosphate compounds, manure, fish sludge or food waste P-sources feature a wide range of complex P compounds with various solubility (Brod et al., 2015; Krogstad et al., 2005). The application of secondary fertilizers with poor plant-availability can thus worsen in the long run the accumulation of P in the soil.

Spatial discrepancies in the distribution of the resource

Activities that are identified as net producers of nutrients should ideally be able to export them to activities that show a need for nutrients, to avoid on-site accumulation of said surplus for the former and dependence on mineral fertilizers for the latter. In agriculture, the intensification of the production in developed countries during the 20th century led to a progressive segregation of mixed-farming systems towards separate, intensive arable farming and animal husbandry (Ashley et al., 2011). This results today in a common pattern of regional differences in soil P balance in European countries (including Norway), with livestock-dense areas often prone to a surplus fertilization while crop-based farming areas mostly rely on fertilizers' imports (Bateman et al., 2011; Hanserud et al., 2016; Senthilkumar et al., 2012). A better distribution of the secondary P resources is today economically unattractive, both for 1) farmers with animal-dense productions that lack incentives to export their excess manure over long distances and for 2) farmers with a need for fertilization, that usually minimize the costs with mineral fertilizers (Hanserud et al., 2016). A similar reasoning can be applied to fish sludge in the Norwegian aquaculture industry, with a majority of the resource concentrated along the Atlantic coastline, and to sewage sludge, mostly available in the surroundings of urban human settlements.

Technological gaps

Aforementioned spatial discrepancies in the distribution of nutrients result in significant collection and transportation costs that affect directly the economic competitiveness of recycled fertilizers. A main issue with animal manure as an organic fertilizer regards for example the large weight loads that limit its transportability: technologies already exist for processing the resource and cope with this limitation (Foged et al., 2011; Spruit, 2019), but are not implemented at large scale yet. When it comes to fish sludge, the main issue remains the recovery of valuable resources that often end up taken away by coastal currents. Different solutions are today investigated, like land-based aquaculture infrastructures for facilitated waste collection (Cripps & Bergheim, 2000) or Integrated Multi-Trophic Aquaculture (IMTA), that couples offshore aquaculture systems with the culture of seaweeds in order to absorb nutrients in waste flows (Troell et al., 2009). However, neither of those have reached large scale implementation in Norway yet.

1.2.4 Environmental consequences

The over-application of fertilizers and consequent build-up of soil P levels discussed above are not only a concern for agronomic efficiency. The accumulation of P and N in agricultural soils through excess fertilization leads to increased losses through erosion and runoff, thereby accelerating the release of nutrients in surface waters (Sharpley et al., 1994). The associated increase of P concentration in water bodies (lakes, rivers, wetlands but also coastal marine ecosystems) stimulates eutrophication through excessive growth of algae and cyanobacteria (Smith, 2003), damaging directly local biodiversity due to both oxygen shortages (underwater species) and degradation of the quality of drinking water (terrestrial species).

1.3 Past and current research on the P cycle in agriculture

Increased resource efficiency and sounder management of nutrients used for soil fertilization prove to be crucial for both food security and agronomic efficiency as well as environmental protection. There is a therefore a pressing need for a holistic consideration of the main obstacles that hinder the re-circulation of nutrients. The MIND-P project, for MINeral Phosphorus INDependence, is an example of initiative that aims to address the inefficient management of phosphorus at the national scale of Norway (MIND-P, 2016). It analyzes pathways towards the establishment of a bio-economy based on phosphorus recycling, with the target of reaching a mineral P independence by 2030. Through a collaboration of several research entities (NTNU Industrial Ecology, NIBIO, NTNU Biology, DTU) and an advisory board of relevant stakeholders (among which governmental institutions like the Norwegian Environment Agency - *Miljødirektoratet*, the national statistics institute Statistisk Sentralbyrå (SSB), or industrial businesses like Lerøy Midt or Avfall Norge), the project objectives for the implementation of such a bio-economy are threefold:

- Estimate the Norwegian secondary P supply potential through a system perspective;

- Analyze the cross-sectoral synergies and trade-offs for utilizing this potential;

- Test different strategies and technologies in model simulations and scenarios, developed in close collaboration with key stakeholders.

The cross-sectoral approach based on a system understanding is a key feature of the MIND-P project and of any other bio-economy strategy, without which it is not possible to get a comprehensive picture of the complexity of the cycle of nutrients. In the frame of the present project, that aims to inform such strategies, the focus is set on the agricultural sector, and especially on the problematic spatial discrepancies of secondary P fertilizers within this sector. The following subsections aim therefore to present the research that exists on the circulation of P in the agricultural sector, including peer-reviewed scientific research conducted at different scales as well as other initiatives in the form of farm-level advisory tools.

1.3.1 Substance Flows Analyses of P

Substance Flow Analysis (SFA), defined in Brunner and Rechberger (2004) as the systematic assessment of the flows and stocks of materials/elements within a system defined in space and time, is an excellent tool to conduct a comprehensive evaluation of the P cycle in agricultural systems.

National-level SFAs

Many studies using this methodology were performed at country scale and provide a good basis for policy-making at the national level, which is particularly relevant to address issues linked to food security or international trade. Examples include phosphorus SFAs of Finland (Antikainen et al., 2005), China (Chen et al., 2008), The Netherlands (Smit et al., 2015) and even a study integrating the EU Member States (Van Dijk et al., 2016). The use of a national scale is particularly relevant to identify cross-sectoral opportunities for the recycling of P as fertilizer. Hamilton et al. (2016) developed for instance a national P flow analysis for Norway, including not only the agricultural sector but also fisheries and the aquaculture industries. The authors found that, unlike in many countries in which P is mostly mobilized by agricultural activities, the Norwegian P cycle is influenced on similar levels by both aquaculture and agriculture, the former being even expected to grow five-fold by 2050. Exploiting this growth through cross-sectoral synergies could significantly curb the demand for mineral P in the Norwegian agriculture.

However, a clear downside of SFAs conducted at national level is their lack of spatial disaggregation. By design, merging thousands of nutrient-intensive productions (crop, livestock, salmon farming) into a single system makes it impossible to map geographically the supply or the demand of secondary P, and thereby to identify opportunities for a better distribution of the resource. As discussed by Hamilton et al. (2016), spatial aggregation to country scale probably leads to an overestimation of the P recycling potential, as ignoring regional discrepancies also means neglecting the transport requirements of secondary P and associated technological challenges. Spatially aggregated systems are often characterized by a low resolution on system definition as well. For example, Antikainen et al. (2005) and Hamilton et al. (2016) did not differentiate cultivated area from pasture meant for grazing within their agricultural soil process, and the animal manure was assumed to be entirely returned to this undifferentiated soil without intermediate collection process. There are of course exceptions with higher resolution on the system definition: Chen et al. (2008) and Smit et al. (2015) have developed systems in which a distinction is made between crops and grazing grasslands, and that include an intermediate manure collection process that allows for a selective redistribution of the bio-resource on the two considered agricultural areas. But even with more detailed system definitions, the spatial aggregation necessarily impacts the system quantification through the use of data and parameters taken as national averages, therefore masking regional differences. A good example can be the yields of cultivated areas, that are very dependent on location-specific parameters like climatic conditions or soil types and can therefore considerably differ across regions, especially in a geographical extended country like Norway.

Regional-level SFAs

Other phosphorus SFAs used more disaggregated systems, both in terms of spatial resolution and system definition. Bateman et al. (2011) developed a regionally-explicit SFA of phosphorus in England, through which they could visualize regional P surpluses or deficits of agricultural land after balancing application of local animal manure and total fertilization needs of crops. A similar methodology was used by Senthilkumar et al. (2012) in a case study investigating the soil P budgets of 21 regions in France. The results highlighted a strong influence of the regional agricultural production systems on said budgets: a soil balance in P could only be reached with the use of P fertiliser in crop farming regions, while regions rather characterized by animal farming were prone to steady accumulation of P in their soil. More recently, Hanserud et al. (2016) developed a multi-regional P balance in the Norwegian agricultural soil in order to assess the potential of animal manure and sewage sludge as secondary fertilizer resources. On the national scale, they found that the total P content of Norwegian manure and sewage sludge can more than meet the P fertilizer requirements on Norwegian crops. The spatial-disaggregation at county level enabled the visualization of regional discrepancies, again characterized by larger fertilization surplus and soil P accumulation in areas with high animal density and fertilization deficits in crop (mostly cereals) farming areas. The authors took also into account the past accumulation of P in the soil for one of their fertilization regimes (FR2), for which they corrected the fertilization requirements in function of county-specific soil levels of plant-available P. In the case of those studies, the disaggregation of the system, both spatially and with increased resolution in the definition, provides valuable insights regarding 1) the localization of the supply and the demand of nutrients within a country territory 2) the order of magnitude of the secondary fertilizer potential generation relative to soil fertilization requirements.

Although such county/region-scale models are a good starting point for spatially-explicit SFA and mapping of secondary resource distribution, their resolution does not seem to be fine enough to fully address the aforementioned spatial discrepancies. Hanserud et al. (2016) underline indeed that there are “important insights to be gained from further disaggregating regional data to see how bioresources vary in relative importance on a smaller scale” (Hanserud et al., 2016, p. 318). Higher resolutions enable in theory to reduce the level of uncertainty associated to some crucial model variables (e.g. yields, runoff parameters), provided of course that corresponding data is available. Moreover, going down to the municipality or even farm level appears more policy-relevant in terms of secondary P-redistribution, since the few manure exports that are currently registered happen most of the time between neighbouring farms (technologies for competitive, long-distance transport are not yet widely available). The farm scale even enables to capture and better understand the impact of decisive practices linked to internal flows, like the pasture management or the fertilization strategies, thereby providing a better framework for targeted policy.

A significant amount of scientific articles focused on P balances of individual farms in the last decades. The benefits of tracking nutrients flows at such a fine resolution are numerous.

At first, it often involves an improved disaggregation of the system definition, including for example internal farm flows, which contributes to give a more representative picture of the physical circulation of nutrients. Steinshamn et al. (2004) developed for example a SFA of P and N in a Norwegian organic dairy production, through which they took into account variables as crucial as the differentiation of crops and pasture lands (both for forage production and manure excretion) or the collection and management of manure (including exports). Their results suggested the importance of monitoring such internal flows in order to move towards a sounder nutrient management.

Conducting studies at farm level enables in addition to compare different types of productions and thereby to identify patterns and develop relevant, type-specific indicators. Haygarth et al. (1998) calculated for instance the P budgets of an intensive dairy farm and a sheep farm in the UK, with results underlining the important influence of different animals' diets and metabolisms on the circulation of P in the farm.

In a similar fashion, mapping farm flows allows for comparison of productions delivering the same kind of products but with different characteristics when it comes to the farming intensity (conventional or organic), geographic location, soil type, etc (Gourley et al., 2012; Modin-Edman et al., 2007).

These scientific studies at farm level are however characterized by the use of very diverse methodologies or system definitions, which can sometimes make transverse comparisons quite difficult. For example, some studies take pasture grazing into account (Gourley et al., 2012; Haygarth et al., 1998; Steinshamn et al., 2004) while other do not differentiate agricultural land (Modin-Edman et al., 2007). Moreover, some farm typologies, especially dairy productions, are given more attention than others in the literature, probably because they are characterized by higher nutrient accumulation rates (in $kgP.ha^-1$) and lower nutrient efficiencies (% of nutrients input converted into farm products). Because of said differences in methodologies, targeted typologies, combined to different geographical locations (Gourley et al. (2012) explain that grazing happens year-round in Australia as opposed to seasonal grazing in Europe), research at farm level is by design seldom upscaled.

If an upscaling approach is undertaken, it can come at the cost of the system definition or the calculation method. For example, (Buckley et al., 2015) recently used volume based data from the National Farm Survey (NFS) in the Republic of Ireland in order to derive N and P indicators at the agricultural sector level. The methodology employed is particularly interesting, as it features the use of one central database to derive N and P indicators for more than 70,000 farm systems embedded in the model. The fact that every farm is monitored in a similar fashion enables the upscaling of farm results at national level, and forms a promising starting point for comparison of nationally representative indicators, since the NFS is part of the EU Farm Accountancy Data Network (FADN). But the individual farm P balances are in this study calculated by subtracting the total exports of P (in kg.ha^{-1}) from the total imports, which means that internal flows are not taken into account. Missing data can also lead to the exclusion of processes/farm typologies if the model relies entirely on reported flows (in this study, pig and poultry farms are not included for example).

Finally, farm-level studies are by design less directed towards the implementation of a bio-economy based on the recycling of nutrients than towards an evaluation of environmental risks. Indeed, they are often mapping the farm's nutrient flows in order to derive a build-up of nutrients in the soil and link it to erosion and runoff losses, but it is seldom that they compare manure generation to fertilization requirements of crops in order to visualize a potential surplus. Farms reporting imports or exports of manure fertilizers were for example excluded by Buckley et al. (2015), since no quantitative values were available in the dataset. This probably reflects the fact that water quality monitoring, very dependent on farm-specific practices but also localized parameters related to soil type, soil nutrients levels or erosion/runoff, is by nature bound to high resolution studies. On the contrary, focusing on P recycling by addressing the key barrier of uneven spatial distribution requires a mapping of nutrients hotspots, with a possibility to upscale results at intermediate, more aggregated scales that suit policy-design (for example at municipality level).

1.3.2 Advisory frameworks for the management of nutrients at farm level

Parallel with peer-reviewed scientific publications, a certain number of personalized consultancy tools for nutrients' management have been implemented in the past decades. Often developed as a close collaboration between governmental institutions (e.g. Landbruksdirektoratet in Norway), farming unions (e.g. Norsk Landbruksrådgiving, Bondelaget) and regional municipalities (e.g. Trøndelag Fylkeskommune), these advisory schemes are usually organized around farm visits featuring a direct collaboration with individual farmers, and provide probably the most detailed picture of nutrients' circulation at farm-level.

Examples of such initiatives include the *Greppa Näringen* tool in Sweden (Greppa Näringen, 2011), the Annual Nutrient Cycling Assessment (ANCA) project in the Netherlands (Aarts & De Haan, 2013), that was later exported in Norway under the name of Kretsløpstolken and used by Norsk Landbruksrådgiving (Norsk Landbruksrådgiving, 2017).

These tools usually produce a certain number of relevant indicators, including total manure production, feeding and fertilization efficiencies or soil/farm surpluses in nutrients. In addition, the fact that these models are fed by data retrieved through multiple farm visits, with a guidance generally spanning over years, enables the dynamic tracking of these indicators and the visualization of the farms' evolution over time.

All stakeholders can benefit from such frameworks:

- Farmers can use the advisors' expertise to monitor nutrient management of their own activity, an enhanced involvement that often translates into a minimization of costs and local pollution;

- National or regional institutions, including those involved into water quality management, could get access to very detailed, disaggregated data in form of farm-specific indicators that provide valuable insights for targeted policy-making;

- Industrial processors of farm products (e.g. TINE for dairy production in Norway) could use these analyzes as a sort of environmental label, to guarantee to their consumers that their products come from environmentally sustainable practices.

When it comes to exploring the secondary fertilizer potential in agricultural productions however, these approaches seem limited in several ways. It is worth mentioning first that unlike the aforementioned scientific studies, these advisory tools are not really transparent regarding the methodology that they use (system definition, flows quantification, etc.), which makes any kind of comparison of the results with other approaches difficult. There is also a significant number of farms for which data is missing through those frameworks. Some of these consultancy tools are limited to very specific farm types, like *ANCA* and *Kretsløpstolken* that only cover dairy productions (Aarts & De Haan, 2013; Norsk Landbruksrådgiving, 2017) - *Greppa Näringen* is comparatively more comprehensive as it proposes type-specific advice, covering for example crop farms, pig and cattle productions, but a farmer needs for example to farm more than 50 hectares of land and/or have more than 25 livestock units in order to qualify for the individual farm visits (Greppa Näringen, 2011). Additionally, all farms cannot be covered even within the eligible production types, since the approach is based on volunteering from farmers. This limitation in the number of businesses that benefit from the consultancy makes these advisory tools a questionable basis for an upscaling of nutrient balances. Finally, the follow-up of farm-specific indicators through time is a real advantage of those framework, but is quite labour-intensive requires a considerable amount of farm visits (more than 35,000 for *Greppa Näringen* since 2001).

1.3.3 Synthesis - Research gaps

Phosphorus flows analysis performed at national level provide a good basis for estimating a secondary fertilizers potential generation at country scale, as well as for investigating cross-sectoral synergies that exist to optimize the utilization of valuable waste flows. However, they are probably overestimating said recycling potential because they ignore the spatial discrepancies in the distribution of the supply and demand for these resources. Few economic incentives and technological gaps result today in significant marginal costs that make the transport of organic fertilizers like animal manure or fish sludge economically unattractive. Partial disaggregation of systems through regionally-explicit SFAs enables a first crude visualization of this uneven resource distribution. Regions with high animal densities are often prone to an excess accumulation of P in the soil while regions rather characterized by intensive crop/cereal production would be deficient in soil P if they could not import mineral fertilizers (Hanserud et al., 2016; Senthilkumar et al., 2012). But multi-regional approaches resolve only partially the problematic overestimation of the recycling potential of organic fertilizers, since they do not capture the need for redistribution within their territory (that is between municipalities or farm). It is actually the farm level that seems to be the most policy-relevant, as it enables to capture internal practices that considerably influence both the accumulation of P in the soil and the potential resource recovery (e.g. fertilization strategy, pasture management, manure collection and storage, etc.). Literature already exists for the circulation of nutrients at farm-level, both in the form of peer-reviewed publications and private-public consultancy frameworks that advise farmers on their nutrients management. These high resolution approaches give probably the most realistic picture of the P cycle within farms, but the use of different methodologies coupled to reduced samples of productions in types or absolute number make them hardly upscalable. There is therefore a clear need for a data infrastructure that can not only host this valuable farm level data but also aggregate it to higher scales that suit targeted policy-design (that is municipality, county and national levels).

1.4 Aim and scope of this thesis

This thesis aims to address the issue of spatial discrepancies in the distribution of animal manure as a secondary P fertilizer in Norway, by the means of i) calculating a P balance of the agricultural soil of all Norwegian farms through the development of an integrated, multi-level SFA model, ii) evaluating the consequences of different fertilization practices on the utilization of animal manure as secondary fertilizer, iii) identifying key opportunities and barriers in the agricultural sector that might foster or hinder the implementation of a bio-economy based on P recycling. This should help addressing the following research questions:

1) What are the main characteristics of the P cycle in Norwegian farms of different types? How can a SFA model capture those differences at multiple scales (farm, municipality, county) to provide a refined understanding of the spatial discrepancies in the distribution of secondary P fertilizer? What are the main strengths and weaknesses associated to this approach?

2) How do different fertilization strategies in agricultural productions influence both the stock change of P in the soil and the potential surplus of animal manure available as secondary P fertilizer?

3) How can the system-based framework developed in this project contribute, at different decision levels, to the implementation of a bio-economy based on P recycling? What are the main opportunities and challenges for this approach to better inform policymakers and facilitate the shift towards a sounder management of P?

2 METHODOLOGY

This section presents the methodology that was followed in order to build a multi-level SFA model of P in the Norwegian agriculture, spatially-explicit at the municipality and county level. The subsection 2.1 presents the system that was defined and quantified in order to capture the P cycle of all Norwegian farms, with associated uncertainties. The subsection 2.2 explains how the aforementioned system was digitally implemented in order to calculate results at multiple scales (farms/municipality/county) and visualize them with different tools. The subsection 2.3 sums up the Methodology section and features a schematic representation of the model developed in this project.

2.1 SUBSTANCE FLOW ANALYSIS OF P IN NORWEGIAN FARMS

2.1.1 SYSTEM DEFINITION

SYSTEM BOUNDARIES

It was decided in this project to define a system that captures not only the agricultural soil but also other relevant farming activities, including trade of crop products, animal husbandry and manure storage. In this system, agricultural soil is differentiated between cultivated area, on which crop products are harvested, and non-cultivated area, which are not harvested and are used for grazing only. The system features five internal processes, that are described further: *Crops*, *Farm pasture*, *Storage*, *Animals* and *Manure storage*. Markets for fertilizers, feed/fodder/crop products, for livestock as well as slaughterhouses, dairy processors, egg packaging and wool industry are set outside of the system boundaries and exchange materials with the system through imports and exports flows. A differentiation is made between the seasonal grazing of animals on pasture inside the farm (that is on *Farm pasture*) and outside the farm on uncultivated land (i.e. forests, mountain pastures or coastal terrains). Pasture area outside the farm is external to the system, meaning that the grass grazed on uncultivated land is considered as an import flow of grass to the system while the manure excreted there is considered as an export flow.

PROCESSES AND FLOWS

CROPS

The *Crops* process represents the soil of cultivated area, that is the fields and meadows that are harvested and which soil is ploughed, either to normal depth (*fulldyrket jord* in Norwegian) or in surface (*overflatedyrket jord*), as defined by NIBIO (2017). The different crops included in the *Crops* process, gathered under the categories *Forage crops*, *Cereal/Oilseeds*, *Vegetables/Fruits* and *Other crops* are presented in Table 1. In order to produce plants for both human and animal consumption, those crops are fertilized with either local resources (i.e. housed manure if the farm has animals) or imported fertilizers. Phosphorus exits this process both through the nutrient uptake of harvested crop products and through the losses due to erosion and runoff. Harvest residues, i.e. roots and plant parts that remains on field, are considered to be returned to the soil and therefore do not leave the process as an output. That is at the exception of straw from cereal and oilseeds crops, that can be harvested under certain conditions (see A.2 Straw removal). Atmospheric P deposition was not considered in the study since P, unlike C and N, does not have a stable gaseous phase in the atmosphere (Mahowald et al., 2008).

Table 1: Crop categories included in the *Crops* process

Crop group	Crop category	Crop products
Forage crops	Cultivated pastures	Grass
	Other forage crops	Other green forage
Cereals/Oilseeds	Barley crops	Barley grain, straw
	Oats crops	Oats grain, straw
	Wheat crops	Wheat grain, straw
	Rye crops	Rye grain, straw
	Oilseeds crops	Oilseeds, straw
Vegetables/Fruits	Vegetables fields	Potatoes, carrots, broccoli, etc.
	Greenhouses	Tomatoes, cucumbers, etc.
	Orchards	Apples, pears, plums, cherries, strawberries, etc.
Other crops	Legumes crops	Peas, beans, etc.
	Meadow seeds crops	Meadow seeds

Farm pasture

The *Farm pasture* (*innmarksbeite* in Norwegian) is a process that represents the soil of agricultural area inside the farm that is used only for animal grazing, meaning that its yields (e.g. grass, legumes) are not harvested (NIBIO, 2017). On top of fertilization from local or external resources, the *Farm pasture* receives an additional P input in the form of raw manure dropped by grazing animals. In the system, grazing takes place on *Farm pasture* as a starting point, but grazing animals can also be sent to *Uncultivated land* (*utmarksbeite* in Norwegian) if the farm's resources in pasture grass are not sufficient.

Storage

The *Storage* process acts as an intermediate between cultivated area, the feed/fodder/crop products markets and animals raised on farm, and is composed of six sub-processes: *Forage* (including grass from cultivated pastures stored as hay or silage), *Grains and Oilseeds*, *Vegetables and Fruits*, *Other crop products*, *Bedding* (including straw potentially harvested on cereal and oilseeds crops and sawdust, exclusively imported) and *Concentrate feed* (always imported). This process does not represent a physical reality, since different products like animal bedding and concentrate feed are probably not stored at the same place within a farm. However, it enables to make a clear distinction between trade flows (e.g. exported cereal grains) and farm products used locally (e.g. local grass stored as silage and used as winter forage). Inputs to this process are the harvest of crops' products as well as imports of products that cannot be produced on site, i.e. concentrate feed, animal bedding (if no cereal crops) or forage (if no cultivated pastures). Output flows from this process are the concentrate feed, forage and bedding provided to animals during winter indoors, as well as the exports of harvested crops' products.

ANIMALS

The *Animals* process include all domesticated animals that are registered on the farm. They are gathered into the categories *Cattle*, *Sheep/Goats*, *Pigs*, *Poultry* and *Horses*, which characteristics are detailed in Table 2. Diet flows are the general inputs to this process, including winter diets for the time spent indoors (forage, concentrate feed) and pasture grass for animals grazing in spring and summer. For some specific farms, there is an additional input in the form of animals imported from the Livestock market. A first output from that process is the raw manure excreted by animals, that is either collected in the barn, or dropped on *Farm pasture*/ *Uncultivated land* depending on whether animals graze or not. Other outputs are the export of animals to the livestock market and the exports of animal products including meat, milk, eggs and wool.

Table 2: Animal categories included in the *Animals* process. GDE = *Manure Animal Unit*, 1 GDE is equivalent to the excretion of 14 kg P/yr (Source for the number of animals/GDE: Forskrift om husdyrgjødsel (2002)

Animal group	Grazing	Products	Animal category	Animals/GDE
Cattle	Yes	Meat, milk	Dairy cows	1
			Meat cows	1,5
			Young cattle	3
Sheep/Goats	Yes	Meat, milk, wool	Ewes	7
			Lambs	42
			Dairy goats	7
			Young goats	19
Pigs	No	Meat, animals	Adult sows	2,5
			Young sows	8
			Slaughter pigs	18
			Piglets	50
Poultry	No	Meat, eggs	Layers	80
			Broilers	1400
			Turkeys	240
Horses	Yes	-	-	2

MANURE STORAGE

The *Manure storage* process acts as an intermediate between the collection of bedding and raw manure from animals confined during the winter and the spreading of housed manure on agricultural soil for fertilization purposes. Both *Crops* and *Farm pasture* can receive housed manure as a fertilizer. Depending on the fertilization strategy followed at farm level (see 2.1.2, Fertilization), this process can see a positive stock change, i.e. a surplus of housed manure from a year to another.

An aggregated representation of the described system is presented in Figure 2 below, while a disaggregated version including all sub-processes and sub-flows is presented in Figure 3.

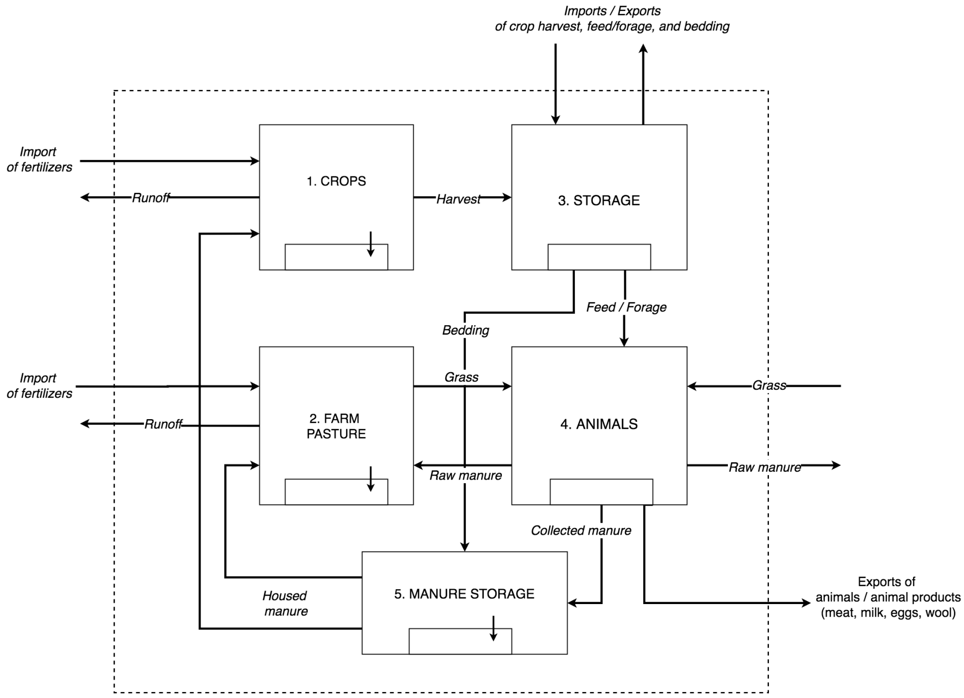


Figure 2: System definition.The dashed line represent the system boundaries. Processes are numbered and represented by boxes, flows by arrows. The inner boxes and associated small vertical arrows represent stocks and stock changes respectively.

INTEGRATION OF A DIVERSITY OF PRODUCTION TYPES

In order to quantify this system and calculate a P balance of agricultural soil for all types of Norwegian farms, there was a need to use a system definition that could capture the significant diversity of agricultural productions in terms of products and/or management.

A first approach that was investigated for that purpose was to derive criteria (or typologies) in order to sort each and every farm into a given category, with a specific system definition for each of those categories. A criterion could have been for instance to classify the farms according to their dominant production (that is crops, dairy, eggs, etc.), like done by Greppa Näringen (2011). A problem that was quickly identified with this approach was that it would have led to an important underestimation of the phosphorus flows for a significant number of farms in the model, especially the ones with mixed production. With this methodology for example, a farm with 7,500 layer spots but also 10 registered cows would probably be considered as an intensive egg production, which system definition would not include any cattle-related process or flow: this would lead in that case to the omission of the annual amount of raw manure produced by 10 cows. Even more problematic: how to account for the variety of combination between the types of animals reared on farm and the types of crops that are grown? There are of course common patterns that have been identified, like in Trøndelag where a considerable number of agricultural productions fall into combinations like *Pigs + Cereal crops*, *Dairy + Meat + Forage crops*, or *Vegetables only* (Forbord, 2020). But how to account in that framework for farmers that run a dairy production and a cereal production?

It is clear that using this typology-based approach would have led to a need for crude assumptions and associated underestimation of P stocks and flows. This is why it was rather decided to adopt an integrated system definition, including a diversity of sub-processes and sub-flows (see Figure 3) in order to be able to capture a maximum number of Norwegian farms while minimizing the aforementioned uncertainty. The aforementioned typology-based approach is taking as a starting point that a farm belongs to one specific category, and cuts all processes/flows that are irrelevant to that production type regardless of the farm's real status. The integrated approach presumes on the contrary that each farm has a versatile production <u>before</u> removing the flows and processes that are in practice not relevant for this farm. This is illustrated below in Figures 4a and 4b, that respectively show how this integrated system definition can be applied both to an intensive slaughter pig production, where animals are confined year-long, and to a sheep farm where animals are grazing on uncultivated land during most of the summer season.

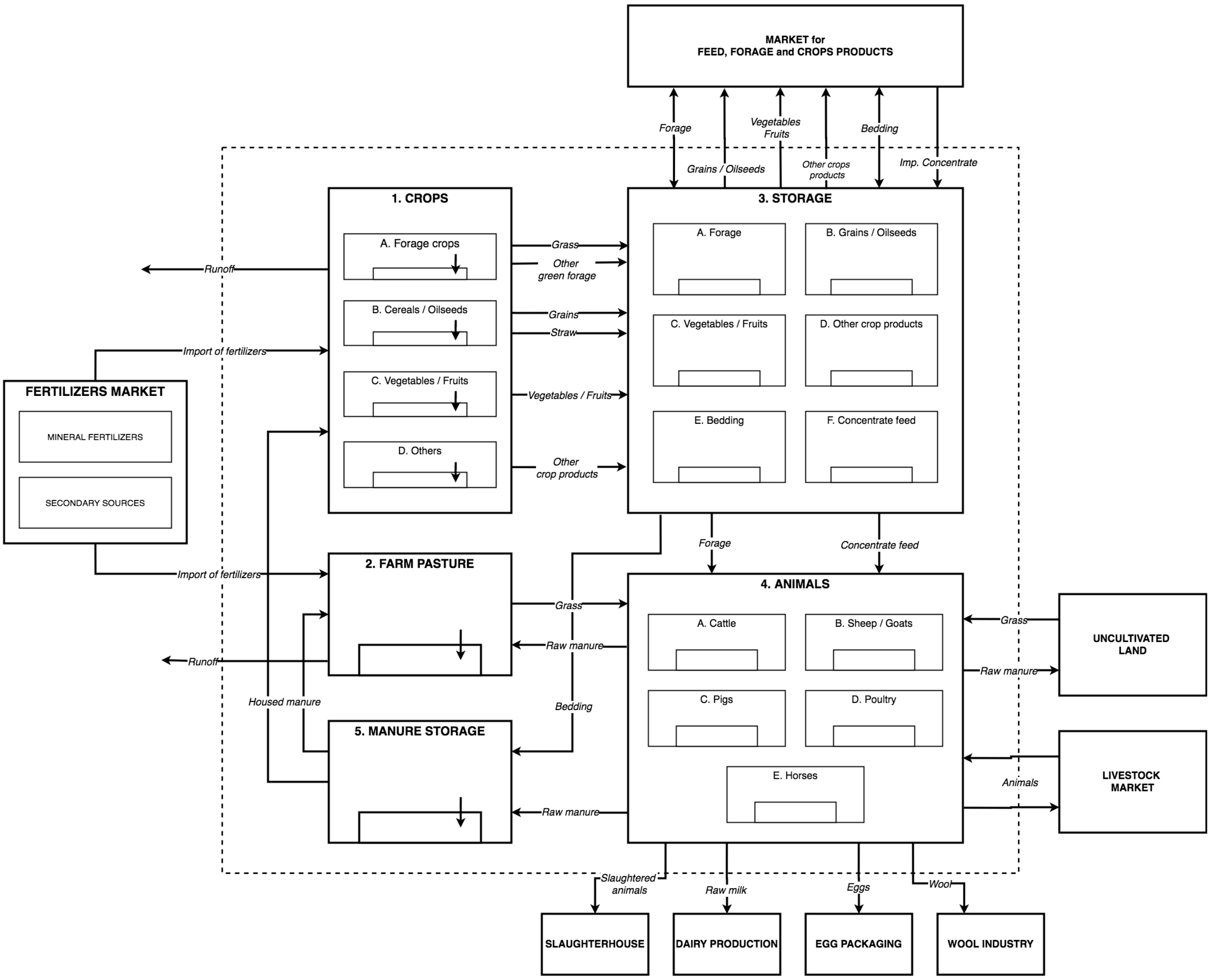
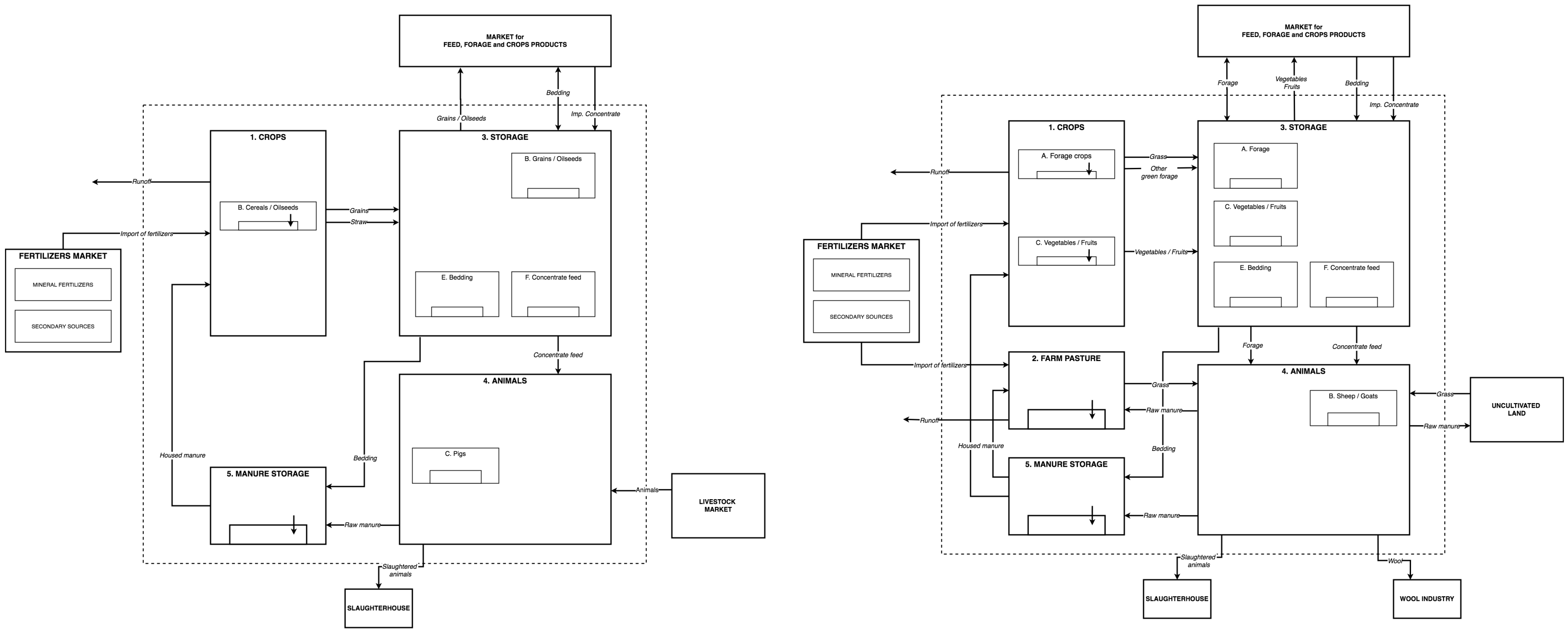


Figure 3: Disaggregated system definition. The *Crops*, *Storage* and *Animals* processes are divided in subcategories. This representation of the system definition also features external processes, like *Uncultivated land* or *Slaughterhouse*.



(a) Slaughter pigs production

(b) Sheep farm

Figure 4: Integration of different types of agricultural production in the system definition. Processes linked to grazing and winter forage flows are removed from the system in (a) since the pigs are confined indoors and assumed to be fed with concentrate only. Both Farm pasture and Uncultivated land are accounted for in the case of the sheep production (b).

2.1.2 System quantification

Data availability

The quantification of the system presented above required the use of statistical data when it was available, completed by parameters or estimates for the flows that were not reported.

Production statistics

Annual statistics of Norwegian farms are available through a data-set owned by *Landbruksdirektoratet* and published on *Data Norge*'s website (Landbruksdirektoratet, 2018a, 2018b, 2018c, 2018d, 2018e). These farm-specific statistics are collected through the annual process of application to agricultural subsidies, and therefore feature mostly data that is relevant for authorities to estimate the economic support deserved by each individual farm.

Landbruksdirektoratet (2018e) gathers parameters such as the areas of each crop category and pasture (in daa), the number of animals in the farm in spring and autumn for each animal category, the number of animals grazing for at least 12/16 weeks annually (depending on the region, see A.9 Regional parameters), the number of animals grazing at least for 5 weeks on *Uncultivated land* and the sales of hay or silage harvested on cultivated pastures, among other parameters that are maybe less relevant for the scope of this project. Landbruksdirektoratet (2018d) includes, for each farm selling animals to slaughterhouses, the slaughtered weights reported by abattoirs for each animal type (in kg dead-weight). This data-set also includes the exports of wool for farms with sheep (in kg). Landbruksdirektoratet (2018c) details the exports of raw milk (in L) from dairy cows and dairy goats productions to the dairy industry. Landbruksdirektoratet (2018a) communicates the exports of eggs (in kg) from egg productions with layers to the egg packaging industry. Finally, Landbruksdirektoratet (2018b) records, for each kind of cereal, peas/beans and oilseeds crops, the exports of grain to human food production, animal feed market and seed market.

These farm-specific statistics retrieved from *Data Norge* enable therefore the quantification of most of the exports flows of each farm, and provide very important parameters like the number of animals of each type or the crop and pasture areas. The material flows that were quantified using these statistics are represented in green in the overview displayed in Figure 5 below. All the aforementioned farm-specific parameters are in addition gathered in A.6 Farm-specific parameters.

Parameters

The whole system could not be quantified only with farm-specific statistics, as those statistics are by design not covering internal flows, imports or losses through runoff for example. A significant number of the model's parameters were therefore retrieved from national/regional statistics, scientific literature and other relevant sources.

County-specific yields for crops and farm pasture were mostly retrieved from *Statistics Norway* (Statistisk Sentralbyrå, 2020a, 2020b, 2020c, 2020e) and enabled to quantify harvest and grazing flows, both for farms that reported a cultivated area but no associated exports and for productions in which crop products are used internally (e.g. as animal winter forage). Oilseeds, peas and beans crop yields at national scale were estimated from NIBIO (2020b), while the yields of meadow seeds crops were calculated from Landbruksdirektoratet (2013).

Animal winter diets, in daily or annual quantities of concentrate feed and winter forage, were collected from a variety of animal-specific sources (Agria, 2015; Aune, 2016; Grøva et al., 2004; Karlengen et al., 2012; Kjos et al., 2019; Spruit, 2019), along with parameters used to quantify pasture flows like the amount of grass eaten per animal (Asheim & Hegrenes, 2006; NIBIO, 2020b) or the time spent by animals on pasture (Forskrift om hold av storfe, 2004; Forskrift om velferd for hest, 2005; Forskrift om velferd for småfe, 2005; Landbruksdirektoratet, 2018f).

The excretion of animal manure was quantified for almost each animal category by using a report from NMBU (Karlengen et al., 2012), while their need for bedding was estimated with several reports/regulations (Forskriften om hold av høns og kalkun, 2001; Løberg, 2012; Nesheim & Halvorsen Sikkeland, 2013; Uhlig & Fjelldal, 2005).

Runoff flows were estimated after reviewing several sources with different disaggregation levels for the P-losses factor in kg P/ha (Hauken, 2018; Zabrodina, 2013).

Finally, data for the Dry Matter (DM) and/or P concentration of each material flowing in the system was taken from Allison, Anderson, et al. (1951), Antikainen et al. (2005), Böhme et al. (2010), Karlengen et al. (2012), Mattilsynet (2019a).

Those general parameters collected from a diversity of sources enabled to quantify most of the flows that are not particularly relevant for the application to agricultural subsidies and are consequently not reported by farmers to *Landbruksdirektoratet*. The material flows that were quantified using these parameters are represented in blue in the overview displayed in Figure 5 below. Additionally, flows in red represent flows that were derived from the aforementioned blue flows using the mass-balance principle (e.g. there is no accumulation of concentrate feed in the *Storage* process, all imports are assumed to be consumed). The complete set of general parameters used in the model is presented in A.7 General parameters.

Informed estimates

There were finally some flows in the system that were very dependent on management practices within the farm and on each farmer's own judgement/experience. That is for example the case of the fertilization of crops/pasture with housed manure, the optional removal of straw from cereals and oilseeds fields as well as the management of the grass harvested on cultivated pastures (that can be exported or used locally as winter forage). For these flows, that are represented in black in Figure 5, production statistics or general parameters were not sufficient and additional assumptions based on informed estimates had to be used. Said assumptions are further detailed in section 2.1.2 System quantification.

Synthesis

An overview of the data availability for the system quantification is illustrated in Figure 5. It is important to mention that there is no flow in the system that is purely quantified from statistics. Even the flows associated to production statistics and represented in green in Figure 5 are the result of a calculation involving parameters, since the system's P layer is quantified by coupling the material layer with the DM or P contents presented in A.8 Material contents. Therefore, this diagram is not meant to give an exact picture of which kind of sources enabled to quantify each flow, but rather an approximate representation of the "dominant" data source used to quantify the flow.

Quantification methods

Crops

The harvest of *vegetables*, *fruits*, *other green forage* and *meadow seeds* was always calculated as a product between the crop area reported in Landbruksdirektoratet (2018e) and the yields retrieved from Landbruksdirektoratet (2013), Statistisk Sentralbyrå (2020a, 2020b). For *cereals*, *oilseeds*, *peas and beans*, for which the reporting of exports is a bit more consistent in the production statistics, the farm's yields were as a starting point assumed equal to the farm's exports (Landbruksdirektoratet, 2018b). If there was a reported cultivated area for those categories but no exports in production statistics, then the harvest flows were calculated as the product between reported areas (Landbruksdirektoratet, 2018e) and estimated yields (NIBIO, 2020b; Statistisk Sentralbyrå, 2020e), and the whole harvest was supposed to be exported.

The approach used for the quantification of the flows of *grass* harvested on cultivated pasture (and associated imports and exports of forage) as well as the possible harvest of *straw* on cereals and oilseeds crops is not really straightforward, as it required a set of additional assumptions (hence the representation of those flows in black on Figure 5). These assumptions are further detailed in A.1 Forage management and A.2 Straw removal respectively.

The P layer of the aforementioned harvest flows was finally derived by multiplying the material flows by their associated DM and/or P contents, retrieved from Antikainen et al. (2005) (cereals and oilseeds, peas, potatoes, grass, hay and silage) and Mattilsynet (2019a) (horticulture products).

The losses of P through erosion and runoff flows were only calculated for the P layer (no material flow was calculated), as a product between the total area of *Crops* and a runoff factor of 1 kg P running off the system per ha (Zabrodina, 2013).

Farm pasture

The consumption of pasture grass by grazing animals was generally calculated as the product of the number of animals on pasture with their daily intake of grass and their number of days on pasture. Because the most robust data available for the daily amount of pasture grass eaten by each grazing animal category was in FEm (Asheim & Hegrenes, 2006), the equivalent grass intake in kg was calculated by multiplying with a factor of $m_{grass/FEm}$ = 5,7 kg/FEm, adapted from NIBIO (2020b). Since grazing animals in the present system can graze on both *Farm pasture* and *Uncultivated land*, the quantification of the number of animals and the time they spent on *Farm pasture* needed some additional assumptions that are further detailed in A.3 Pasture management.

The flow of raw manure dropped on *Farm pasture* by grazing animals was calculated as a fraction of their annual excretion, based on the time they spent on *Farm pasture*. Annual excretion of raw manure was quantified by multiplying the number of animals in each category by the annual excretion of manure per animal reported by Karlengen et al. (2012). The pasture time used to estimate the

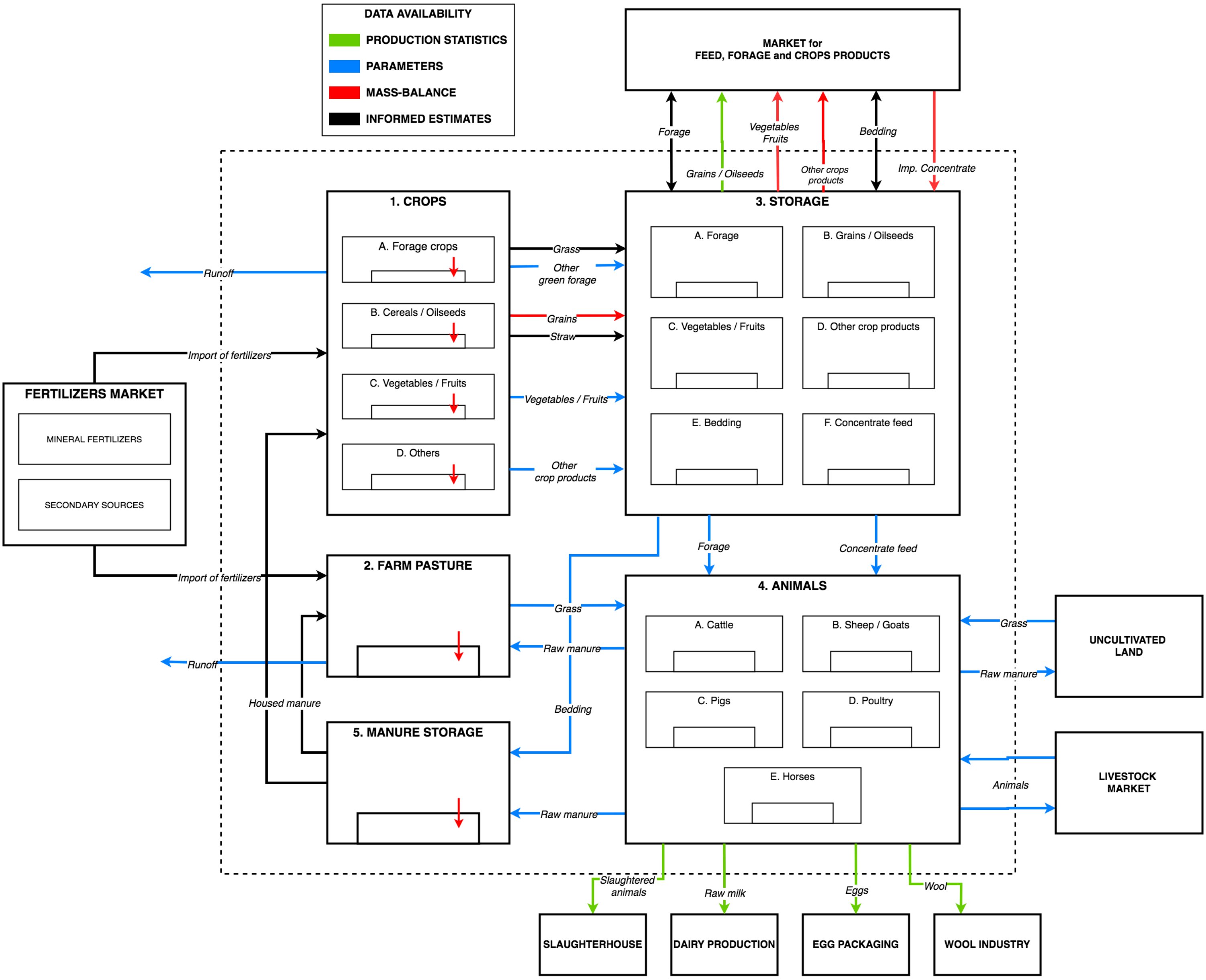


Figure 5: Overview of the data availability.

fraction of annual excretion dropped on *Farm pasture* was similar to the number of days used for the quantification of the grass flows, in order to have a mass-balance consistency.

The P layer of raw manure flows was derived by multiplying their material layer by the DM and/or P contents retrieved from Karlengen et al. (2012).

The losses of P through erosion and runoff were calculated with the same method that the one used for *Crops* : *Farm pasture* area was multiplied with the same runoff factor of 1 kg P/ha (Zabrodina, 2013).

STORAGE

It is important to understand that the *Storage* process does not represent a storage of products from a year to another, but is rather a process that was added as an intermediate between the farm and external markets for crop products, animal feed and forage. There is therefore no stock change in this process, i.e. the sum of the inputs equals the sum of the outputs (hence the absence of vertical arrows in Figure 3). Consequently, the amount of exported crop products (that is for *Grains and Oilseeds*, *Vegetables/Fruits* and *Other crop products*) is always equal to the amount harvested. Concentrate feed for animals, although cereal-based, is assumed to be produced exclusively outside the system boundaries and is necessarily imported in the system (wood-based bedding as well). Imports of concentrate feed and wood-based bedding are presumed to perfectly match the consumption by animals, meaning that the diet and bedding flows are driving the imports of those materials. The inputs and outputs of forage and straw are also balanced, but that is the results of hypotheses that are not straightforward and are therefore presented in A.1 Forage management and A.2 Straw removal.

ANIMALS

The winter diet material flows were quantified for all animal categories as the product of a number of animals (or spots) by a consumption of each type of feed per animal (or spot). For daily amounts in particular, it was important to multiply the number of animals and the daily consumption by the number of days spent indoors (that is 365 days - grazing days). The estimation of the number of animals on farm was in this model category-specific (see A.4 Number of animals for a detailed explanation). Daily quantities of silage and concentrate given to cattle (dairy cows, meat cows and young cattle) were adapted from Spruit (2019). Daily quantities of hay and concentrate given to horses were estimated based on Agria (2015). Annual quantities of hay, silage and concentrate fed to ewes were extracted from Grøva et al. (2004), while lambs were assumed to only eat pasture grass between birth and slaughter. Data on daily silage and concentrate fed to goats (both dairy and young goats) was retrieved from Aune (2016). Annual amount of concentrate fed to animals belonging to the poultry category (layers, broilers and turkeys) were taken from Kjos et al. (2019). Amount of concentrate distributed per adult sow, young sow and piglet, as well as the annual amount of concentrate per slaughter pig spot were found in Karlengen et al. (2012).

The total consumption of pasture grass by grazing animals was calculated as the product of the number of animals on pasture with their daily intake of grass and their number of days on pasture. This total quantity of grass was then distributed between *Farm pasture* and *Uncultivated land* depending on the respective number of days spent by animals on those (see A.3 Pasture management).

A similar approach was followed with the raw manure flows, for which a total annual excretion was calculated and then distributed between *Farm pasture*, *Uncultivated land* and *Manure storage* (for the raw manure deposited indoors and therefore available for collection). For non-grazing animals, i.e. *Poultry* and *Pigs* categories, all the manure excreted is collected indoors, while for grazing animals (i.e. *Cattle*, *Sheep/Goats* and *Horses*), a significant fraction ends up on agricultural or uncultivated soil.

In the model, the import or export of living animals from and to the *Livestock market* are only considered for intensive pig productions, i.e. slaughter pigs productions that import piglets and breeding pig productions that export them. The exports of piglets from breeding pigs production was calculated as the number of adult sows in the farm multiplied by the number of piglets weaned per sow and per year (Kjos et al., 2019). For intensive slaughter pig productions, the opposite import flow of piglets was calculated as the product of the number of slaughter pig spots in the farm by an average number of 3,3 slaughter pigs growing cycles per year (Karlengen et al., 2012). For both the imports and the exports of piglets, a piglet weight of 30 kg was used to derive the material flows (Karlengen et al., 2012).

For the flows of animal products (meat, milk, eggs, wool), the material layer was directly derived with the data retrieved from production statistics and given in kg, at the exception of milk and meat products. For the former, the exports reported in Landbruksdirektoratet (2018c) are in liters of dairy cow/goat milk, and needed thereby to be multiplied by milk density (1,034 g/mL). For meat products, the exports gathered in Landbruksdirektoratet (2018d) represent the weight measured by slaughterhouses after slaughter. In order to derive an export of *living* animals from the farm, those weights were multiplied for each animal category by living:carcass weight ratios retrieved in the literature (Bagley, 2013; Spruit, 2019; Svin, 2017).

The P layer of the flows related to the *Animals* process was derived by multiplying the material layer by the DM and/or P contents of said flows, retrieved from Antikainen et al. (2005) (grass, hay, silage, P concentration in animals), Karlengen et al. (2012) (concentrate feed, manure excretion for each category), Mattilsynet (2019a) (milk and eggs) and Böhme et al. (2010) (wool).

It is important to mention that the *Animals* process is the only process in the system that is not balanced in mass. This is because all flows related to that process were quantified either with production statistics or parameters, necessarily leading to a need for data reconciliation. Even if such a data reconciliation procedure could provide interesting insights and would also enable the calculation of a consistent farm balance, it was not considered in the scope of this project, since a balance of the *Animals* process was not required in order to derive the main variables of interest (soil P balance and manure surplus).

MANURE STORAGE

In the system, the bedding materials (straw and/or wood-based products) are flowing directly from the *Storage* process to the *Manure storage* process. These flows were calculated for almost all categories as a daily/monthly amount of bedding per animal (Løberg, 2012; Uhlig & Fjelldal, 2005) multiplied by the number of animals in each category and the time spent indoors, except for animals in the *Poultry* category. For *layers*, *broilers* and *turkeys*, an annual amount of bedding per square meter (Nesheim & Halvorsen Sikkeland, 2013) was multiplied by an estimation of the area of indoor facilities, calculated with the number of animals on farm and the legal maximum animal densities reported in Forskriften om hold av høns og kalkun (2001). For the kind of bedding used, it was assumed that all animals categories confined indoors had access to an organic bedding in the form of either straw or wood-based material, while animals in the *Poultry* and *Horses* categories were only provided wood-based products (Løberg, 2012). For *Cattle*, *Sheep/Goats* and *Pigs*, the material was decided depending on the straw availability on the farm: if there were cereals/oilseeds crops registered in Landbruksdirektoratet (2018e), the animals were provided straw as a bedding material, while farms without such a straw capacity were assumed to use wood-based solutions.

The P layer of bedding flows was derived by multiplying the material layer by the DM and/or P contents of said flows, retrieved from Antikainen et al. (2005) (straw) and Allison, Anderson, et al. (1951) (wood-based products).

A total quantity of housed manure was calculated by summing all the flows of raw manure collected indoors and the bedding flows. This quantity was further available for use as secondary fertilizer on both *Crops* and *Farm pasture*.

Fertilization

There was no data available at farm level regarding the fertilization of agricultural soil. Sales of mineral fertilizer are made public at county level (Mattilsynet, 2019a), but this data remains private at the farm scale. Additional assumptions were therefore needed in order to quantify the flows of recycled manure, imported fertilizers and the potential surplus of housed manure in the *Manure storage* process. It was decided to investigate three different Fertilization Strategies (FS), corresponding to different practices for the utilization of fertilizers in the farm and resulting in different consequences for the key system variables (P balance of agricultural soil and potential surplus of housed manure).

FS1-Fertilization status with farm resources only

In this strategy, it is assumed that all the manure that has been collected and stored during the year (housed manure) is applied evenly on agricultural land, i.e. on *Crops* and *Farm pasture* in proportion with their respective areas. However, it has to happen within the limits of current regulations on manure spreading (Forskrift om husdyrgjødsel, 2002), stating that a farm must have at least 4 daa available for spreading per animal manure unit (1 GDE = 14 kg manure-P). This corresponds to a maximum amount of 3.5 kg manure-P that can be spread per daa. For the farms that do not comply with this because of a high animal-density, a remaining fraction of housed manure cannot be spread on the fields and is therefore stored as a surplus in the *Manure storage* process. The imports of fertilizers are ignored in this premise, that tries to capture whether the resources of each single farm lead to a fertilization surplus or a fertilization deficit. For a majority of farms, this FS only leads to an accumulation or depletion of P in agricultural soil, even though a surplus of housed manure can possibly happen for farms that do not comply with the regulations on spreading area requirements.

FS2- Restrictive spreading regulations

This second strategy features the same ground assumptions that FS1, but the application of housed manure on farm is limited by more stringent spreading area requirements. Instead of a minimum area of 4 daa per GDE, it is chosen to increase this legal minimum to 10 daa/GDE, equivalent to a maximum of 1,4 kg manure-P spread per daa instead of 3,5 kg. This value was chosen as a compromise between a value of max. 1 kg P/daa that would make sense in order to minimize environmental risks through runoff (Rebbestad, 2020), and a maybe more realistic value of max. 2 kg P/daa that was used in one of the scenarios investigated by A. K. F. Øgaard et al. (2017). The implications of this fertilization strategy on the model's variables are similar to those of FS1, but it is expected that more farms will show a surplus of housed manure.

FS3-Fertilization plans based on NIBIO guidelines

In this last strategy, available housed manure is applied in quantities that comply with NIBIO fertilization recommendations for each type of *Crops* as well as for *Farm pasture*. Recommended quantities of P were adapted from NIBIO (2020b), with crop-specific values detailed in A.5 Fertilization guidelines of NIBIO. For farms that have more P in form of housed manure than the sum of P-fertilization amounts recommended by NIBIO, it means that a surplus of housed manure is generated in the *Manure storage* process. At the opposite, farms that do not have enough housed manure to comply with those fertilization guidelines can, in this strategy, import additional fertilizers from the *Fertilizers market*. It is important to mention that no difference is made between primary and secondary fertilizers for the import flows, that only represent a need for additional fertilization resources (the equations of these import flows are displayed in 1 and 2 below). Since the guidelines are meant to make the inputs (i.e. fertilizers) better balance the outputs (i.e. plant uptake and losses) of the agricultural soil processes, this fertilization strategy can be expected to 1) lead to a reduction of the soil P accumulation in farms that show a net fertilization surplus in FS1, with the generation of a manure surplus 2) counteract the depletion of soil P in farms with a net fertilization deficit.

$$\text{Imported fertilizers}_{\text{crops}} = \left(\sum_{i=1}^{N_{\text{crops}}} \text{area}_i \times \text{fertilization}_i\right) - \text{Housed manure}_{\text{crops}} \tag{1}$$

$$\text{Imported fertilizers}_{\text{pasture}} = (\text{area}_{\text{pasture}} \times \text{fertilization}_{\text{pasture}}) - \text{Housed manure}_{\text{pasture}} \tag{2}$$

where the term between brackets are the aggregated fertilization requirements of crops/pasture, derived by summing the product of the different areas (area_i) by the corresponding NIBIO fertilization recommendation per daa (fertilization_i).

It is important to underline that these three strategies do not aim to represent a reality behind fertilization at farm level: FS1 and FS2 follow a premise in which there is no trade of fertilizers, while FS3 takes a starting point in a design of fertilization plans that follows a very specific set of recommendations (NIBIO's) among many existing guidelines, some of which are probably much more actual in the Norwegian agricultural production (e.g. advisors and experts from *Norsk Landbruksrådgiving*). These fertilization strategies should also not be confused with scenarios meant to describe pathways to different futures, since they only describe several perspectives of a system quantified for the year 2018.

Overview

The general equations used to quantify the material flows in the system, as well as the sources used for the corresponding concentrations of DM and P are gathered in Table 3.

Table 3: Methods used for the quantification of P flows. DM = *Dry Matter*, IP = *Farm pasture*, OP = *Uncultivated land*, FS = *Fertilization Strategy*, GDE = *Manure Animal Unit (14 kg P/yr)*.

Flow category	General equations	Material quantity sources	DM/P content sources
Harvest of crops' products	*Vegetables, fruits, other green forage and meadow seeds* : Area × yields *Cereals, oilseeds, peas and beans* : Production statistics (area × yields when no reported exports) *Grass and straw* : See **??** **??** for detailed explanation	M1, M2, M3, M4, M5, M6, M7	P1, P2
Trade of crops' products	*Imports of concentrate and wood-based bedding* : Mass-balance *Trade of forage and straw* : See A.1 and A.2 in Appendix for detailed calculations		
Animal diets	*Winter forage* : Number of animal indoors × feed/forage consumption per animal.day × number of days indoors *Grass from pasture (IP and OP)* : Number of animal grazing × grass quantity per animal.day × number of grazing days *Grass from IP* : min (grass from pasture, area_{IP} × yield_{IP}) *Grass from OP* : Grass from pasture - grass from IP	M1, M8, M9, M10, M11, M12, M13, M14, M15, M16	P1, P3
Animal products	*Meat, milk, eggs and wool* : Production statistics *Animals (piglets)* : See **??**-**??** for detailed explanation	M1, M8, M12, M13, M17, M18, M19, M20, M21	P1, P2, P4
Raw manure	*Dropped on pasture (IP and OP)* : Number of animals grazing × (number of grazing days / 365) × annual excretion of manure per animal *Dropped on IP* : Raw manure dropped on pasture × (grass from IP / grass from pasture) *Dropped on OP* : Raw manure dropped on pasture × (grass from OP / grass from pasture) *Collected indoors* : (Number of animals × annual excretion of manure per animal) - raw manure dropped on pasture	M1, M13, M14, M15	P3
Bedding	*Cattle, Sheep/Goats, Pigs, Horses* : Number of animals × bedding quantity per animal.day *Poultry* : (Number of animals / legal maximum animal density) × bedding quantity per m^2.year	M1, M14, M15, M22, M23, M24, M25	P1, P5
Housed manure applied on agricultural soil	*FS1* : min (Available housed manure, housed manure quantity corresponding to 4 daa/GDE) *FS2* : min (available housed manure, fertilization recommendations) *FS3* : min (Available housed manure, housed manure quantity corresponding to 6,5 daa/GDE)	M1, M6, M26, M27	P1, P3, P5
Import of fertilizers	*FS1* : 0 *FS2* : max (fertilization recommendations - available housed manure,0) *FS3* : 0	M1, M6, M26, M27	P1, P3, P5
Erosion and runoff	Area × runoff factor	M1, M28	

Sources: M1: (Landbruksdirektoratet, 2018e); M2: (Landbruksdirektoratet, 2013); M3, M4: (Statistisk Sentralbyrå, 2020a, 2020d); M5: (Landbruksdirektoratet, 2018b); M6: (NIBIO, 2020b); M7: (Statistisk Sentralbyrå, 2020e); M8: (Spruit, 2019); M9: (Agria, 2015); M10: (Grøva et al., 2004); M11: (Aune, 2016); M12: (Kjos et al., 2019); M13: (Karlengen et al., 2012); M14: (Landbruksdirektoratet, 2018f); M15: (Forskrift om hold av storfe, 2004; Forskrift om velferd for hest, 2005; Forskrift om velferd for småfe, 2005); M16: (Asheim & Hegrenes, 2006); M17: (Landbruksdirektoratet, 2018d); M18: (Landbruksdirektoratet, 2018c); M19: (Landbruksdirektoratet, 2018a); M20: (Bagley, 2013); M21: (Svin, 2017); M22: (Løberg, 2012); M23: (Uhlig & Fjelldal, 2005); M24: (Nesheim & Halvorsen Sikkeland, 2013); M25: (Forskriften om hold av høns og kalkun, 2001); M26: (Forskrift om husdyrgjødsel, 2002); M27: (A. K. F. Øgaard et al., 2017); M28: (Zabrodina, 2013); P1: (Antikainen et al., 2005); P2: (Mattilsynet, 2019a); P3: (Karlengen et al., 2012); P4: (Böhme et al., 2010); P5: (Allison, Anderson, et al., 1951)

P BALANCE CALCULATIONS

In all or part of the aforementioned fertilization strategies, two main variables were calculated in order to illustrate the farm's fertilization status: the P balance of agricultural soil processes and the stock change of the *Manure storage* process.

P BALANCE OF AGRICULTURAL SOIL

The accumulation (or depletion) of P on the *Crops* and *Farm pasture* processes (respectively ΔS_{crops} and $\Delta S_{pasture}$) were derived by subtracting the outputs to the inputs of those processes, as displayed in equations 3, 4 and 5.

$$\Delta S_{crops} = \text{Housed manure}_{crops} + \text{Imported fertilizers}_{crops} - \text{Runoff}_{crops} - \text{Harvest of crop products} - \text{Harvest of straw} \quad (3)$$

$$\Delta S_{pasture} = \text{Raw manure}_{pasture} + \text{Housed manure}_{pasture} + \text{Imported fertilizers}_{pasture} - \text{Runoff}_{pasture} - \text{Grass eaten} \quad (4)$$

$$\Delta S_{agricultural\ soil} = \Delta S_{crops} + \Delta S_{pasture} \quad (5)$$

SURPLUS OF HOUSED MANURE

The surplus of housed manure ΔS_{manure} observed in the *Manure storage* process is in each fertilization strategy calculated as a mass-balance of said process. The total amount of housed manure in the system, called $\text{Housed manure}_{tot}$ in equation 6, never changes. However, the fraction of this available housed manure that is effectively applied on agricultural soil depends on the fertilization strategy.

$$\Delta S_{manure} = \text{Housed manure}_{tot} - \text{Housed manure}_{crops} - \text{Housed manure}_{pasture} \quad (6)$$

2.1.3 Uncertainties linked to data quality

Farm-specific parameters

As mentioned in 2.1.2, Data availability, the production statistics that were used in this project (Landbruksdirektoratet, 2018a, 2018b, 2018c, 2018d, 2018e) are collected when farmers apply for agricultural subsidies. They provide to that extent a good basis for key model variables (crops, animals), but are not designed with the purpose of tracking the nutrient cycle of each farm. They are therefore a source of uncertainty with regards to some parameters.

The number of animals present on farm (for each category) is calculated as an average between a number measured in spring and a number measured in autumn. Even though further investigation would be needed to understand in which conditions said measurements are done and to what extent they matter for the application to subsidies, there is nevertheless a clear error associated to that calculation. This error would be reduced with more frequent measurements (e.g. four times a year) or if the number of animals was reported at a frequency adapted to the lifetime of each animal category. Indeed, it seems reasonable to report a dairy cow only twice a year, but what about broilers that only spend 30 days on farm before being sent to slaughterhouse? It would be more consistent for the latter to report the number of spots rather than the number of animals at a certain point in time.

Some inconsistencies were found between different data-sets of the production statistics. For example, there are many farms that have no registered oilseeds crops in Landbruksdirektoratet (2018e) but still report exports of oilseeds in Landbruksdirektoratet (2018b). There are also farms that report 7,500 layers both in spring and autumn, but are not registered as eggs exporters in Landbruksdirektoratet (2018a). Even though these inconsistencies remain seldom and regard a minority of productions, they result in a low confidence in the system quantification for said productions. A better understanding of the data-sets' interconnection or additional assumptions could significantly reduce this uncertainty.

There is a rather high uncertainty associated to the data-set for the exports of animals to slaughterhouses (Landbruksdirektoratet, 2018d). What is measured in this data-set is indeed unclear and not really specified in the data description: is it the weight of living animals delivered to slaughterhouses, the weight after slaughter of the animals delivered to slaughterhouses or the post-slaughter weight of the animal parts that will be send to food production? It is particularly crucial to access this information, as the outflows of animals from the farm to slaughterhouses is in the model defined as living animals. Because it was better matching with the animal stocks measured in intensive meat productions, which exports are rather stable over years, and because a similar assumption was taken by Spruit (2019), it was assumed that the variable measured in the data-set was the dead weight of animals after slaughter. Further investigation would be needed to better understand what those weights represent and to adjust the model's transfer coefficient accordingly.

Finally, for farms with grazing animals, the pasture management is a key parameter to get economic support from *Landbruksdirektoratet*. However, the categories to be filled in the application form are not really suited to the model developed in this project. As mentioned in 2.1.2 Quantification methods, the calculation of the grass and raw manure flows on both *Farm pasture* and *Uncultivated land* depends on 1) the number of animals grazing, 2) the place they are grazing at and 3) the number of days they spend on that place. But the only categories made public in Landbruksdirektoratet (2018e) are:

- *the number of animals grazing for at least 12/16 weeks* (without mention of the place they are grazing at or the real time they spend grazing);

- *the number of animals that graze for at least 5 weeks on* Uncultivated land (without mention of the real time they spend grazing).

It is furthermore not mentioned how many animals are not grazing at all: non-castrated young cattle males older than six months are for example not allowed on pasture in Norway (Forskrift om hold av storfe, 2004). There was therefore a significant data gap when it comes to pasture management, resulting in a relatively high uncertainty on associated flows because of crude assumptions that had to be taken (see A.3 Pasture management).

General parameters

Parameters retrieved in additional sources in order to quantify flows that were not available through production statistics were also a source uncertainty for the calculations.

A clear source of error is that most of those parameters (for example some of the crop yields, but also animal diets and manure excretion as well as bedding requirements) were only found at the national scale. Some parameters were regionalized, like cereals, potatoes and forage yields as well as pasture times, for which it was made a difference between counties (see A.9 Regional parameters). However, a majority of general parameters were presumed applicable everywhere in Norway, thereby creating uncertainty by omitting regional patterns or farm level practices.

This is particularly true for animal winter diets, with forage and feed rations that can be expected to depend significantly on the farmer's experience, on the type of production (conventional/intensive vs organic), but also on the conditions of animal captivity (are animals kept in infrastructures with free motion – *løsdrift* - or restricted motion – *båsfjøs* ?). A lower uncertainty can be expected for pasture diet, since the amount of grass eaten by free-grazing animals (in FEm/day) can reasonably be assumed quite homogeneous in Norway, as it is more animal-specific and depends less on farm-specific conditions.

Almost all manure excretions were taken from a NMBU report published in 2012, often cited as a privileged reference for Norwegian studies that need an estimation of the nutrient content of animal manure (Karlengen et al., 2012). Since the diets in the Norwegian animal husbandry can be reasonably assumed not to have changed substantially in the past 8 years, there is in the model a medium uncertainty associated to manure flows.

On the contrary, there is a very low confidence (i.e. very high uncertainty) associated to the animal bedding flows. This is firstly because very few studies were found to report the bedding requirements (in type and quantity) for each animal category. It is also because the kind and amount of bedding depend on a wide range of parameters, including the farmers' own judgment and experience, the nature of production (conventional vs organic, with the consequences that it implies on animal welfare), regional habits or opportunities (Uhlig & Fjelldal, 2005), but also synergies at local scale (e.g. proximity of the farm either to cereal productions or sawmills from wood industry). For this model, that cannot capture such synergies because a lack of trade data, the assumption was made that straw was used as bedding material in farms that have cereals and oilseeds crops and therefore available harvest residues, while wood-based bedding was used for the rest of the productions. Even though it seems to be a fair assumption, it does not really reduce the uncertainty associated to this flow. Generally speaking, the P-bedding flows can be expected to be overestimated in the model, but remain nevertheless quite small in comparison with the raw manure flows.

The largest uncertainty in the model's parameters is probably associated to the runoff factor, used to quantify the losses of P to surface waters through erosion and runoff. A single value of 1 kg P lost per ha and year was used for all Norwegian farms (Zabrodina, 2013), although a monitoring program of nutrient leakages from agricultural soil conducted at national scale, the JOVA project (for *JOrd- og VAnnovervåking i landbruket*), showed a significant standard deviation for this parameter over the past decades (Hauken, 2018). That is because nutrient losses are caused by parameters that are extremely local, including regional climate and local weather inducing different precipitation patterns, slope of agricultural fields, soil type (sand or clay), but also the timing of fertilization/manure spreading or whether the soil is ploughed in autumn or not, etc. In addition, the soil P level also play a role, as a significant accumulation of plant-unavailable P will tend to release more nutrients to surface waters in the long-term (Hamilton et al., 2017). It appears therefore vital to spatially disaggregate this parameter, in order to track the release of P in water bodies more accurately. Regional data, built as a weighted average of samples taken in every county, was used by Hanserud et al. (2016) in order to have county-specific runoff flows. But it is very unlikely that using regional data would have contributed to reduce the uncertainty of the runoff flows in the present project, that focuses on the farm level as a starting point. It was therefore decided to keep a single value for the runoff factor, while acknowledging for the need to further refine this parameter.

Finally, there is overall a low uncertainty associated to the dry matter (DM) and phosphorus (P) contents of the different materials flowing within the system.

QUALITATIVE OVERVIEW

Both data quality and model assumptions affect the level of confidence associated to each system flow. It seems therefore relevant to have an overview of the aforementioned uncertainties before looking at the model results. This overview is provided below in Table 4, where every flow category is associated to a qualitative level of uncertainty.

A quantitative analysis of the model uncertainties would be required in order to rigorously estimate the variance of the variables of interest (soil P balances and surplus manure). Such an approach would involve 1) assigning to each of the model's parameters a standard deviation based on their respective relative errors, 2) conducting a sensitivity analysis by propagating those errors to the system variables (flows/stock changes), for example with a Monte-Carlo simulation. However, the qualitative insights gained through this section were considered sufficient in order to both have an informed look on the model results (section 3) and discuss the opportunities for further improvement of the model (section 4).

Table 4: Overview of the uncertainties associated to the system flows. The uncertainties related to the DM and P contents of material flows are not considered here. IP = *Farm pasture*, OP = *Uncultivated land*, RM = *Raw Manure*, FS = *Fertilization Strategy*.

Flow category	Flow sub-category	Uncertainty level	Sources of uncertainty
Harvest of crops' products	Based on exports	Low	Assumption of no storage of crop products (harvest = exports)
	Based on yields	Medium	Very good confidence in crops' areas. Yields only available at regional/national scale.
Trade of crops' products	Feed/Wood-based bedding	High	Propagation of the combined uncertainties of winter diets (*Medium*) and bedding flows (*Very High*)
	Forage/straw	Very High	Propagation of uncertainty linked to straw bedding flows. Assumptions for forage and straw management (see A.1 and A.2) were not validated.
Animal diets	Winter forage/feed	Medium	Quite good confidence in number of animals and time spent indoors. Lower confidence in national, rather conventional winter diets.
	Pasture grass	High	Good confidence daily grass uptakes. Low confidence on time / number of animals on IP/OP.
Animal products	Meat/milk/eggs/wool	Low	Good confidence in reported animal products exports. Lower confidence for exports to slaughterhouses (uncertainty on transfer coefficient)
	Animals (piglets)	Medium	Good confidence in : piglets weight, number of weaned piglets per sow.yr, number of SP growing cycles/yr. Lower confidence in fraction of weaned piglets that is exported to SP productions.
Raw manure	Collected	Medium	Quite good confidence in number of animals and time spent indoors. Annual excretions per animal retrieved at national scale.
	Dropped on pasture	High	Good confidence in annual excretion values, quite good confidence in time spent indoors. Low confidence on time / number of animals on IP/OP.
Bedding	-	Very High	Quite good confidence in number of animals and time spent indoors. Very low confidence in both kind and quantity of bedding used.
Housed manure applied on agricultural soil	FS1	High	High uncertainty as a sum of the uncertainties of RM and bedding flows (weighted according to their relative size).
	FS2	Very High	Very high uncertainty since based on the assumption that NIBIO fertilization recommendations are followed.
	FS3	High	Similar to FS1.
Import of fertilizers	FS1	-	Propagation of the uncertainty of the flow of applied housed manure.
	FS2	Very High	
	FS3	-	
Erosion and runoff	-	Very High	Very good confidence in crops' areas. Very low confidence in runoff factor (use of a single value for a very site-specific parameter).

2.2 Integration in a spatially-explicit model at municipality and county levels

2.2.1 Implementation

The different model parameters described in 2.1, i.e. production statistics and general parameters, were retrieved from their respective sources and gathered in *Excel* tables. The chosen modelling year was 2018, since farm-specific data for 2019 was not available yet by the start of this project's data collection process: the production statistics from *Landbruksdirektoratet* published on *Data Norge* (Landbruksdirektoratet, 2018a, 2018b, 2018c, 2018d, 2018e) are annually updated around April/May. These tables of parameters were further implemented in a *Python* environment equipped with the *pandas* package (McKinney, 2020), particularly suited to handle tabular data with heterogeneously-typed columns like the data involved in this project. System flows and stock changes could therefore be calculated for all Norwegian farms by the means of operations on *pandas.Series* or *pandas.Dataframes.*

2.2.2 Upscaling at municipality and county levels

The model developed in the present project is spatially-explicit at municipality and county levels, meaning that each Norwegian farm of the database is associated to a municipality (by a *Kommunenr*) and a county (by a *Fylkenr*). It was therefore possible, with data manipulation tools from the *pandas* package, to group farms by municipality and municipalities by counties, and thereby to upscale the results obtained at farm level.

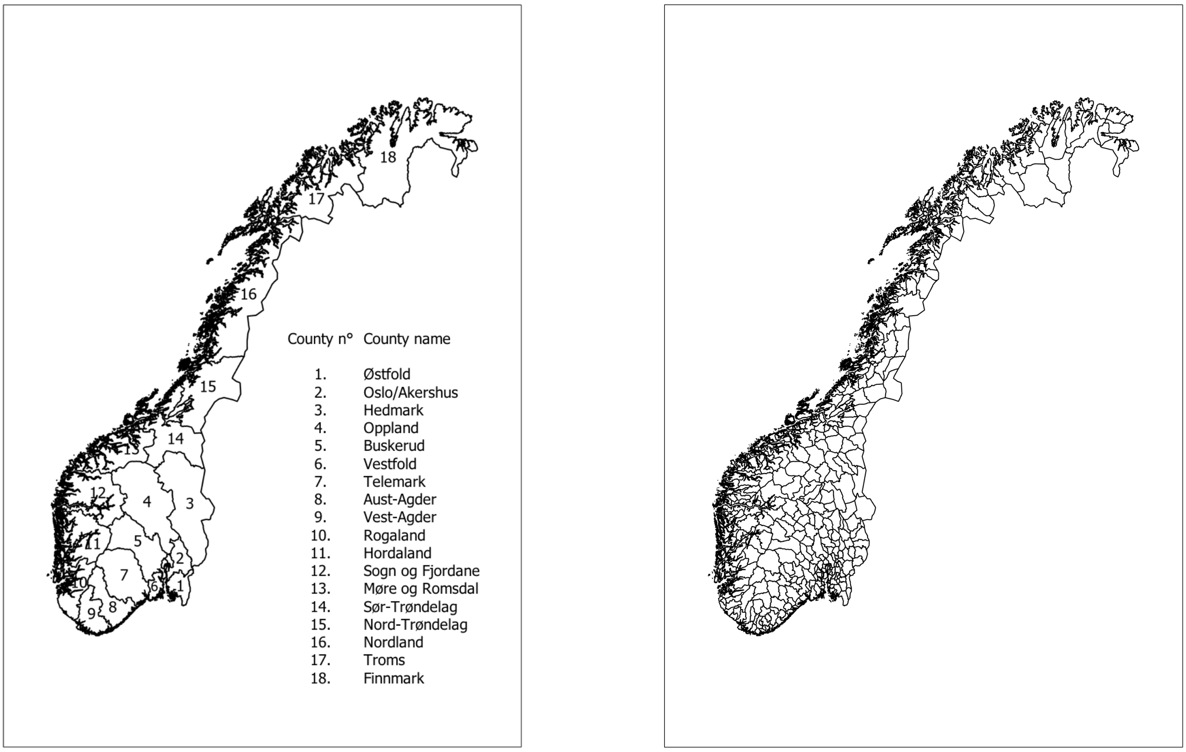
It was however required to consider the administrative boundaries that were in place in 2018, taking into account the recent county/municipality reforms (Regjeringen, 2020). This was done for all counties except for Trøndelag, for which the segregation between Sør-Trøndelag and Nord-Trøndelag, outdated from 01/01/2018, was kept for the sake of comparison of the results with those of past regional case studies of Norway (Hanserud et al., 2016). For the same comparison purpose, the counties of Oslo and Akershus were merged. Giving municipalities a similar treatment (i.e. converting the current *Kommunenr* into those of 2018) resulted in the end in a total number of 18 counties (displayed on the map in Figure 6a) disaggregated in 415 municipalities (which boundaries are displayed in Figure 6b).

2.2.3 Visualization tools

Farm results

Results at farm level, presented in Figure 8, Figure 12 and Figure 13 in the Results section, could be visualized through Sankey diagrams created with *FloWeaver*, the open-source *Python* tool developed by Lupton and Allwood (2017). Sankey diagrams usually enable to emphasize the major flows within a system by representing those flows with a width proportional to their size, which make them a particularly relevant tool in this project to identify the most important flows in the P cycles of different farms. Although it is rather common for such diagrams to show conserved quantities within the system boundaries, it was not exactly verified in this project for two processes:

- As mentioned in 2.1.2 System quantification, the *Animals* process is not balanced in the system because no data reconciliation was conducted in the frame of this project. This results naturally in



(a) County level

(b) Municipality level

Figure 6: Spatial definition of the system

unbalanced inflows and outflows to and from this process in the Sankey diagrams of the Results section;

- For the soil processes (*Crops* and *Farm pasture*), an excess fertilization leads to an accumulation of P in agricultural soil (i.e. a net positive stock change in these processes) while a remaining need for fertilization leads to a depletion of soil P (i.e. net negative stock change). Even though the original idea of Sankey diagrams is to represent material flows, it is of interest in this project to represent stock changes as well, since soil P stock change and surplus of housed manure are the key system variables. But Sankey diagrams are not really suited to represent negative quantities: instead, a depletion of soil P is visualized here by inputs to soil processes being smaller than outputs. Accumulation of soil P and surplus of housed manure can however be represented as normal flows.

Since the results derived at farm level are rather interpreted qualitatively in this report, all the flows were not explicitly quantified on the Sankey diagrams. However, import flows as well as recycled housed manure flows were quantified in order to give a crude scale of the size of the other system flows.

MUNICIPALITY/COUNTY RESULTS

Upscaled results could be visualized on a set of different maps after coupling the multi-level SFA model to a *Geographic Information System* (GIS) with the software *ArcGIS Pro*. It is worth mentioning that the aggregation of farm results and associated coupling to the GIS was conducted for all Norwegian municipalities displayed in Figure 6b. However, it was decided for this report to focus on the municipalities of *Sør-Trøndelag* and *Nord-Trøndelag* only, as a case study meant to facilitate the interpretation and discussion of the results.

The different maps presented in the Results section (Figure 10, Figure 11, Figure 14, Figure 15, Figure 16 and Figure 17) contain up to two types of information for the system variables (soil P stock change and manure surplus):

- an absolute value in tons P/yr, displayed with numerical labels;

- a relative value in kg P/ha, displayed for each administrative entity by the means of a captioned color scale.

2.3 Model representation

An overview of the approach followed in this project and presented in this Methodology section is provided in Figure 7 below.

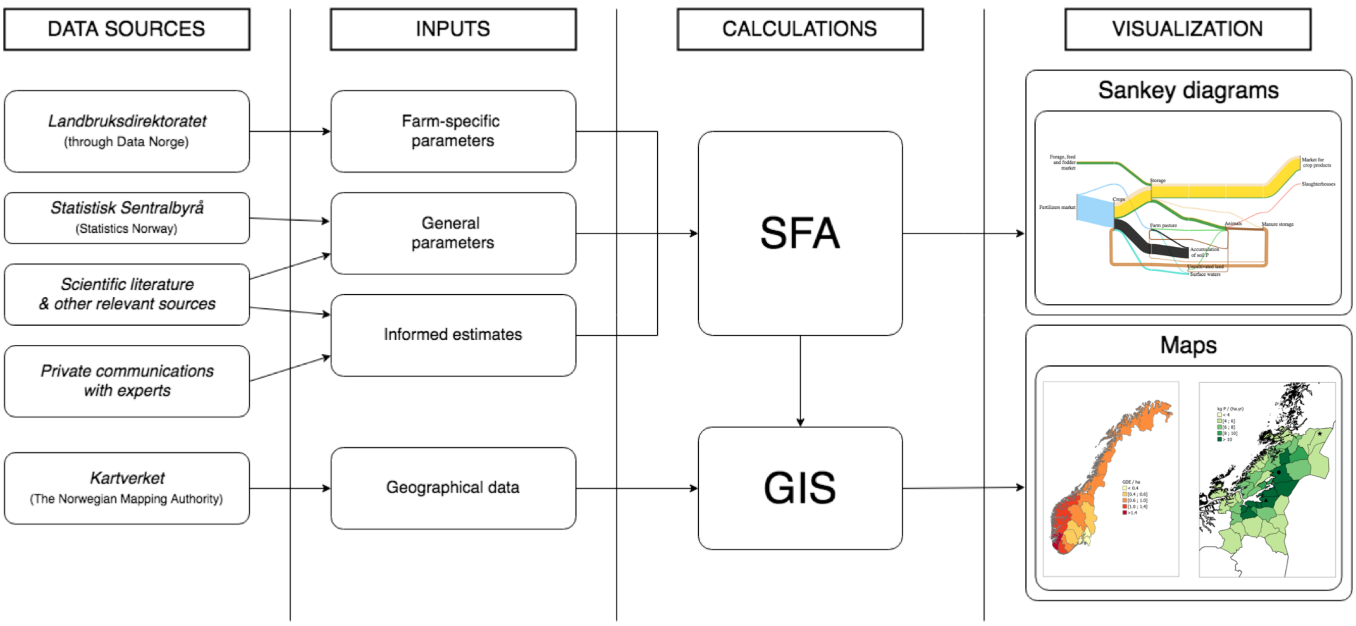


Figure 7: Schematic representation of the multi-level, spatially-explicit model developed in this project.

3 RESULTS

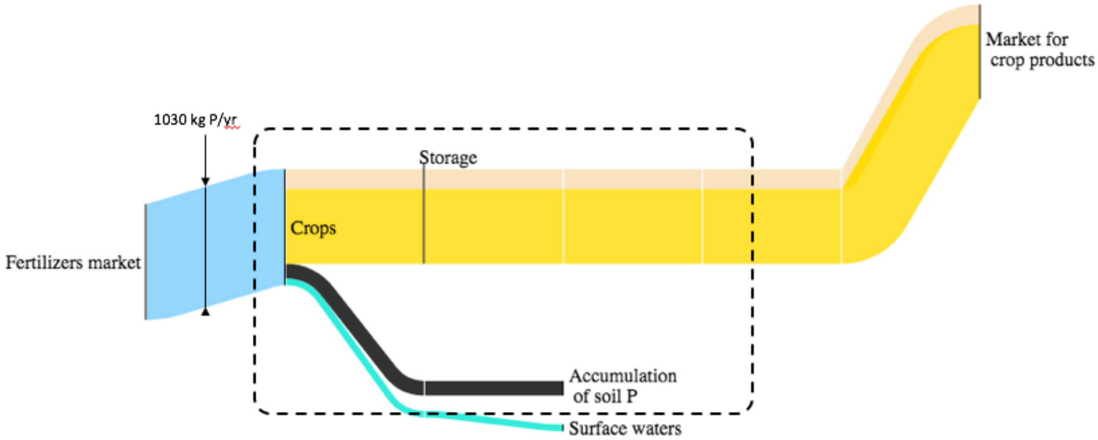
This section aims to present the results of the multi-level, spatially-explicit model developed in this project. The subsection 3.1 illustrates i) the influence of the type of agricultural production on the circulation of P at farm level and ii) the spatial discrepancies in production types revealed by the aggregation of farms by municipality and county. The subsection 3.2 presents the consequences of the implementation of the different fertilization strategies at all levels (farm/municipality/county) on the key system variables (P balance of agricultural soil and surplus of animal manure). The subsection 3.3 compare the results of the present model at very aggregated levels (county and country scale) with those of previous scientific studies conducted on the Norwegian P cycle (Hamilton et al., 2016; Hanserud et al., 2016).

3.1 CHARACTERISTICS OF THE P CYCLE FOR DIFFERENT TYPES OF AGRICULTURAL PRODUCTION

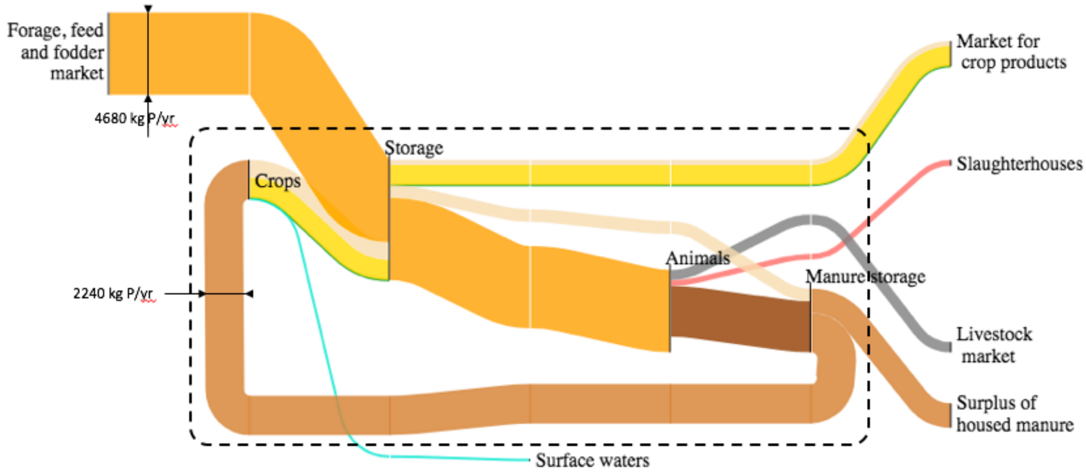
The influence of the type of agricultural production on the circulation of P at farm level can be visualized in Figure 8 including Sankey diagrams of a cereal farm (Figure 8a), a breeding pig production (Figure 8b) and a sheep farm (Figure 8c). These productions were arbitrarily selected within the database because they feature interesting characteristics that could fuel the description provided below. It is important to mention that the results displayed in Figure 8 are the model's results for Fertilization Strategy n°3 (FS3), since it is the only perspective that allows for the import of fertilizers.

It can be noticed at first that the presence of animals on farm has a clear impact on the global shape of the P circulation. Specialized farming systems, like the intensive cereal production displayed in Figure 8a, are very dependent on the imports of fertilizers from external sources in order to secure yields. Since there are no animals and therefore no manure generation, the circulation of P is mostly linear in this kind of productions, which cycle is dominated by imports of fertilizers and exports of crop products. At the opposite, mixed-farming systems, where animals and crops coexist (Figures 8b and 8c), benefit from a re-circulation of the P resource in house manure, applied as organic fertilizer on *Crops* and *Farm pasture*.

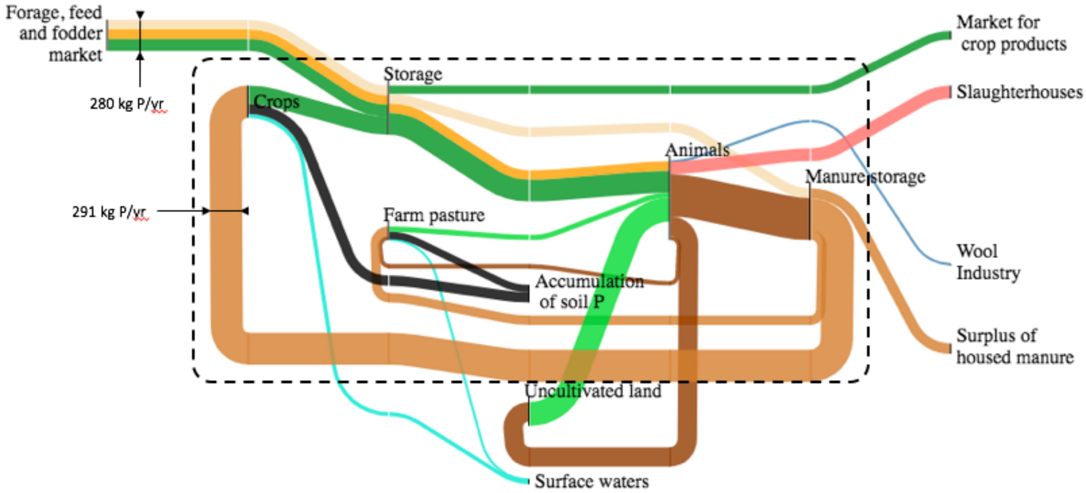
The degree of self-sufficiency of mixed farming systems relative to the import of nutrients depends on several parameters. The category of animals raised on farm is one of them, as different animals come with different diets and pasture patterns. For example, the breeding pig production (Figure 8b) is entirely dependent on the imports of concentrate feed, while a reasonable fraction of the sheep's diet can be provided by local farm resources (grass harvested on *Crops* and stored as winter forage, combined to grazing on *Farm pasture*). The raw manure from animals that are confined year-long (*Poultry* and *Pigs*) is also entirely collected and assumed available for spreading, while a significant fraction of the raw manure from grazing animals (*Cattle*, *Sheep/Goats*, *Horses*) is dropped on pasture and cannot be retrieved. The animal density of the farm, that can be measured as the number of manure animal units (GDE) per ha, has also a significant influence. For example, in a sheep farm with a given grass production capacity (*Crops* and *Farm pasture* combined), an increase of the herd size from a year to another will result in an increased need for winter forage imports and/or a larger fraction of pasture grass retrieved on *Uncultivated land*. The animal density also reflects the fertilization self-sufficiency of the farm, as it directly impacts whether the farm has a surplus of housed manure relative to fertilization requirements (here the case for both productions) or at the opposite a remaining need for fertilizers.



(a) P cycle of a cereal farm.



(b) P cycle of a breeding pigs production.



(c) P cycle of a sheep farm.

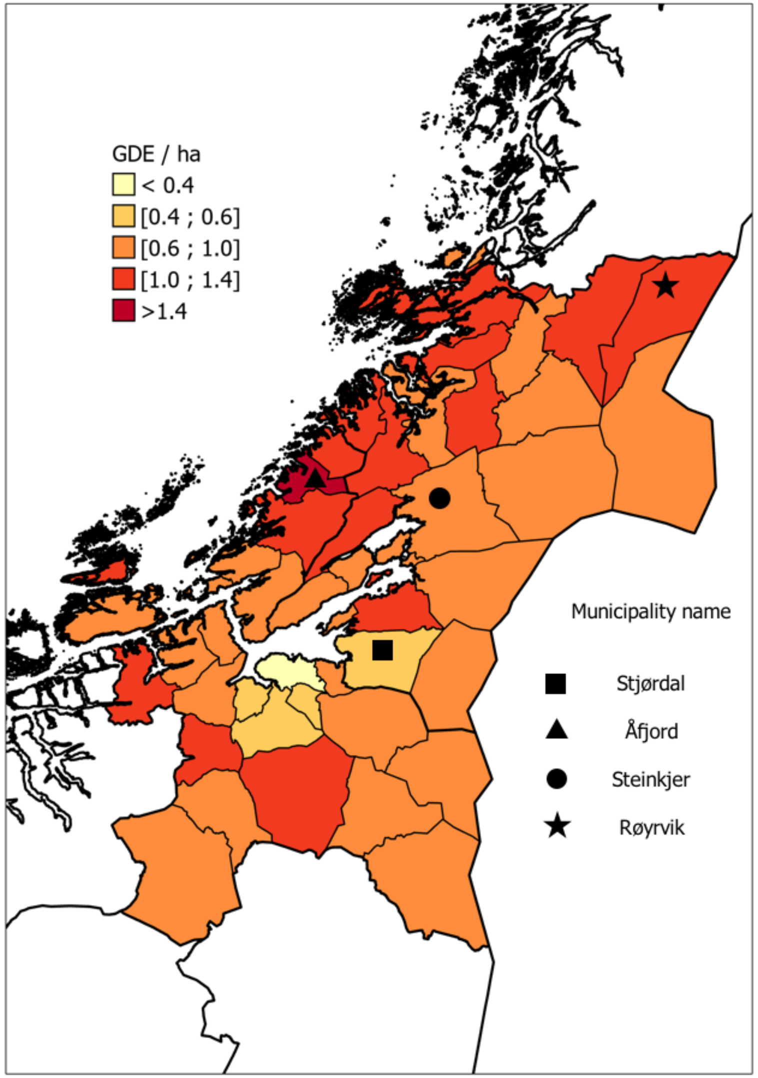
Figure 8: Circulation of P at the farm level for different types of agricultural productions. The dotted line represents the farm system boundaries. The system flows are not quantified but the size of the imports and recycled manure flows give an idea of the quantities of P flowing in the system. The color code of the flows is given in Figure 9.

Figure 9: Legend for the flows in the Sankey diagrams.

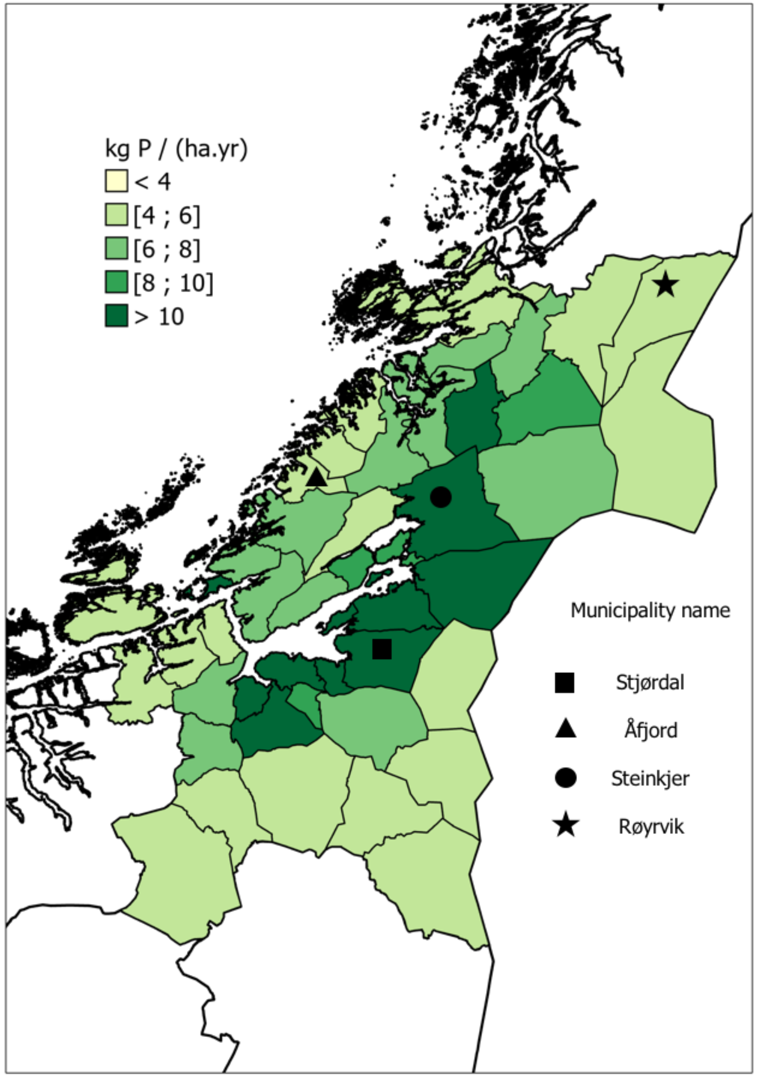
Grouping individual farms per administrative entity reveals spatial discrepancies in the agricultural production patterns, both in Trøndelag (Figure 10) and Norway (Figure 11). On both levels, the municipalities/counties that show the most animal manure units per ha (Figures 10a and 11a), i.e. animal dense areas, are often associated to a small harvest intensity (Figures 10b and 11b), and vice versa. The harvest intensity, measured in kg P harvested/ha, is actually an indirect representation of the kind of crops that are grown: cereal and oilseeds crops usually take up more P per ha compared to forage crops (see A.8 Material contents). That means that areas coloured in dark green on Figures 10b and 11b are most probably characterized by a dominant cereal production.

In Trøndelag (Figure 10), crop-based farming appears to be concentrated in the center of the county (Figure 10b), where municipalities like Stjørdal show more than 10 kg of harvested P per ha of agricultural soil. Animal husbandry seems rather distributed on the periphery, especially on the coastline, where the Åfjord municipality even has more than 1.4 GDE/ha of agricultural soil. Some municipalities, probably characterized by a more diversified agricultural production, show intermediate values on both graphs, i.e. between 0.6 and 1.0 GDE/ha and between 6 and 8 kg P harvested/ha respectively.

In Norway (Figure 11), the Atlantic coast seems to concentrate the animal husbandry activities (Figure 11a), especially the south-western counties like Sogn of Fjordane, Hordaland or Rogaland, characterized by traditional livestock farming practices. The south-eastern corner appears to concentrate arable farming (Figure 11b), with counties like Østfold or Vestfold characterized by an intensive cereal production. Among all counties, Oppland, Sør-Trondelag and Nord-Trøndelag show intermediate values on both scales, illustrating a rather mixed agricultural production system for those counties.

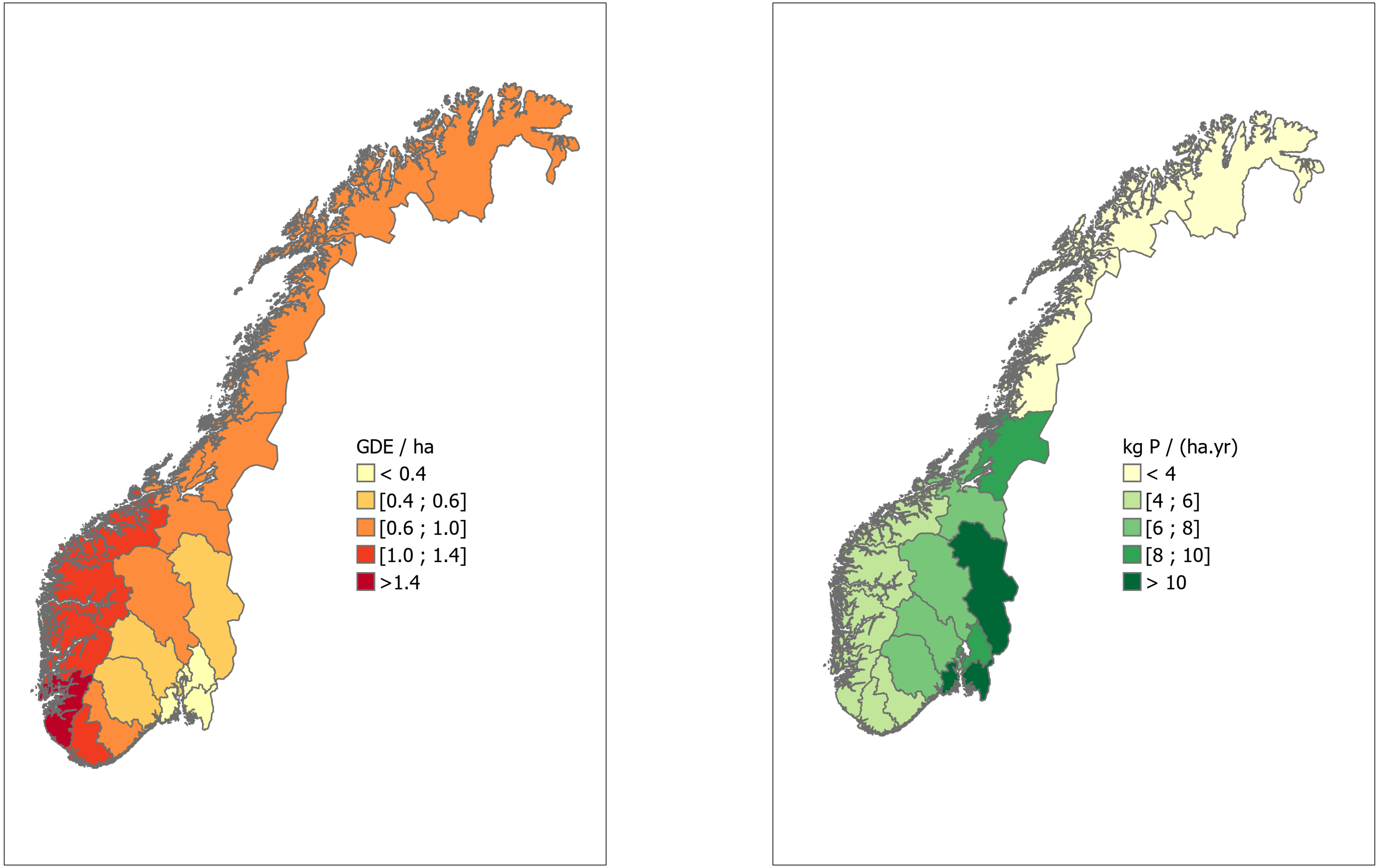


(a) Number of manure animal unit per ha



(b) Total P harvested per ha

Figure 10: Number of animal units and total P harvested per ha for every municipality in Trøndelag. Municipalities coloured in red in (a) are characterized by high animal densities, while municipalities in dark green in (b) have the most significant harvest intensity



(a) Number of manure animal unit per ha

(b) Total P harvested per ha

Figure 11: Number of animal units and total P harvested per ha for every county in Norway. Counties coloured in red in (a) are characterized by high animal densities, while counties in dark green in (b) have the most significant harvest intensity

3.2 Influence of fertilization practices

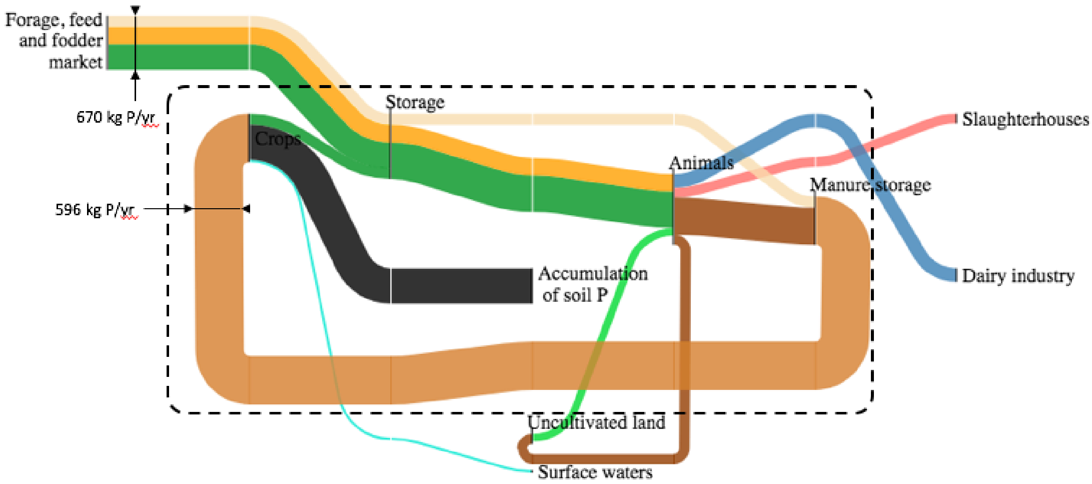
3.2.1 Farm level

The influence of the fertilization strategies defined in 2.1.2, Fertilization on the circulation of P at farm level is visualized for two given production systems in Figure 12 and Figure 13 below. Instead of selecting said farms on the basis of their type of production like in 3.1, it was rather decided to choose one farm showing a net fertilization excess in FS1 (Figure 12), and another farm showing a net fertilization deficit in FS1 (Figure 13), in order to observe how their P cycle and especially the key system variables (soil P balance, manure surplus) were affected by a change in fertilization strategy.

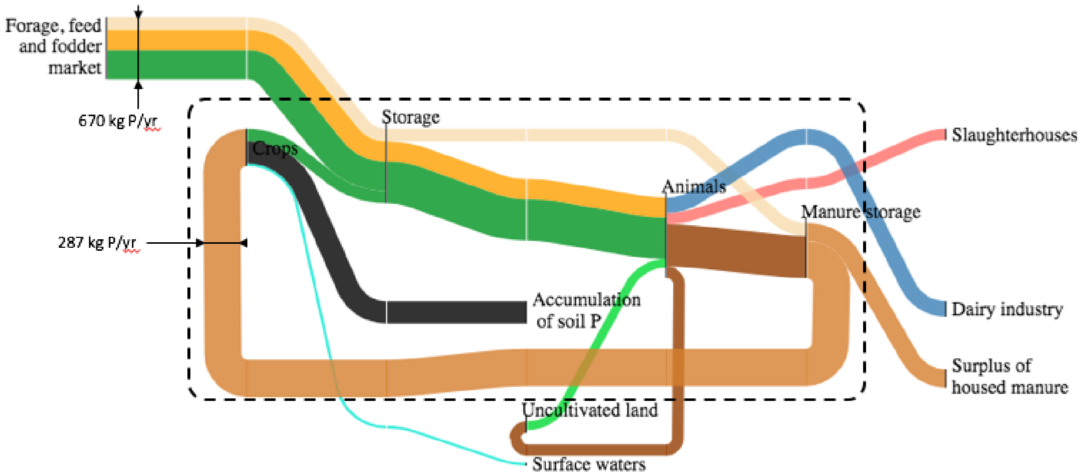
For the milk production displayed in Figure 12, a rather high animal density (1.33 GDE/ha) leads in FS1 to a net fertilization excess and to a significant accumulation of P in agricultural soil (Figure 12a). The fact that there is no generation of any manure surplus is a sign that the manure spreading requirement of min. 4 daa/GDE is in that case not sufficient to limit this accumulation of soil P. Enforcing more stringent regulations in the frame of FS2 (min. 10 daa/GDE) limits by design the amount of available housed manure that can be applied on agricultural soil in animal dense farms like this one. Complying with this strengthened regulation leads here to the generation of a positive stock change in the *Manure storage* process, contributing to curb the accumulation of soil P in agricultural soil (Figure 12b). A similar but stronger effect is observed while implementing FS3 (Figure 12c), in which the application of housed manure follows NIBIO's fertilization guidelines. A larger manure surplus and smaller soil P stock change are observed relative to FS2, because the guidelines result for this specific farm in a P application per area unit that is smaller than 1.4 kg/daa.

For the cereal production with animals displayed in Figure 13, a low animal density (0.15 GDE/ha) limits the availability of house manure as fertilizer and leads in FS1 to a net fertilization deficit (Figure 13a). For this production, FS2 does not cause any changes in the system flows (Figure 13b): this is because the animal density is too low for the farm to be concerned with the change in spreading regulations. For this production, FS3 leads to a neutralization of the fertilization deficit by the means of an import of fertilizers from external sources (Figure 13c). It is even observed a positive soil P stock change on both *Crops* and *Farm pasture*: this is because the NIBIO guidelines applied to this particular farm (with associated kind of crops and regional yields) are overestimating the fertilization requirements.

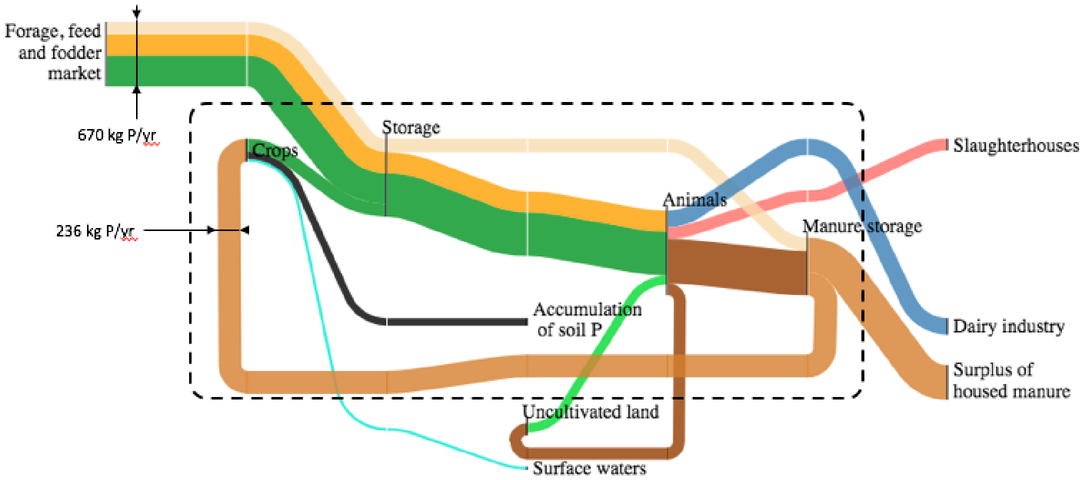
These insights at farm level show that the fertilization strategies investigated in this project have different influences on the system's flows, depending on whether the considered farm initially has a fertilization surplus or deficit. This is important to have in mind before scaling the results up to municipality and county level.



(a) FS1

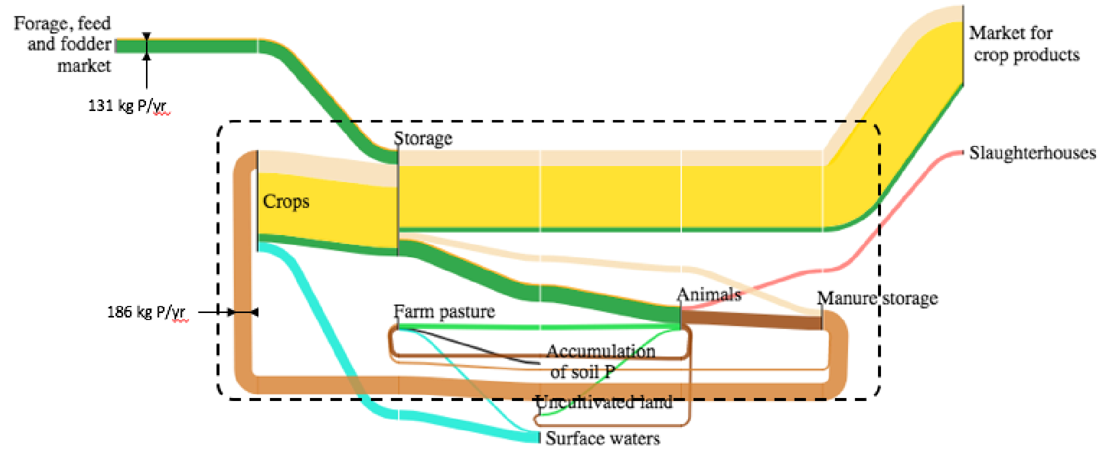


(b) FS2

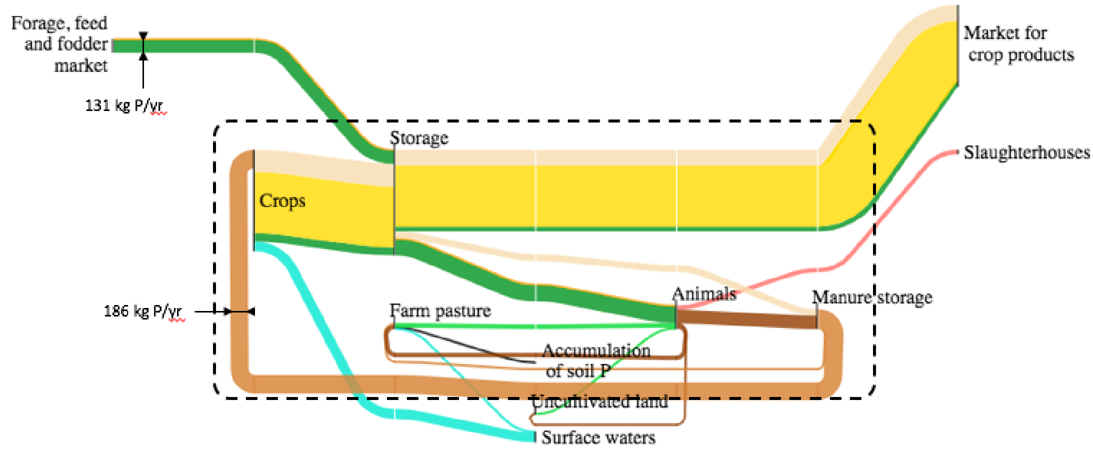


(c) FS3

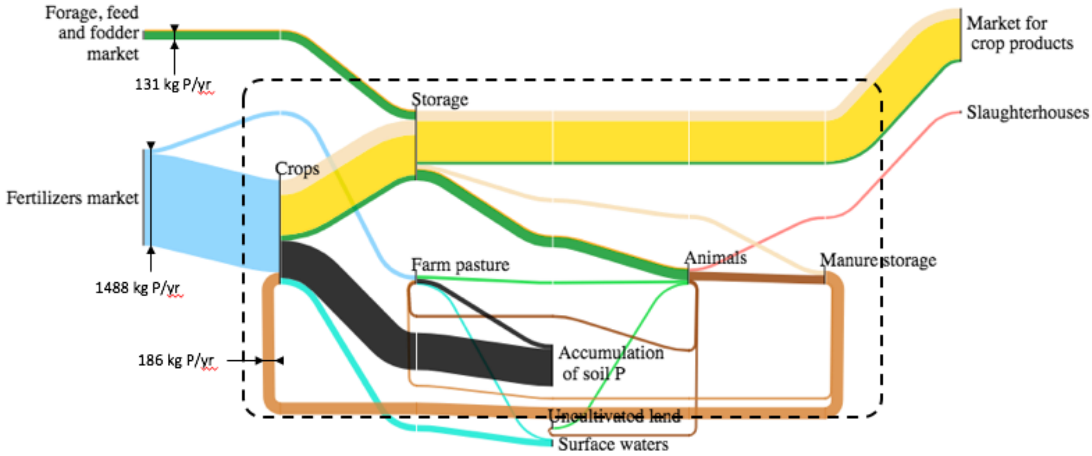
Figure 12: Influence of the fertilization strategy on the P cycle in a production with a high animal density. (a) FS1: Spreading available housed manure in the limits of current regulations (max 3.5 kg P/ha). (b) FS2: More stringent spreading regulations (max 1.4 kg P/ha). (c) FS3: Following NIBIO fertilization guidelines, with possible import of fertilizers.



(a) FS1



(b) FS2



(c) FS3

Figure 13: Influence of the fertilization strategy on the P cycle in a production with a low animal density. (a) FS1: Spreading available housed manure in the limits of current regulations (max 3.5 kg P/ha). (b) FS2: More stringent spreading regulations (max 1.4 kg P/ha). (c) FS3: Following NIBIO fertilization guidelines, with possible import of fertilizers.

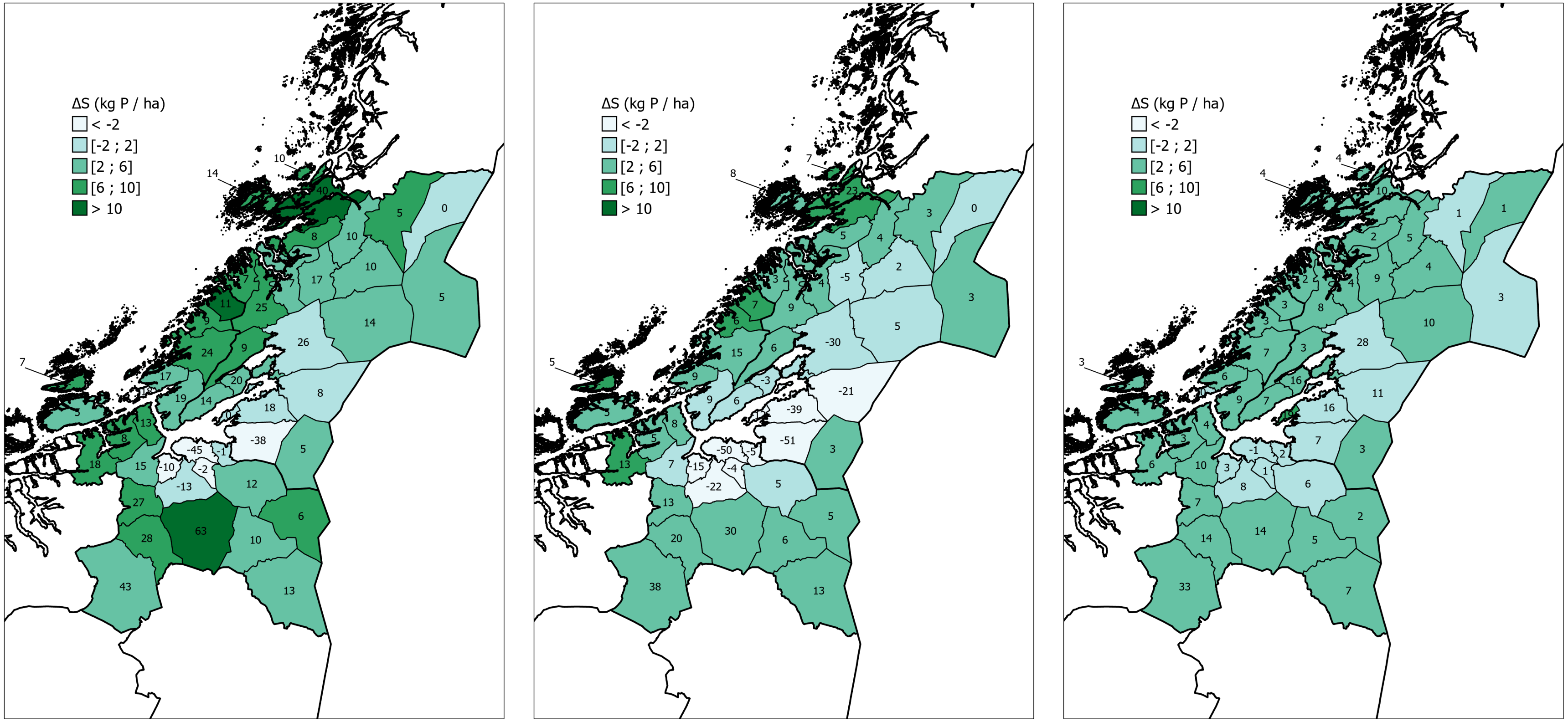
3.2.2 Trøndelag

The aggregation of the model's results for individual farms to the municipality level enables to visualize the influence of the three fertilization strategies on the soil P balances and potential surpluses of animal manure within a specific county (Trøndelag in this report).

A global pattern can be identified when comparing the maps of manure animal units per ha (Figure 10a), harvested P per ha (Figure 10b) and the municipal results for FS1 (Figure 14a): municipalities showing the highest accumulation of soil P per ha are mostly the ones with high animal densities, while municipalities characterized by larger P harvest per ha rather show small or negative soil P stock changes. Conservative spreading regulations leads in FS1 to the application of most of the available housed manure, resulting in globally small manure surpluses in Trøndelag (Figure 15a). There are some exceptions, like *Røyrvik* municipality (indicated with a star on Figures 10a and 10b), that has a rather high animal density but no soil P accumulation. Considering that this municipality has a quite significant manure surplus for FS1, it can reasonably be hypothesized that it is mostly composed of farms that do not comply with the current spreading regulations (e.g. slaughter or breeding pigs' productions).

The effects that were observed at farm level for the implementation of more stringent spreading regulations (FS2) have expected repercussions at the municipality level. All farms that do not comply with those more demanding regulations must limit their application of housed manure on fields, which leads for almost all municipalities to a reduced accumulation of P in agricultural soil (Figure 14b) and an increased absolute surplus of manure in tons/yr (Figure 15b). Unlike the farm level, for which the implementation of FS2 had no effects for productions that were already fertilizer-deficient in FS1, the aggregation to municipality level can widen soil P deficits observed in Figure 14a (e.g. *Stjørdal* municipality, indicated with a triangle on Figures 10a and 10b). This is because the status of P-deficient farms does not change, while the accumulation of soil P in farms with an initial P excess is reduced, leading thus to a smaller sum when the results are aggregated.

The implementation of FS3 has a two-fold impact at the municipality level. At first, the manure surplus in the *Manure storage* process increases in all municipalities compared to FS1 and FS2 (Figure 15c), while the municipalities that had a positive soil P stock change in FS1 and FS2 see this accumulation of P further reduced (Figure 14c). Secondly, all municipalities that were P deficient in either FS1 or FS2 move towards a fertilization surplus when individual farms follow NIBIO fertilization guidelines, which is in line with the excess fertilization observed at farm level (Figure 13c). For some municipalities, like *Steinkjer* marked with a disk on Figures 10a and 10b, the over-application of fertilizers in farms that are initially P-deficient is larger than the beneficial reduction of P accumulation in farms with an initial fertilization surplus. This results in a larger soil P balance in FS3 than in FS1 for those municipalities.

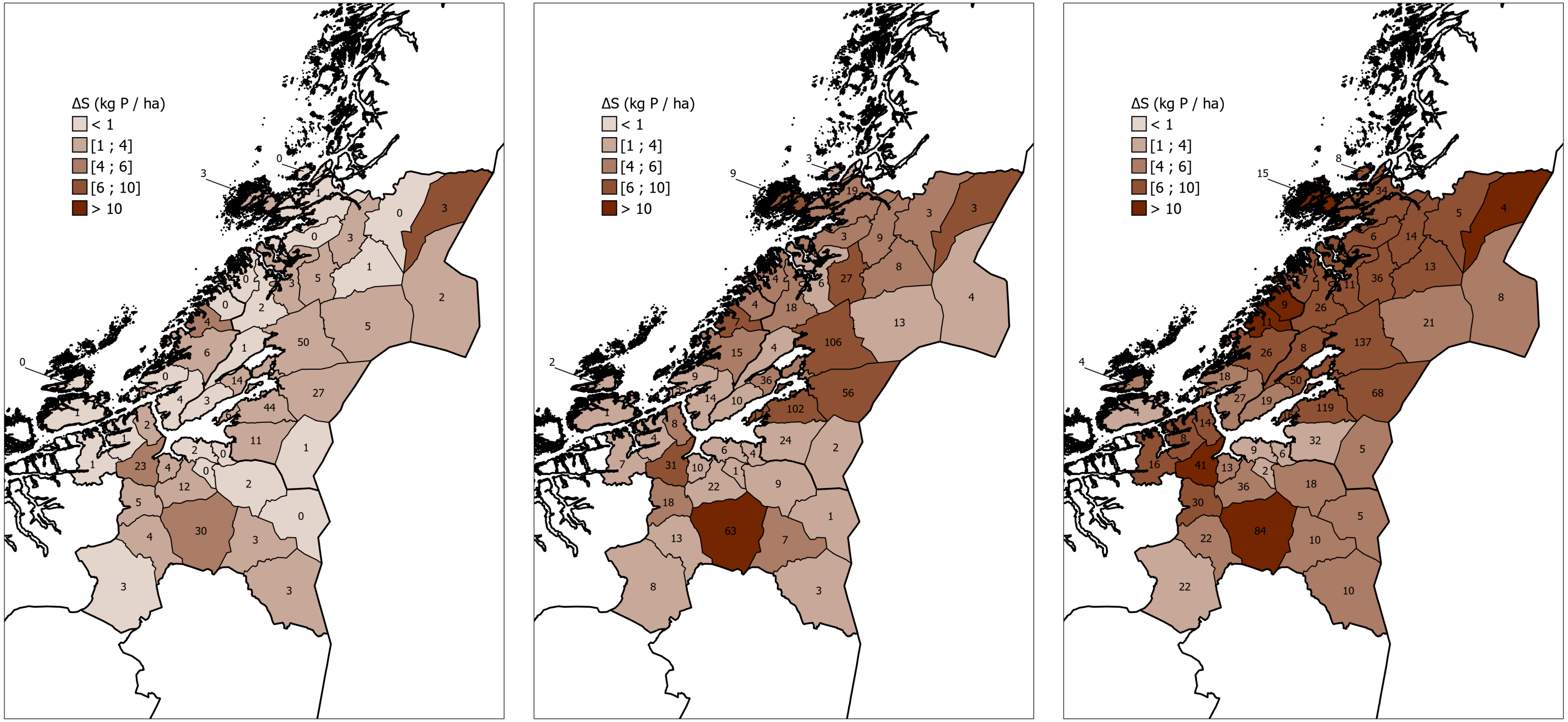


(a) FS1

(b) FS2

(c) FS3

Figure 14: Influence of the fertilization strategy on the P balance of agricultural soil for every municipality in Trøndelag. Absolute stock change in tons P/yr. Net stock change per hectare in kg P/ha. (a) FS1: Spreading available housed manure in the limits of current regulations (max 3.5 kg P/ha). (b) FS2: More stringent spreading regulations (max 1.4 kg P/ha). (c) FS3: Following NIBIO fertilization guidelines, with possible import of fertilizers.



(a) FS1 **(b) FS2** **(c) FS3**

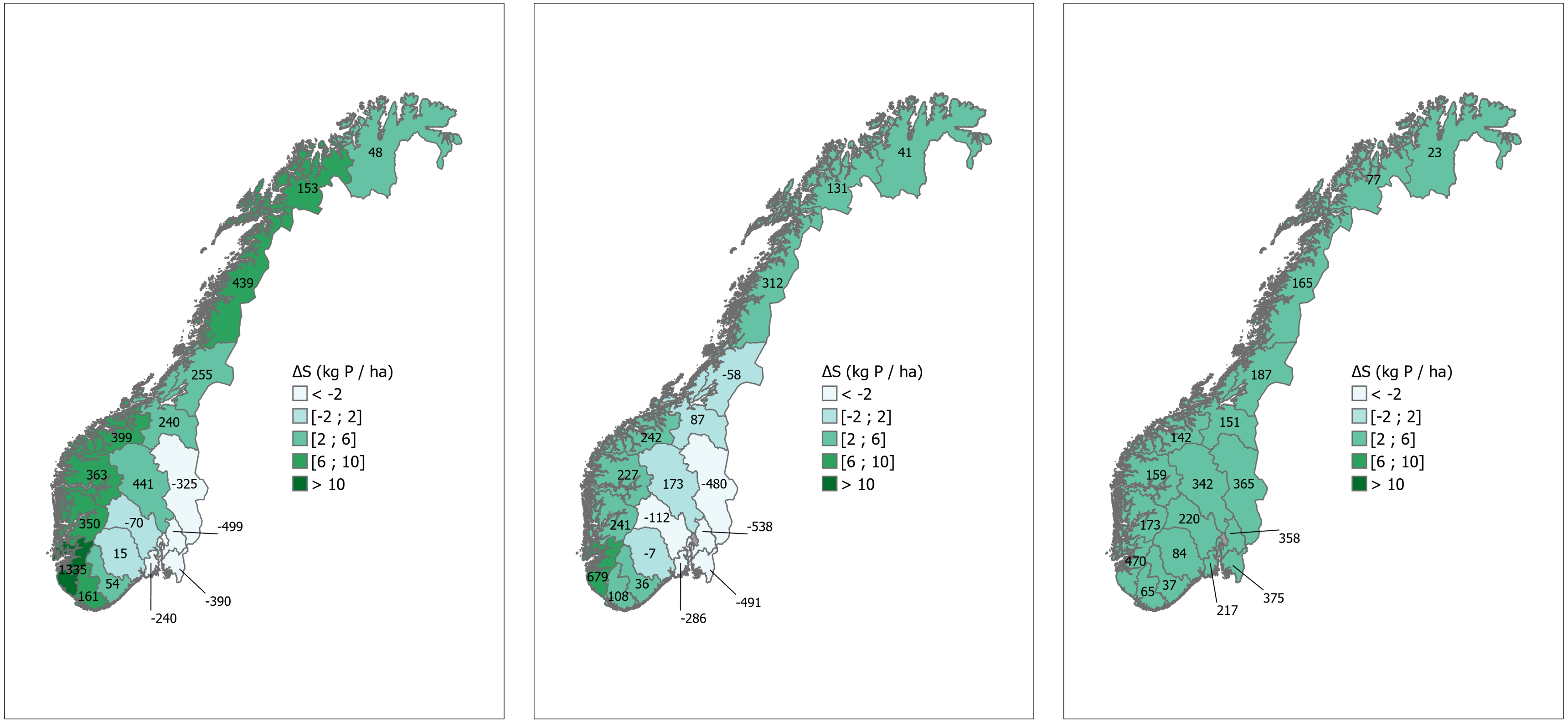
Figure 15: Influence of the fertilization strategy on the surplus of housed manure for every municipality in Trøndelag. Absolute stock change in tons P/yr. Net stock change per hectare in kg P/ha. (a) FS1: Spreading available housed manure in the limits of current regulations (max 3.5 kg P/ha). (b) FS2: More stringent spreading regulations (max 1.4 kg P/ha). (c) FS3: Following NIBIO fertilization guidelines, with possible import of fertilizers.

3.2.3 Norway

Further aggregation of the model's results to the county level enables to visualize the influence of the three fertilization strategies on the soil P balances and potential surpluses of animal manure within Norway. Similar conclusions that those mentioned for the municipality level can be drawn at the county level.

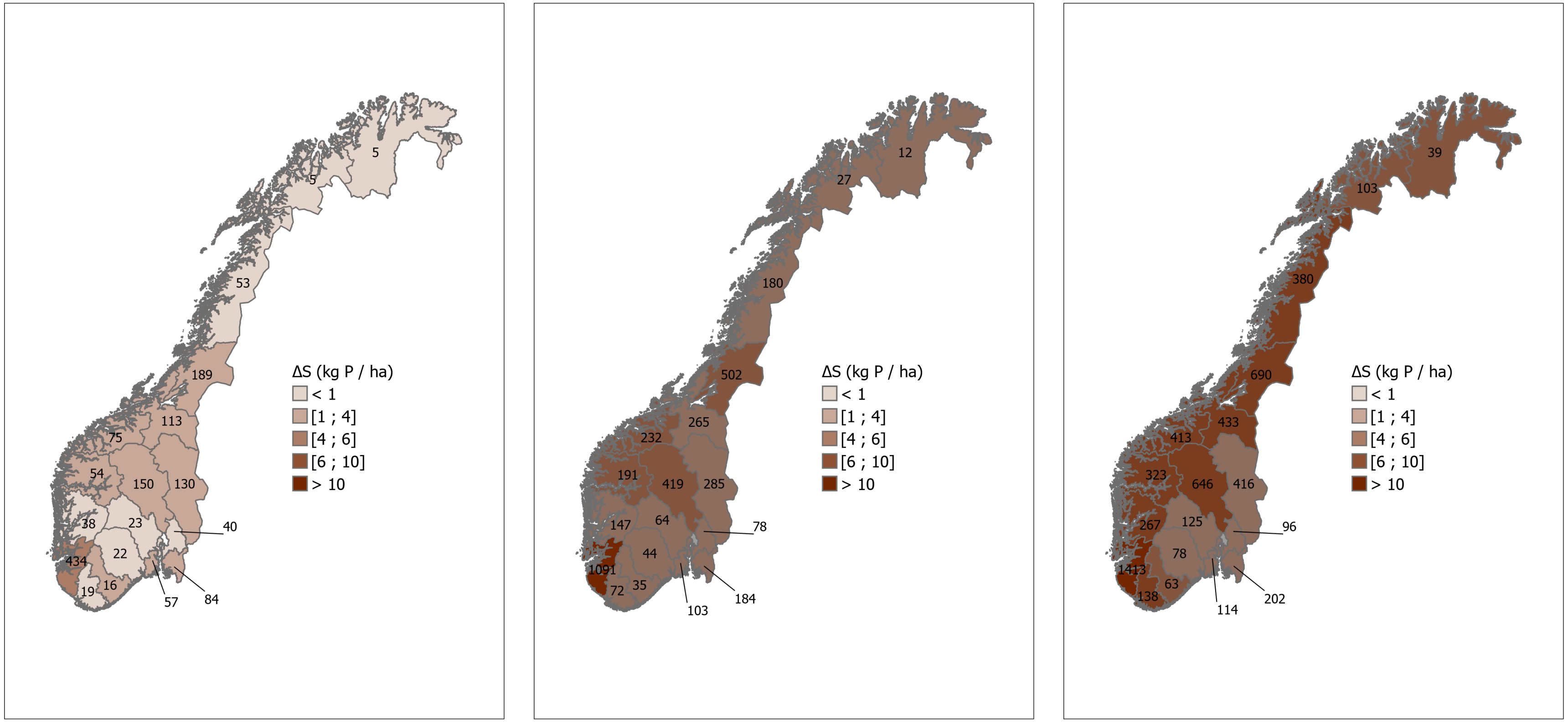
In FS1, which results are displayed in Figures 16a and 17a, the counties with a significant soil P accumulation are mostly the ones with high animal densities in Figure 11a (e.g. south-western counties like Rogaland and Hordaland), while counties showing a global deficit of P in agricultural soil correspond to intensive P harvest per ha in Figure 11b (e.g. south-eastern counties like Vestfold, Østfold or Oslo/Akershus, characterized by an intensive cereal production).

The surplus of manure increases in all counties with the successive implementation of FS2 and FS3 (Figures 17b and 17c). Regarding the soil P balance, FS2 is curbing soil P accumulation of counties that showed a net surplus in FS1 and widening P deficits of counties that already had a depletion of soil P in FS1 (Figure 16b). FS3 is homogenizing the soil P balance at the national scale towards a global positive stock change (Figure 16c), with 1) a reduced P accumulation for counties that showed a surplus in FS1 and/or FS2, and 2) an over-application of imported fertilizers in counties that were P-deficient in FS1 and/or FS2, that leads to a fertilization surplus in those counties. The very small deviation in the values of the soil P stock change per hectare among Norwegian counties in Figure 16c reflects the fact that the fertilization guidelines from NIBIO take into account regional yields through a correction of the recommended P inputs.



(a) FS1 **(b) FS2** **(c) FS3**

Figure 16: Influence of the fertilization strategy on the P balance of agricultural soil for every county in Norway. Absolute stock change in tons P/yr. Net stock change per hectare in kg P/ha. (a) FS1: Spreading available housed manure in the limits of current regulations (max 3.5 kg P/ha). (b) FS2: More stringent spreading regulations (max 1.4 kg P/ha). (c) FS3: Following NIBIO fertilization guidelines, with possible import of fertilizers.



(a) FS1 **(b) FS2** **(c) FS3**

Figure 17: Influence of the fertilization strategy on the surplus of housed manure for every county in Norway. Absolute stock change in tons P/yr. Net stock change per hectare in kg P/ha. (a) FS1: Spreading available housed manure in the limits of current regulations (max 3.5 kg P/ha). (b) FS2: More stringent spreading regulations (max 1.4 kg P/ha). (c) FS3: Following NIBIO fertilization guidelines, with possible import of fertilizers.

3.3 Validation of the results against previous research

The aggregation to county and national level of the system variables linked to agricultural soil processes provides a good basis for comparison of the results with previous P flows analyses conducted in Norway. As mentioned in the Introduction, Hamilton et al. (2016) developed a cross-sectoral analysis of the Norwegian P cycle (including Aquaculture, Fisheries as well as Agriculture). The main purpose of this publication was to investigate the potential synergies existing between these production sectors in order to optimise P use at national scale. Even though such an analysis falls off the scope of the present project, results related to the agricultural sector can still be compared. Results from Hanserud et al. (2016) provide a maybe more interesting opportunity for comparison since 1) the focus was set on animal manure as secondary P fertilizer and 2) the model they used is spatially-explicit at county level. The maps of the multi-regional soil P balance calculated by Hanserud et al. (2016) for different Fertilization Regimes (FR) are reproduced in Figure 18, to facilitate comparison with the county-specific balances calculated in this project and displayed in Figure 16. National-scale results for the three Fertilization Strategies (FS) of this project, for the three Fertilization Regimes (FR) of Hanserud et al. (2016) as well as for the baseline scenario of Hamilton et al. (2016) are gathered in Table 5.

3.3.1 Comparison with Hanserud et al. (2016) (county level)

Figure 18 is extracted from Hanserud et al. (2016), and displays the results obtained for the three Fertilization Regimes (FR) investigated in this paper:

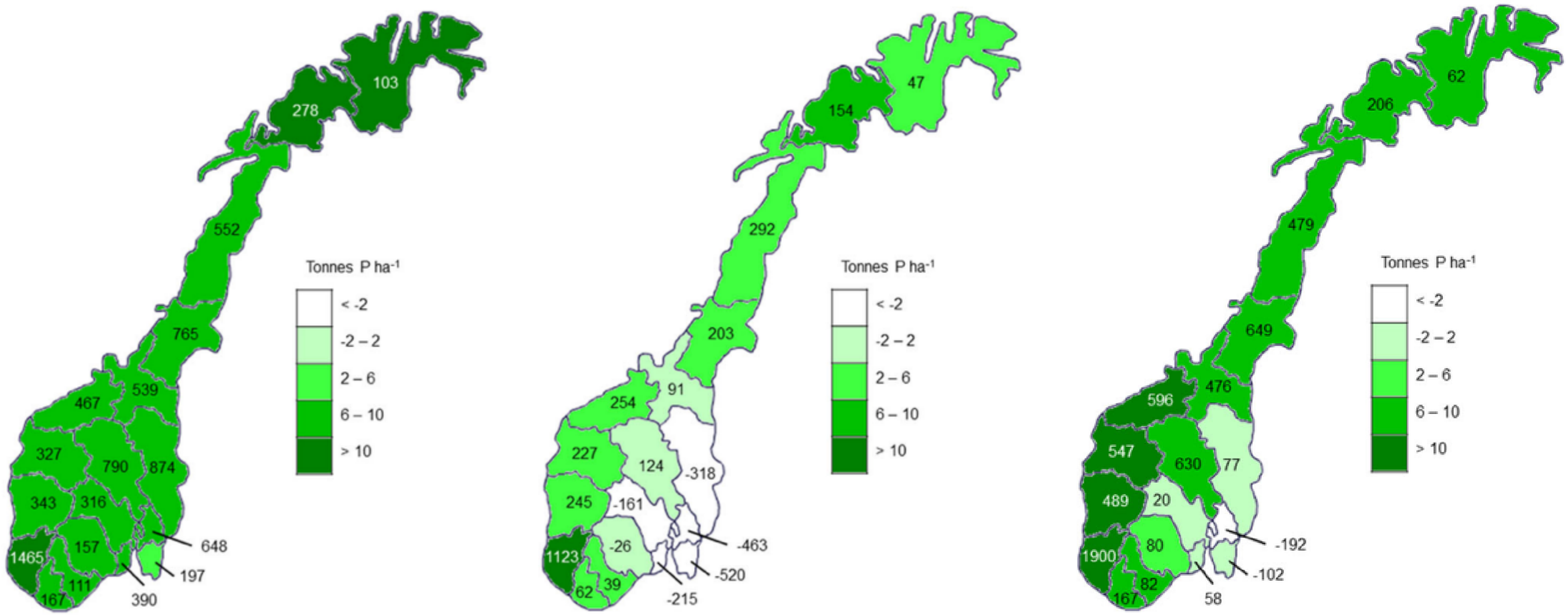
- FR0: Status quo soil P balance, based on available statistics for all inputs and outputs flows of P for agricultural soil.

- FR1: Soil P balance without mineral fertilizers and with a maintenance strategy (required fertilizer input equals P removed through plant yields).

- FR2: Soil P balance without mineral fertilizers and with a transition fertilization strategy (required fertilizer input from FR1 is corrected with plant-available P concentration in soil, measured in P-AL values)

Table 5: Comparison of the input and output flows for agricultural soil and resulting soil P balance for the fertilization perspectives explored in this project, Hanserud et al. (2016) and Hamilton et al. (2016). FS = Fertilization Strategy; FR = Fertilization Regime; MF = Mineral Fertilizers, OF = Organic Fertilizers (excluding housed manure); HM = Housed Manure used as secondary fertilizer; PM = Raw manure dropped by animals grazing on agricultural area (*Farm pasture*).

<table>
<tr><th rowspan="2"></th><th colspan="4">Inputs</th><th colspan="2">Outputs</th><th rowspan="2">Stock change</th><th rowspan="2">Manure surplus</th></tr>
<tr><th>MF</th><th>OF</th><th>HM</th><th>PM</th><th>Yields</th><th>Runoff</th></tr>
<tr><td>FS1</td><td>0</td><td>0</td><td>10278</td><td rowspan="3">670</td><td rowspan="3">7236</td><td rowspan="3">980</td><td>2732</td><td>1507</td></tr>
<tr><td>FS2</td><td>0</td><td>0</td><td>7855</td><td>309</td><td>3930</td></tr>
<tr><td>FS3</td><td colspan="2">5335</td><td>5851</td><td>3640</td><td>5934</td></tr>
<tr><td>FR0 (Hanserud et al., 2016)</td><td>7875</td><td>1009</td><td rowspan="3">8825</td><td rowspan="3">2350</td><td rowspan="3">10525</td><td rowspan="3">1046</td><td>8488</td><td>0</td></tr>
<tr><td>FR1 (Hanserud et al., 2016)</td><td>0</td><td rowspan="2">1864</td><td rowspan="2">1468</td><td>0</td></tr>
<tr><td>FR2 (Hanserud et al., 2016)</td><td>0</td><td>0</td></tr>
<tr><td>Hamilton et al. (2016)</td><td>8400</td><td>2500</td><td colspan="2">12000</td><td>10700</td><td>1200</td><td>11000</td><td>0</td></tr>
</table>



(a) FR0 **(b) FR1** **(c) FR2**

Figure 18: Results from Hanserud et al. (2016) - Annual soil P stock change (a) or surplus fertilization (b,c) for three different Fertilization Regimes (FR), in absolute (tons P.yr^{-1}) and per hectare (kg P.ha^{-1}.yr^{-1}) values. FR0 = Status quo soil P balance, based on available statistics for all inputs and outputs flows of P for agricultural soil. FR1 = Soil P balance without mineral fertilizers and with a maintenance strategy (required fertilizer input equals P removed through plant yields). FR2 = Soil P balance without mineral fertilizers and with a transition fertilization strategy (required fertilizer input from FR1 is corrected with plant-available P concentration in soil, measured in P-AL values).

It is very important to highlight that the results of FR1 and FR2 that are shown in Figure 18 represent a fertilization surplus, which calculation is shown in Equation 7 below, while the maps in Figure 16 are displaying the soil P stock change resulting from this project's Fertilization Strategies (FS).

$$\begin{aligned}\text{Surplus fertilization} = &\ \text{Housed manure} + \text{Manure from grazing animals} \\ &+ \text{plant available P in total sewage sludge} - \text{fertilizer requirement}\end{aligned} \tag{7}$$

This makes the comparison of the results technically irrelevant for FR1 and FR2, even though it is possible to notice that FS1 and FS2 (Figures 16a and 16b) show deficit/surpluses patterns for Norwegian counties that are similar to those of FR1 (Figure 18b). This is because the calculation of the soil P stock change for FS1 and FS2, shown in Equation 5 of the 2 section, has almost the same formulation than the surplus fertilization in Equation 7 (except for the sewage sludge that is not accounted for in the present project). FR2 features a correction of the fertilization requirements based on county-specific soil plant-available P contents (P-AL values), an aspect that is ignored in this project. This explains why the results of the surplus fertilization for this regime (Figure 18c) are not comparable to the soil P balances in FS1 and FS2.

A relevant comparison is however possible between Figure 18a, that displays the soil P balance calculated under FR0 in Hanserud et al. (2016), and the soil P balances derived under the different FS of this project (Figure 16). FS1 (Figure 16a) and FS2 (Figure 16b) result both in soil P balances that are very different from those of FR0. This is mostly due to the fact that they represent perspectives in which a farm can only count on its own resources for crops fertilization, whereas FR0 describes a status quo in which mineral fertilizers and sewage sludge can be applied on agricultural soil. FS3 (Figure 16c) results in soil P balances that are closer to those of FR0, because this perspective allows for the import of fertilizers in farms where there is a remaining need for fertilization and is therefore more realistic, hence closer to the status quo. FS3 and FR0 are both characterized by a general over-application of fertilizers on agricultural soil, that results in positive soil P balances for all counties. However, it can be noticed that 1) the soil P stock changes are more homogeneous in FS3 than in FR0, with all counties showing a P balance between 2 and 6 kg P/ha, and 2) the over-application of P to agricultural soil is significantly higher for FR0 than for FS3 (both in absolute and per ha values), at the exception of the Østfold county.

3.3.2 Comparison with Hanserud et al. (2016) and Hamilton et al. (2016) (national level)

Since the SFA conducted in the present project was quantified for the year 2018, it seems reasonable to expect different results for the key system variables while comparing them to equivalent flows in Hanserud et al. (2016) and Hamilton et al. (2016), calculated as an average for the period 2009-2011. Table 5 enables to compare the sizes (in tons P/yr) of the main inputs and outputs to agricultural soil, the soil P balance as well as the potential fertilization surplus associated to the FS of this project, the FR from Hanserud et al. (2016) and the Baseline scenario of Hamilton et al. (2016).

The table illustrates at first that different resolutions were considered in the three studies for some of the system flows. For instance, Hanserud et al. (2016) and Hamilton et al. (2016) differentiate mineral and organic fertilizers, while the import flow of fertilizers in this project's FS3 does not (hence a single value of 5335 tons P/yr that captures both sources). Similarly, Hamilton et al. (2016) does not differentiate animal manure dropped on pasture and housed manure. The table also reveals important differences in the fertilization approach. The FR developed in Hanserud et al. (2016) correspond to different fertilization requirements and allow or not the use of mineral fertilizers, but the quantity of housed manure applied on agricultural soil (calculated from statistics) is the same in each of the FR (8825 tons P/yr). On the contrary, the FS developed in the present project correspond to different managements of animal manure depending on the individual farms' characteristics (e.g. animal density) and the ground assumptions of those strategies (e.g. spreading regulations). This results in different flows for housed manure used as secondary fertilizer and different values for the surplus of manure in the *Manure storage* process (column on the right in Table 5). It is not really relevant for this reason to compare the inputs of housed manure to agricultural soil.

The imports of fertilizers in FS3 appear to be significantly smaller than the combined use of mineral and organic fertilizers calculated in Hanserud et al. (2016) (FR0) and Hamilton et al. (2016). The quantity of manure-P dropped by grazing animal on agricultural area (i.e. on *Farm pasture*) is also small in the present model (670 tons P/yr) compared to that in Hanserud et al. (2016) (2350 tons P/yr).

The aggregated losses through erosion and runoff (980 tons P/yr) seem reasonably close to those calculated at the national scale by Hanserud et al. (2016) and Hamilton et al. (2016), 1046 and 1200 tons P/yr respectively. The aggregated flows of P harvested through yields (7236 tons P/yr) are however significantly smaller than those of the two papers (10525 and 10700 tons P/yr respectively). Since the uncertainty associated to harvest flows in the system is either low or medium (see Table 4 in 2.1.3 Uncertainties linked to data quality), this large gap probably reflects more the fact that 2018 was a pretty bad year yields-wise compared to the period 2009-2011 (Statistisk Sentralbyrå, 2019).

Both the aforementioned differences in ground assumptions and the identified gaps between flows that should theoretically be of comparable sizes lead to different values for the soil P balance of agricultural soil and the surplus of animal manure. The soil P balances of all FS are significantly smaller than those of the two other studies, mostly because the present model is the only one that calculates a theoretical manure surplus. Adding this surplus manure to the soil P balance results in FS3 (3640 + 5934 = 9574 tons P/yr) being the closest perspective to FR0 of Hanserud et al. (2016) (8488 tons P/yr) and Hamilton et al. (2016) (11,000 tons P/yr).

4 DISCUSSION

The aim of this last section is to 1) identify both the strengths and shortcomings of the methodology followed in this project and their implications, 2) interpret the model's results in the light of the main issues in the management of P as fertilizer (e.g. spatial discrepancies of secondary resource, unsustainable fertilization practices, etc.) and 3) discuss the relevance of this model for informing policy design directed towards a sounder management of P at various scales.

4.1 STRENGTHS AND WEAKNESSES OF METHODOLOGY

The model developed in the present project can foster in many ways the implementation of a better management of P for agricultural purposes. At the same time, the level of confidence in its results is not only influenced by the uncertainty associated to data quality (see 2.1.3 Uncertainties linked to data quality) but also by inherent shortcomings that are discussed here below.

4.1.1 ADVANTAGES AND POSSIBLE IMPROVEMENTS

Conducting a SFA of P for all Norwegian farms provides a solid basis to derive farm-specific indicators (e.g. feeding or general nutrient efficiency), that could be aggregated to produce statistics on different types of production and thereby contribute to inform targeted policy-making. It will nevertheless require further improvements in order to do so: a data reconciliation on the *Animals* process is needed in order to derive a proper farm balance of P, while getting access to trade data for the imports of feed and fertilizers could significantly increase the level of confidence in the system quantification.

Choosing the farm resolution as a starting point enables also to map the supply and demand of secondary fertilizers at the most relevant scale, with the possibility of identifying synergies between productions that have an excess of housed manure and productions with a net fertilization deficit. Said synergies already exist to a small extent, with the export of excess manure between neighbouring farms, but these trade flows remain quite small in comparison to the overall quantity of available housed manure (see Table A76 from Olav Kolle and Oguz-Alper (2018, p. 88)). Mapping fertilization surpluses and deficits among agricultural productions can only contribute to the development of said manure trade flows.

In addition to valuable insights at farm-level, the model developed in the present project provides results that can be scaled up to higher decision levels, thanks to an integrated system definition coupled to a geographic information available for each production. Results for both soil P balance and manure surplus at municipality level (Figure 10, Figure 14 and Figure 15) can provide a valuable overview of the fertilizer resource distribution within a county to local policymakers in charge of organizing a more efficient management of nutrients. It makes particular sense to give regional public authorities access to this type of data, because:

- they are at the interface between a wide range of stakeholders involved in the local phosphorus cycle with either common or competing interests, and therefore have a crucial organizational role to play in the implementation of the desired bio-economy of nutrients;

- water quality monitoring projects are often conducted at municipality or county level, and could benefit from an improved resolution of soil P balances in order to design adapted mitigation policies.

Further aggregation of the model's results to county level enables to identify and visualize spatial discrepancies in the resource distribution between different regions of Norway (Figure 11, Figure 16 and Figure 17), which makes this type of model a privileged tool for informing national scale strategies, like the MIND-P project's goal of mineral P independence by 2030. The multi-level analysis enabled for example to confirm key findings of previous studies performed at more aggregated levels (Hamilton et al., 2016; Hanserud et al., 2016): Norway has the potential to become a net exporter of P-fertilizers since the mere generation of housed manure already exceeds the global Norwegian need for fertilizers (see Table 5), but this potential is significantly hindered by an uneven distribution of the resource at the national scale (Figure 16). However, additional improvements would be needed in order for this model to practically inform decision-making at different scales. The results produced by coupling the SFA model to the Geographic Information System need in the long-term to be enhanced resolution-wise, in order to produce maps of the resource distribution between farms within a chosen municipality. This could be done in a fashion similar to that of NIBIO's *Gårdskart*, that shows area characteristics of a significant number of agricultural productions (NIBIO, 2020a). In addition to area figures, this interactive tool could display for each farm a set of calculated indicators and/or a fertilization status (quantified surplus/deficit).

4.1.2 Shortcomings and implications

Soil processes

The present model ignores the pre-existing P level of the farms' agricultural soil. Indeed, as mentioned in the Introduction, past over-application of fertilizers on agricultural soil has led to a significant build-up of both plant-available and residual P in arable soils, which is both affecting fertilization efficiency (through the law of diminishing returns followed by yields) and increasing environmental risks. In Norway, plant-available P in soil is estimated by extraction with an ammonia-acetate-lactate solution (Egnér et al., 1960)) in mg P-AL per 100 g soil. Norway, like many other developed countries, has seen an accumulation of plant-available P in agricultural soil in the past decades, as illustrated in Figure 19 extracted from Brod (2018), that shows an aggregation at county level of P-AL levels measurements.

To that extent, neglecting the stocks of P in agricultural soil processes in this project necessarily leads to an overestimation of fertilization requirements at farm level. In addition to a yield correction, the NIBIO guidelines used in FS3 (NIBIO, 2020b) also feature a fertilization correction relative to P-AL levels: those were ignored in this project, assuming that every farm had an optimal soil P status. This is obviously wrong, but was again decided because of a lack of data for the scale of interest: since 2016, soil P-AL measurements conducted at farm level are no longer made public (Hanserud, 2020). A more systematic documentation of this kind of data by land users would contribute to design, at farm-level, fertilization strategies including a correction of fertilization requirements based on soil levels in plant-available P, as conducted at county scale by Hanserud et al. (2016) and displayed on Figure 18c.

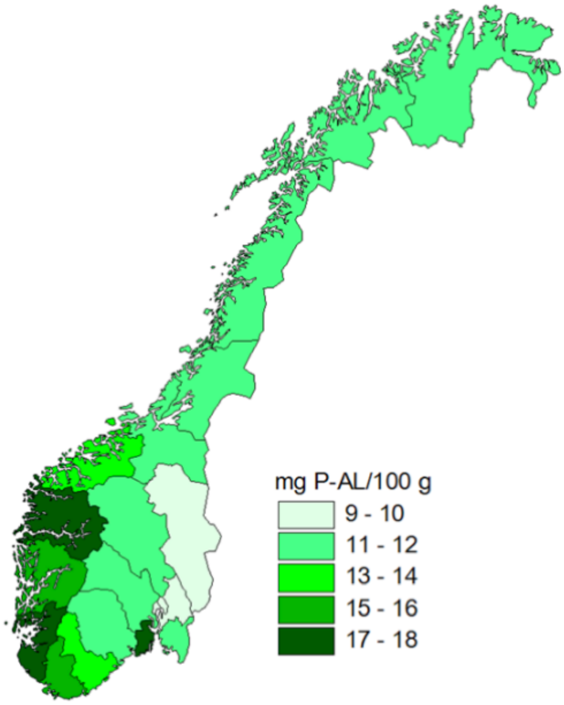


Figure 19: Norwegian soil-P status in 2014. Soil phosphorus status is calculated in mg P-AL/100g, the unit of the Norwegian standard soil test. An optimal P-AL level ranges between 5 and 7 mg/100g soil (Krogstad et al., 2008). Extracted from Brod (2018).

A further disaggregation of the runoff factor would also make the model more relevant for the assessment of the environmental risks linked to the losses of P to surface waters, as already mentioned in 2.1.3 Uncertainties linked to data quality. This was considered off the scope of the present project but could be conducted in further research, either by 1) incorporating in the model high-resolution meteorological data and very specific farm parameters/practices (fields slopes, tillage in automn, etc.) or by 2) using fields measurements like the ones of the JOVA project (Hauken, 2018), with a refined resolution.

TRADE FLOWS

As explained in section 2.1.2 2.1.2, the statistics available at farm level are only related to production, as it is the farm's production capacity that is reviewed by *Landbruksdirektoratet* when evaluating the economic support that each farm should receive. It was therefore not possible in this project to access data related to imports, meaning that those input flows were always quantified by mass-balance (e.g. the import of concentrate feed is presumed to match perfectly its consumption by animals). It seems to be a quite reasonable assumption, necessary to quantify the system at farm level, but it results by design in a high or very high uncertainty for those import flows (see Table 4 in 2.1.3 Uncertainties linked to data quality).

The absence of trade data also results in inconsistencies for imports and exports flows when up-scaling the system at higher aggregation levels. For instance, grouping the imports of straw as animal bedding to the municipality level implies that the trade of straw between farms within this municipality is ignored, and leads to the conclusion that all the straw used in this municipality is imported. Another example: if the exports of sheep to slaughterhouses happening in every sheep production of a county are upscaled to that county level by a simple sum of the export flows, it will necessarily result in this county being considered a net exporter of sheep, although said slaughterhouses might probably be within this county. This illustrates that it is impossible, in the system as it is currently defined, to maintain the system boundaries when changing level. This could be addressed in the long term by enriching the model with high resolution trade data, which again is dependent on more documentation of said flows by farmers. It is however important to mention that these challenges linked to system upscaling only applies to trade flows, as it is completely possible and consistent to upscale internal flows as well as stock changes in both agricultural soil and *Manure storage* processes. For example, the agricultural soil P balance of a municipality really is the sum of the soil P balances of each farm within this municipality.

Finally, the absence of trade data in the model (especially for imports) resulted in the impossibility to validate some key assumptions that were taken because of the lack of data on internal flows. This is typically the case of hypotheses made for the removal of straw on cereals and oilseeds crops, or for the management of forage in farms with a winter forage demand (see A.1 Forage management and A.2 Straw removal). It was especially problematic for the flow of imports of fertilizers from external sources, that could not be validated against statistics, resulting in high / very high uncertainty associated to the input flows to agricultural soil (see Table 4 in 2.1.3 Uncertainties linked to data quality).

ANIMALS

Despite the significant number of animal categories taken into account in the model and the overall good data availability for the *Animals* process, there is some room for improvement regarding the resolution in the definition of this process. Indeed, there are many category-specific flows that could not be captured in the scope of the present project in order to keep a reasonable data intensity. In farms with dairy cows, it is for example common that a fraction of the milk production is used for the feeding of calves in their first month (Spruit, 2019). It was also assumed that pigs are fed with concentrate feed only, although it can happen in many farms that they are given locally grown potatoes, carrots, or even bio-waste from external industries like breweries (Rebbestad, 2020). For animals consuming winter forage, it was assumed that they do not eat straw, although this is probably not verified for exceptionally dry years with low meadow yields like in 2018 (Norsk Landbruksrådgiving, 2018). These three examples illustrate that the model is not able to capture the true reality of animal diets, but a similar reasoning applies to animal bedding as well: only straw and wood-based bedding were considered, but it seems common in some regions to use peat (*torvstrø*) as bedding material (Uhlig & Fjelldal, 2005). It is however important to highlight that this low resolution on the *Animals* process was chosen on purpose, as a compromise between the inclusion a maximum of animal categories and a reasonable amount of model parameters.

A main limitation of the model regarding animals is that it does not account for the dynamics within the *Animals* process. Internal flows between animal categories (for example between cows and young cattle through birth and maturing), the growth of animals (that would be represented as a positive stock change) or the casual deaths of animals (typical for sheep grazing on uncultivated land) were considered off the scope of this project. That results necessarily in an increased uncertainty for the feed and manure flows, that a model accounting for animals' age distribution or accidental mortality could contribute to reduce. Such a model including animal stocks dynamics could also provide a solid basis in order to estimate trade flows with the livestock market for all categories, while it is only considered for intensive pig productions in this model.

PASTURE MANAGEMENT

It was mentioned in 2.1.3 Uncertainties linked to data quality that all animals belonging to grazing animals categories are assumed to spend time outside, although it is in reality not true for a fraction of them. For example, non-castrated male calves older than 6 months are not allowed on pasture in Norway (Forskrift om hold av storfe, 2004). This leads in the model to an overestimation of the deposition of raw manure on agricultural soil, and therefore to less manure available for collection.

A lack of resolution similar to that of the *Animals* process is also an inherent weakness of the *Farm pasture* process, that does not capture practices or characteristics that are specific to each animal category. For example, animals are only assumed to eat grass although it is a common practice to give them supplementary feed in form of concentrate. It can also happen that dairy cows grazing on *Farm pasture* are only allowed on pasture for half a day, because needed indoors for milk production (Spruit, 2019).

A key simplification of the model is finally that grazing within the farm is presumed to only happen on *Farm pasture*. Although non-cultivated pasture area is usually privileged for the grazing that happens on agricultural land, many farmers allow in practice their livestock on cultivated pastures as well when grass goes scarce, in sheep productions especially (Rebbestad, 2020). In this model however, the remaining grass needed to satisfy the animals' energy requirements over the grazing period is only retrieved from *Uncultivated land*. This probably leads to an overestimation of the flows from and to *Uncultivated land*, and explains to some extent why the aggregated flows of animal manure dropped on pasture are more than half smaller than those calculated by Hanserud et al. (2016) (see Table 5 in 3.3 Validation of the results against previous research). Accounting for grazing on *Crops* in the model would probably lead to an increased input of manure-P to agricultural soil, but also in increased forage imports, since the grazing on crops would directly compete with the production of winter forage. As mentioned in 2.1.3 Uncertainties linked to data quality, the model could account for these aspects if the categories of Landbruksdirektoratet (2018e) related to pasture management were further refined to incorporate information on the place of grazing.

FERTILIZATION

Although the Fertilization Strategies (FS) explored in this project enable to get a first picture of the secondary fertilizer potential of Norwegian housed manure at different scales (see 4.3 Importance of fertilization practices for a detailed discussion), there are many important aspects of the fertilization process that were not covered.

For FS3, in which there is a potential import of fertilizers for farms that do not have enough housed manure, there is no difference made between mineral fertilizers and secondary fertilizers from organic sources. Instead, the import flow only represents a remaining need for P-fertilization, i.e. a demand for P fertilizers, and it was considered out of the scope of this project to couple this demand to the different supply sources that exist, especially because of the lack of trade data. No differentiation of imported fertilizers seems to be a reasonable assumption when it comes to the mere calculation of farm-level soil P balances, but a more holistic assessment of the P cycle across relevant sectors (food production value chain, bio-gas production, wastewater treatment, etc.) would require such a segregation of imported fertilizers in several categories in order to accurately map the resource's flows. This is especially relevant since different P-fertilizers have different plant-availability (Hamilton et al., 2017). It would have also been interesting to design a fourth fertilization strategy, with ground assumptions similar to those of FS3 but based on more actual fertilization guidelines (e.g. from *Norsk Landbruksrådgiving*), to be able to compare the influences of different fertilization plans on the system variables.

Housed manure is in the model assumed to be uniformly spread on agricultural soil, which is a very strong shortcoming. Indeed, for both economical and practical reasons, it is rather common that the resource is applied on fields which access is most convenient to the farmer, especially in terms of operational costs (distance from manure storage, soil damaged by heavy manure tank rolling on crops, etc.). The assumption of a uniform manure spreading leads to overlooking the spatial discrepancies within the farm for the fertilization of agricultural soil, and thereby to a significant underestimation of the imports of fertilizers. In reality, fields that are considered not suitable for manure spreading are usually fertilized with mineral fertilizers, while local secondary resource (housed manure, compost) accumulates on areas that are judged more cost-efficient (Svenningsen, 2020). This expected underestimation of the import of fertilizers explains to some extent the strong gap identified for the use of external fertilizers between FS3 and both Hanserud et al. (2016) (FR0) and Hamilton et al. (2016) (see Table 5 in 3.3 Validation of the results against previous research). Absolute and per hectare values for soil P accumulation at county level are also significantly smaller for FS3 (Figure 16c) than for the status quo perspective of Hanserud et al. (2016) (Figure 18a). The crude assumption of an evenly spread housed manure is undoubtedly a major contributor to said underestimation, but it was considered out of the scope of this project to take these spatial discrepancies within the farm into account. Because an even distribution can also be considered as an ideal scenario in terms of resource efficiency, it was considered relevant to keep this approach while acknowledging for its weaknesses.

In addition to the uniform spreading of housed manure, the timing of manure fertilization is not really accounted for in the model. It is usually advised to wait for the spring or summer season in order to spread housed manure, because it reduces the risks of immediate losses with precipitations and also is an optimal time for plants' uptake of nutrients (Kristoffersen & Korsæth, 2008). It was as well considered off the scope of this project to account for this, although a time-explicit manure application could definitely impact the model's runoff flows.

Last, but not least, the model does not capture the fact that fertilization plans are often not designed to balance the phosphorus uptake of crops' harvest but rather the nitrogen uptake (Kristoffersen & Korsæth, 2008). Frequent application of housed manure as fertilizer according to crop N requirements usually results in an additional accumulation of P in the soils, because of the generally low N:P ratios of animal manure (< 4:1) compared to that of most crops' requirements (around 8:1) (Szoegi et al., 2015)). This is not accounted for in this model, especially in FS3 in which the followed fertilization guidelines are the ones advised by NIBIO for P.

4.2 Spatial discrepancies in the distribution of manure as secondary P fertilizer

Results presented in Figure 8 of 3.1 Characteristics of the P cycle for different types of agricultural production illustrate how the circulation of P can change from a type of farm to another. In Norway like in many other developed countries, the progressive segregation of food production systems towards separate and intensive arable farming and animal husbandry led to an uneven distribution of animal manure as organic fertilizer. Intensive cereal productions in Norway are reliant on the import of fertilizers in order to secure their yields, while intensive animal farming activities (e.g. slaughter pigs productions) are often characterized by an excess of manure-P relative to the fertilization requirements of crops. For mixed-farming systems, that combine animal husbandry and arable farming and therefore benefit from a local re-circulation of nutrients, many animal-related parameters influence the shape of the P cycle. The diet of animals raised on a farm determines for example the degree of self-sufficiency this production has to feed its animals, since concentrate feed is necessarily imported while winter forage can be produced on-site. Whether animals are grazing or not influences considerably the total quantity of manure that can be collected and stored. Regardless of the type of animals, the density of those animals on farm directly determines the fertilization status (surplus or deficit) of this production in the model. Improving the current management of nutrients at farm level implies to take into account this diversity of the P cycle in agricultural productions, by the design of targeted policies based on farm-specific indicators (e.g. nutrient accumulation rates in kg P.ha $^{-1}$, or nutrient efficiency in % of nutrients input converted into farm products).

Grouping agricultural productions per administrative entities through a spatially-explicit model at municipality resolution enabled the visualization of the spatial discrepancies that exist in the distribution of animal husbandry and crop-based farming. Results presented for Trøndelag in the present report reveal that the uneven distribution of agricultural activities across the county (Figure 10) can be directly linked to the accumulation of P in agricultural soil, especially for FS1 in which farms can only rely on their own fertilization resources (Figure 14a). In this premise, peripheral/coastal municipalities characterized by high animal densities are inefficiently spreading more animal manure than required on agricultural soil, while central municipalities, characterized by dominating arable farming, experience a fertilization deficit linked to the impossibility to import fertilizers. At national level, the model's results are similar to those of Hanserud et al. (2016) and reveal spatial discrepancies as well between counties (Figure 11, Figure 16a). South-western counties that concentrate animal husbandry activities are indeed characterized by the most important accumulations of soil P in FS1, while south-eastern counties with intensive cereal productions experience significant fertilization deficits. These discrepancies underline the necessity to expand the existing (but scarce) trade of organic fertilizers between neighbouring farms to consistent redistribution strategies at county or national level, in order to practically achieve an independence from mineral fertilizers in the long term. Such strategies will rely on the identification of relevant synergies and potential trade-offs regarding the distribution of nutrients, in order to better optimize the routing of the resource from areas with a surplus to areas with a net demand. However, this redistribution of the resource cannot be practically implemented without coupling the mapping of fertilizer supply and demand to research that 1) surveys the social acceptance of the use of housed manure as secondary fertilizer, 2) evaluates the marginal costs of transporting such a bulky resource over longer distances (Liu et al., 2008), and 3) investigates technologies that could help reduce said costs (Foged et al., 2011; Spruit, 2019). Ignoring those side challenges will necessarily lead to an overestimation of the P recycling potential (Hamilton et al., 2016; Hanserud et al., 2016; Senthilkumar et al., 2012).

4.3 Importance of fertilization practices

The fertilization strategies investigated in the present project strongly suggest that both the implementation of draconian spreading measures and the revision of fertilization plans towards more nutrient efficiency could significantly alter the current use of organic manure and facilitate its redistribution.

FS1 is built on the premise that farmers can only rely on their farm's resources to fertilize the soil. It does not try in that sense to represent any status quo or baseline, but enables to map the theoretical demand and supply of secondary P fertilizers in a fictional context where there is no trade of fertilizers of any sort. As mentioned above in 4.2, the results for this fertilization strategy (Figures 14a,15a, 16a and 17a) suggest that a sustainable shift towards the independence from mineral fertilizers can only be achieved with an effective redistribution of organic fertilizers at various scales.

While all housed manure in FS1 was spread on agricultural land (within the limits of current spreading regulations), resulting in rather small manure surpluses in the *Manure storage* process (Figures 15a and 17a), FS2 reveals that more ambitious spreading regulations would considerably increase the amount of secondary fertilizer resource potentially available for trade (Figures 15b and 17b). This underlines the importance of said spreading regulations and to a larger extent of policymaking for both improved resource efficiency and the mitigation of environmental risks. It is clear however that, in the present context where many animal husbandry activities have become intensive, such restrictive regulations could hardly be implemented without adapted regulatory and economic incentives for farmers in livestock-dense areas to export their resource surplus (Knutsen & van Zanten Magnussen, 2011).

Both FS1 and FS2 exclude the use of mineral fertilizers, although it represented a 8.9 kt P input to the Norwegian agricultural soil in 2018 (Mattilsynet, 2019b), but the third and last fertilization strategy of the present project (FS3) incorporates the import of fertilizers in farms with a net fertilization deficit in FS1/FS2. Following NIBIO's fertilization guidelines results in the largest accumulation of surplus manure among the three FS (Figures 15c and 17c). At national level (Table 5), the associated manure-P supply potentially available for trade (5934 tons P/yr) appears to outweigh the aggregated need for imported fertilizers (5335 tons P/yr). These results underline the importance of fertilization planning for a more efficient use of P as fertilizer, and illustrate how decisions taken at the farm level can have significant implications on aggregated levels. The comparison of soil P balances in FS3 and the status quo fertilization regime from Hanserud et al. (2016) (see 3.3) revealed a global underestimation of the application of imported fertilizers in FS3, partly because of the assumption of a uniform manure spreading, but probably also because conservative fertilization plannings lead to an over-application of P to secure yields. This last fertilization strategy therefore strongly suggest the need to raise awareness about:

1) current soil levels in plant-available P (Figure 19), in order to adjust the quantity of applied fertilizers and implement a long-term transition fertilization strategy as investigated in Hanserud et al. (2016);

2) the value of secondary organic resources as fertilizer, today globally unknown to farmers or ignored (Nesme et al., 2011), in order to operate a shift in the quality of fertilizer employed for agricultural purposes.

4.4 Further steps towards an optimized P management

A crucial insight from this project is the importance of a bottom-up understanding of the circulation of P in agricultural productions. Further research needs to go beyond the present resolution chosen for this model and to investigate practices that are common within agricultural productions. This regards at first the access to farm-level data that is currently unavailable but would significantly change the model results. A better documentation of tillage practices, timing of manure spreading or slopes of terrains would enable to gain resolution on the runoff parameter and contribute to quantify associated environmental risks with increased confidence. Gaining access to soil analyses (that are not made public anymore since 2016) would contribute to design transition fertilization strategies adapted to current status of soil plant-available P (e.g. FR2 in Hanserud et al. (2016)). An enhanced resolution on common practices within the system boundaries could also help validating reasonable but uncertain assumptions that have been made in this project due to missing information, typically assumptions for straw and grass harvest flows (see A.2 and A.1 respectively), and give a totally new perspective for very crude assumptions like the presumed even spreading of housed manure. A more targeted data collection procedure from public authorities (e.g. *Landbruksdirektoratet*) would generally contribute to expand the knowledge on farm practices and therefore reduce the model's uncertainties.

As an alternative approach to gain access to such valuable farm insights, it was initially planned in the scope of this project to organize site visits in different farms in Trøndelag. These visits were planned after reaching out to local farmers enthusiastic about the topic, with the help of Jon Olav Forbord from *Norsk Landbruksrågiving Trondelag* (Forbord, 2020). The original idea was to organize standardized interviews based on participatory techniques, in order to 1) validate the system representation made of those farms with the farmers' perspective, 2) compare the model's results for those farms to other accounting tools that said farmers could have possibly employed (e.g. *Kretsløpstolken*), 3) get a deeper understanding of the daily challenges faced by farmers, especially regarding the local management of nutrients. Unfortunately, these visits were eventually cancelled because of the Covid-19 outbreak. Online interviews were not considered as a meaningful alternative to physical visits, since the initial purpose of this approach was to sharpen the understanding of internal farm functioning, hardly tangible through a Skype meeting. Nevertheless, such participatory frameworks including farmers should definitely be considered for further research, in order to both validate models' assumptions/results and adopt a bottom-up approach that integrates the specific challenges faced by land users.

Although the calculation in this project of a net manure-P surplus for different fertilization perspectives was a good starting point for assessing synergies/trade-offs in terms of resource distribution, the practical use of a model of this sort by public authorities would require the development and maintenance in the long term of a consistent digital infrastructure to store and update this valuable information. The implementation of a standardized framework for the management of nutrients at municipality/county scale could definitely save time and costs in the long term compared to advisory tools like *Kretsløpstolken* or *Greppa Näringen*, which today still provide the most accurate picture of the nutrient cycle in farms but are hardly upscalable (see 1.3.2Advisory frameworks for the management of nutrients at farm level). Such a centralized data infrastructure could prove to be an essential tool in order to achieve bio-economy goals at the regional (Trøndelag Fylkeskommune, 2019) or national level (Regjeringen, 2018).

It would finally be desirable for the present model to expand its system boundaries by integrating other key sectors of the Norwegian phosphorus cycle, like the aquaculture or the wastewater treatment industries, characterized as well by spatial discrepancies (e.g. aquaculture farms are located on the coast, while sewage sludge is mostly available in urban areas). Combining a cross-sectoral approach (as done by Hamilton et al. (2016)) with a refined resolution as the one explored in this project appears as the next logical step in order to get a comprehensive picture of the Norwegian P cycle and effectively exploit existing synergies for a sounder management of phosphorus.

5 CONCLUSIONS

Phosphorus is an essential nutrient for plant growth, making its access especially crucial for food production. Norway, as many other countries, is today dependent on the imports of mineral fertilizers in the form of phosphate rock, a non-renewable, scarce and geographically concentrated resource. The use of fertilizers for agronomic purposes has become at the same time very inefficient. An over-application of primary fertilizers leads to the accumulation of P in agricultural soil and increases environmental risks linked to eutrophication of water bodies. Secondary fertilizers from organic sources, like animal manure, have the potential to meet global crop fertilization requirements, but spatial discrepancies in the distribution of these resources make today their use economically unattractive.

There is a therefore a clear need to address said discrepancies in order to foster the re-distribution and recycling of P as fertilizer. A sounder management of nutrients can be informed by systems approaches like Substance Flow Analyses. In this project, focused on the Norwegian agricultural sector, a SFA of P was conducted on the 39,652 farms that applied for subsidies in the year 2018. An integrated system definition enabled to account for the diversity of those productions, and the system flows could be quantified by using a combination of production statistics, parameters and estimates. Different perspectives were considered for fertilization practices at farm-level, in order to assess their influence on both the soil P balance of agricultural soil and a surplus of animal manure potentially available for trade. Using geographic data associated to each individual farm enabled to upscale the analysis to both municipality and county level through a spatially-explicit model.

The diversity of Norwegian agricultural productions was found to result in very different dynamics for the P cycle at farm-level, especially regarding the fertilization status of those farms. Productions with animal husbandry as a main activity or more generally farms with a high animal density are characterized by large amounts of animal manure and by a significant accumulation of soil P if all said housed manure is applied on fields. At the opposite, crop-based or extensive mixed-farming systems experience a fertilization deficit in a premise where there is no trade of fertilizers.

The aggregation at national scale of those contrasting nutrient cycles confirmed the findings of previous research with regards to the potential of animal manure alone to supply the P fertilizer requirements of Norwegian crops (Hamilton et al., 2016). The results at both county and municipality levels confirmed the uneven distribution of this pool of secondary fertilizer, also identified in previous research (Hanserud et al., 2016) but refined here at the municipality resolution. The Fertilization Strategies (FS) explored in this project showed that increasing the area requirement for spreading of organic fertilizer from 4 daa/GDE to 10 daa/GDA (FS2) or following standardized fertilization guidelines from NIBIO (FS3) could both curb the accumulation of P in agricultural soil and increase the amount of manure available for redistribution.

These findings suggest therefore:

- that a shift towards independence from mineral fertilizers requires a redistribution of secondary resources at all scales, and thus a mapping of the supply/demand of such resources (FS1);

- that regulatory frameworks regarding fertilization practices can have a significant influence on the theoretical amount of manure-P fertilizer available for said redistribution (FS2);

- that a more sustainable fertilization planning at farm-level, through a consideration of both current soil P levels and the value of secondary fertilizers, is necessary to increase fertilization efficiency (FS3).

The interpretation of the results and the identification of key model limitations highlighted the general need for a better documentation of internal farm practices (fertilization, pasture management, etc.) in order to move the analysis towards a real bottom-up understanding of the agricultural P cycle. More transparency on farm practices would not only contribute to a higher confidence in the model's results through refined assumptions, but also foster the inclusion of land users and their daily challenges in the discussion on nutrient management. If they incorporate such aspects, models like the one developed in this project can prove to be powerful tools for the implementation of a bioeconomy based on P recycling. However, they need in the long term to be embedded in consistent digital infrastructures, for storage and update of their results and practical use by policymakers.

Future work can extend on this study in many ways. The reconciliation of the system flows with high resolution trade data would enable the calculation of farm P balances and associated indicators that could inform targeted policy. A deeper understanding of the fertilization practices, and especially of the uneven spreading of housed manure on agricultural area, would give a more realistic picture of the current imports of fertilizers (underestimated in this study). The resolution of the spatially-explicit model could further be extended to the farm-level, in order to map the spatial discrepancies in the resource distribution within a municipality territory. Finally, an approach similar to that used in the scope of this project could be conducted for other sectors that are relevant to the P cycle (e.g. aquaculture or wastewater treatment industries), in order to get a holistic picture of nutrient flows and associated synergies at high resolution.

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A Appendix

A.1 Forage management

The approach used to quantify the flows of grass harvested on cultivated pasture, imports and exports of forage was less straightforward than for other crop products and required additional assumptions. Unlike other crops, which products were assumed to be exported only, the cultivated pasture yields can indeed be used to feed local animals, either in form of hay or silage. After calculating the local consumption of winter forage by animals and accounting for reported forage exports in form of hay or silage, the model differentiates several types of farms:

- Farms with a cultivated pasture area but no local consumption of winter forage are most probably productions specialized in forage export, with said export reported in Landbruksdirektoratet (2018e). In this case, the harvest flows were taken as equal to the reported exports. It can also happen that there is no exports reported for some of those farms, maybe because the cultivated pasture area is rented by other farmers as additional grazing area. In this specific case, the harvest flow was calculated with areas (Landbruksdirektoratet, 2018e) and regional grass yields (Statistisk Sentralbyrå, 2020c) and assumed to be entirely exported.

- At the opposite, farms with a winter forage demand but no cultivated pasture area were assumed to import all the hay and/or silage that they needed in order to satisfy this demand and ensure that their animals' nutritional requirements were met;

- For the farms that have a cultivated area, a winter forage demand and reported exports: exports were kept such as reported, harvest flows were calculated with area and regional grass yields while imports were derived by mass-balance (*imports* = *exports* + *winter forage demand* - *harvest*);

- For the farms that have a cultivated area, a winter forage demand but no reported exports: the harvest was calculated like in the previous case (area × yield), covered as much as possible the forage demand (imports were created if the harvest was not sufficient), and exports were created only if a surplus remained after subtracting the local forage demand (P layer) from the harvested grass (P layer).

The equations for the flows of grass harvested on cultivated pasture, for the imports and the exports of forage in farms of different characteristics are gathered in Table A1 below.

Table A1: Calculation of the P flows of grass harvested on cultivated pasture, of imports and exports of forage for different types of farms.

Farm characteristics			Flows calculation			Sources
Cult. pasture	Forage demand (FD)	Reported exports	Harvest of grass (H)	Forage imports (I)	Forage exports (E)	
No	Yes	No	0	FD	O	S1
Yes	No	Yes	E	0	reported exports	S2
Yes	No	No	area × yield	0	H	S3
Yes	Yes	Yes	area × yield	E + FD - H	reported exports	S1, S2, S3
Yes	Yes	No	area × yield	max(0 , FD - H)	max(0 , H - FD)	S1, S3

Sources: S1: (Agria, 2015; Aune, 2016; Grøva et al., 2004; Spruit, 2019); S2: Landbruksdirektoratet (2018e); S3: Statistisk Sentralbyrå (2020c).

A.2 Straw removal

The collection or non-collection of straw on *Cereals* and *Oilseeds* crops is also not straightforward in the model. Indeed, it is usually recommended not to remove harvest residues from the fields more often than every 3-4 years (Energigården, 2020), in order to avoid the depletion of valuable nutrients that can be directly returned to the soil. Yet, harvest of straw can in practice happen for two main reasons:

1) In the case of very dry years, which generally results in poor forage crops yields, there is a need to complement animal diets with other nutrient sources, and cereal straw treated with ammonia is often a practical, low-cost solution (Norsk Landbruksrådgiving, 2018);

2) More generally, straw remains a common material to use as bedding for animals that are confined in a barn for the winter.

In the model developed in this project, the animals are never fed with straw. As for the straw as a bedding material, the idea was initially to associate one bedding material (straw or sawdust/woodchips) to each animal category and adapt the harvest and imports flows to that internal bedding demand. However, when upscaled to national level, this first approach resulted in imports of straw around 10 times larger than straw exports, pointing either towards an overestimation of the straw consumption as bedding or an underestimation of the straw collected on fields. Since there is a very high uncertainty associated to the kind of bedding used by each farmer for most animal categories, it was in the end considered more relevant to use straw as bedding only when there were cereals or oilseeds crops on the farm, and to use sawdust/woodchips beddings otherwise (A. F. Øgaard, 2020). The straw collection or non-collection on fields was finally implemented as follows. At first, a total amount of straw available on field was calculated from the straw/grain ratio retrieved from Schiere et al. (2004) (1 kg of grain harvested on field generates 1,3 kg of straw).

- For farms with available straw and no bedding demand (because no animals or only animals that are not provided straw as bedding, like poultry or horses), it was assumed that 25% of this available straw was harvested and sold, in order to comply with aforementioned agronomic recommendations (Energigården, 2020).

- For farms with a straw bedding demand however, it was assumed that as much straw as needed could be harvested from the field (within the yields limit that is), since the bedding is supposed in the model to return to the soil anyway when housed manure is spread. This is a bold assumption, nevertheless in accordance with the conclusions drawn by Riley et al. (2012) in a NIBIO report from 2012 : "Under Norwegian conditions, we suggest that up to 75% of the straw can be removed from a cultivation system using some animal manure in the farm cycle and/or cultivating meadow aside cereal crops" (Riley et al., 2012, p. 55). For those farms, a straw import was generated if the resource available on farm was not sufficient. On the contrary, if there was a surplus of straw after using some of it for bedding, it was assumed that up to 25% of the straw produced on the fields could be exported (Energigården, 2020).

The calculation of the flows of straw harvested on Cereals and Oilseeds crops, of the imports and the exports of straw as bedding material are given in the set of equations below.

$$\text{Local straw used as bedding} = \min(\text{straw bedding demand}, \text{available straw}) \tag{A.1}$$

$$\text{Exports of straw} = \min(0.25 \times \text{available straw}, \text{available straw} - \text{Local straw used as bedding}) \tag{A.2}$$

$$\text{Imports of straw} = \text{straw bedding demand} - \text{Local straw used as bedding} \tag{A.3}$$

$$\text{Harvest of straw} = \text{Exports of straw} + \text{straw bedding demand} - \text{Imports of straw} \tag{A.4}$$

A.3 Pasture management

The number of animal.days on *Farm pasture* (IP in this section) is not explicitly documented in the form for application to agricultural subsidies Landbruksdirektoratet (2018f): instead, farmers are only asked to fill in for each category 1) the number of animals that graze for at least 5 weeks on *Uncultivated land* (OP) without mention of the real time they spend grazing there, and 2) the number of animals grazing for at least 12/16 weeks (without mention of the place they are grazing at between IP and OP or the real time they spend grazing). Additional assumptions were therefore needed in order to quantify, for each farm with grazing animals, the flows from and to both IP and OP.

It was first calculated a first number of animal.days spent outdoors, with no differentiation made between IP and OP. All grazing animals were assumed to be on pasture for at least the legal minimum number of weeks, specific to each category (Forskrift om hold av storfe, 2004; Forskrift om velferd for hest, 2005; Forskrift om velferd for småfe, 2005). The reported number $N_{\text{animals,past. max}}$ of animals grazing at least 12 or 16 weeks (depending on geographical areas, see A.9) was presumed to graze for this exact amount of time (12/16 weeks). Animal.days on pasture (IP and OP) during the grazing period could then be calculated for each category as:

$$N_{\text{animal.days,past.}} = N_{\text{animals,past. max}} \times t_{\text{past. max}} + (N_{\text{animals,tot}} - N_{\text{animals,past. max}}) \times t_{\text{past. min}} \tag{A.5}$$

A total grass requirement over the grazing period could then be derived for each category by using the daily requirements from Asheim and Hegrenes (2006):

$$m_{\text{grass,tot}} = N_{\text{animal.days,past.}} \times m_{\text{grass/(animal.day)}} \tag{A.6}$$

A similar calculation enabled to quantify the total excretion of raw manure (RM) outdoors from the total annual excretion of manure $m_{\text{RM/(animal.yr)}}$ quantified from Karlengen et al. (2012):

$$m_{\text{RM,tot}} = N_{\text{animal.days,past.}} \times \frac{m_{\text{RM/(animal.yr)}}}{365} \tag{A.7}$$

Once the total amount of grass eaten and manure excreted outside were calculated, they were distributed on IP and OP. This was done by prioritizing *Farm pasture* over *Uncultivated land* for grazing, i.e. assuming that the animals were grazing on *Farm pasture* until there was no grass left. The amount of grass eaten on IP was therefore derived by comparing the total grass requirement (sum over all grazing animals categories) to the grass production capacity of *Farm pasture*. The amount of grass eaten on OP was finally calculated by mass-balance, presuming that animals were finding on *Uncultivated land* a sufficient supply of grass to satisfy their energy requirements over the grazing period.

$$cap_{\text{grass,IP}} = area_{\text{IP}} \times yield_{\text{grass}} \tag{A.8}$$

$$m_{\text{grass,IP}} = \min(cap_{\text{grass,IP}}, m_{\text{grass,tot}}) \tag{A.9}$$

$$m_{\text{grass,OP}} = m_{\text{grass,tot}} - m_{\text{grass,IP}} \tag{A.10}$$

Finally, the distribution of outdoor manure flows was done in order to have the intake of grass and the manure deposition proportional on both IP and OP:

$$m_{\text{RM,IP}} = m_{\text{RM,tot}} \times \frac{m_{\text{grass,IP}}}{m_{\text{grass,tot}}} \tag{A.11}$$

$$m_{\text{RM,OP}} = m_{\text{RM,tot}} - m_{\text{RM,IP}} \tag{A.12}$$

A.4 Number of animals

For most of the animal categories considered in this model (*Cattle*, *Horses*, *Goats* and *Poultry*), the number of animals in the farm was calculated as the average of the numbers measured in spring and automn and reported in Landbruksdirektoratet (2018e).

For ewes, only the spring measurement was available. For lambs, assumed in the model to be exclusively fed from grazing on pasture before being slaughtered in automn, the number was estimated from the reported number of lambs on pasture in Landbruksdirektoratet (2018e).

For animals in the *Pigs* category, only the number of *adult sows* spots was calculated normally, that is as an average of measured number of animals in spring and automn. For other types of animals in the *Pigs* category, it was decided to make a difference between intensive productions (both breeding pig and slaughter pig productions) and farms where pigs are raised as domestic pets. This is because intensive productions are either exporting or importing piglets in the model, while farms with domestic pigs keep them year-round. Moreover, it can happen that animals registered in the slaughter pigs category in Landbruksdirektoratet (2018e) are not meant to be slaughtered since, this category also includes pigs between 20 and 50 kg. For those reasons, it was decided for all farms reporting pigs whether they were intensive pig production or regular farms with domestic pets. The sorting criteria were the following:

-Slaughter pigs production

$$(N_{SP} \neq 0) \text{ and } (N_{\text{adult sows}} = 0) \text{ and } (N_{\text{young sows}} = 0) \text{ and } (N_{\text{piglets}} = 0) \\ \text{and } (M_{\text{slaughtered,pigs}} > N_{SP} \times \frac{m_{\text{slaughtered,SP}}}{R_{\text{living:dead weight, pigs}}} \times \frac{n_{\text{cycles/yr, SP}}}{2}) \tag{A.13}$$

- Breeding pigs production

$$(N_{AS} \neq 0) \text{ and } (M_{\text{slaughtered,pigs}} \neq 0) \text{ and } (M_{\text{slaughtered,sows}} \neq 0) \\ \text{and } (M_{\text{slaughtered,sows}} > 2 \times M_{\text{slaughtered,pigs}}) \tag{A.14}$$

- Regular farm with domestic pigs: every production with pigs that cannot be considered as a slaughter pigs production or a breeding pigs production.

Sorting farms with pigs into those three categories enabled to differentiate the calculations for the number of animals:

- For farms identified as slaughter pig productions, the number of slaughter pigs spots was calculated as the aforementioned spring/automn average, while the import of piglets was calculated as the product between this number of spots and the average number of growouts per year (that is 3,3 according to Karlengen et al. (2012));

- In farms that were not slaughter pig productions, the number of young sows was calculated as the spring/automn average of both *Young sows* and *Slaughter pigs* categories from Landbruksdirektoratet (2018e);

- In farms that were not breeding pig productions, the number of piglets was calculated as the spring/automn average of the *Piglets* category from Landbruksdirektoratet (2018e);

- For farms identified as breeding pig productions, the number of piglets was calculated as the product of the number of adult sows by the number of weaned piglets per sow per year (Kjos et al., 2019).

A.5 Fertilization guidelines of NIBIO

For one of the Fertilization Strategies explored in this project (FS3), recommendations from NIBIO for the quantity of P to apply per ha and type of crop were used (NIBIO, 2020b). In order to suit different types of productions from different regions of Norway, these guidelines feature different types of corrections of the fertilization requirement: yield-based corrections, P-AL measurements based corrections and even corrections in case of a removal of harvest residues for cereal productions. In the scope of this project, it was decided to account for the yield corrections only, and this was only made for cereal crops, cultivated pastures, other forage crops and potatoes (i.e. the only crops that have county specific yields in the model, see A.9 Regional parameters). Those fertilization recommendations for P are presented below in Table A2, in which an example of the yield correction is presented for the county of Sør-Trondelag.

Table A2: Crop-specific P fertilization guidelines from NIBIO. RPF = Recommended P Fertilization, ΔP = Change in P fertilization for 100 kg change in yield

Crops	Expected yield	RPF (NIBIO)	ΔP	RPF (Sør-Trøndelag)
	kg/daa	kg/daa	(kg/daa)/100 kg	kg/daa
Grass	2276	1.60	0.05	0.82
Green fodder	1470	2.10	0.05	2.30
Barley	500	1.75	0.35	1.20
Oats	500	1.75	0.35	1.15
Wheat	500	1.75	0.35	1.28
Rye	600	2.10	0.35	0.96
Oilseeds	200	2.00		2.00
Peas	400	2.50		2.50
Meadows seeds	50	0.60		0.60
Potatoes	2000	3.00	0.05	3.20
Apples	834	1.50		1.50
Pears	462	1.50		1.50
Plums	357	1.50		1.50
Cherries	362	1.50		1.50
Strawberries	555	1.50		1.50
Other fruits	500	1.50		1.50
Vegetables grown on fields	3316	3.51		3.23
Vegetables grown in greenhouses	58469	61.96		61.96

A.6 FARM-SPECIFIC PARAMETERS

Table A3: Farm-specific parameters.

Parameter name	Parameter description	Units	Source
A_{crops}	Total cultivated area (*Crops* process)	daa	S1
$A_{pasture}$	Area of non-cultivated pasture (*Farm pasture* process)	daa	S1
$A_{cult.\ pasture}$	Area of cultivated pasture	daa	S1
$A_{other\ forage}$	Area of other forage crops	daa	S1
A_{barley}	Area of barley crops	daa	S1
A_{oats}	Area of oats crops	daa	S1
A_{wheat}	Area of wheat crops	daa	S1
A_{rye}	Area of rye crops	daa	S1
$A_{oilseeds}$	Area of oilseeds crops	daa	S1
$A_{potatoes}$	Area of potatoes crops	daa	S1
A_{apples}	Area of apples crops	daa	S1
A_{pears}	Area of pears crops	daa	S1
A_{plums}	Area of plums crops	daa	S1
$A_{cherries}$	Area of cherries crops	daa	S1
$A_{strawberries}$	Area of strawberries crops	daa	S1
$A_{other\ fruits}$	Area of other fruits crops	daa	S1
$A_{vegetables,fields}$	Area of vegetables fields (excluding potatoes)	daa	S1
$A_{greenhouse}$	Area of greenhouses	daa	S1
A_{peas}	Area of peas crops	daa	S1
$A_{meadow\ seeds}$	Area of meadow seeds crops	daa	S1
Exp_{hay}	Export of hay	kg	S1
Exp_{silage}	Export of silage	kg	S1
Exp_{barley}	Export of barley grain (to food, animal feed and seed market)	kg	S2
Exp_{oats}	Export of oats grain (to food, animal feed and seed market)	kg	S2
Exp_{wheat}	Export of wheat grain (to food, animal feed and seed market)	kg	S2
Exp_{rye}	Export of rye grain (to food, animal feed and seed market)	kg	S2
$Exp_{oilseeds}$	Export of oilseeds	kg	S2
Exp_{peas}	Export of peas	kg	S2
$N_{dairy\ cows}$	Number of dairy cows	animals	S1
$N_{meat\ cows}$	Number of meat cows	animals	S1
$N_{young\ cattle}$	Number of young cattle	animals	S1
$N_{dairy\ cows,\ pasture\ max}$	Number of dairy cows grazing at least 12/16 weeks	animals	S1
$N_{meat\ cows,\ pasture\ max}$	Number of meat cows grazing at least 12/16 weeks	animals	S1
$N_{young\ cattle,\ pasture\ max}$	Number of young cattle grazing at least 12/16 weeks	animals	S1
$M_{slaughtered,\ cows}$	Cows sent to slaughter (dead weight)	kg	S3

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Parameter name	Parameter description	Units	Source
$M_{slaughtered,\ young\ cattle}$	Young cattle sent to slaughter (dead weight)	kg	S3
$V_{milk,\ cow}$	Volume of cow milk sent to dairy production	L / yr	S4
N_{horses}	Number of horses	animals	S1
$N_{horses,\ pasture\ max}$	Number of horses grazing at least 12/16 weeks	animals	S1
$N_{dairy\ goats}$	Number of dairy goats	animals	S1
$N_{young\ goats}$	Number of young goats	animals	S1
$N_{dairy\ goats,\ pasture\ max}$	Number of dairy goats grazing at least 12/16 weeks	animals	S1
$N_{young\ goats,\ pasture\ max}$	Number of young goats grazing at least 12/16 weeks	animals	S1
$M_{slaughtered,\ goats}$	Goats sent to slaughter (dead weight)	kg	S3
$M_{slaughtered,\ young\ goats}$	Young goats sent to slaughter (dead weight)	kg	S3
$V_{milk,\ goat}$	Volume of goat milk sent to dairy production	L / yr	S4
N_{ewes}	Number of ewes	animals	S1
N_{lambs}	Number of lambs	animals	S1
$M_{slaughtered,\ ewes}$	Ewes sent to slaughter (dead weight)	kg	S3
$M_{slaughtered,\ lambs}$	Lambs sent to slaughter (dead weight)	kg	S3
M_{wool}	Quantity of wool sold to the wool industry	kg	S3
N_{layers}	Number of layers	animals	S1
$N_{broilers\ spots}$	Number of broilers spots	spots	S1
$N_{turkeys\ spots}$	Number of turkeys spots	spots	S1
$M_{slaughtered,\ layers}$	Layers sent to slaughterhouse (dead weight)	kg	S3
$M_{slaughtered,\ broilers}$	Broilers sent to slaughterhouse (dead weight)	kg	S3
$M_{slaughtered,\ turkeys}$	Turkeys sent to slaughterhouse (dead weight)	kg	S3
M_{eggs}	Quantity of eggs sent to the egg packaging industry	kg	S5
$N_{adult\ sows}$	Number of adult sows	animals	S1
$N_{young\ sows}$	Number of young sows	animals	S1[1]
$N_{SP\ spots}$	Number of slaughter pigs spots	animals	S1[1]
$N_{piglets}$	Number of piglets	animals	S1[1]
$M_{slaughtered,\ pigs}$	Pigs sent to slaughter	kg	S3
$M_{slaughtered,\ sows}$	Sows sent to slaughter	kg	S3
$Imp_{piglets}$	Import of piglets from breeding pigs production	animals	S1[1]
$Exp_{piglets}$	Export of piglets to slaughter pigs production	animals	S1[1]
N_{GDE}	Number of GDE on farm	GDE	S1[2]

[1] : see Number of animals

[2] : Calculated as $N_{animals} \times N_{animals/GDE}$ (see Table A4 below)

Sources: S1: Landbruksdirektoratet (2018e); S2: Landbruksdirektoratet (2018b); S3: Landbruksdirektoratet (2018d); S4: Landbruksdirektoratet (2018c); S5: Landbruksdirektoratet (2018a)

A.7 General parameters

Table A4: General parameters.

Parameter name	Parameter description	Value	Units	Source
$m_{grass/FEm}$	Mass of grass equivalent to 1 FEm	5.7	kg/FEm	S1
$R_{straw:grain}$	Straw available for 1 kg of grain harvested (plant characteristic)	1.3	/	S2
$R_{residues:straw}$	Non-harvestable fraction of available straw (machine-specific)	0.2	% DM	S2
$m_{P\ runoff/daa}$	P losses of agricultural soil per area unit	0.1	kg P/daa	S3
$m_{P/GDE}$	Amount of phosphorus per manure animal unit	14.0	kg/GDE	S4
$E_{grass/day,\ cows}$	Daily energy requirement of cows on pasture	7.2	FEm/animal.day	S5
$E_{grass/day,\ young\ cattle}$	Daily energy requirement of young cattle on pasture	4.8	FEm/animal.day	S5
$E_{grass/day,\ horses}$	Daily energy requirement of horses on pasture	7.0	FEm/animal.day	S5
$E_{grass/day,\ goats}$	Daily energy requirement of goats on pasture	1.2	FEm/animal.day	S5
$E_{grass/day,\ sheep}$	Daily energy requirement of sheep on pasture	1.0	FEm/animal.day	S5
$n_{dairy\ cows/GDE}$	Number of dairy cows per manure animal unit	1.0	animals/GDE	S4
$n_{meat\ cows/GDE}$	Number of meat cows per manure animal unit	1.5	animals/GDE	S4
$n_{young\ cattle/GDE}$	Number of young cattle per manure animal unit	3.0	animals/GDE	S4
$m_{feed,\ dairy\ cows}$	Daily consumption of concentrate per dairy cow	6.8	kg/animal.day	S6
$m_{feed,\ meat\ cows}$	Daily consumption of concentrate per meat cow	0.5	kg/animal.day	S6
$m_{feed,\ young\ cattle}$	Daily consumption of concentrate per young cattle	0.3	kg/animal.day	S6
$m_{silage,\ dairy\ cows}$	Daily consumption of silage per dairy cow	42.9	kg/animal.day	S6
$m_{silage,\ meat\ cows}$	Daily consumption of silage per meat cow	32.1	kg/animal.day	S6
$m_{silage,\ young\ cattle}$	Daily consumption of silage per young cattle	18.6	kg/animal.day	S6
$m_{manure,\ dairy\ cows}$	Raw manure produced yearly per dairy cow	21000.0	kg/animal.yr	S7
$m_{manure,\ dairy\ cows}$	Raw manure produced yearly per meat cow	10680.0	kg/animal.yr	S7
$m_{manure,\ dairy\ cows}$	Raw manure produced yearly per young cattle	6480.0	kg/animal.yr	S7
ρ_{milk}	Density of raw milk	1.034	g/mL	S6
$m_{straw,\ cattle}$	Daily amount of straw used as bedding per animal (cattle)	2.4	kg/animal.day	S8
$m_{sawdust,\ cattle}$	Daily amount of sawdust used as bedding per animal (cattle)	3.8	kg/animal.day	S8
$n_{horses/GDE}$	Number of horses per manure animal unit	2.0	animals/GDE	S4
$m_{hay,\ horses}$	Daily consumption of hay per horse	8.3	kg/animal.day	S9
$m_{feed,\ horses}$	Daily consumption of concentrate per horse	0.6	kg/animal.day	S9
$m_{manure-P,\ horses}$	P emitted annually in raw manure per horse	8.0	kg/animal.yr	S10
$m_{sawdust,\ horses}$	Monthly amount of woodchips used per horse	100.0	kg/animal.mth	S11
$n_{ewes/GDE}$	Number of ewes per manure animal unit	7.0	animals/GDE	S4
$n_{lambs/GDE}$	Number of lambs per manure animal unit	42.0	animals/GDE	S4[1]
$m_{feed,\ ewes}$	Annual consumption of concentrate per ewe	69.0	kg/animal.yr	S12

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Parameter name	Parameter description	Value	Units	Source
$m_{\text{hay, ewes}}$	Annual consumption of hay per ewe	58.5	kg/animal.yr	S12
$m_{\text{silage, ewes}}$	Annual consumption of silage per ewe	693.0	kg/animal.yr	S12
$m_{\text{manure−P, ewes}}$	P emitted annually in raw manure per ewe	2.0	kg/animal.yr	S10
$n_{\text{dairy goats/GDE}}$	Number of dairy goats per manure animal unit	7.0	animals/GDE	S4
$n_{\text{young goats/GDE}}$	Number of young goats per manure animal unit	18.9	animals/GDE	S4[2]
$m_{\text{silage, dairy goats}}$	Daily consumption of silage per dairy goat	4.9	kg/animal.day	S13
$m_{\text{feed, dairy goats}}$	Daily consumption of concentrate per dairy goat	0.9	kg/animal.day	S13
$m_{\text{manure−P, dairy goats}}$	P emitted anually in raw manure per dairy goat	2.0	kg/animal.yr	S10
$m_{\text{silage, young goats}}$	Daily consumption of silage per young goat	2.1	kg/animal.day	S13
$m_{\text{feed, young goats}}$	Daily consumption of concentrate per young goat	0.04	kg/animal.day	S13
$m_{\text{straw, sheep/goats}}$	Daily amount of straw used as bedding per animal (sheep/goat)	0.5	kg/animal.day	S8
$m_{\text{sawdust, sheep/goats}}$	Daily amount of sawdust used as bedding per animal (sheep/goat)	0.7	kg/animal.day	S8
$R_{\text{living:dead weight, C/S/G}}$	Living : Slaughtered weight ratio (Cattle / Sheep / Goats)	2.0	/	S6[3]
$n_{\text{layers/GDE}}$	Number of layers per manure animal unit	80.0	animals/GDE	S4
$n_{\text{broilers/GDE}}$	Number of broilers per manure animal unit	1400.0	animals/GDE	S4
$n_{\text{turkeys/GDE}}$	Number of turkeys per manure animal unit	240.0	animals/GDE	S4
$m_{\text{feed, layers}}$	Annual consumption of concentrate per layer	39.3	kg/animal.yr	S14
$m_{\text{manure, layers}}$	Raw manure produced yearly per layer	40.1	kg/animal.yr	S10
$d_{\text{max, layers}}$	Legal maximum density of layers	9.0	animals/m^2	S15
$m_{\text{feed, broilers spot}}$	Annual consumption of concentrate per broiler spot	21.1	kg/spot.yr	S14
$m_{\text{manure, broilers spot}}$	Raw manure produced yearly per broiler spot	18.1	kg/spot.yr	S10[4]
$d_{\text{max, broilers}}$	Legal maximum density of broilers	34.0	kg/m^2	S15
$m_{\text{feed, turkeys spot}}$	Annual consumption of concentrate per turkey spot	75.7	kg/spot.yr	S14
$m_{\text{manure, turkeys spot}}$	Raw manure produced yearly per turkey spot	66.8	kg/spot.yr	S10[5]
$d_{\text{max, turkeys}}$	Legal maximum density of turkeys	38.0	kg/m^2	S15
$m_{\text{sawdust, poultry}}$	Annual amount of sawdust applied per m^2 in poultry productions	1.0	kg/m^2.yr	S7
$R_{\text{living:dead weight, poultry}}$	Living : Slaughtered weight ratio (poultry)	1.49	/	S16
$n_{\text{adult sows/GDE}}$	Number of adult sows per manure animal unit	2.5	animals/GDE	S4
$n_{\text{young sows/GDE}}$	Number of young sows per manure animal unit	8.2	animals/GDE	S4[6]
$n_{\text{SP/GDE}}$	Number of slaughter pigs per manure animal unit	18.0	animals/GDE	S4
$n_{\text{piglets/GDE}}$	Number of piglets per manure animal unit	103.8	animals/GDE	S4[7]
$n_{\text{piglets/sow.yr}}$	Annual number of weaned piglets per sow	26.7	piglets/sow.yr	S14
m_{piglets}	Final weight of piglets	30.0	kg	S10
$m_{\text{feed, piglets}}$	Consumption of concentrate per piglet	33.0	kg/animal	S10
$m_{\text{manure, piglets}}$	Raw manure produced per piglet	76.4	kg/animal	S10
$m_{\text{feed, young sows}}$	Annual consumption of concentrate per young sow	605.1	kg/animal.yr	S10
$m_{\text{manure, young sows}}$	Raw manure produced yearly per young sow	1449.0	kg/animal.yr	S10

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Parameter name	Parameter description	Value	Units	Source
$m_{feed, adult sows}$	Annual consumption of concentrate per adult sow	1370.0	kg/animal.yr	S10
$m_{manure, adult sows}$	Raw manure produced yearly per adult sow	4736.9	kg/animal.yr	S10
$n_{cycles/yr, SP}$	Average number of growing cycles per year (slaughter pigs productions)	3.3	cycles	S10
$m_{slaughtered, SP}$	Average weight of slaughtered pigs	78.2	kg	S10
$m_{feed, SP spot}$	Annual consumption of concentrate per slaughter pigs spot	701.2	kg/spot.yr	S10
$m_{manure, SP spot}$	Raw manure produced yearly per slaughter pig spot	1684.0	kg/spot.yr	S10
$m_{straw, pigs}$	Daily amount of straw used as bedding per animal (pigs)	0.4	kg/animal.day	S8
$m_{sawdust, pigs}$	Daily amount of straw used as bedding per animal (pigs)	0.6	kg/animal.day	S8
$R_{living:dead weight, pigs}$	Living : Slaughtered weight ratio (pigs)	1.47	/	S17

[1,2] : $n_{lambs/GDE}$ and $n_{young goats/GDE}$ were calculated respectively from $n_{ewes/GDE}$ and $n_{goats/GDE}$ (S4) using a diet-based proportionality factor.

[3] : $R_{living:dead weight, cattle}$ was extracted from S6, and the ratio was assumed similar for sheep and goats

[4,5] : For broilers and turkeys, the raw manure per spot was calculated as $n_{growing cycles}$ (S14) × $m_{slaughtered, animal}$ (S14) × $m_{manure/kg slaughtered}$ (S10).

[6,7] : $n_{young sows/GDE}$ and $n_{piglets/GDE}$ were calculated from $n_{adult sows/GDE}$ (S4) using a diet-based proportionality factor (diets given in S10).

Sources: S1: NIBIO (2020b); S2: Schiere et al. (2004); S3: Zabrodina (2013); S4: Forskrift om husdyrgjødsel (2002); S5: Asheim and Hegrenes (2006); S6: Spruit (2019); S7: Nesheim and Halvorsen Sikkeland (2013); S8: Uhlig and Fjelldal (2005); S9: Agria (2015); S10: Karlengen et al. (2012); S11: Løberg (2012); S12: Grøva et al. (2004); S13: Aune (2016); S14: Kjos et al. (2019); S15: Forskriften om hold av høns og kalkun (2001); S16: Bagley (2013); S17: Svin (2017).

A.8 Material contents

Table A5: Material contents. % DM = *Dry Matter content*, % P/WW = *Phosphorus content in Wet Weight*, % P/DM = *Phosphorus content in Dry Matter*

Material	% DM	% P/WW	% P/DM	Source
Grass	18.5		0.31	Antikainen et al. (2005)
Other forage	23.0		0.33	Antikainen et al. (2005)
Barley	86.0		0.38	Antikainen et al. (2005)
Oats	86.0		0.39	Antikainen et al. (2005)
Wheat	86.0		0.40	Antikainen et al. (2005)
Rye	86.0		0.36	Antikainen et al. (2005)
Oilseeds	92.0		0.86	Antikainen et al. (2005)
Peas	86.0		0.47	Antikainen et al. (2005)
Meadows seeds	86.0		0.40	Antikainen et al. (2005) [1]
Potatoes	22.0		0.21	Antikainen et al. (2005)
Apples		0.01		Mattilsynet (2019a)
Pears		0.02		Mattilsynet (2019a)
Plums		0.02		Mattilsynet (2019a)
Cherries		0.02		Mattilsynet (2019a)
Strawberries		0.03		Mattilsynet (2019a)
Other fruits		0.06		Mattilsynet (2019a)
Vegetables grown on fields		0.04		Mattilsynet (2019a)
Vegetables grown in greenhouses		0.03		Mattilsynet (2019a)
Hay	83.0		0.24	Antikainen et al. (2005)
Silage	28.0		0.31	Antikainen et al. (2005)
Concentrate (cattle / horses)	88.0		0.51	Spruit (2019)
Concentrate (sheep / goats)	88.0		0.51	Grøva et al. (2004)
Concentrate (layers)		0.45		Karlengen et al. (2012)
Concentrate (broilers)		0.51		Karlengen et al. (2012)
Concentrate (turkeys)		0.65		Karlengen et al. (2012)
Concentrate (piglets)	89.0	0.50		Karlengen et al. (2012)
Concentrate (young sows)	89.0	0.41		Karlengen et al. (2012)
Concentrate (adult sows)	89.0	0.42		Karlengen et al. (2012)
Concentrate (slaughter pigs)	89.0	0.43		Karlengen et al. (2012)
Cattle/Sheep/Goats		0.71		Antikainen et al. (2005) [2]
Poultry		0.67		Antikainen et al. (2005)
Svine		0.55		Antikainen et al. (2005)
Milk (raw)		0.10		Mattilsynet (2019a)
Eggs		0.20		Mattilsynet (2019a)
Wool	95.2	0.10		Böhme et al. (2010)

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Material	% DM	% P/WW	% P/DM	Source
Raw manure (dairy cows)	10.4	0.07	0.70	Karlengen et al. (2012)
Raw manure (meat cows)	12.6	0.07	0.58	Karlengen et al. (2012)
Raw manure (young cattle)	11.0	0.08	0.70	Karlengen et al. (2012)
Raw manure (ewes)	12.0	0.11	0.92	Karlengen et al. (2012)
Raw manure (layers)	30.0	0.36	1.19	Karlengen et al. (2012)
Raw manure (broilers)	30.0	0.30	1.00	Karlengen et al. (2012)
Raw manure (turkeys)	30.0	0.45	1.50	Karlengen et al. (2012)
Raw manure (piglets)	7.3	0.07	1.00	Karlengen et al. (2012)
Raw manure (young sows)	7.8	0.11	1.40	Karlengen et al. (2012)
Raw manure (adult sows)	6.5	0.09	1.40	Karlengen et al. (2012)
Raw manure (slaughter pigs)	7.8	0.08	1.00	Karlengen et al. (2012)
Straw (bedding)	86.0		0.40	Antikainen et al. (2005)
Wood-based products (bedding)	95.0		0.20	Allison, Anderson, et al. (1951)

[1] : The P content of meadows seeds (% P/DM) was crudely estimated as the average of those of cereals

[2] : The P content of animals in the *Cattle* category (% P/WW) was taken from Antikainen et al. (2005), and it was supposed identical for the two other categories (*Sheep* and *Goats*) that have a rather similar diet (quality-wise)

A.9 Regional parameters

Table A6: County-specific yields for the crop products considered in the system (counties n° 1 to 9). Yields for oilseeds, peas, meadows seeds, vegetables and fruits could only be retrieved at the national scale.

Crops	Østfold	Oslo/Akershus	Hedmark	Oppland	Buskerud	Vestfold	Telemark	Aust-Agder	Vest-Agder	Source
Grass	821	827	762	814	673	797	647	630	729	S1
Other forage	1836	1509	1805	1908	1540	1665	1681	1853	2095	S2
Barley	391	371	410	363	341	374	318	276	299	S3
Oats	402	384	372	354	358	386	345	286	345	S3
Wheat	447	431	482	434	415	417	371	321	286	S3
Rye	454	428	524	366	373	520	447	230	230	S3
Oilseeds	200	200	200	200	200	200	200	200	200	S4
Peas	400	400	400	400	400	400	400	400	400	S4
Meadows seeds	50	50	50	50	50	50	50	50	50	S4
Potatoes	2537	2835	2794	2540	2678	2616	2227	2018	2100	S1
Apples	834	834	834	834	834	834	834	834	834	S5
Pears	462	462	462	462	462	462	462	462	462	S5
Plums	357	357	357	357	357	357	357	357	357	S5
Cherries	362	362	362	362	362	362	362	362	362	S5
Strawberries	555	555	555	555	555	555	555	555	555	S5
Other fruits	500	500	500	500	500	500	500	500	500	S5
Vegetables (fields)	2414	2414	2414	2414	2414	2414	2414	2414	2414	S5
Vegetables (greenhouses)	58469	58469	58469	58469	58469	58469	58469	58469	58469	S5

Sources: S1: Statistisk Sentralbyrå (2020c); S2: Statistisk Sentralbyrå (2020a); S3: Statistisk Sentralbyrå (2020e); S4: NIBIO (2020b); S5: Statistisk Sentralbyrå (2020b)

Table A7: County-specific yields for the crop products considered in the system (counties n° 10 to 18). Yields for oilseeds, peas, meadows seeds, vegetables and fruits could only be retrieved at the national scale.

Crops	Rogaland	Hordaland	Sogn of Fjordane	Møre og Romsdal	Sør-Trøndelag	Nord-Trøndelag	Nordland	Troms	Finnmark	Source
Grass	892	702	748	791	802	802	601	419	392	S1
Other forage	3412	2731	2881	1354	1854	1854	1419	1242	1223	S2
Barley	384	325	263	263	342	342	237	342	342	S3
Oats	358	191	224	224	329	329	168	329	329	S3
Wheat	334	275	275	275	366	366	366	366	366	S3
Rye	230	373	366	275	275	275	275	275	275	S3
Oilseeds	200	200	200	200	200	200	200	200	200	S4
Peas	400	400	400	400	400	400	400	400	400	S4
Meadows seeds	50	50	50	50	50	50	50	50	50	S4
Potatoes	2578	1584	2065	2669	2397	2397	1317	1572	1153	S1
Apples	834	834	834	834	834	834	834	834	834	S5
Pears	462	462	462	462	462	462	462	462	462	S5
Plums	357	357	357	357	357	357	357	357	357	S5
Cherries	362	362	362	362	362	362	362	362	362	S5
Strawberries	555	555	555	555	555	555	555	555	555	S5
Other fruits	500	500	500	500	500	500	500	500	500	S5
Vegetables (fields)	2414	2414	2414	2414	2414	2414	2414	2414	2414	S5
Vegetables (green-houses)	58469	58469	58469	58469	58469	58469	58469	58469	58469	S5

Sources: S1: Statistisk Sentralbyrå (2020c); S2: Statistisk Sentralbyrå (2020a); S3: Statistisk Sentralbyrå (2020e); S4: NIBIO (2020b); S5: Statistisk Sentralbyrå (2020b).

For each crop product with a county-specific yield in Tables A6 and A7, the value displayed is the average yield measured by *Statistisk Sentralbyrå* between 2001 and 2018. For some reasons, yield data was not available or could not be published for some counties/years, especially for the northern counties (Norland, Troms and Finnmark). When less than 3 values were available for the whole time period for one crop/county, the value chosen was that of the closest county geographically.

Table A8: Minimum number of days on pasture required to get economic support from *Landbruksdirektoratet* for grazing activities. Source: Landbruksdirektoratet (2018f).

Animals	Østfold	Oslo/Akershus	Hedmark	Oppland	Buskerud	Vestfold	Telemark	Aust-Agder	Vest-Agder
Cows	112	112	84	84	84	112	84	84	84
Young cattle	112	112	84	84	84	112	84	84	84
Horses	112	112	84	84	84	112	84	84	84
Goats	112	112	112	112	112	112	112	112	112
Sheep	112	112	112	112	112	112	112	112	112

Animals	Rogaland	Hordaland	Sogn of Fjordane	Møre og Romsdal	Sør-Trøndelag	Nord-Trøndelag	Nordland	Troms	Finnmark
Cows	84	84	84	84	84	84	84	84	84
Young cattle	84	84	84	84	84	84	84	84	84
Horses	84	84	84	84	84	84	84	84	84
Goats	112	112	112	112	112	112	112	112	112
Sheep	112	112	112	112	112	112	112	112	112

The application for agricultural subsidies (Landbruksdirektoratet, 2018f) features a category where farmers need to fill in the number of animals (for each category) that have been grazing at least 12 weeks (84 days) or 16 weeks (112 days) on pasture (both inside and outside the farm). Whether it is 12 or 16 weeks depends on the location of the farm in Norway: zones 1 to 4 on Figure 20 have a 16 weeks requirement while it is 12 weeks for zones 5 to 7. In the scope of the present project, a county was assumed to belong to the 16 weeks zone only if its whole territory was covered by the zone on Figure 20. This results necessarily in an uncertainty for the farms that belong to the 16 weeks zone <u>and</u> to a county that is not entirely covered.

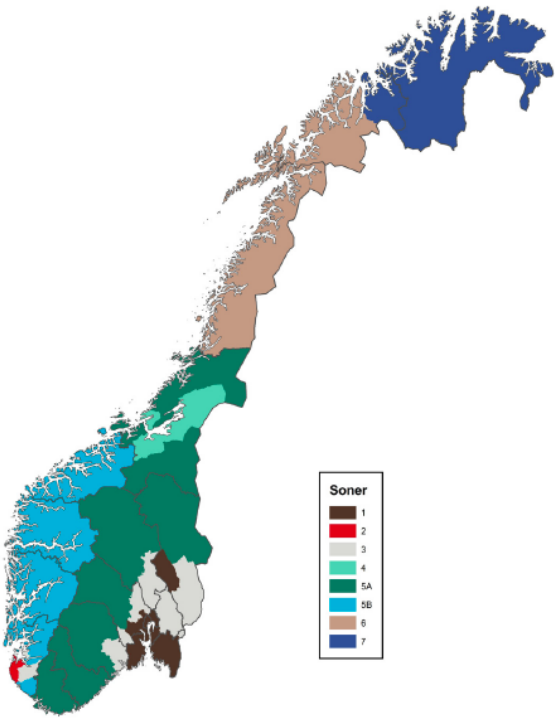

Figure 20: Zones defined for area-specific agricultural subsidies. Extracted from Landbruksdirektoratet (2018f)

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