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Multi-scale analysis of the agricultural phosphorus cycle in Norway to inform farm, regional, and national resource efficiency strategies

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KEYWORDS

Phosphorus; Substance Flow Analysis (SFA); Agriculture; Resource efficiency; Circular Economy; Bioeconomy

AUTHOR CONTRIBUTION

Conceptualization: DBM, MH, TG, ND, AP; *Methodology*: DBM, MH, ND, FB, TG, AØ; *Software / Formal Analysis*: FB, ND, MH, TG; *Investigation / Data Curation*: TG, MH, AL, FB. *Writing - Original Draft*: MH, FB, MC, ND, RB; *Writing - Review & Editing*: DBM, RB, MH, FB, ND, MC, AØ; *Visualization*: FB, MH, MC; *Supervision / Project administration / Funding acquisition*: DBM.

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ABSTRACT

Ineffective phosphorus (P) management in agriculture raises concerns about resource depletion, supply security, eutrophication, and biodiversity loss. A major barrier to more circular and resource-efficient P management is the spatial imbalance between farms: livestock farms often accumulate surplus P from manure in soil, whereas crop farms typically face P deficits that are met with mineral fertilizers. Yet models capable of testing strategies to address these spatial inefficiencies remain limited.

We study how a multi-scale analysis can guide strategies to reduce P imports and soil accumulation in Norway. Using Substance Flow Analysis, we quantify the P cycles of ~40,000 farms (2019–2023) and aggregate results to municipal, county, and national levels. We then test four manure-redistribution strategies: on-farm optimization, and trade at the municipal, county, and national levels.

Norwegian agriculture applies 22,1 kt $P \cdot yr^{-1}$ to cropland; 4% is lost to runoff and 41% accumulates in soils, particularly in the livestock-dense Western regions. Livestock dominates P demand, while only 9% of harvested crop P is destined for human consumption. On-farm optimization reduces mineral P use by 38% and soil accumulation by 36%; municipal and national

77 trade of manure lower P imports by 61% and 78%, respectively. National trade nearly eliminates
78 accumulation, with remaining surpluses linked to waste-based fertilizers and imported feed.

79 Our results show that a multi-scale P analysis can be developed in countries with farm
80 subsidy statistics. Such models help identify spatial barriers to circular P strategies, indicating
81 where local management is sufficient and where further processing and trade are required.

82

1 Introduction

Phosphorus (P) is an essential resource for global food production, yet access to P fertilizer depends on geographically concentrated deposits, making supply strategically vulnerable. About 68% of the present reserves lie in Morocco, including the disputed region of Western Sahara (U.S.Geological Survey, 2024). However, farmers have traditionally overapplied P (Lemercier et al., 2008). Over time, surplus P has accumulated in soils, where it partially becomes unavailable to plants (George et al., 2016; Gustafsson et al., 2023; Wang et al., 2015), or runs off into water systems, amplifying eutrophication risk (Carpenter & Bennett, 2011). These inefficiencies have pushed the P cycle beyond its planetary boundary (Richardson et al., 2023; Rockström et al., 2009).

Designing a more resilient food production system involves optimizing nutrient management and improving P recycling, while accounting for the spatial heterogeneity of agricultural systems. Differences in farm structure, land use, legacy P in the soil, and the sourcing of feed lead to coexisting local surpluses and deficits of P (Raniro et al., 2025). This spatial heterogeneity, often not considered in the existing literature, needs to be better described in order to rebalance P cycles at the local level.

Indeed, while Substance Flow Analyses (SFAs) at the global, EU, or national level provide essential overviews of stocks and flows (Hamilton et al., 2016; Liu et al., 2008; Ott & Rechberger, 2012; van Dijk et al., 2016; Zoboli et al., 2016), their coarse resolution can average out the differences between contrasting production systems, masking the heterogeneity at smaller scales (Bateman et al., 2011; Hanserud et al., 2016). Farm-level studies offer greater detail on processes and performance indicators (Haygarth et al., 1998; Modin-Edman et al., 2007; Steinshamn et al., 2004). They enabled accurate tracking of nutrient flows in these farms and hence developing farm-

level nutrient management strategies; however, nutrient cycles in selected individual farms is insufficient to inform regional strategies, for example for nutrient redistribution between farms. A few bottom-up studies (Buckley et al., 2015; Vingerhoets et al., 2023) attempted to address the spatial heterogeneity of agricultural operations by analysing harmonized high resolution data. However, they still lack the capacity to capture intra-farm nutrient dynamics, limiting their ability to quantify the potential for nutrient redistribution, both within individual farms and across multiple farming operations. Therefore, regional strategies need to be informed by nutrient cycles of all farms within the region.

To fill the gap in integrated, multi-scale phosphorus analysis, we quantify the average annual P flows over the period 2019-2023 of harmonized, farm-level systems for nearly all Norwegian farms (≈40 000 per year), covering 20 crop types and 18 animal species. Using a generic system definition consistent across scales, we aggregate this detailed analysis to municipal, county, and national levels. Building on these SFAs, we quantify the potential to reduce mineral P inputs and soil accumulation through a sequence of strategies, from farm-level optimization of manure use to redistribution within municipalities, counties, and nationally. Our analysis reveals the drivers and spatial distribution of P surpluses and deficits in Norway and evaluates how nutrient redistribution within and between farms can reduce the reliance on mineral P imports through a more efficient and circular agricultural P system.

2 Methods

2.1 System definition

The P cycle was analysed for individual farms using a generic system definition (Figure 1), following the SFA methodology described by Baccini & Brunner (1991). Using a generic

system definition allows for i) comparison across farms, regardless of their animal and crop composition, and ii) aggregation of the flows at municipal, county, and national levels.

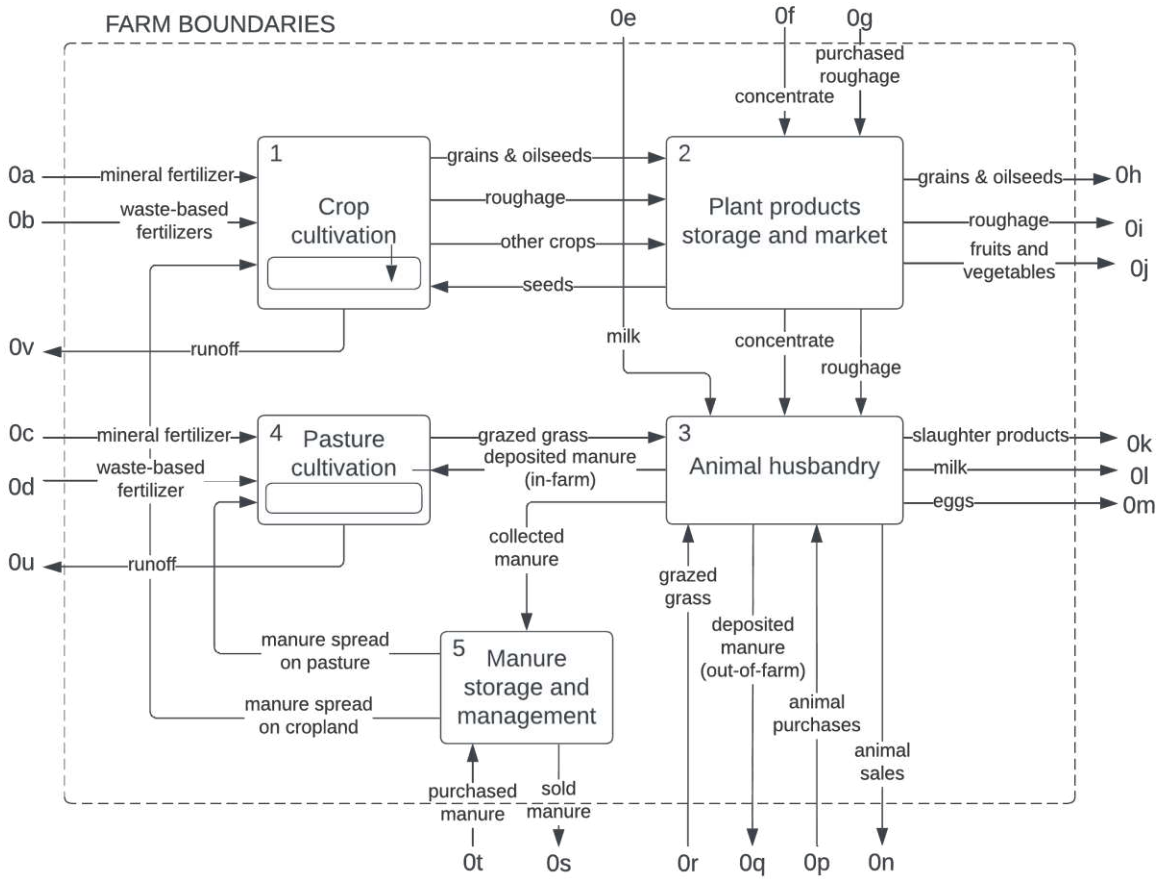


Figure 1: Generic system definition for the multi-scale Norwegian Agricultural P cycle - Example of a farm.

The generic system uses 5 main processes to capture the P metabolism of individual Norwegian farms. *Crop cultivation (1)* represents the cropland soil and the crops. Inputs are seeds and fertilizer from mineral and recycled origins (manure, or waste-based fertilizers, i.e. sewage sludge and biological waste). Outputs are the harvested crops, runoffs of nutrients to the environment, and accumulation of P in the soil (represented as a stock change). *Storage and market*

137 *for plant-based products (2)* represents the management of harvested crops in the farm. Its inputs
138 are crop products from the farm itself and purchased concentrate and roughage. Its outputs are the
139 feed for animals, products sold on the market, and seeds to crops (a share of own grains
140 production). *Animal husbandry (3)* represents all the livestock. It receives animal feed from pasture
141 and purchases, as well as livestock individuals to be reared. It delivers animal products and reared
142 individuals to the markets, and manure to the collection systems or directly to the soil. *Pasture*
143 *cultivation (4)* represents the pastureland soil and plants, receiving fertilization and delivering
144 grass to the animals, plus P runoff to the environment. *Manure storage and management (5)*
145 represents the collection and management of manure on the farm, receiving the collected manure
146 from stabled animals and delivering manure as fertilizers to the soil. Trade flows of manure are
147 only used by some of the strategies described in section 2.4. The yearly agricultural production of
148 all the farms over time is assumed to be in a steady state. Therefore, stocks and stock changes are
149 only considered in the processes representing soil, where P accumulation happens over the years.
150 Trade of fertilizers, animal feed, crop products and livestock, as well as processing industries like
151 slaughterhouses, dairy processors and egg packaging industries are considered flows to/from
152 outside of the system. P losses from the soil due to runoff are represented as an outflow towards
153 outside the system in processes 1 and 4. The seasonal grazing of animals on pastures outside the
154 farm on uncultivated land (i.e. forests, mountain pastures or coastal terrains), and the manure
155 deposition during that period are also considered flows to/from outside of the system.

156 **2.2 Quantification**

157 We quantified the farm-level P flows for the approximately 40 000 farms that applied for
158 production grants in the Norwegian Ministry of Agriculture and Food. Norwegian agriculture is
159 only viable thanks to government support and shows the highest dependence on subsidies in the

OECD (OECD, 2021). It was therefore assumed that the subsidized farms are representative of the whole agricultural sector. The quantification was done with averaged data reported during the period 2019 – 2023 to absorb fluctuations in the agricultural operations.

Farm-level data on the number and type of livestock individuals were obtained from the *Production and replacement subsidies to agricultural enterprises* (Landbruksdirektoratet, 2019). Additional data were derived from national/regional statistics, scientific literature, Norwegian agriculture industry recommendations, or any other relevant sources to quantify the P flows in animal feed and animal products. The P content in manure was then determined through mass balancing at the animal level. Manure generated in the barn was assumed to be collected, while manure generated on grazing land was assumed to be deposited and not collected. The share between the two was estimated based on the time the animals spend grazing.

Data about cultivated area, types of crops, and the amount of crop products sold on the market were obtained from Norwegian subsidy statistics. This data was used in combination with parameters from various sources to calculate the production of roughage, grains, vegetables and fruits on each farm. Runoff flows were estimated by multiplying the agricultural area with a factor of 1 kg P/(ha.yr), calculated as an average of the losses measured in different locations across Norway (Eggestad et al., 2001). Runoff is highly influenced by local soil and weather conditions. While applying a single value for all farms does not accurately reflect conditions at the farm level, it can still serve as a reasonable estimate for national or regional resource use because runoffs tend to be small compared to the total P turnover.

The fertilization demand of individual farms was derived from county and municipality statistics (Mattilsynet, 2024). To estimate fertilizer application, it was assumed that manure is

never traded, and that farmers use all the available manure to evenly fertilize their crops. These results were then aggregated to the regional level: the theoretical regional demand for additional fertilizer was determined through mass balancing and compared with regional statistics for the use of mineral and waste-based fertilizers. Finally, regional surplus and detailed fertilizer use were allocated to individual farms, proportionally to their fertilization demand. This approach assumes that farmers do not apply mineral fertilizer in amounts exceeding the total P requirements of their cropland. As a simplification of the relative agronomic efficiency (RAE) indicators used in (Hamilton et al., 2017), we assume that 100% of the mineral P and P in animal manure, 52% of the P in organic fertilizer from food waste and 29% of the P in organic fertilizer from sewage sludge added to the soil becomes readily available to the crops. The remainder was assumed to accumulate in the soil. The detailed procedure for surplus allocation is explained in the Supplementary Information 2.3. and the code used by the model is available at *https://zenodo.org/records/17853620*.

2.3 Manure utilization strategies

To assess the potential of circularity strategies in Norwegian agriculture to reduce mineral fertilizer imports and thus reduce soil P accumulation, four manure utilization strategies were modelled. Each scenario progressively expands the spatial scale of manure exchange between farms at the municipal, county, and national levels, thereby influencing the demand for mineral P fertilizer. In the scenarios, the crop production and the animal density and thus the fertilization demand remain unchanged relative to the *Status Quo*, affecting only the redistribution of animal manure. Waste-based fertilizers are not modified compared to the *Status Quo*, and other potential future sources of fertilizers, such as fish sludge from aquaculture, were not included.

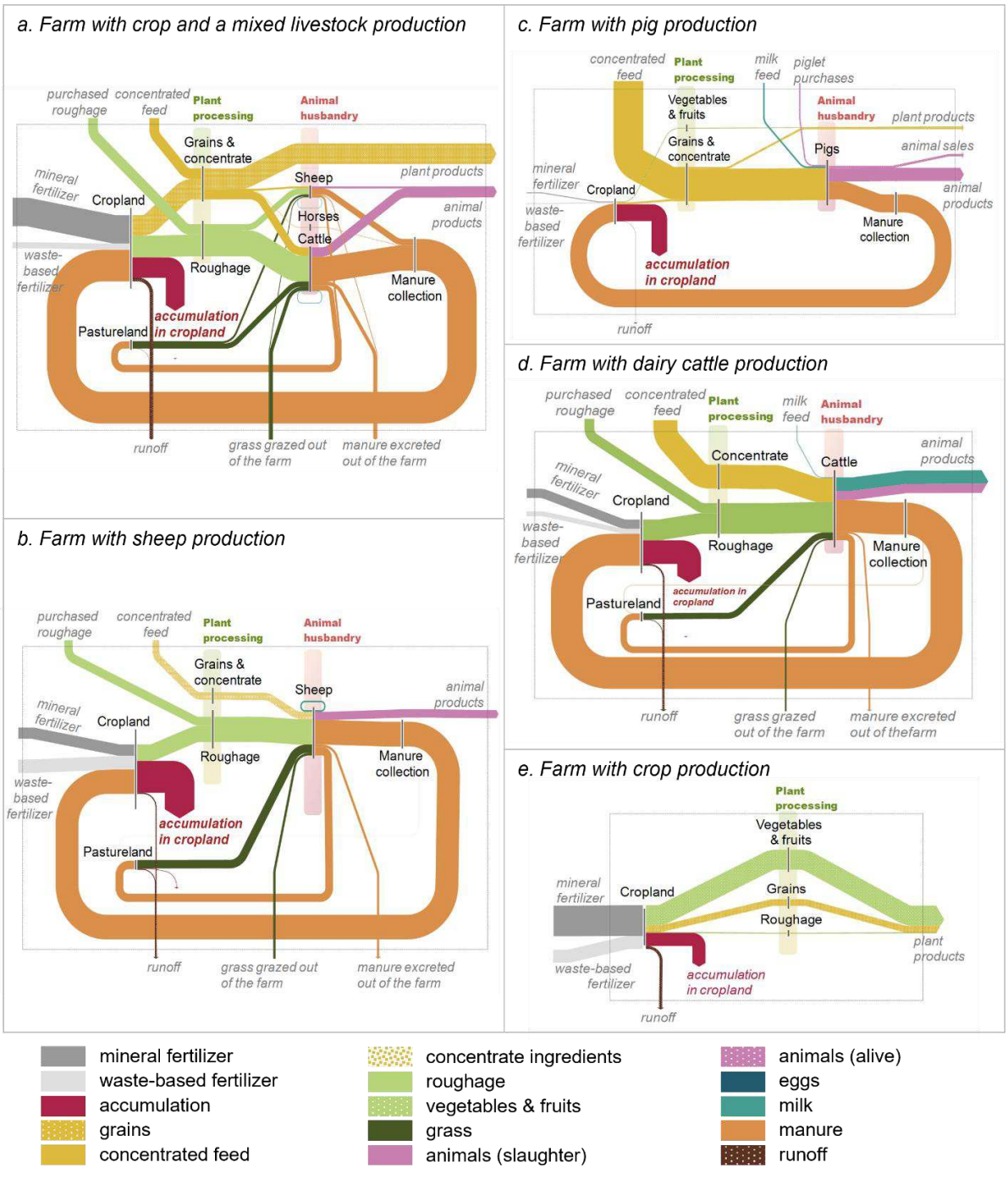
The *Farm Optimization* strategy showcases a scenario in which farmers reduce mineral fertilizer inputs by optimizing the use of manure within their farm, assuming perfect information on fertilization needs as well as no technical and economic limitations for using the secondary P. Farms with no or not enough manure P would still use mineral fertilizer P to cover the gap in fertilization demand. In the 3 other scenarios, we modelled the trade of manure between farms in addition to *Farm Optimization*:

- The *Municipal Market* strategy restricts manure trade between farms belonging to the same municipality, which is consistent with what can be economical in terms of current transport costs.
- *County Market* extends trade to farms with the same county.
- *National Market* allows for unrestricted manure trade within the whole country.

3 Results

3.1 P cycle at the farm level

The production volumes of crops and different livestock determine the P cycle of individual farms. In Figure 2, we show the flow of P through five example farms focusing on producing sheep (b), pigs (c), cattle (d), crops (e), or a mix of these (a). The production values and corresponding P flows of these farms can be found in the SI.



221

222 **Figure 2:** Examples of P cycle in individual farms across the country: (a) farm in Trøndelag

223 county with 1,75km^2 of cropland, 0,12km^2 of cultivated pastures, ~300 units of beef cattle, ~580

224 sheep, 2 horses, (b) farm in Innlandet county with 0,43 km^2 of cropland, 0,31 km^2 of cultivated

225 pastures ~1 498 sheep, (c) farm in Rogaland county with 0,2 km^2 of cropland, ~1 009 pigs, (d)

226 farm in Innlandet county with 0,50 km^2 of cropland, ~175 units of dairy cattle (~40% of them
227 milk-producing cows and ~60% calves), (e) farm in Viken county with 1,00 km^2 of cropland.
228 Values are given in kt $P \cdot yr^{-1}$ for the 5-year average between 2019-2023; subfigures have different
229 scales.

230 The source and magnitude of P flows in animal husbandry are conditioned by the animal
231 types and their feed. For farms raising primarily ruminants (i.e. >90% of the animals are
232 ruminants), such as the farms a, b, and d in Figure 2, grazing and roughage drive on average 19%
233 and 56% of the P inflows to animal husbandry respectively, and the rest of the P is taken up from
234 concentrate feed. For farms producing mostly poultry or pigs, such as farm c, the largest P inflow
235 in the system is concentrated feed.

236 Most of the P entering the animal husbandry process exits as manure which remains on the
237 farm, while the remainder exits the farm as animal products. On average, Norwegian farms with
238 animals convert 24% of the P in the various feed sources to P in animal products (slaughter
239 products, milk, egg and animal sales). Farms raising primarily pigs (i.e. >90% of the livestock are
240 pigs) are the most efficient, with a 44% average P to animal products conversion rate. Poultry,
241 cattle, and sheep farms convert on average 38%, 32% and 16% respectively.

242 In Norway, 28,5% of farms have no animals and exclusively produce crops, fruits or
243 vegetables, such as farm e. For these, assuming that no manure is traded across farms, all P applied
244 to cropland comes from mineral or waste-based fertilizers. Conversely, approximately 44% of the
245 farms with animals could cover their annual P requirements for crop growth with their own
246 collected manure. Still, the additional application of mineral P fertilizers causes a surplus of P that
247 accumulates in the soil.

3.2 P cycle at the national level

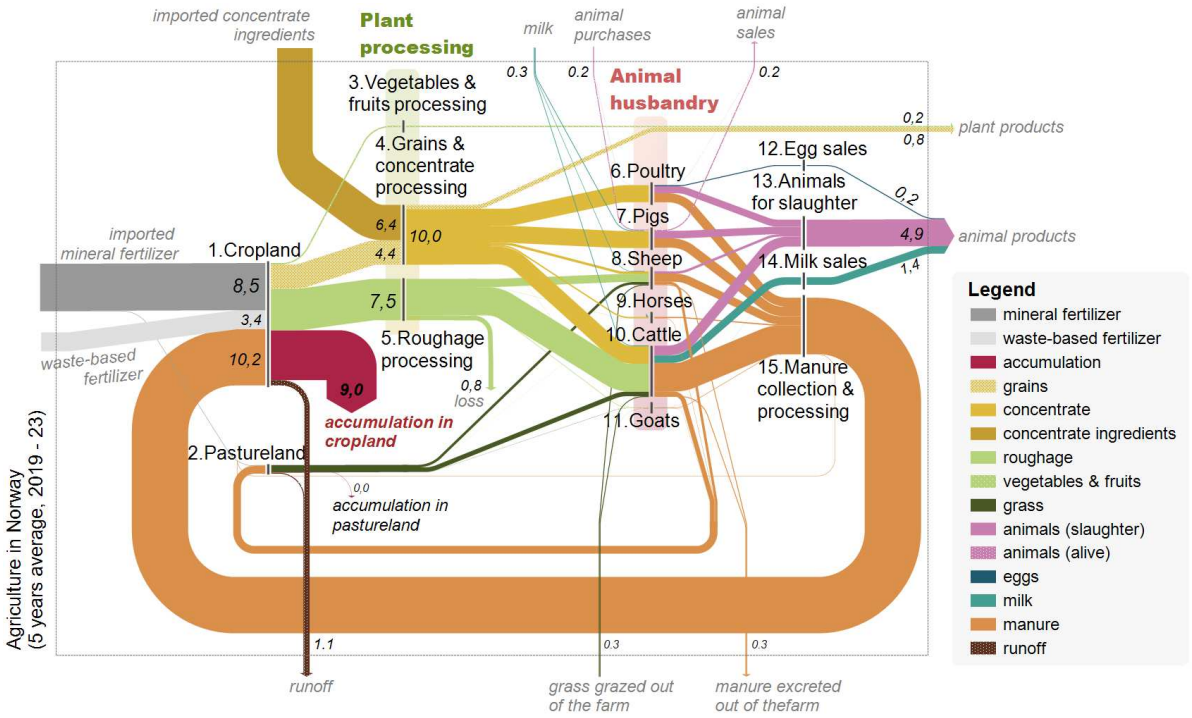


Figure 3: P cycle in Norwegian agriculture. Values are given in kt P·yr^{-1} for the 5-year average between 2019-2023.

The quantification of the P flows in all farms is aggregated to municipal, regional and national levels (Figure 3). Norwegian farmers apply 22,1 kt P·yr^{-1} to cropland, of which 8,5 kt P·yr^{-1} is from mineral origins, 3,4 kt P·yr^{-1} from organic waste and municipal sewage, and 10,2 kt P·yr^{-1} from in-farm collected manure. Crops take up 11,6 kt P·yr^{-1}, 1 kt P·yr^{-1} is estimated to run off to water bodies and the remaining surplus of 9,0 kt P·yr^{-1} is assumed to accumulate in the soil. Approximately 9% of the P in harvested crops is allocated to human consumption, while the rest is used as livestock feed, complemented by an import of 6,4 kt P·yr^{-1} as concentrate feed ingredients. Animal husbandry requires an input of 18,7 kt P·yr^{-1}, out of which 34% becomes primary agricultural products.

3.3 Spatial distribution of P in Norway

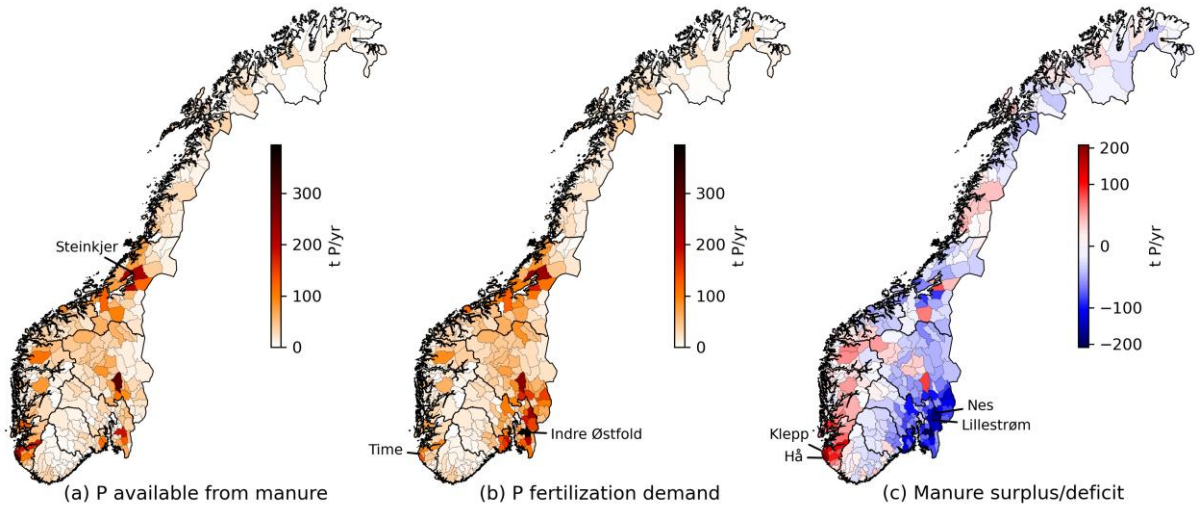


Figure 4: P distribution in Norwegian agriculture by municipality: (a) P available from manure, (b) P fertilization demand from crops, and (c) the balance between P supply (manure + waste-based fertilizers) and fertilization demand, indicating surplus (positive values) and deficit (negative values).

Results at the municipality level reveal regional contrasts in manure availability and P demand across Norway, as shown in Figure 4. Mid Norway presents a mixed pattern, with both animal husbandry and significant crop production, illustrated by Steinkjer, the municipality with both the highest manure generation (+223 t P·yr^{-1}) and crop P fertilization demand (+237 t P·yr^{-1}). Eastern Norway is characterized by crop P demand that exceeds locally available manure, with persistent deficits in municipalities such as Nes (-162 t P·yr^{-1}), Indre Østfold (-147 t P·yr^{-1}), and Lillestrøm (-111 t P·yr^{-1}). By contrast, Western Norway is an oversupply hotspot, where intensive livestock areas such as Hå (manure 344 t P·yr^{-1}; surplus +206 t P·yr^{-1}), Klepp (248 t P·yr^{-1}; +149 t P·yr^{-1}), and Time (222 t P·yr^{-1}; +156 t P·yr^{-1}) produce more manure P than can be absorbed locally.

3.4 Status quo and optimization strategies at different scales

Different manure trade strategies are explored to decrease mineral fertilizer use and thereby accumulation. Figure 5 compares, for each strategy, the total P applied to soil with fertilizer demand, while Figure 6 maps the resulting soil P accumulation by municipality.

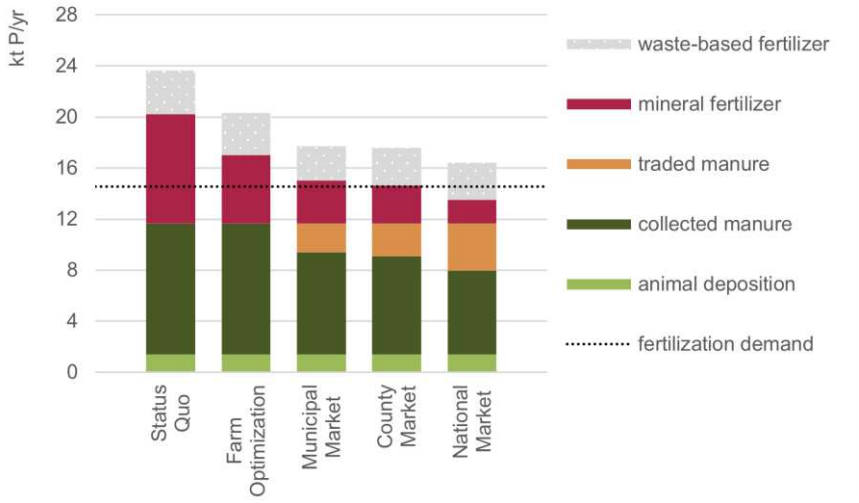
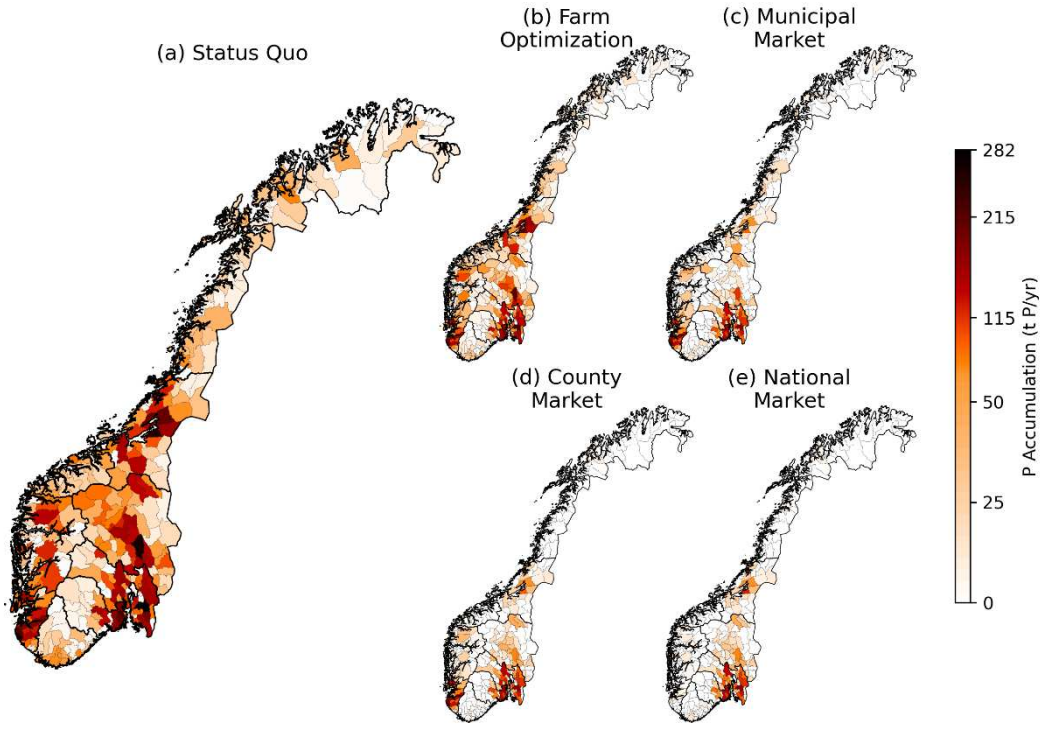


Figure 5: Status quo and scenarios for optimization of P use at different scales.

Farm-level optimization could reduce the need for mineral P by 38% and simultaneously lower P accumulation to 5,8 kt P.yr^{-1} (−36% compared to the status quo). Trading manure within municipalities could reduce P accumulation to 3,2 kt P·yr^{-1} (−65%) and cut P imports by ~5,5 kt P·yr^{-1} (−61%). Extending trade to the county level brings only a negligible additional benefit (~4% further reduction in imported P, 2% in accumulation). A national manure P trade could nearly eliminate soil P accumulation and reduce mineral P demand to about 1,9 kt P·yr^{-1} (−78%), corresponding to ~6,7 kt P·yr^{-1} lower imports, while enabling maximum utilization of secondary P resources in Norwegian agriculture. The residual accumulation is due to waste-based fertilizers, whose P cannot be fully absorbed by plants. It is most pronounced around Oslo, where high population density drives biowaste and sewage sludge generation.



294

295 **Figure 6**: P accumulation in soil per municipality in Norway (t $P \cdot yr^{-1}$) for (a) the status quo and
296 for four scenarios: (b) *Farm Optimization* strategy, (c) *Municipal Market* strategy, (d) *County*
297 *Market* strategy, and (e) *National Market* strategy.

298

4 Discussion

4.1 Validation and Robustness

Species-specific P excretion factors from our model align closely with the reported Norwegian standards across the main livestock categories (Nesheim & Halvorsen Sikkeland, 2013), and sit within the ranges reported by international compilations (Jeff Lorimor et al., 2004; Sheldrick et al., 2003), typically toward the lower end, consistent with Norway's less intensive, pasture-oriented husbandry (the underlying values are shown in the SI2 "Validation" tab). For crops, aggregated crop harvests by type match national statistics (Statistisk sentralbyrå, 2025). At the regional scale, the aggregation of farm results reproduce the established geographical distribution of manure availability and is coherent with earlier Norwegian P-mapping and balance studies (Hamilton et al., 2017; Hanserud et al., 2016).

The generic system definition allowed us to capture farm-specific details while keeping the farm definition identical for all farms, which in turn enabled data harmonization between farms. However, several model parameters were not observed at farm level but estimated using proxies from literature or from national statistics. For example, we allocated mineral P inputs to each farm by distributing county level purchases from official statistics matching the estimated P fertilization needs per farm, keeping surpluses in proportion to farm manure generation and fertilization demand. These simplifications introduce high uncertainties at the single-farm level, however, the impact decreases with higher aggregation levels. It is important to note that the model is not designed to provide accurate farm-level cycles, but to provide a first-order estimate of the spatially resolved regional P cycle. The bottom-up design enables scalable, high-resolution modelling across municipal, county, and national levels. This approach ensures our results align with

independent statistics and previous assessments and supports robust testing of spatial redistribution strategies under realistic structural constraints.

The analysis does not consider potential recycled P from aquaculture (~17 kt P yr^{-1} are currently emitted to water bodies; Pandit et al., 2023); given the sector's growth and increasing regulatory pressure on recovery, a coordinated cross-sector assessment will be needed to synchronize strategies and avoid creating new hotspots of P accumulation.

Lastly, our scenarios optimize P use only, but a successful nutrient management strategy should also consider Nitrogen (N) and Potassium (K) balances and operational constraints (timing, soil trafficability, emissions from handling and transport, and product acceptance). Moreover, possible tradeoffs that may arise when optimizing for nutrient efficiency, such as other impacts on animal welfare reduction and biodiversity loss (Schröder et al., 2011), were not assessed in the study.

4.2 The Norwegian agricultural P cycle

Norway's agriculture converts only ~45% of the P inputs into primary agricultural products, placing Norway in the lower half of European agricultural P-use efficiencies (41-76%; Biswas Chowdhury & Zhang, 2021). Our results show that this low efficiency is structurally linked to the predominance of livestock production and the spatial disparity between animal farms and the origin of their feed (i.e crop farms abroad, and in other regions of Norway). Although a large share of the P inputs to the system consists of imported mineral fertilizer and waste-based fertilizer applied to cropland, ~91.5 % of the P in the crop produced in Norway ultimately enters animal husbandry as feed. Because most ingested P is excreted as manure, only a small fraction is

converted into animal products. This is particularly true in ruminant systems with low P-conversion efficiencies.

At the farm level, we find that mineral fertilization is applied even when P from manure can theoretically meet crop P needs. In most cases, the combined application of mineral P and manure exceeds crop demand, contributing directly to the 9.0 kt P yr^{-1} accumulation in soil that we observe. The farmers' ability to align manure application with crop demand is constrained by storage, timing, spreading capacity, acceptability of waste-derived products and cross-farm exchange limits (Barquet et al., 2020; Buckwell & Nadeu, 2016; Hou et al., 2018).

The Norwegian geography reinforces this imbalance: while concentrate feed and roughage flow toward livestock-intensive areas, manure rarely flows back toward crop-dominated regions, and never abroad, despite ~38% of the P fed to animals coming from imports. Although our model is not spatially explicit within farms, similar mechanisms likely operate at finer scales: fields easier to access are more likely to receive manure applications than distant or hard-to-reach areas. This asymmetry, also observed in other countries (Bateman et al., 2011; Parchomenko & Borsky, 2018), points to the need for circulating manure-derived P from surplus to deficit areas.

4.3 Scaling Manure Utilization Strategies

We quantified how P-efficient manure use within farms and local exchange can reduce mineral P dependence and soil accumulation, and when national redistribution becomes necessary. The combination of farm-level optimization and enabling municipal trade could lower mineral P imports by up to ~61%. The gains are highest in municipalities with a balanced mix of crop and animal farms. There, the recycling potential can be realized with short-distance logistics, provided adequate storage, spreading capacity, and advisory support are in place. This would require

364 investments either by individual farmers or through local clusters, as well as site-specific
365 knowledge of soil P levels.

366 Extending manure trade from municipal to county scale has only a marginal potential to
367 reduce further P soil accumulation and fertilizer import dependency. This can be explained by
368 Norway's geography and its large regional disparity in farming practices, because Norway's
369 strongest imbalances are interregional. The redistribution of manure at national level has the
370 potential to reduce mineral P by up to ~78%. Soil accumulation could be nearly eliminated, but
371 residual accumulation remains where waste-based fertilizers dominate, especially around major
372 population centers, due to their lower plant-available P fraction. Realizing these longer-distance
373 flows requires converting raw manure into transportable biobased fertilizers (BBFs) with a lower
374 water content. Still, our results show that the greatest optimisation potential is at the farm/local
375 level, and there is a risk of competition between local trade of manure and centralised, capital
376 intensive large-scale redistribution pathways. Multi-scale nutrient models can help identify where
377 local management is sufficient and where regional or national redistribution of phosphorus is
378 required.

379 Our results indicate that, with targeted interventions, Norway could deliver the EU's
380 ambition to halve P losses by 2030, as set out in the Integrated Nutrient Management Action Plan
381 (Grizzetti et al., 2023). The 2025 regulatory updates provide the instruments to operationalize this
382 scale-dependent strategy. The new fertilizer regulation in Norway applies P-based caps to all
383 nutrient sources and requires plans, journals, and recent soil tests (Gjødselbrukforskrift, 2025),
384 enabling farm-level optimization of manure use and local trade. The new regulation enables
385 moving recycled P over longer distances via BBFs by regulating circular fertilizer products
386 through raw material lists, product quality, hygiene, and labeling rules (Gjødselvareforskriften,

2025). Embedding our farm-resolved mass balance framework into compliance and advisory workflows would deliver harmonized accounting that scales from farm to municipality and county levels, while informing recycled P market instruments (e.g., a blending mandate/certificate for recycled P; Gulden, 2024) and infrastructure placement so that local and national routes do not compete but complement each other.

4.4 Food security constraints of a livestock-oriented system

Our results indicate that spatial manure redistribution strategies are necessary but insufficient for P self-sufficiency. Even with efficient manure application and redistribution, a large, one-way inflow of P embedded in concentrate feed remains outside the domestic Norwegian crop-livestock-manure loop. This P arrives as imported feed, is largely transformed by farms into manure, and ends up accumulating in the soil, creating a linear trade pattern that spatially decouples sourcing from recycling, thereby leading to high P concentrations in high animal density areas. Such a linear trade pattern not only complicates efforts to achieve national circularity, but also contributes to resource depletion, land-use change, and nutrient imbalances in exporting countries (Nesme et al., 2018).

To bridge the remaining circularity gap, one option would be to process manure to return the imported P to the countries from which the feed ingredients originate, in the form of transportable BBFs. While theoretically possible, developing reverse international P trade flows comes with significant technological, logistical, and economic challenges. Besides, an over-reliance on international P trade also creates a food sovereignty risk, intensified by the specialization of the Norwegian agriculture toward animal products, which exhibit a lower P efficiency. Norway is currently close to self-sufficiency for animal products (milk and dairy ≈98%,

meat ≈96%), but far from it for vegetables and fruits (~20% when excluding potatoes; Landbruksdirektoratet, 2025). The apparent self-sufficiency of the domestic meat and dairy production, maintained by very high tariffs restricting imports of final products (Ministry of Agriculture and Food, 2021), is also limited by its reliance on feed grown locally, but supported by imported mineral P.

An alternative would be to implement structural shifts in production mix and cross-sector flows. Redirecting part of the agricultural production toward human edible crops would lower conversion losses and reduce the need for feed-P imports. The fruit and vegetables sector accounts for roughly 12% of total agricultural value creation in Norway, yet receives only around 2% of subsidies; it also gets less policy support compared to other agricultural branches (Pettersen & Dombu, 2025). Despite a low arable land share in Norway of 2.2% (World Bank, 2023), recent reports (Svendgård-Stokke et al., 2025) and sector roadmaps (Landbruksdirektoratet, 2020) show substantial margin to expand vegetables and legumes if less land and subsidies were tied to livestock. Future research should integrate nutrient flow mapping with spatial assessments of soil and climatic potential to identify regions where plant crop production can be most effectively developed and contribute to optimised nutrient management.

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