ENVIRONMENTAL RESEARCH
FOOD SYSTEMS

PURPOSE-LED PUBLISHING™

Part of the ENVIRONMENTAL RESEARCH SERIES

PAPER • **OPEN ACCESS**

Exploring the option space for phosphorus reduction in livestock production: modelling results from a Swiss watershed

To cite this article: Anja Heidenreich *et al* 2026 *Environ. Res.: Food Syst.* **3** 025011

ENVIRONMENTAL RESEARCH
FOOD SYSTEMS

Check for updates

OPEN ACCESS

RECEIVED
7 October 2025

REVISED
17 February 2026

ACCEPTED FOR PUBLICATION
20 April 2026

PUBLISHED
19May 2026

PAPER

Exploring the option space for phosphorus reduction in livestock production: modelling results from a Swiss watershed

Anja Heidenreich[1,2,*], **Catherine Pfeifer**[1], **Johan Six**[2] and **Adrian Muller**[1]

[1] Research Institute of Organic Agriculture (FiBL), Ackerstrasse 113, Frick, Switzerland
[2] Department of Environmental Systems Science, Sustainable Agroecosystems, ETH Zurich, Universitätstrasse 2, Zürich, Switzerland
[*] Author to whom any correspondence should be addressed.

E-mail: anja.heidenreich@fibl.org

Keywords: regional livestock production, livestock model, agroecosystems, environmental modelling, phosphorus, watershed level

Supplementary material for this article is available online

Abstract

Livestock production is a major driver of phosphorus (P) surpluses, threatening nutrient-sensitive regions, such as the watershed of Lake Sempach in Switzerland. While reducing livestock density may alleviate these impacts, it risks undermining food production and rural livelihoods. This study investigates regionally adapted strategies to reduce livestock-related P excretion while maintaining animal-source protein (ASP) production. Using the dynamic LEAF.livestock model, we simulated nearly five million combinations of herd structures and management practices. Each scenario was assessed across five key indicators: P excretion, ASP output, land use, food-feed competition, and manure fertilizing potential. Region-specific ecological and production constraints were applied, including limits on P excretion, maintenance of ASP output, and adherence to available land. No scenario fulfilled all constraints simultaneously. When the land-use constraint was relaxed, over 514'000 viable and 7'174 Pareto-optimal scenarios emerged, showing clear trade-offs between livestock density, herd composition, feed sourcing, and nutrient outputs. Pareto-optimal scenarios consistently required reduced livestock density (65%–90% of business-as-usual (BAU)), pig shares ⩾20%, and fewer suckler cows. Pig-dominated scenarios performed best on P excretion and ASP output but required more arable land and intensified feed-food competition. Dairy-dominated scenarios used less arable land and had better N:P ratios, but produced less ASP, though equal or greater than BAU. Similar results emerged therefore from different strategies, highlighting the importance to identify local optima rather than rely on a single global solution. In all scenarios, more plant-source protein than ASP could be produced if the same land were used directly for food production. To maintain the current ASP production, many scenarios relied on external land for feed production, manure export, or off-site rearing, shifting environmental burdens beyond the catchment. This study provides a model-based foundation for designing ecologically sound and socially acceptable livestock transition pathways, highlighting region-specific trade-offs and actionable strategies to reduce P surpluses while maintaining food production within environmental limits.

1. Introduction

Nutrient surpluses, particularly phosphorus (P), are a pressing environmental concern in Europe, contributing to challenges such as water eutrophication and ultimately exceeding the carrying capacity of ecosystems (Rockström *et al* 2020). Livestock production plays a key role in these surpluses (Bouwman *et al* 2013, Leip *et al* 2015). Addressing these surpluses requires farming systems to operate within ecological limits, yet livestock farming remains essential in many rural economies, shaping agricultural practices and livelihoods. This creates a tension between mitigating environmental impacts and maintaining viable farming systems.

The watersheds of Lake Sempach and Lake Baldegg in Switzerland exemplify this challenge. With one of the highest livestock densities in the country, the region faces significant P surpluses and accumulation of P in the soil (Binderheim 2021, Yerly-Brault and Jakob 2022, UWE and AfU 2023). Current regulations in the catchments allow a P balance of up to 90% at farm level, i.e. P supply is restricted to a maximum of 90% of crop P demand. This is more restrictive than national regulations, but experience shows that these regulations can still result in a net P supply of up to 105% (Stoll *et al* 2019). Thus, P removal from the soil is slow, and accumulated legacy P can continue to contribute to P losses to surface waters even when current inputs are reduced, thereby delaying observable water-quality improvements (Sharpley *et al* 2013, Zou *et al* 2022). Stricter measures are therefore needed. Reducing P balances to below 80%, i.e. restricting P supply to a maximum of 80% of crop P demand, would be necessary for significant reductions of current P surpluses (Stoll *et al* 2019). Reducing livestock P excretion to meet this target could help mitigate eutrophication risks and accelerate the depletion of excess soil P reserves.

At the same time, livestock production is integral to the region's identity, economics and national food production (Landert *et al* 2021). This tension has made calls by environmental NGOs and government agencies to reduce livestock numbers highly contentious (Luzerner Zeitung 2018, 12/14/2023, SRF 1/23/2024, SRG.D 2024). While reducing livestock populations is one way to address P surpluses, it risks disrupting food production and rural economies. Therefore, alternative strategies to influence the amount of livestock P excretion should be considered as well. Various management practices can help to achieve the necessary reductions in P excretion. For instance, adjusting the mix of livestock types can enhance feed conversion efficiency (Poore und Nemecek 2018). Prioritizing locally producible feed reduces external P inputs provided that mineral fertilizer P inputs remain unchanged, and helps to close nutrient cycles. Additionally, modifying feed rations and adjusting production intensity can help balance nutrient supply and demand within the catchment. Also, calf-rearing pathways influence total P excretion, with shorter cycles like veal production generally leading to lower nutrient accumulation than longer-term beef fattening.

These levers effectively reduce P excretion, but they also influence the production of meat and other livestock-derived products. The extent of these impacts varies by strategy, with some approaches leading to significant reductions in production while others maintaining higher production levels. Finding the right balance between implementing environmental measures, food production, and ensuring practicability that gains farmer acceptance is a key challenge. In any case, the quantitative potential of and interactions between these strategies and their combined effects are not yet fully understood. Investigating these dynamics is essential to identify practical, sustainable pathways that reduce nutrient surplus while preserving the viability of livestock systems.

The aim of this study is therefore to explore the option space for strategies to reduce P excretion from livestock production while maintaining animal-source protein (ASP) production, all within the ecological limits of the watershed. Specifically, we address the following research question: ***what are the impacts of P reduction strategies on P excretion, ASP production, and dependence on externally sourced feed inputs in the watershed of Lake Sempach?*** To answer this, we applied the dynamic livestock model LEAF.livestock to the watershed of Lake Sempach in Switzerland to evaluate measures to reduce nutrient outputs from livestock production. Informed by both region-specific recommendations and broader scientific insights, we analysed their effects on (a) P excretion by livestock, (b) human edible protein produced by livestock, and (c) the land area required to produce the feed locally. Additionally, we (d) contextualized the efficiency of ASP production in terms of land use competition, by comparing it to the potential quantity of plant-source protein (PSP) that could instead be produced on the arable and grassland used for feed production. We also examined (e) the fertilizing potential of manure under each scenario. Furthermore, we compared the scenarios with P balance target set at 80% of the status quo.

Often, studies on alternative livestock futures emphasize the potential of circular food systems, with considerably lower animal numbers and animal source food shares in diets (Tirado *et al*, Bajželj *et al* 2014, Ipsos UK 2024, Röös *et al* 2017, Willett *et al* 2019, Clark *et al* 2020, van Zanten *et al* 2018). Here, we take a different route to better relate to the realities and acceptability in the case study region, which is strongly linked to livestock production. We focus on alternative strategies that produce similar levels of ASP—which is a proxy for ensuring economic viability and value generation within a largely unchanged market context. We complement this with an assessment of the plant-based human-edible protein production potential of the areas used, to also provide the context of much more drastic changes within circular strategies focusing on avoidance of food-feed competition, without modelling such strategies in detail, though. Similarly, we do not model fully localized production systems but allow for flows in feed, manure and animals to closer relate to current practices.

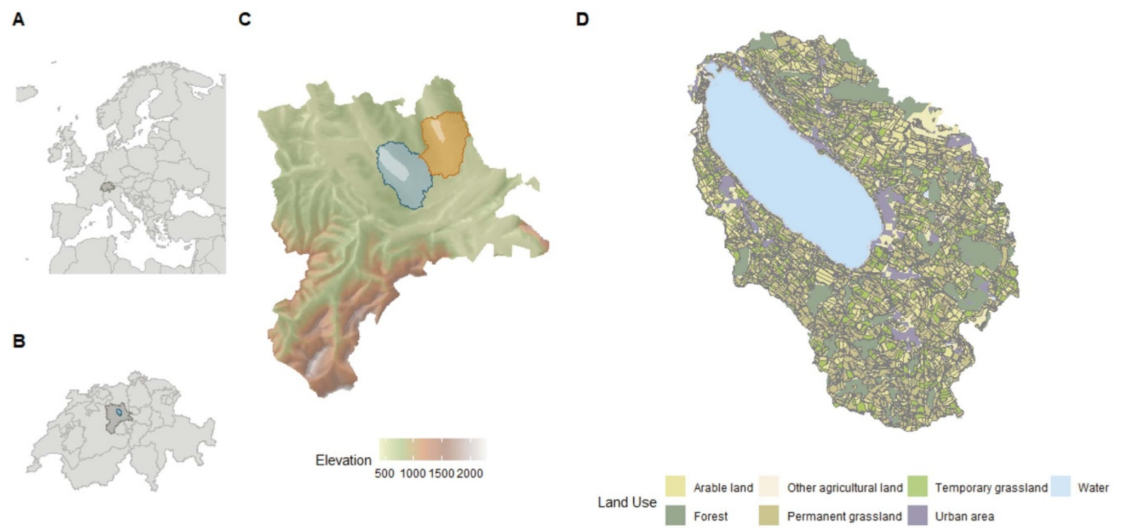

Figure 1. (A) Location of Switzerland within Europe; (B) Location of the canton of Lucerne and the catchment of Lake Sempach within Switzerland; (C) location of Lake Sempach and its catchment area (blue), shown alongside the catchment of Lake Baldegg for comparison (orange), within the canton of Lucerne; (D) Land use within the catchment of Lake Sempach. *Sources*: Swiss land use statistics (FSO 2023), Agricultural land under cultivation: types of use (rawi 2019), Topographical catchment areas of Swiss waterbodies (FOEN 2019), Lake boundaries (FOEN 2023), National and cantonal borders (swisstopo 2024), Hillshaded relief (swisstopo 2017, Grossenbacher and Zehr 2021), Digital height model (swisstopo 2022).

2. Materials and methods

2.1. Case study

The watershed of Lake Sempach is located in the Swiss Central Plateau in the canton of Lucerne (figure 1). It covers 75.38 km^2, with an average elevation of about 586 m.a.s.l. (from 502 to 839 m.a.s.l.) and an average slope of 12.8%. 85% per cent of the catchment area are classified as agricultural 'valley zone,' the remaining 15% falls within the 'hilly zone'. About 69% (4'183 ha) of the catchment's terrestrial area is agricultural land, comprising 2'042 ha arable land (33.5% of the terrestrial area), of which 44% are classified as temporary grassland, and 2'008 ha permanent grassland (32.9% of the terrestrial area) (rawi 2019). 133 ha are 'other agricultural land' (such as orchards or other permanent cultures). With 2.39 LSU/ha in 2019 (Kanton Luzern 2021), the region has one of the highest livestock densities in Switzerland (national average 1.24 LSU/ha, Federal Statistical Office (2025))[3]. In Lippenrütibach, a sub-catchment of the Lake Sempach watershed, cattle account for 52%–66% of livestock P excretion, pigs for 32%–47%, and other livestock for only 1%–2% (Prasuhn and Lazzarotto 2005). The comparable neighbouring Lake Baldegg catchment shows similar figures for 2017, with 59% of P excretion from cattle, 33% from pigs, and 8% from other livestock (Stoll *et al* 2019). These consistent patterns across comparable sub-catchments support the initial assumption of a similar livestock composition for the entire Lake Sempach catchment.

Over the last decades, agriculture in this region resulted in P accumulation in soils, with around 58% of arable land and 70% of permanent grassland belonging to the highest P supply classes D (surplus) and E (enriched)[4] (Hirte, J.—personal communication 9/22/2023). The lake has long been depleted of oxygen due to high P inputs from the surrounding intensive agriculture and, in the past, from wastewater rich in P from detergents (Scharrer 2013). Since 1982, the lake has been artificially aerated and steps have been taken to reduce P pollution from agriculture: the so-called 'Phosphorus Project' has been running since 1999, with an average of 63% of the farms in the area participating between 2005 and 2022 (Stadelmann, F.—personal communication 6/5/2023, Kanton Luzern 2021). This project includes subsidies for farmers for the implementation of P reducing measures, such as restricted P balances, buffer strips along water bodies, restrictions on manure spreading in winter, and incentives for alternative income sources. The interventions decreased P concentration in the lake, but the target values for P inputs and P concentration in the water are still being exceeded (UWE and AfU 2023).

[3] Note: Livestock units (LSU) are defined according to Swiss agricultural statistics, where 1 LSU corresponds to one adult dairy cow. Detailed livestock type-specific conversion factors are provided in the appendix of BLW (2024).

[4] Note: Class D corresponds to soil P concentrations of approximately 0.93–4.35 mg P kg soil, while class E exceeds 1.55 mg P kg soil, with threshold values depending on soil properties such as texture, pH, and organic carbon content (Flisch *et al* 2017).

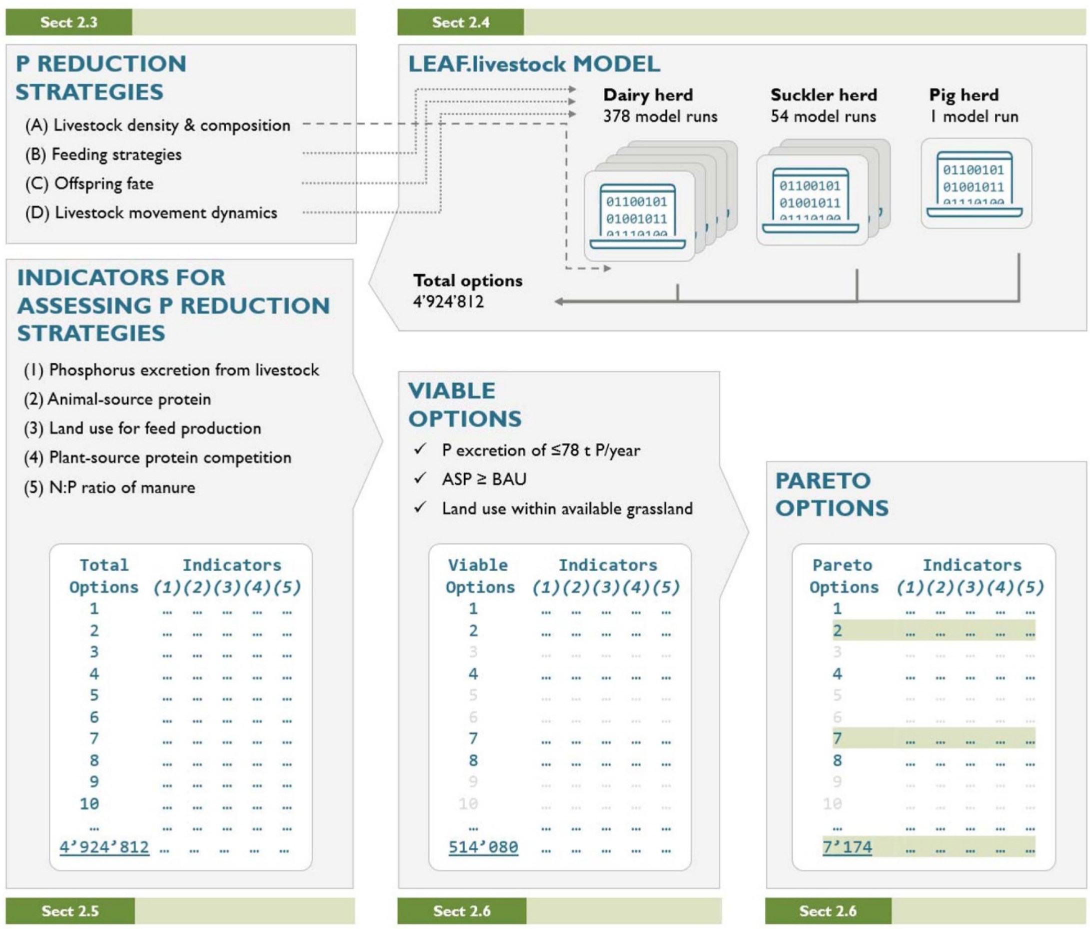

Figure 2. Schematic representation of the research approach. The sections that illustrate the different methods and approaches behind each step are shown in the green boxes. P refers to phosphorus; N, to nitrogen; ASP, to animal-source protein, BAU, to business-as-usual, and t, to tonnes.

2.2. Research approach

We systematically explored the option space for strategies to reduce P excretion from livestock production (figure 2). For this, we selected a diverse set of P reduction strategies across three livestock herds (dairy, suckler, and pigs[5]) encompassing adjustments of livestock density and composition (A), feeding strategies (B), offspring management (C), and movement dynamics (D) (section 2.3). The P reduction strategy (A) was implemented as an overarching constraint, with all herd-level results subsequently combined. To generate these herd-level results, the LEAF.livestock model (section 2.4) was run for each livestock herd and for each relevant combination of the P reduction strategies (B), (C), and (D). This resulted in 378 model runs for the dairy herd, 54 model runs for the suckler herd, and one model run for the pig herd. These runs were then combined and scaled according to varying herd proportions (in 20% steps) and total livestock densities (in 5% steps) to comply with strategy (A). The approach resulted in 4'924'812 combinations, each describing a potential scenario for the livestock management in the region, in their totality providing the so-called 'option space' for this region. These scenarios were analysed to assess the effects of the P reduction strategies on five key indicators: P excretion from livestock, ASP production, land use for feed production, PSP competition, and the respective N:P ratios (section 2.5). To define the viable options in the option space, we applied three constraints: (1) P excretion of lower or equal to 78 t P yr^{-1}, (2) ASP production equal to or greater than for the business-as-usual situation (BAU), and (3) land use for feed production smaller or equal to the available arable plus grassland (section 2.6.1). From this subset of viable scenarios, Pareto-optimal scenarios were identified (section 2.6.2).

[5] Due to their minor contribution (8% of LSU), other livestock (e.g. poultry, horses) were excluded from the modelling, where we focused on the main P sources: cattle and pigs.

Table 1. Overview of P reduction strategies and variation ranges applied.

Strategy group	P reduction strategy		Variation range
(A) Livestock density and composition	A1	Livestock density	45%–100% of BAU LSU/ha, 5% steps
	A2	Share of cattle vs pigs	0%–100% of total LSU/ha, 20% steps
	A3	Share of dairy herd vs suckler herd within the cattle population	0%–100% of total LSU/ha, 20% steps
(B) Feeding strategy	B1	BAU feeding	applied to 0%, 50%, or 100% of cattle
	B2	Maximized locally producible forage and feed utilization	applied to 0%, 50%, or 100% of cattle
	B3	Maximized locally producible grassland-based feed utilization	applied to 0%, 50%, or 100% of cattle
(C) Offspring fate	C1	Dairy offspring sold at 2 months	0%, 50%, or 100% of dairy offspring
	C2	Remaining dairy offspring into calf fattening	10%, 50%, or 100% of remaining dairy offspring
(D) Livestock movement dynamics	D1	Dairy/suckler cows leaving for rearing phase	0%, 50%, or 100% of dairy/suckler cows
	D2	Cattle seasonally absent (Jul–Oct)	0%, 50%, or 100% of cattle

2.3. P reduction strategies

The scenarios have been designed to capture a wide range of P reduction strategies aimed at reducing P excretion. Livestock density and composition (A) are explored through three adjustments. First, overall livestock density is varied from 45% to 100% of BAU LSU/ha in steps of 5% (A1) (see table 1). Second, the share of cattle relative to pigs is adjusted such that cattle contribute between 0% and 100% of total LSU/ha, in steps of 20% (A2). Third, the share of dairy herd versus suckler herd within the cattle population is varied from 0% to 100% of cattle LSU/ha, also in steps of 20% (A3). Feeding strategies (B) include three mutually exclusive options: the BAU system applied to 0%, 50%, or 100% of cattle (B1); a strategy that maximizes the use of locally producible forage and feed from grassland and arable land (B2); and a strategy that maximizes the use of grassland-based feed resources (B3), all applied to 0%, 50%, or 100% of cattle. The fate of offspring (C) is captured by varying the share of dairy offspring sold at two months of age between 0%, 50%, and 100% (C1), and by allocating 10%, 50%, or 100% of the remaining offspring to calf fattening (C2). 0% was excluded as a starting point for C2 to account for agronomic constraints, as it is not feasible for 100% of the offspring from a dairy herd to enter beef fattening (Hietala *et al* 2014). Movement dynamics (D) are modelled by varying the proportion of cattle that leave the catchment for the rearing phase (D1) and those that are seasonally absent between July and October (D2), both ranging from 0% to 100% of animals. A brief reasoning for each intervention is given in SM1.

We did not include additional P reduction strategies for pig herds than those covered in A1 and A3. The reason is that pig production has long been a focus of efforts to reduce P losses, with notable success in improving efficiency. Advances such as phase feeding and the use of phytase in pig diets have significantly increased P uptake, thereby lowering the P content in manure and reducing the environmental impact of livestock production without compromising productivity (Hongliang Wang *et al* 2020; In K. Han *et al* 2000). These improvements are also evident in the Lake Sempach watershed. In the Lippenrütibach sub-catchment, for example, P excretion from pigs was reduced by more than half between 1992 and 2003, despite a 9% increase in pig numbers (Prasuhn and Lazzarotto 2005). Given the already high efficiency of pig production due to phase feeding and feed additives and the resulting limited scope for further P reduction through additional system adjustments, we decided to include only one type of pig production in our modelling approach.

We also acknowledge that this study covers only a subset of the possible strategies for reducing P excretion in livestock production. Improved manure management including salt addition or liquid-solid separation (Kleinman *et al* 2020), reduction of P overfeeding in lactating cows, enhancing feed efficiency in lactating cows through practices like bovine somatotropin injections (Bosch *et al* 2006), which are not permitted in Switzerland, or other strategies aimed at lowering the P content in animal diets

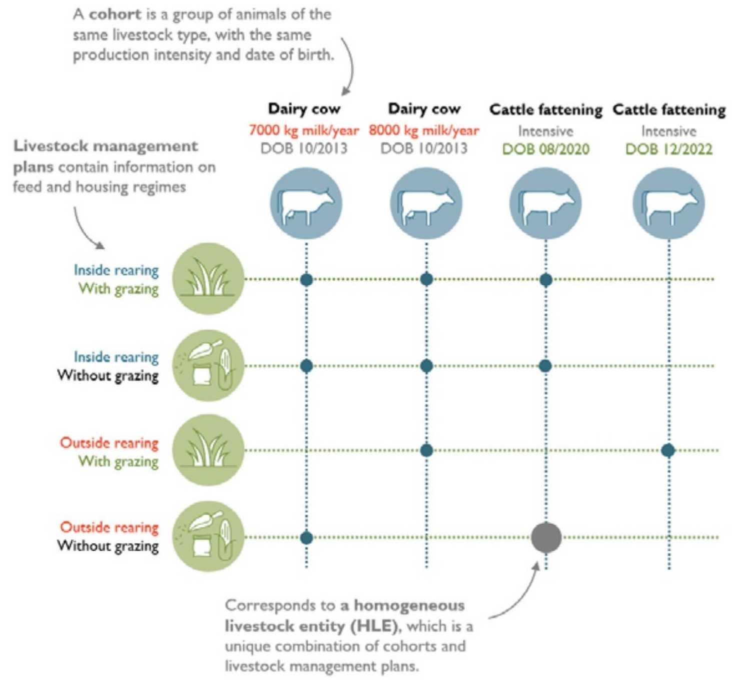

Figure 3. Conceptual framework of the LEAF.livestock model illustrating and defining livestock cohorts, livestock management plans, and homogeneous livestock entities (HLE). DOB—date of birth.

(Schoumans *et al* 2014) are not addressed. Nevertheless, our analysis presents a diverse range of measures across key aspects of livestock systems, including herd density and composition, production systems and intensities, and animal movement strategies. The selected measures are chosen due to their practical relevance and central role in the ongoing discussions within Swiss agriculture and the specific case study region.

2.4. LEAF.livestock model

LEAF.livestock is a dynamic livestock model that generates time series data at daily, monthly, or yearly intervals. These data contain detailed information on the livestock population over the modelled period, the outputs produced, such as milk, meat and manure, and the feed requirements to produce these outputs. The model is programmed in R (RStudio Team 2020, R Core Team 2022) and connected to a SQLite 3 database (Hipp 2020). Both the code and a comprehensive description of the implementation can be accessed at https://doi.org/10.5281/zenodo.15277174 (Heidenreich *et al* 2025).

Modelling approach. The smallest unit of analysis at which the model operates are homogeneous livestock entities (HLEs), which are unique combinations of cohorts and livestock management plans (figure 3). A cohort is defined as a group of animals of the same livestock type and with the same production intensity and date of birth. In the model, life stages are defined for each livestock type according to the level of detail selected by the user. For dairy cattle, this may include calf rearing, cattle rearing, the first calving and subsequent first lactation, the second and subsequent lactations, and finally the end of life in the form of slaughter. For each life stage, the commencement and conclusion ages, as well as the nutrient requirements, production quantities, and mortality rates, are specified. During the model run, cohorts progress to the subsequent life stage upon the attainment of the final age of the current stage. In contrast, livestock management plans contain information on feed and housing regimes. Consequently, animals belonging to the same HLE have the same feed requirements, feeding plans, and produce the same output, at each time step.

Model sequences. The model runs through sequential phases—growth, production, movement, and feeding—at each time step (figure 4—model run). Each phase simulates a key process in the livestock system: During model setup, users define reference data such as livestock types with nutrient needs and production levels at different life stages, feed types with nutritional values, and scenario data including initial cohorts, management plans, and their allocation to the cohorts. At each time step and for each HLE, the model sequentially simulates growth (aging and life stage progression), production (milk,

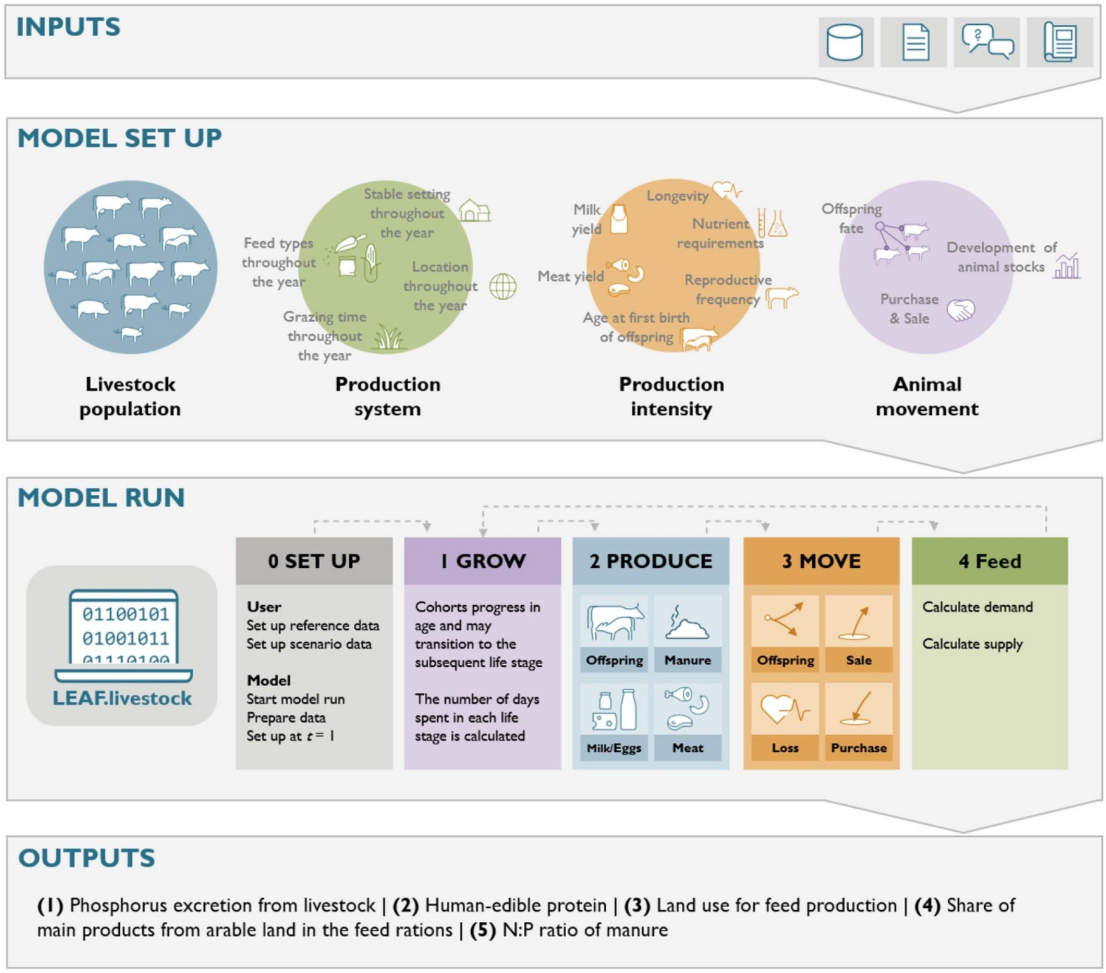

Figure 4. Flowchart illustrating the overall model structure, from data inputs through model setup and execution to output generation. During model setup, key components such as livestock population, production systems, production intensities, and animal movement patterns are defined. The model run proceeds through the sequential phases: set up, grow, produce, move, and feed.

manure, offspring, and meat output), movement (animal losses, market transactions, and offspring allocation), and feeding (calculation of nutrient requirements and feed quantities needed to fulfil these requirements with the defined feeding plans). A more detailed description of each sequence can be found in SM1.

Model setup and data. The LEAF.livestock model was set up for the period from January 2011 to January 2021 with monthly time steps. In the scenario runs, this period was simulated as if the respective P reduction strategies had been implemented from the outset, providing counterfactual trajectories that contrast with the BAU developments. Input data, derived from the Swiss Animal Movement Database (AMD 2023), literature sources, and expert knowledge (table 2), were prepared to represent the livestock population, reflecting the production systems, production intensities, and animal movements (figure 4—model set up). Cattle and pig populations were characterized at $t = 0$ for the BAU and P reduction scenarios, with livestock types defined based on animal traits, and scenario-specific adjustments made for production intensities and feeding plans. An overview of the final livestock types and selected characteristics is provided in table 3; additional information is available in SM1, section 2.2.1. Production intensity and nutrient requirements were defined for each livestock type based on lifespan, life stages, and yields (milk, meat, manure), using AMD records and literature sources to calculate daily growth, feeding needs, reproductive parameters, and nutrient excretion across scenarios, with adjustments for production systems and feeding strategies (SM1, section 2.2.2). Production systems were defined through livestock-specific housing and feeding plans that accounted for location, grazing duration, seasonal dynamics, and feeding strategies, with BAU configurations derived from AMD and adapted under scenario settings D1, D2, B2, and B3 to reflect changes in animal movement and feed rations using literature sources (SM1, section 2.2.3). The model setup furthermore included the identification of detailed animal movement

Table 2. Data and sources used in model setup.

	Usage									
	Livestock population		Production intensity			Production system		Animal movement		
Source	Livestock types	Animal numbers	Yield	Nutrient requirements	Reproduction	Feeding plans	Housing plans	Offspring fate	Temporary absences	Sales/ Purchases
AMD (2023)[6]	X	X	X				X	X	X	X
Gassmann (3/28/2024)	X		X			X				
Agroscope (2021)			X	X		X				
Agroscope (2016)				X						
AGRIDEA (2023)			X			X				
Gruber *et al* (2006)			X	X						
Agroscope (2017), Schlegel *et al* (2020a), Schlegel *et al* (2020b), AGRIDEA and BLW (2023)			X							
Swiss Animal Welfare Programme RAUS (Federal Office for Agriculture FOAG 2022), Swiss Animal Welfare Ordinance (TSchV, SR 455.1, Swiss Federal Council (2/1/2025))							X			
AGRIDEA (2022), LfL (2024), Kamm (11/25/2024), Universität Zürich (2011-2016)						X				
Expert knowledge (FiBL, BioInspecta, private sector companies)	X	X	X	X	X	X	X	X	X	X

Table 3. Livestock types and their characteristics. B1, B2, and B3 refer to scenario settings B—feeding strategies. Slaughter weights and ages, except for 'Cattle and ox fattening,' are based on median values from the AMD (2023), while 'Cattle and ox fattening' data come from AGRIDEA (2023). Dressing percentages for all livestock and the age at slaughter for pigs are also derived from AGRIDEA (2023). Daily weight gain data for bull, cattle, and ox fattening cover the period from 125 kg live weight to slaughter, while for dairy and suckler cows, they refer to the period from 125 kg live weight to seven months into the first gestation.

	Dairy herd						Suckler herd		Pig herd	
	Dairy cow[7]	Calf fattening	Bull fattening	Ox fattening	Cattle fattening	Cattle and ox fattening	Suckler cow	Suckler cow husbandry	Finishing pig	Breeding sow
Present in BAU, B1 and B2	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Present in B3	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes
Slaughter weight (in kg)	291	129	297	297	287	292	326	231	89	144
Dressing percentage	46%	59%	57%	52%	52%	53%	52%	55%	89%	72%
Average daily weight gain (in g/day)	650	1'177	1'392	1'127	940	761	625	1'200	880	
Age at slaughter (in days)	2'315	150	395	507	563	663	2'573	316	168	1'100

patterns, purchase and sales dynamics, and offspring fates (SM1, section 2.2.4). A full description of the baseline livestock composition, offspring flows, seasonal absences, and associated feeding strategies used in the BAU model run is provided in SM2, section 1.

The model was then executed for both BAU and 433 individual model runs, covering all relevant combinations of scenario settings *B—feeding strategies, C—offspring fate, and D—livestock movement dynamics*. This resulted in 378 model runs for the dairy herd, 54 for the suckler herd, and 1 for the pig herd. The scenarios were run with the assumption that all relevant P reduction strategies are implemented at the beginning of the model period in 2011 and remained unchanged throughout the 10 year simulation. The results of BxCxD were then linearly scaled to reflect the scenario settings defined

[6] The **Animal Movement Database (AMD)** is the mandatory, nationwide registry for cattle and pigs in Switzerland. It holds records of all holdings, individual cattle and movements of cattle and pigs between farms. The database is operated by Identitas AG, a company commissioned by the Swiss Confederation to manage livestock identification and traceability systems.

[7] **Note:** Milk production intensity levels under BAU conditions were derived from breed composition data AMD (2023) and regional milk volume data Gassmann (2024). The resulting distribution comprised 15% low-intensity, silage-free systems (6,000 kg milk per cow), 43% low-intensity, silage-based systems (7,000 kg), 11% high-intensity, silage-free systems (7,000 kg), and 31% high-intensity, silage-based systems (8,000 kg).

under *A—livestock density and composition*. Subsequently, indicators for assessing P reduction strategies were calculated.

2.5. Indicators for assessing P reduction strategies

To assess the P reduction strategies (cf. section 2.3) and, explore the option space for reducing P excretion from livestock production while maintaining ASP production within the watershed's ecological limits, we computed the following four indicators. The indicator values are calculated as annual mean values over the whole modelling period.

(1) The **P excretion from livestock** was used to assess the pressure of the livestock system on the local ecosystem. Based on the modelled annual manure quantities, we computed the average P excretion from livestock in tons P per year. Exporting farmyard manure is a common practice to reduce P loads in the region and an increase has been suggested to have a high potential (Stoll *et al* 2019). However, challenges associated with increased exports have been noted, such as nutrient imbalances due to the export of not only P but also nitrogen, potassium, and magnesium, requiring replacement with mineral fertilizers at additional cost and environmental impact. Further challenges include transport costs and uncertain demand from potential recipients (Stoll *et al* 2019) and potential oversupply in the target regions, i.e. leakage effects. Therefore, we assumed that current P exports are at their maximum and used the export rate from the Lake Baldegg catchment (Stoll *et al* 2019) to estimate the status quo (20.3 t P yr^{-1}) for the Lake Sempach catchment. This fixed amount was subtracted from the total P excretion in all scenarios to determine the net P available for use within the catchment boundaries.

(2) The ASP produced by the livestock population, measured in tons ASP/year, was calculated to assess the nutritional value of the livestock system. This was done by linking the modelled meat and milk production with their human-edible protein content based on the Swiss Food Composition Database (FSVO 2023). As whole milk and whole milk powder are used for calf rearing, it was assumed that these are supplied by the dairy cows in the catchment. Therefore, the corresponding modelled feed requirements were subtracted from the total milk production, reducing the final ASP quantity.

(3) **Land use for feed production** was calculated in ha per year for both arable land and grassland to assess the degree of nutrient cycle closure. To avoid additional P inputs from external feed sources, it is preferable that livestock production relies as much as possible on feed grown within the catchment. This approach would help to close nutrient cycles. Based on the modelled amounts of feed required for each scenarios, we computed the area needed to produce them by first linking the individual feed components (e.g. soybean cake or soybean oil) to the primary crops (e.g. soybeans), using their respective extraction rates (e.g. 1.15 tons of soybeans for 1 ton of soybean cake) (Zimmermann A. *et al* 2017, FAO 2025). The quantities of primary crops required were then linked to yield data to estimate the area of arable and grassland required for their production. Yield estimates were based on production under local conditions, using average yield data for Switzerland (FAO (ed) 2025). For feed components derived from by-products (e.g. sunflower seed meal), we assumed no additional land use, as these by-products do not drive the production of the primary crop. For the land use associated with animal sourced feed products (i.e. milk/milk powder and some animal fats and fishmeal), we relied on data from Poore and Nemecek (2018) and assumed that the whole milk (and whole milk powder) used for calf rearing is produced by livestock in the catchment and the animal fats count as by-products without additional land demand. Therefore, the related land use is already accounted for through the feed of the dairy cows. In addition, no land has been allocated for the production of feed additives.

(4) To contextualize the efficiency of ASP production in terms of land use competition, we compared it to the potential quantity of PSP that could instead be produced on the arable and grassland used for feed production. This **PSP competition score** was calculated as shown in equation (1),

$$\text{PSP competition} = \frac{\begin{array}{c}\text{Alternative PSP}_{\text{arable land}} + \text{Alternative PSP}_{\text{convertible perm. grassland}} \\ +\text{Additional PSP}_{\text{unutilized arable land}} + \text{Additional PSP}_{\text{unutilized convertible perm. grassland}}\end{array}}{\begin{array}{c}\text{ASP} \\ +\text{Additional PSP}_{\text{unutilized arable land}} + \text{Additional PSP}_{\text{unutilized convertible perm. grassland}}\end{array}}. \tag{1}$$

For a gross indicative estimate of alternative PSP from arable land, we calculated the quantity of protein that could be produced on the area used for feed production by assuming an illustrative crop allocation consisting of 44% temporary grassland, 38% cereals, and 19% grain legumes. Thereby, 44% temporary grasslands grassland reflects the catchment-specific temporary grassland share (see SM1). For choosing illustrative yields, we assumed 'wheat' as a representative for 'cereals' (with national average yields from FAO (2025) and human-edible protein contents from FSVO (2023) and 'peas' for 'grain legumes'. The latter produces a rather conservative protein yield of 0.6 (±0.12) t protein per ha, compared to e.g. soy with 1.07 (±0.17) t protein per ha (Keller *et al* 2024). The alternative PSP from convertible permanent grassland was calculated similarly on the basis of the area of permanent grassland used for feed production that could be converted to arable land. Based on agricultural suitability classes (FOAG 2000), 74% of permanent grassland in the catchment was deemed convertible, and of this, 56% was considered usable as arable land, reflecting the catchment-specific temporary grassland share of 44% (see SM1). If less than the available arable land and/or permanent grassland in the catchment was used for feed production, additional PSP quantities from unutilized arable land and/or convertible permanent grassland were calculated using the same method. Additional potential PSP production from unutilized arable land and convertible permanent grassland is included to ensure a consistent comparison of overall system performance by accounting for land that becomes available due to feed-area-efficient livestock production and could be used for additional plant-based protein production. Clearly, converting grassland to cropland comes with a number of negative effects such as soil carbon losses, but here, the focus is on a comparison of the food production potential and in the consistent logic of this, areas capable for cropland use should be used like this (see also the discussion section).

(5) To evaluate the fertilizing potential of manure, the **N:P ratios** were computed. The calculation considered only the nitrogen available for fertilization in manure (Richner *et al* 2017) and further adjusted for the constant farm yard manure (FYM) export, which reduced the nitrogen supply according to the scenario-specific P export fraction. The desirable N:P ratio was determined based on the fertilization recommendations for the crops grown in the catchment (Sinaj *et al* 2017) and weighted according to the cropping area (rawi 2019). The P recommendations were adjusted for soil P content, reflecting the proportions of P supply classes separately for arable and grassland (Hirte, Flisch *et al* 2017,). This resulted in an overall desirable N:P ratio for the catchment of 5.33, with a range of 3.76–8.43, depending on the crop type and area.

2.6. Narrowing the option space

2.6.1. Defining the viable scenarios for P reduction

We defined a set of targets based on real-world constraints to narrow down the scenarios from the possible to the viable option space for P reduction in livestock production. To ensure broad acceptance among farmers and decision-makers, we considered only scenarios with ASP production equal to or greater than that of the BAU scenario as viable. To evaluate whether a scenario remains within the watershed's ecological limits, P excretion was compared against a reduction target. Given that the current livestock system supplies up to 105% of P demand, it was proposed to reduce supply to below 80% of P demand to mitigate eutrophication and accelerate the removal of excess soil P, with corresponding depletion times of 15–30 years, depending on soil P content (Stoll *et al* 2019). This would require reducing P excretion to 78 t P yr^{-1} (representing 80% of demand), which corresponds to 76% of BAU P excretion, respectively. Therefore, we classified only scenarios with P excretion equal to or less than 78 t P yr^{-1} as viable. Lastly, we compared the land use for feed production with the available arable land and grassland in the catchment. According to rawi (2019), 2'898 ha (69%) of the agricultural land is used for permanent and temporary grassland, while 1'152 ha (28%) is used for arable land, thus resulting in a total area for potential feed production of 4'050 ha in the region.

2.6.2. Identifying Pareto-optimal scenarios

To identify the most promising scenarios, we utilized the notion of Pareto-optimality. Pareto-optimal scenarios represents a set of scenarios where no single indicator can be improved without compromising another (Goldberg 1989, Groot *et al* 2010). These scenarios are called non-dominated and are assigned the Pareto rank-1. After removing the rank-1 scenarios, a new set of non-dominated scenarios, which are assigned rank-2, can be identified and so on. We utilized the R package rPref (Roocks 2016) to compute the Pareto rank for each viable scenario based on the following indicators: minimizing P excretion, arable land use, and PSP competition, while maximizing ASP production and the N:P ratio. To further illustrate trade-offs, we analysed the extreme Pareto solutions, i.e. those solutions showing the minimal or maximal values in each indicator. To identify the extreme scenarios for each indicator used to evaluate P reduction strategies individually, all viable scenarios were sorted by the indicator's optimization

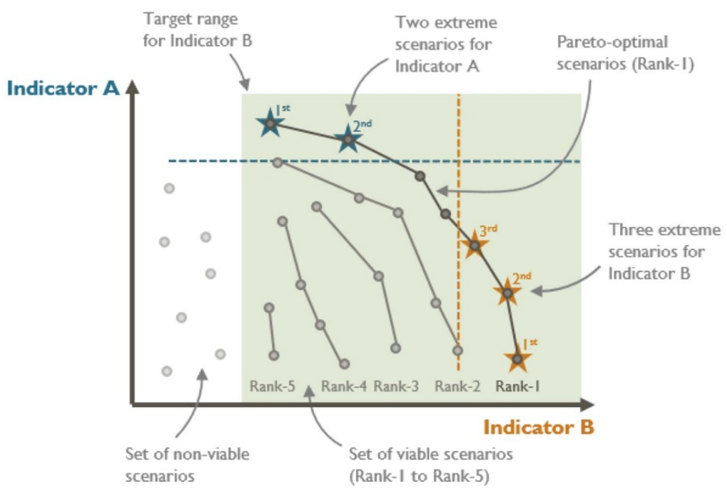

Figure 5. Conceptual 2D plot of non-viable, viable, Pareto-optimal, and extreme scenarios for two illustrative indicators. The target range for Indicator B is indicated by a transparent green box. Dark grey points represent rank-1 (Pareto-optimal) scenarios; medium grey points represent viable (aka target-fulfilling) scenarios (Pareto rank-2 to rank-5); light grey points represent non-viable scenarios. Blue stars mark the extreme scenarios for Indicator A, obtained by sorting all viable scenarios by Indicator A and retaining rank-1 scenarios as long as they outperform the best rank-2 (or higher) scenario. Orange stars show the corresponding extreme scenarios for Indicator B.

direction (i.e. ascending for minimization, descending for maximization). All scenarios with a Pareto rank of 1 were then selected sequentially until the first scenario with a Pareto rank-2 (or higher) was encountered. This approach resulted in a distinct set of indicator-specific Pareto rank-1 extrema, illustrating the range of optimal trade-offs depending on the chosen evaluation focus (see figure 5).

3. Results

3.1. Reference scenario: BAU

The LEAF.livestock model was calibrated to observed data and literature values. For **animal numbers**, we fitted the modelled time series to recorded figures from the animal movement data (AMD 2023) at each time step, refining factors like the number of animals at $t = 0$, purchases/sales, the fate of offspring, age at first calving, and calving frequencies (see SM2, section 2.1). Similarly, we aligned modelled animal births with recorded data (AMD 2023) and accounted for monthly fluctuations. For **production quantities**, we compared modelled outputs for milk, meat, and manure per animal, life stage, and day with literature values, adjusting as necessary (SM2, section 2.2). For **feed quantities**, we fine-tuned the model by matching the nutrient requirements and feed demand per animal to literature values. Finally, we verified aggregated values, such as LSU/ha, total P excretion, and the share of P from pig versus cattle production, against comparable literature values (SM2, section 2.3).

For the BAU scenario, the model estimated a P excretion of 123 tons P per year, of which 20.3 tons of P were exported from the system via FYM (table 4). The remaining P excretion in the catchment was 102.4 tons per year, with 62% originating from the dairy herd, 10% from the suckler herd, and 28% from the pig herd. ASP production amounted to 1’256 tons per year. The total land use for feed production was 6’492 ha per year, with 3’599 ha from arable land and 2’894 ha grassland. If this land were used to produce food for direct human consumption instead of feed, it could generate 2.4 times as much PSP than the above-mentioned ASP. The resulting available N:P ratio was 3.36.

3.2. Assessment of P reduction strategies

3.2.1. General overview

We analysed all 4’924’812 individual scenarios in the option space, comparing P excretion from livestock, ASP produced by livestock, land use for feed production, PSP competition and the respective N:P ratios. Across all scenarios, the average P excretion was 63.2 ± 20.4 tons P per year (figure 6, col. A, row 2; SM2, table 3), accompanied by an average ASP production of 975.4 tons per year, with a range from 75.3 to 2’084.2 tons. The average area required for feed production was 2’606 ha of arable land and 1’873 ha of grassland, with considerable variability. On average, this land could produce 1.8 ± 0.2 times as much PSP for direct human consumption than ASP. The average N:P ratio of FYM was 3.3, ranging

Table 4. Business-as-usual (BAU) values for indicators used to assess P reduction strategies. PSP competition for each livestock herd was calculated based on their share of available arable and grassland areas weighted by LSU.

Variable	Overall	Dairy herd	Suckler herd	Pig herd	Share dairy herd	Share suckler herd	Share Pig herd
LSU *(per year)*	8'208.61	4'649.47	935.52	2'623.63	57%	11%	32%
Total P excretion *(tons P per year)*	122.67	76.51	12.46	33.71	62%	10%	28%
Via FYM exported P excretion *(tons P per year)*	20.31	12.66	2.06	5.58	62%	10%	28%
In catchment remaining P excretion *(tons P per year)*	102.37	63.84	10.4	28.13	62%	10%	28%
Animal-source protein *(tons ASP per year)*	1'256.08	565.17	24.74	666.16	45%	2%	53%
Land use for feed production: arable land *(ha per year)*	3'599.36	1'059.90	14.89	2'524.56	29%	0%	70%
Land use for feed production: grassland *(ha per year)*	2'893.57	2'402.96	490.61	0	83%	17%	0%
Plant-source protein competition *(score)*	2.4	2.23	1.92	2.24			
$N_{available}$:P ratio of FYM	3.36	3.58	3.79	2.69			

from 2.7 to 3.8. As this is well below the desirable ratio of 5.33 for the catchment, mineral N fertilizer is required even under the BAU scenario, despite the abundance of manure, owing to its unfavourable N:P composition. These findings highlight the variability in P excretion, ASP production, land use, and nutrient management across scenarios.

Based on the P reduction strategies A2 and A3 (changed livestock composition), we differentiated the entire set of scenarios into four groups: Pig-dominated scenarios (with an LSU composition of ⩾60% pigs), dairy-dominated scenarios (with an LSU composition of ⩾60% dairy cattle), suckler-dominated scenarios (with an LSU composition of ⩾60% suckler cattle), and mixed scenarios (⩽60% dairy, ⩽60% suckler, ⩽60% pigs). Across all groups, most scenarios resulted in lower P excretion than BAU, with many meeting the P excretion target of ⩽78 t P yr^{-1} (figure 6, col. D; SM2, table 3). The biggest differences between scenario groups emerged in ASP production, land use for feed, PSP competition, and the N:P ratio. Pig-dominated scenarios had the highest average ASP production (1'243.3 t yr^{-1}), followed by mixed (914.7 t yr^{-1}) and dairy-dominated (881.2 t yr^{-1}), while suckler-dominated scenarios produced the least (476.2 t yr^{-1}, range: 75.3–978 t yr^{-1}). No suckler-dominated scenario reached the BAU ASP production. Arable land use was on average highest in pig-dominated systems (3'988 ha yr^{-1}) and lowest in suckler-dominated (776.9 ha yr^{-1}). The mean PSP competition was highest in pig-dominated systems (1.9), compared to mixed (1.8), suckler-dominated (1.8), and dairy-dominated scenarios (1.6). Regarding fertilizer quality, pig-dominated systems had on average the lowest N:P ratio of FYM (2.7), while dairy- and suckler dominated systems had the highest (3.6).

3.2.2. Defining the viable option space

To identify a viable option space for P reduction in livestock production, we applied the following constraints (cf. section 2.6.1): P excretion ⩽78 t P yr^{-1}; produced ASP ⩾ ASP_{BAU}, i.e. 1'256 tons ASP per year; using ⩽4'050 ha total land (arable plus temporary and permanent grassland) to produce the necessary feed. Figure 7 visualizes P excretion (y-axis), land use for feed production (x-axis), and ASP production (dot colour), with each dot representing a scenario across all P reduction strategies. The BAU values are marked by a red dot, along with a dotted red horizontal and vertical line for reference. Scenarios that do not meet the ASP constraint (i.e. ASP lower than BAU) are displayed with reduced opacity. Additionally, the target range for P excretion (⩽78 t P yr^{-1}) is highlighted with a transparent green horizontal box, while the available agricultural land in the catchment is indicated by a transparent green vertical box (4'050 ha).

Figure 7 shows that no fully opaque scenarios fall within the intersection of the target range for P excretion and the total available land (darker green box). In other words, none of the scenarios simultaneously satisfied all three constraints. Most notably, the current level of ASP production could not be maintained without relying on feed imports. However, since feed from arable land is commonly traded across regions, its production is less strictly tied to local conditions. By contrast, grassland-based feed is rarely traded, making regional grass production potential the more binding limitation. To account for this, we relaxed the target for arable land use and instead adjusted the land use constraint to focus on scenarios that remained within the grassland area currently available in the catchment.

When the land use constraint was relaxed to allow scenarios using more than the arable land available in the catchment, 514'080 scenarios (10.4%) could be categorized as viable options (see darker

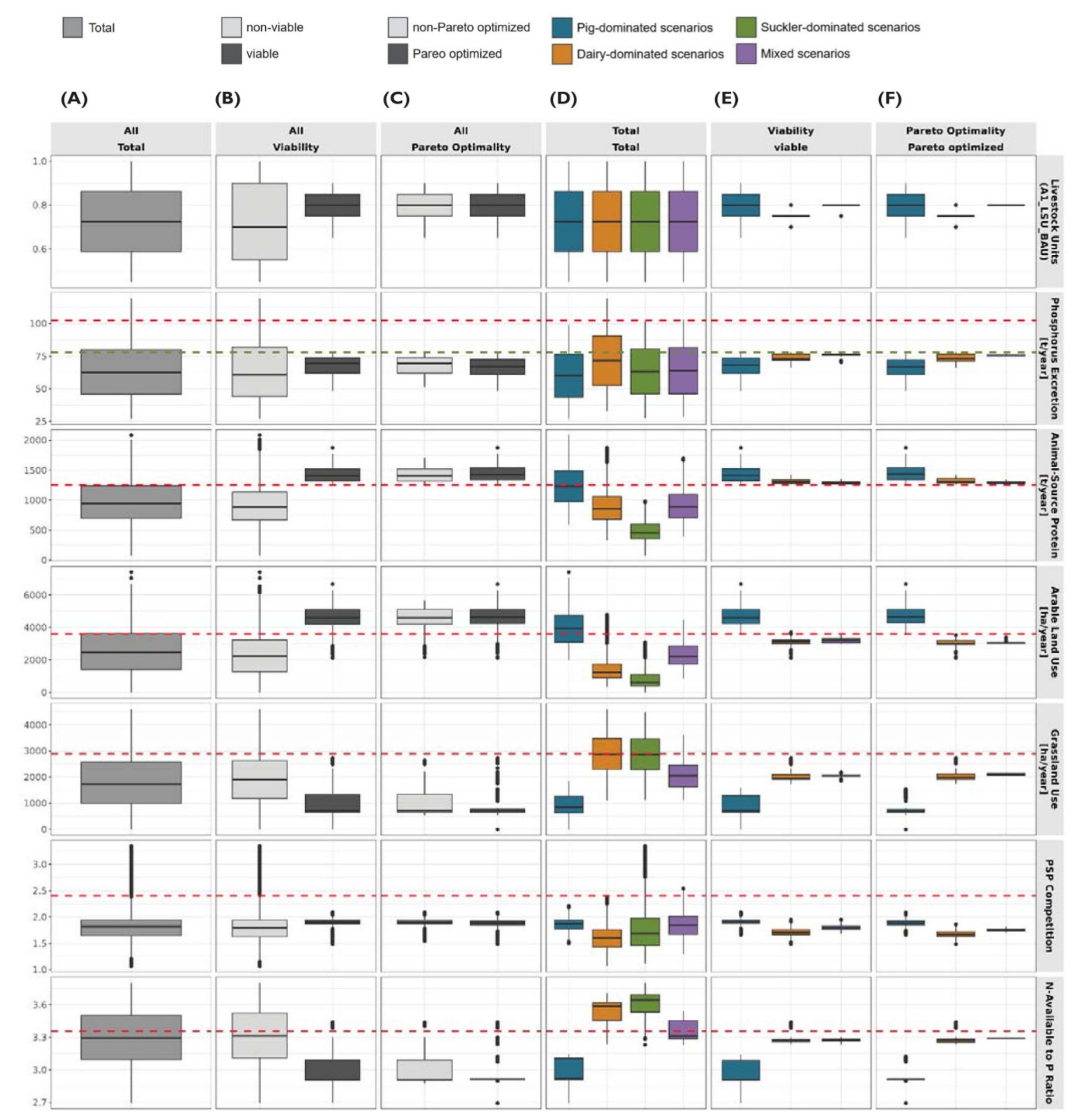

Figure 6. Performance of scenarios across all indicators for assessing P reduction strategies (horizontal rows) plus share of LSU compared to BAU. The columns (A) and (D) show the results for all scenarios, (B) and (E) show viable and (C) and (F) Pareto optimized scenarios. (D), (E), and (F) Divide the scenarios into pig-dominated scenarios, dairy-dominated scenarios, suckler-dominated scenarios (with an LSU composition of ⩾60% suckler cattle), and mixed scenarios. Since no suckler-dominated scenarios met the viability criteria, they do not appear in the last two columns. The red dashed lines show the BAU. Green dashed line indicates the P excretion target of 78 t P yr^{-1}. Note that the y-axes for LSU compared to BAU, P excretion, PSP competition, and N:P ratio of FYM are truncated and do not start at zero, to better visualize differences between scenarios. The reader is referred to SM2, figures 58–61, for enlarged versions of these figure.

green box in figure 8). The diagonal clusters of points in figure 8 illustrate the influence of P reduction strategy A2, which varies the share of cattle versus pigs (SM2, section 3.2). These clusters emerge from the discrete variation steps applied: the leftmost single-dot line represents scenarios with 100% pigs, followed by diagonals corresponding to 80%, 60%, 40%, and 20% pigs. The BAU scenario, with a pig share of 32%, falls between the 40% and 20% clusters, while the cluster with 0% pigs, which display the widest spread, appears on the far right. The vertical spread within each diagonal cluster reflects differences in overall livestock density (P reduction strategy A1), with higher total LSU values resulting in higher P excretion. Furthermore, none of the suckler-dominated scenarios fulfilled the viability criterion, as all resulted in lower ASP production compared to the BAU scenario and thus failed to meet the ASP constraint.

3.2.3. Performance of viable and Pareto scenarios

As illustrated above, out of the full option space, 514’080 scenarios (10.4%) met the three constraints: (1) P excretion ⩽78 t P yr^{-1}, (2) ASP production ⩾ASP_{BAU}, and (3) land use within the available

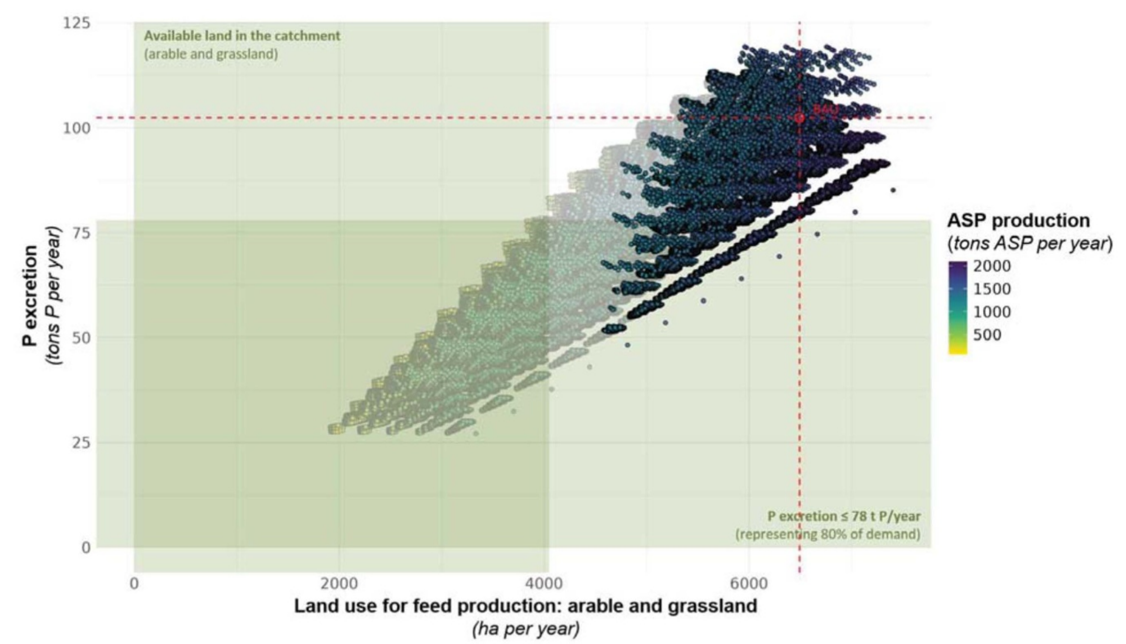

Figure 7. Relationship between phosphorus (P) excretion (y-axis), agricultural land use for feed production (x-axis), and animal-source protein (ASP) production (dot colour). Each dot represents one scenario; BAU is marked by a red dot and red dashed lines. Scenarios not meeting the ASP constraint (i.e. lower ASP than BAU) are shown with reduced opacity. The target range for P excretion ($\leqslant$78 t P yr^{-1}) and the available agricultural land in the catchment (4'050 ha) are indicated by transparent green boxes.

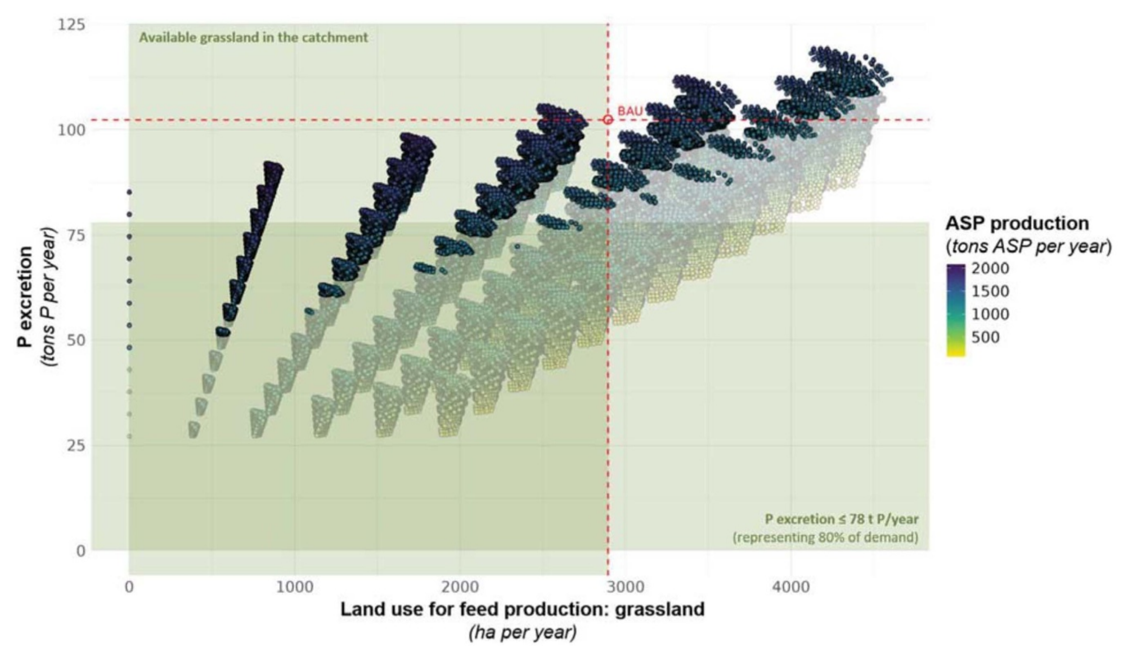

Figure 8. Relationship between phosphorus (P) excretion (y-axis), grassland use for feed production (x-axis), and animal-source protein (ASP) (dot colour). Each dot represents one scenario; BAU is marked by a red dot and red dashed lines. Scenarios not meeting the ASP constraint (i.e. lower ASP than BAU) are shown with reduced opacity. The target range for P excretion ($\leqslant$78 t P yr^{-1}) and the available grassland in the catchment (2'898 ha) are indicated by transparent green boxes.

grassland. Such scenarios were categorized as viable (figure 6, col. B; SM2, table 4). Within this viable option space, 7'174 scenarios had Pareto rank-1 (0.15% of all scenarios, 1.4% of viable ones) (figure 6, cols. C/F; SM2, Table 5). Together, these subsets provide insight into both the boundaries of viability and the maximal performance in a context of competing objectives. Their performance is described along the five key indicators: ASP production, P excretion, land use and PSP competition, and the N:P ratio of farmyard manure (figure 6, rows 2–7).

ASP production. Viable scenarios produced on average 1’427 t ASP per year (114% of BAU, range: 100%–149%), well above both the BAU reference and the mean of non-viable scenarios (923 t). Pareto scenarios performed slightly better, averaging 1’443 t (115% of BAU) and reaching a maximum of 1’876 t, which was about 1.1 times as high as the best-performing non-Pareto viable scenario.

P excretion. Non-viable scenarios excreted on average 62.6 t P yr, but this lower value was achieved only in scenarios that failed to meet the constraints for ASP production and/or grassland use. In contrast, viable scenarios excreted 68.2 t on average (67% of BAU, range: 48–78) while fulfilling all constraints. Pareto scenarios showed a slightly lower average of 66.7 t (65% of BAU), with minimum and maximum values similar to the viable scenarios.

Land use and PSP competition. A major difference between viable and non-viable scenarios lay in land use. Viable scenarios required on average 4’617 ha of arable land (128% of BAU, compared to 2’372 ha in non-viable scenarios) but used much less grassland, averaging 919 ha (32% of BAU, compared to 1’984 ha in non-viable scenarios). Pareto scenarios showed similar patterns, with slightly lower average grassland use (856 ha). If used for PSP production instead of livestock feed, these areas could yield almost twice as much PSP as ASP. PSP competition scores show this trade-off clearly, averaging 1.9 in both viable and Pareto scenarios, with values ranging from 1.5 to 2.1.

N:P ratio of farmyard manure. Viable scenarios produced FYM with an average N:P ratio of 3.0, somewhat lower than both BAU (3.36) and the mean of non-viable scenarios (3.3). Pareto scenarios showed almost identical averages (3.0), with minima dropping slightly further (2.7 vs 2.9 in viable but non-Pareto scenarios).

3.2.4. Strategies underlying the viable and Pareto scenarios

The performance patterns described above were the result of distinct strategy combinations. Examining these strategies reveals which P reduction strategies underpinned the viable scenarios and distinguished the Pareto-optimal subset from the wider set of viable options (SM2, figures 66–68).

Livestock density and composition (A1–A3). Both viable and Pareto scenarios were restricted to livestock densities between 65% and 90% of BAU levels. On average, viable scenarios reached 80% of BAU LSU and Pareto scenarios 79%. This indicates that reducing livestock density was a necessary precondition for achieving viability and optimality under the given constraints. Suckler-dominated scenarios consistently failed to achieve viability. Across the entire viable option space, the share of suckler cows never exceeded 32%, and this only in mixed configurations where pigs accounted for at least 40% of the total LSU. In Pareto-optimal scenarios, the share of suckler cows never exceeded 16%, again only in cases with $\geqslant$40% pigs. Dairy-dominated scenarios could achieve viability, but only when complemented by at least 20% pigs. Among these viable dairy-dominated scenarios, 35% reached Pareto-optimality. By contrast, only 1.4% of viable pig-dominated scenarios were Pareto-optimal. These patterns were largely driven by the low ASP productivity of suckler systems compared to, for example, pig systems. Meeting the productivity and P excretion target was therefore only possible when a sufficient share of pigs was included in the livestock composition.

Feeding strategies (B1–B3). For dairy herds, the distribution of feeding plans did not differ substantially between viable and non-viable scenarios. In Pareto-optimal scenarios, however, a clear dominance of the local grass-based plan (B3) emerged, often applied to 100% of the dairy herd, particularly in pig-dominated and mixed scenarios. These cases benefited from the high ASP productivity per unit of P excreted in pig systems, which ensured sufficient ASP supply under the P excretion constraint. At the same time, the share of the dairy herd assigned to B3 feeding maximized grassland utilization and minimized arable land demand. An even stronger pattern was observed for suckler herds, where Pareto scenarios relied exclusively on either full adoption of the grass-based plan (B3) or a 50/50 mix of that plan with the local forage-and-feed plan (B2).

Offspring fate (C1, C2). For dairy herds, there were no major differences in offspring strategies between viable and non-viable scenarios. Within the Pareto-optimal subset, early sale at two months (C1) became more common: the share of scenarios with no offspring sold at that age was smaller than in the rest of the viable set. This indicates the unfavourable efficiency of beef production, as offspring retained for fattening increase P excretion and feed demand disproportionately relative to their contribution to ASP output.

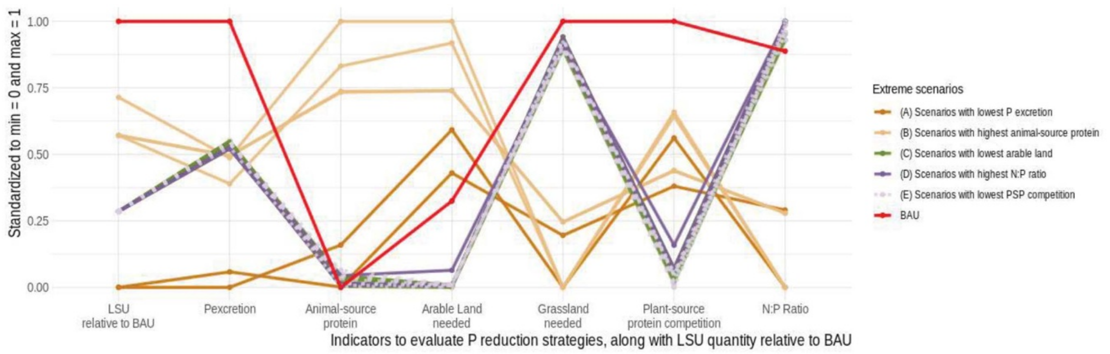

Figure 9. Performance of extreme scenarios across indicators used to evaluate P reduction strategies, together with livestock units (LSU) relative to BAU. For comparison, the BAU scenario is also shown. All indicators were rescaled to a 0–1 scale.

Patterns for calf fattening (C2) also shifted: in pig-dominated Pareto scenarios, the 10% option appeared more frequently, whereas in dairy-dominated Pareto scenarios the 100% option occurred more often compared to their non-Pareto counterparts.

Livestock movements dynamics (D1, D2). In dairy herds, scenarios with all replacement heifers leaving the catchment for rearing (D1) were slightly more frequent among viable dairy-dominated and mixed scenarios than among non-viable ones. Within the Pareto-optimal subset, this pattern was even more pronounced, with most scenarios showing 100% of replacement heifers leaving the catchment. Pareto scenarios also showed a slightly higher frequency of full seasonal absences (D2), although the difference compared to the wider viable set was small. This pattern is driven by the removal of unproductive life stages that contribute to P excretion and feed demand without yielding ASP output. For suckler herds, all Pareto scenarios involved 100% of cows leaving the catchment for rearing, exceeding the pattern observed in dairy herds for D1. Additionally, in pig-dominated systems, Pareto scenarios more often featured no seasonal absences (D2) compared to their non-Pareto counterparts.

3.2.5. Extreme scenarios

From the group of 7'174 Pareto rank-1 scenarios, we identified in a next step a set of 29 extreme scenarios based on their performance along individual optimization criteria (figure 10). For the indicator P excretion, two Pareto-optimal scenarios (rank-1) were identified before the selection process (cf. Section 2.6.2) encountered a scenario with a higher Pareto rank (⩾2). Four scenarios were identified for maximizing ASP output, nine for minimizing arable land use for feed production, three for maximizing the N:P ratio of FYM, and eleven for minimizing the PSP competition. These indicator-specific extrema illustrate the range of trade-offs within the Pareto frontier, highlighting scenarios that most strongly emphasize individual objectives such as minimizing arable land use or maximizing ASP production. Interestingly, optimal outcomes are partly possible with considerably different strategy combinations, thus illustrating the presence of several local maxima. Figure 9 illustrates the performance of the selected scenarios and their LSU levels relative to BAU. Scenarios with the lowest P excretion (figure 9(A)) showed strong performance in minimizing both P excretion and grassland use, but this came at the expense of all other indicators. Scenarios with the highest ASP output (figure 9(B)) excelled in ASP production and required minimal grassland use. However, they showed poorer performance in arable land use than both the lowest P excretion scenarios and the BAU. P excretion levels were moderate, while performance in all other indicators was weak. In contrast, a largely overlapping set of scenarios achieved the lowest arable land use for feed production, the highest N:P ratio, and the lowest PSP competition (figure 10). These scenarios consistently performed well across these three environmental indicators, though this came at the cost of reduced ASP output and only moderate reductions in P excretion (figures 9(C)–(E)). Nevertheless, all of these scenarios outperformed the BAU baseline across the evaluated indicators.

When examining the P reduction strategies behind the extreme and intermediate scenarios, several general patterns emerged (figure 10). Suckler herds played only a minor role, appearing in just two scenarios with contributions of 4% and 8% to the total LSU, respectively (P reduction strategy A3). In all

				(A) Scenarios with lowest P excretion		(B) Scenarios with highest human edible protein				(C) Scenarios with lowest arable land						(D) Scenarios with highest N:P ratio			(E) Scenarios with lowest PSP competition score				
			Order among extreme scenarios	1st	2nd	1st	2nd	3rd	4th	1st; (E) 3rd	2nd; (E) 7th	3rd; (E) 10th	4th; (E) 8th	6th; (E) 6th	9th	1st; (C) 5th	2nd; (C) 7th; (E) 11th	3rd	1st	2nd	4th	5th; (C) 8th	9th
			P reduction strategies	Pig-dominated scenarios	Pig-dominated scenarios	Pig-dominated scenarios	Pig-dominated scenarios	Pig-dominated scenarios	Pig-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios	Dairy-dominated scenarios
Accross all herd types	(A) Livestock density and composition	A1	Livestock density (% of BAU LSU/ha)	65%	65%	90%	85%	85%	85%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%
			% LSU pig herd	100%	80%	100%	100%	80%	80%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
			% LSU dairy herd		16%			20%	20%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
			% LSU suckler herd		4%																		
Dairy herd	(B) Feeding strategy	B1	BAU feeding (% of cattle)		50%			100%	100%									50%					
		B2	Maximized locally producible forage and feed utilization (% of cattle)							100%							50%		100%	100%	100%	50%	50%
		B3	Maximized locally producible grassland-based feed utilization (% of cattle)		50%						100%	100%	100%	100%	100%	100%	50%	50%				50%	50%
	(C) Offspring fate	C1	Dairy offspring sold at 2 months (% of dairy offspring)		100%			50%	50%	50%		50%	50%	50%	100%	100%	100%	100%	100%	100%	100%	50%	50%
		C2	Remaining dairy offspring into calf fattening (% of remaining dairy offspring)					100%	100%	100%	100%	100%	100%	100%								100%	100%
	(D) Livestock movement dynamics	D1	Dairy/suckler cows leaving for rearing phase (% of dairy cows)		100%			100%	100%	50%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
		D2	Cattle seasonally absent (Jul–Oct) (% of cattle)		100%			100%	50%	100%			50%	100%		50%	100%	100%	100%	50%		50%	
Suckler herd	(B) Feeding strategy	B1	BAU feeding (% of cattle)																				
		B2	Maximized locally producible forage and feed utilization (% of cattle)																				
		B3	Maximized locally producible grassland-based feed utilization (% of cattle)		100%																		
	(D) Livestock movement dynamics	D1	Dairy/suckler cows leaving for rearing phase (% of suckler cows)		100%																		
		D2	Cattle seasonally absent (Jul–Oct) (% of cattle)		100%																		

Figure 10. P reduction strategies (rows) underlying extreme scenarios (columns). Note: several scenarios are optimal across multiple indicators ((A)–(E)), as indicated in the second row.

scenarios that included dairy herds and assumed that 50% of dairy offspring were sold at two months of age (C1), it was also assumed that all remaining offspring entered calf fattening (C2).

A clear distinction emerged between scenarios based on the predominant livestock type: On one hand, the *lowest P excretion* or *highest ASP output*, were exclusively pig-dominated (⩾60% pigs in LSU composition). In these scenarios, total LSU (A1) were reduced to 65%–90% of BAU levels. As a result, these scenarios correspond to pig LSU levels approximately 1.5–2.8 times that of the BAU pig herd LSU, while cattle LSU was reduced to 0%–56% of BAU dairy herd levels and 0%–55% of BAU suckler herd levels. In scenarios where cattle remained, it was assumed that all replacement heifers for dairy and suckler cows were reared outside the catchment (D1). Furthermore, in most of these cases, all cattle were assumed to be temporarily absent from the catchment during one July–October period (D2). Dairy herds in these scenarios typically received the BAU feed ration.

On the other hand, scenarios with the *lowest arable land use for feed production*, the *highest N:P ratio*, or the *lowest PSP competition* were consistently driven by dairy-dominated scenarios (⩾80% dairy cattle in LSU composition). Notably, many of these extreme outcomes were achieved by the same set of scenarios, reflecting substantial overlap across the three indicators. These Pareto-optimal solutions were typically reached with a total livestock population at 75% of the BAU LSU, of which 80% was allocated to dairy and 20% to pigs. This corresponded to dairy LSU levels at approximately 1.1 times those of the BAU herd, while pig LSU levels were reduced to about 50% of the BAU reference. In nearly all of these scenarios, dairy herds followed the local grass-based feeding plan (B3) or a 50/50 mix of that strategy with the local forage-and-feed feeding plan (B2), particularly in scenarios with the lowest PSP competition.

4. Discussion

4.1. Real-world constraints narrow the option space

The option space of more than 4.9 million modelled scenarios provides an encompassing assessment of strategies for reducing P excretion from livestock in the watershed of Lake Sempach. The scenarios varied in their performance across the indicators P excretion from livestock, amount of ASP produced, land needed for feed production, PSP competition, and the resulting N:P ratios of FYM. To strengthen the relevance of our analysis for decision-making, we applied three real-world constraints: (1) P excretion $\leqslant 78$ t yr^{-1}, (2) ASP production ⩾ BAU level, and (3) land use within the total available agricultural land. However, no scenario was able to meet all three targets simultaneously, underscoring the difficulty of achieving environmental and production goals at the same time. When relaxing the land use constraint to grassland only, i.e. considering those scenarios that stay within the available grassland area, 514’080 scenarios emerged as viable. Among these, 7’174 were identified as Pareto-optimal.

While the target to maintain ASP production at or above the BAU level reflects the region’s strong livestock orientation and enhances the realism and acceptability of our results, broader agri-food system objectives, such reducing feed-food competition, remain critical for ensuring long-term sustainability and resilience (Hadjikakou *et al* 2025). Although this aspect was only partially captured by the PSP competition score, our results indicated that, if the same land were used directly for food rather than feed, PSP outputs would be 1.5–2.1 times as high as ASP outputs across all viable and Pareto-optimal scenarios. However, this finding partly relied on the assumption that unused permanent grassland would be converted to arable land. This strategy involves risks, particularly in regions with high soil P levels, where a conversion could lead to increased erosion, nutrient runoff, losses of soil organic carbon, soil compaction, reduced water infiltration, and potentially biodiversity loss (Strock *et al* 2022). Nevertheless, crop production can be implemented in soil-health conserving and sustainable manner that minimizes erosion and nutrient runoff. Particularly on P saturated soils, targeted P mining, where no P is applied and P-demanding crops such as maize are cultivated, can help gradually deplete legacy P (Davies 2025). Legumes may also be incorporated, as they efficiently utilize soil P without requiring additional nitrogen inputs. Complementary measures could involve improving soil structure through reduced tillage or the use of chemical amendments to immobilize soluble P (Schoumans *et al* 2014, Sharpley 2016). Therefore, land use strategies represent an important complement to the livestock strategies presented here, offering additional potential to meet protein production targets or feed requirements. Additionally, we want to note that while animal- and plant-sourced proteins differ in their amino acid profiles, with animal proteins typically exhibiting a more balanced distribution, evidence suggests that in combination, all plant foods contain the full spectrum of essential amino acids and that mixed plant-based diets are thus sufficient to achieve protein adequacy in adults (Mariotti and Gardner 2019, Sarathy *et al* 2025).

4.2. Livestock populations and management for locally adapted systems

Multiple P reduction strategies can lead to comparable environmental outcomes, but through substantially different system configurations. Key distinctions arose mainly from livestock composition, with livestock types differing in P excretion per unit of protein; from feeding strategies, shaped by the origin of feed; and from management practices, including offspring fate and temporary absences during unproductive life stages.

Viable systems require reduced livestock density and a balanced mix, with pigs constituting at least 20% of the total LSU, while suckler cows are limited to a small share. The Pareto-optimal scenarios revealed clear differences in livestock density as well as in livestock composition. A consistent pattern across all viable and Pareto-optimal scenarios was a reduction in total LSU to between 65% and 90% of the BAU level. This aligns with current discussions at policy level, where proposals to limit LSU per hectare are under consideration (Maria Stettler and Probst 2023, Bielza *et al* 2025). Beyond a general reduction in livestock density, the composition of livestock types played a crucial role. Across all Pareto scenarios, pigs always accounted for at least 20% of the total LSU. Suckler cows, on the other hand, appeared only under strict conditions: their share was limited to a maximum of 16% in Pareto-optimal and 32% in viable scenarios, and only when pigs made up at least 40% of the total LSU. This restriction is due to the low ASP productivity of suckler systems. These results stand in contrast to recent developments in Switzerland, where suckler cow numbers continue to rise (Mutterkuh Schweiz 2024, Identitas 2025). Their growing popularity, especially among younger farmers, is often attributed to the labour-saving potential of grassland-based suckler systems (Zorn and Zimmert 2022). Notably, none of the scenarios consisting solely of dairy herds met the viability constraints, underlining the necessity of integrated production systems that combine cattle and pig farming to achieve viable outcomes.

Pig-dominated systems are characterized by low P excretion relative to ASP output but come with increased reliance on arable land and feed-food competition. The choice of livestock composition led to distinct trade-offs between key objectives. Pig-dominated Pareto-scenarios ($\geqslant$60% pigs in LSU composition) achieved on average the lowest P excretion, highest ASP production, and required the least grassland area. However, these advantages were offset by an average 1.3-fold increase in arable land use for feed compared to BAU, along with a PSP competition score of 1.9, indicating that nearly twice as much PSP could be produced on the same land. Moreover, the FYM produced by such systems showed significantly lower N:P ratios compared to the BAU, due to the typically higher P content of pig manure, which has negative implications for crop nutrient management (Richner *et al* 2017). The displayed low P excretion relative to ASP output of pig-dominated scenarios is consistent with findings in the literature (Poore and Nemecek 2018), but they also raise again important concerns about feed-food competition, particularly given the increased reliance on human-edible feed inputs (van Zanten *et al* 2019). These patterns were also evident in the pig-dominated extreme scenarios. If dairy cattle were included in these scenarios, they relied on BAU dairy herd feeding plans. However, interestingly, the majority of pig-dominated Pareto-optimal scenarios featured dairy herds fed according to the B3 strategy, which prioritizes grassland-based feed. This strategy, which maximizes the utilization of locally producible grassland-based feed, contributes to nutrient retention within the catchment and prevents additional P that would result from feed sourced from arable land entering the watershed.

Dairy-dominated systems reduce arable land use and improve N:P ratios but yield less protein, yet remain viable. In contrast, dairy-dominated scenarios ($\geqslant$60% dairy cattle in LSU composition) performed overall better in terms of arable land use (averaging 84% of BAU), N:P ratio, and PSP competition, both of which were comparable to or even improved over BAU levels. Nevertheless, these systems produced lower amounts of ASP and excreted more P than pig-dominated systems, though still within the bounds of the viability constraints. This was well illustrated by the sub-set of dairy-dominant extreme scenarios, most of which used the B3 feed plan for dairy herds.

Optimal systems consistently avoided large-scale livestock fattening—calf fattening was preferred. Across all intermediate and extreme Pareto-optimal scenarios, a notable pattern was the absence of large livestock fattening: if dairy offspring remained in the catchment, they were allocated to calf fattening. This trend reinforces the importance of offspring fate management and suggests that for systems to be optimal, the emphasis needs to be on smaller-scale, more localized livestock fattening strategies.

4.3. Leakages and externalized impacts

Our analysis revealed that many viable and particularly the Pareto-optimal scenarios improved nutrient efficiency and land use not only through internal system adjustments, but also by displacing environmental burdens beyond the catchment. These off-site effects manifest in several key areas.

First, all scenarios relied on feed produced on arable land outside the catchment. Since arable land use for feed systematically exceeded the area available within the region, this resulted in a net import of feed, and with it, additional nutrients into an already P-saturated system. This practice effectively shifts the environmental burden of feed production, including nutrient losses and land use impacts, to other regions.

Second, most Pareto-optimal scenarios employed the C1 offspring fate strategy, with 50% or even 100% of dairy calves sold at two months of age. This practice reduces the resource demands and emissions of calf rearing within the catchment but externalizes these impacts elsewhere. Similarly, a substantial share of scenarios implemented external rearing for replacement heifers for dairy and suckler cows, aligning with the D1 P reduction strategy. In the majority of Pareto-optimal scenarios, this strategy was applied at 100%, meaning all animals were moved out of the catchment during their rearing phase. At first glance, this relieves local environmental pressures but merely shifts emissions and resource use elsewhere. In Switzerland, however, contract rearing often has an inter-regional character: dairy cows are raised in the mountainous regions, while intensive milk production occurs in the lowland. This spatial separation can even yield environment benefits and increase the income of lowland farms (Marton *et al* 2016).

Meanwhile, we assumed that the export of FYM remained constant at BAU levels across all scenarios, implicitly suggesting a continuation of current regional P reduction efforts through manure redistribution. While this assumption reduces the apparent pressure to further lower P surpluses within the catchment, it is also rather conservative, given current trends. In Switzerland, FYM transport volumes have been increasing, with farms in the canton of Lucerne already exporting significant quantities (Möhring 2023). According to Möhring (2023), the average transport distance for FYM in Lucerne is approximately 17 km. Assuming a crop rotation similar to that within the catchment, this enables the fertilization of between 725 and 1’225 ha of arable land annually, depending on the soil’s P content. This underscores the relevance of off-site manure application as a P management strategy—one that is already being practiced and could potentially be scaled up.

Taken together, these patterns underscore the importance of considering off-site effects when evaluating system performance. While local indicators may suggest improvements in nutrient management and land use, these are often achieved by shifting burdens to surrounding regions. On the other hand, such strategies can increase flexibility, making it easier to meet environmental targets while maintaining production, which could enhance farmer acceptance. If implemented effectively, these approaches have the potential to create win–win situations as seen in the case of inter-regional contract rearing (Marton *et al* 2016). A comprehensive assessment, therefore, must go beyond territorial boundaries and include spatial trade-offs in its analysis (Heidenreich *et al* 2024).

4.4. Model improvements and future research directions

While this study focused on a broad set of indicators for P reduction in livestock systems, it is important to acknowledge that livestock systems entail additional environmental burdens not captured in our analysis. For instance, cattle are associated with methane emissions, while manure management practices across both cattle and pig systems also contribute to ammonia emissions (Dong *et al* 2006). These emissions, along with other potential environmental impacts such as biodiversity loss, further complicate the environmental footprint of livestock systems and must be considered in future assessments to provide a more holistic evaluation.

Additionally, while ASP is a useful aggregate indicator, it assumes equal value across different livestock products, despite differences in market value and value-chain requirements for pig meat, beef, and milk. Future research should therefore complement ASP-based analyses with farm-level economic assessments and value-chain perspectives, such as the availability of processing facilities, and assess potential off-site effects, where unchanged national demand for specific ASP types may shift production and associated environmental burdens to other regions (Seppelt *et al* 2011, Friis and Nielsen 2019), thereby addressing key cross-scale blind spots in agricultural landscape modelling (Heidenreich *et al* 2024).

Although our analysis covers a broad set of P reduction strategies, some measures were not represented in the scenarios. These include strategies to enhance feed efficiency in lactating cows, such as recombinant bovine somatotropin (rbST) injections, which have been shown to reduce P excretion per unit of milk by around 12% (Capper *et al* 2008). While currently not permitted in Switzerland, the hypothetical inclusion of such measures in further research could illustrate the potential of animal-level efficiency gains to further reduce P excretion in future livestock systems. In addition, downstream manure management options, such as liquid–solid slurry separation, were not considered (Kleinman *et al* 2020). When combined with increased FYM exports, these interventions may have a great potential to reduce local P surpluses (Stoll *et al* 2019).

Moreover, the final P load entering water bodies is strongly influenced by local topography, climate, soil characteristics, and the rates and timing of crop fertilization (Sharpley 2016). Future research could explore integrating these spatially explicit factors, along with soil and land management practices, which were not included in our model. The LEAF.livestock model developed in this study thus provides a risk assessment, i.e. an indication of which scenarios are more or less likely to result in high P losses to water bodies. However, determining the actual outcomes requires integration with landscape, land management, and hydrological models. The LEAF.livestock model offers great potential for such integration, which would enable more comprehensive environmental assessments and help address key blind spots in agricultural landscape modelling, as identified by Heidenreich *et al* (2024).

To address the nutrient-related challenges in the watershed of Lake Sempach, the model outputs presented here offer a valuable foundation for evidence-based dialogue among stakeholders and policymakers. The broad range of viable and Pareto-optimal scenarios that partly achieve similar results with quite different strategies allows for nuanced assessment of trade-offs and the weighting of indicator priorities. Building on this, future research should incorporate barrier analysis, stakeholder engagement, and a robust evaluation of required adaptations. These steps will be crucial for defining realistic transition pathways, from current systems to more sustainable targets. Guiding questions such as how far farms must shift, and which options demand the least transformation, will be central to enabling feasible and socially accepted change.

5. Conclusion

Using the LEAF.livestock model, we explored over 4.9 million scenarios to identify viable pathways for reducing P excretion from livestock production in the Lake Sempach catchment. Across all Pareto-optimal solutions, a reduction in livestock density to 65%–90% of current levels emerged as a consistent requirement, highlighting the need for structural change in regional livestock systems. The analysis further shows that comparable environmental outcomes can be achieved through different combinations of management strategies, underlining the importance of exploring multiple locally adapted optima rather than relying on single 'best' solutions. At the same time, all viable scenarios rely on leakage effects, such as feed imports, manure export, or off-site rearing, indicating that local P reductions are closely linked to environmental pressures outside the catchment.

Overall, this study demonstrates the value of LEAF.livestock for systematically assessing trade-offs between environmental impacts and protein production. By supporting region-specific and evidence-based insights, the model provides a useful foundation for stakeholder dialogue and policy planning aimed at transitioning livestock systems to operate within ecological limits.

Acknowledgments

The authors would like to thank Rebekka Frick, Jan Landert, and Florian Leiber for their valuable comments on this manuscript. Additional thanks go to Stefan Rieder and Kosuke Ueda from Identitas AG for providing and supporting us with the animal movement data. We are also grateful to the Swiss Federal Office for Agriculture for their permission and to Juliane Hirte (Agroscope) for providing the data on phosphorous levels in soils. Lastly, we thank Rennie Eppenstein, Verena Bühl, Jessica Werner, Mirjam Holinger, Manuela Helbing, and Anet Spengler Neff (FiBL), Nina Marolf (bio.inspecta), and Jessica Kamm (Willi Grüninger AG) for their valuable expert input and support.

This work was supported by the Swiss National Science Foundation [Grant Number 188768].

Data availability statement

The data that supports the findings of this study are openly available in the supplementary files of this article.

SM1 Explanatory Notes: Methods available at https://doi.org/10.1088/2976-601X/ae61b6/data1.

SM2 Calibration & Results available at https://doi.org/10.1088/2976-601X/ae61b6/data2.

ORCID iDs

Anja Heidenreich 0000-0003-1883-2035
Catherine Pfeifer 0000-0001-9738-8758
Johan Six 0000-0001-9336-4185
Adrian Muller 0000-0001-7232-9399

References

AGRIDEA (ed) 2022 REFLEX 2022 Betriebswirtschaftliche Datensammlung

AGRIDEA and BLW 2023 *Weisungen zur Berücksichtigung von nährstoffreduziertem Futter in der Suisse-Bilanz* (Bern: BLW) Zusatzmodul 6 und 7. Version 1.13 (available at: www.blw.admin.ch/dam/de/sd-web/twpmZ2kRDYi-/Weisungen%20Zusatzmodule%206_7%20Suisse-Bilanz%201.13.pdf)

AGRIDEA 2023 Deckungsbeiträge DBKAT Excel Version (available at: https://agridea.abacuscity.ch/de/A∼2888/0∼0∼Shop/Deckungsbeitr%C3%A4ge-DBKAT-Excel-Version)

Agroscope (ed) 2016 Fütterungsempfehlungen für Schweine (Gelbes Buch) (available at: www.agroscope.admin.ch/agroscope/de/home/services/dienste/futtermittel/fuetterungsempfehlungen-schweine.html)

Agroscope (ed) 2021 Fütterungsempfehlungen für Wiederkäuer (Grünes Buch) (available at: www.agroscope.ch/gruenes-buch)

AMD 2023 Animal movement data. Unpublished dataset provided by Identitas AG. Anonymised, regional livestock data from the IT systems developed and operated by Identitas (Tierverkehrsdatenbank, TVD) Data for cattle were received from 2010 to 2022 (individual animals) and for pigs from 2014 to 2022 (animal groups)

Bajželj B, Richards K S, Allwood J M, Smith P, Dennis J S, Curmi E and Gilligan C A 2014 Importance of food-demand management for climate mitigation *Nat. Clim. Change* **4** 924–9

Bielza M, Weiss F, Hristov J and Fellmann T 2025 Impacts of reduced livestock density on European agriculture and the environment *Agric. Syst.* **226** 104299

Binderheim E 2021 Biologischer Zustand der Schweizer Seen. Sponsolim Umweltconsulting. Im Auftrag des Bundesamtes für Umwelt (available at: https://www.bafu.admin.ch/dam/it/sd-web/gbWYsnLWH8N4/biologischer_zustand_der_schweizer_seen.pdf)

BLW 2024 Weisungen und Erläuterungen 2025 zur Verordnung über landwirtschaftliche Begriffe und die Anerkennung von Betriebsformen. *Landwirtschaftliche Begriffsverordnung, LBV; SR 910.91* (available at: www.blw.admin.ch/dam/de/sd-web/FwEg9-OWM5MH/2025%20LBV%20mit%20Weisungen.pdf) (Accessed 14 February 2026)

Bosch D J, Wolfe M L and Knowlton K F 2006 Reducing phosphorus runoff from dairy farms *J. Environ. Qual.* **35** 918–27

Bouwman L, Goldewijk K K, van der Hoek K W, Beusen A H W, Van Vuuren D P, Willems J, Rufino M C and Stehfest E 2013 Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period *Proc. Natl Acad. Sci. USA* **110** 20882–7

Capper J L, Castañeda-Gutiérrez E, Cady R A and Bauman D E 2008 The environmental impact of recombinant bovine somatotropin (rbST) use in dairy production *Proc. Natl Acad. Sci. USA* **105** 9668–73

Clark M A, Domingo N G G, Colgan K, Thakrar S K, Tilman D, Lynch J, Azevedo I L and Hill J D 2020 Global food system emissions could preclude achieving the 1.5° and 2 °C climate change targets *Science* **370** 705–8

Davies J M 2025 Three keys to unlock legacy phosphorus for sustainable crop production: models, budgets, and expert elicitation *PhD Thesis* Lancaster University (available at: https://eprints.lancs.ac.uk/id/eprint/227199/)

Dong H, Mangino J, McAllister T A, Hatfield J L, Johnson D E and Lassey K R 2006 Chapter 10: emissions from livestock and manure management. Volume 4: agriculture, forestry and other land use *IPCC* (available at: www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf)

FAO (ed) 2025 FAOSTAT. Production/crops and livestock products. Food and agriculture organization of the United Nations (available at: www.fao.org/faostat/en/#data/QCL) (Accessed 7 May 2025)

Federal Office for Agriculture FOAG 2022 Tierwohlbeitrag: RAUS—Regelmässiger Auslauf im Freien (available at: www.blw.admin.ch/de/produktionssystembeitraege#Tierhaltung)

Federal Statistical Office (ed) 2025 Beschäftigte, Landwirtschaftliche Betriebe, Landwirtschaftliche Nutzfläche (LN) und Nutztiere auf Klassifizierungsebene 2 nach Kanton *Landwirtschaftliche Strukturerhebung. BFS-Nummer px-x-0702000000_102* (available at: www.bfs.admin.ch/bfs/en.assetdetail.px-x-0702000000_102.html)

Flisch R, Neuweiler R, Kuster T, Oberholzer H, O Huguenin-Elie and Richner W 2017 2/ Bodeneigenschaften und Bodenanalysen *Grundlagen für die Düngung landwirtschaftlicher Kulturen in der Schweiz (GRUD 2017)* vol 8, ed W Richner and S Sinaj (Agrarforschung Schweiz, Spezialpublikation) (available at: www.grud.ch)

FOAG 2000 Digital soil suitability map of Switzerland—crop type: federal office for agriculture (available at: www.blw.admin.ch/de/bodeneignungskarte)

FOEN (ed) 2019 Topographical catchment areas of Swiss waterbodies. Federal office for the environment (available at: www.geocat.ch/geonetwork/srv/api/records/6d9c8ba5-2532-46ed-bc26-0a4017787a56?language=eng) (Accessed 5 May 2025)

FOEN (ed) 2023 Primary surfaces (lakes). Federal office for the environment (available at: www.geocat.ch/geonetwork/srv/eng/catalog.search#/metadata/b3bcb280-b613-4b43-8889-bc386e621e0d) (Accessed 5 May 2025)

Friis C and Nielsen J Ø (Eds.) 2019 *Telecoupling. Exploring Land-Use Change in a Globalised World* (Springer)

FSO (ed) 2023 Swiss land use statistics. Land use and land cover. Federal statistical office (available at: www.bfs.admin.ch/bfs/de/home/dienstleistungen/geostat/geodaten-bundesstatistik/boden-nutzung-bedeckung-eignung/arealstatistik-schweiz.assetdetail.25885691.html) (Accessed 4 May 2025)

FSVO 2023 Federal food safety and veterinary office. Swiss food composition database. V6.5 (available at: https://naehrwertdaten.ch/en)

Gassmann V 2024 Milk volume in the valley zone of the canton of Lucerne, divided into silage-free and silage-based feeding. Email to Anja Heidenreich *Genossenschaft Zentralschweizer Milchproduzenten ZMP* (Accessed 28 March 2024)

Goldberg D E 1989 *Genetic Algorithms in Search, Optimization, and Machine Learning* (Addison-Wesley)

Groot J C J, Jellema A and Rossing W A H 2010 Designing a hedgerow network in a multifunctional agricultural landscape: balancing trade-offs among ecological quality, landscape character and implementation costs *Eur. J. Agron.* **32** 112–9

Grossenbacher T and Zehr B 2021 Bivariate maps with ggplot2 and sf (available at: https://github.com/grssnbchr/bivariate-maps-ggplot2-sf) (Accessed 5 May 2025
Gruber L, Pries M, Schwarz F-J, Spiekers H and Staudacher W 2006 Schätzung der Futteraufnahme bei der Milchkuh Edited by DLG-Arbeitskreis Futter und Fütterung, Bundesarbeitskreis der Fütterungsreferenten in der DLG
Hadjikakou M *et al* 2025 Ambitious food system interventions required to mitigate the risk of exceeding Earth's environmental limits *One Earth* **8** 101351
Han K, Lee J H, Kim J H, Kim Y G, Kim J D and Paik I K P 2000 Application of phase feeding in swine production *J. Appl. Animal Res.* **17** 27–56
Heidenreich A, Muller A, Oggiano P, Pfeifer C, Moakes S, Six J and Stolze M 2024 Model-based agricultural landscape assessments: a review *Environ. Res. Lett.* **19** 073005
Heidenreich A, Pfeifer C, Six J and Muller A 2025 LEAF.livestock. Version v1.0 *Zenodo* **1**
Hietala P, Bouquet P and Juga J 2014 Effect of replacement rate, crossbreeding and sexed semen on the efficiency of beef production from dairy herds in Finland *Acta Agric. Scand. A Anim. Sci.* **64** 199–209
Hipp R D 2020 SQLite (available at: www.sqlite.org/index.html)
Hirte J—personal communication (2023): shares of P supply classes per agricultural areas and permanent grassland per municipality *Email to Anja Heidenreich. Agroscope, Forschungsgruppe Bodenqualität und Bodennutzung* (Accessed 22 September 2023)
Identitas (ed) 2025 Number of registered and living cattle by breed (available at: https://tierstatistik.identitas.ch/en/cattle-breeds.html) (Accessed 2 May 2025)
Ipsos U K 2024 Earth for All Survey 2024. G20+ global report: attitudes to political and economic transformation *Edited by Earth4All and the Global Commons Alliance* (available at: https://earth4all.life/global-survey-2024/#full-data)
Kamm J 2024 *Inquiry on the Composition of Pig Feed for the Modeling of Nutrient Flows. Email to Anja Heidenreich* (Willi Grüninger AG) (Accessed 25 November 2024)
Keller B, Oppliger C, Chassot M, Ammann J, Hund A and Walter A 2024 Swiss agriculture can become more sustainable and self-sufficient by shifting from forage to grain legume production *Commun. Earth Environ.* **5** 40
Kleinman P J A, Spiegal S, Liu J, Holly M, Church C and Ramirez-Avila J 2020 Managing animal manure to minimize phosphorus losses from land to water *Animal Manure* ed H M Waldrip, P H Pagliari and Z He x (ASA Special Publications) pp 201–28
Landert J, Frick R, Müller A and Scharrer B 2021 UNISECO H2020 policy brief: increasing the knowledge about income alternatives to intensive livestock farming of the Swiss Lucerne Central Lakes region
Leip A *et al* 2015 Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity *Environ. Res. Lett.* **10** 115004
LfL 2024 LfL-Deckungsbeiträge und Kalkulationsdaten—Milchkuhhaltung. Kälberaufzucht (Edited by Bayerische Landesanstalt für Landwirtschaft (LfL) (available at: www.stmelf.bayern.de/idb/milchkuhhaltung.html) (Accessed 18 April 2024)
Luzerner Zeitung 2018 Gülle-Problematik: Vorlage des Bundes schürt in Luzern Unsicherheit (Available at https://www.luzernerzeitung.ch/zentralschweiz/luzern/guelle-problematik-vorlage-des-bundes-schuert-in-luzern-unsicherheit-ld.1076322)
Kanton L 2021 Answer to inquiry A 371. Inquiry Howald Simon and Mit. on solutions, deadlines, costs and impact of the cantonal phosphorus project for the midland lakes of the canton of Lucerne (phases I, II, II plus and III) *Regierungsrat* (available at: www.lu.ch/-/klu/ris/cdws/document?fileid=76d530f713b842d7bf741bd6e0079e7e)
Mariotti F and Gardner C D 2019 Dietary protein and amino acids in vegetarian diets-a review *Nutrients* **11** 2661
Marton S M R R, Zimmermann A, Kreuzer M and Gaillard G 2016 Environmental and socioeconomic benefits of a division of labour between lowland and mountain farms in milk production systems *Agric. Syst.* **149** 1–10
Möhring A 2023 Analyse des Hofdüngermarktes in der Schweiz Zeitliche Entwicklung und räumliche Verteilung Agrosc. Sci. **146** 41
Mutterkuh Schweiz (ed) 2024 Jahresbericht 2024 (available at: www.mutterkuh.ch/files/content/Downloads-Deutsch/01-DE-Mutterkuh-Schweiz/Jahresbericht_2024_Endversion_DE.pdf) (Accessed2 May 2025)
Poore J and Nemecek T 2018 Reducing food's environmental impacts through producers and consumers. Processed by our world in data. "Eutrophying emissions per 100g protein" *Science* **360** 987–92 (available at: https://ourworldindata.org/grapher/eutrophying-emissions- protein)
Prasuhn V and Lazzarotto P 2005 Abschwemmung von Phosphor aus Grasland im Einzugsgebiet des Sempachersees (*Schriftenreihe der FAL*, **vol 57**) (available at: https://ira.agroscope.ch/de-CH/publication/24330)
R Core Team 2022 R: a language and environment for statistical computing (R Foundation for Statistical Computing) (available at: www.R-project.org/)
rawi 2019 Agricultural land under cultivation: types of use © Geoinformaton Kanton Luzern/Raumdatenpool—Dienststelle Raum und Wirtschaft
Richner W, Flisch R, Mayer J, Schlegel P, Zähner M and Menzi H 2017 4/ Eigenschaften und Anwendung von Düngern *Grundlagen für die Düngung landwirtschaftlicher Kulturen in der Schweiz (GRUD 2017)* ed W Richner and S Sinaj (Agrarforschung Schweiz 8 (6), Spezialpublikation) (available at: www.grud.ch)
Rockström J, Edenhofer O, Gaertner J and DeClerck F 2020 Planet-proofing the global food system *Nat. Food* **1** 3–5
Richner W and Sinaj S (eds) 2017 *Grundlagen für die Düngung landwirtschaftlicher Kulturen in der Schweiz (GRUD 2017)* vol 8 (Agrarforschung Schweiz, Spezialpublikation)
Roocks P 2016 Computing Pareto frontiers and database preferences with the rPref package *R J.* **8** 393–404
Röös E, Bajželj B, Smith P, Patel M, Little D and Garnett T 2017 Greedy or needy? Land use and climate impacts of food in 2050 under different livestock futures *Global Environ. Change* **47** 1–12
RStudio Team 2020 RStudio integrated development environment for R (available at: httpwww.rstudio.com)
Sarathy S P, Ravikumar H, Nanjan P, Alagesan N and Chua B L 2025 Plant-based protein: a multi-nutritional sustainable alternative to animal foods and their structure, functions, and relationship: a review *Int. J. Biol. Macromol.* **321** 146465
Scharrer B 2013 Dem Sempachersee kommt die Gülle hoch. Das Spannungsfeld zwischen intensiver Tierhaltung und Gewässerschutz im Kanton Luzern 1976–2003) *Nordhausen: Traugott Bautz (Berner Forschungen zur Neuesten Allgemeinen und Schweizer Geschichte,* vol 12) (available at: http://gbv.eblib.com/patron/FullRecord.aspx?p=1987526)
Schlegel P, Hans-Moëvi M and Morel I 2020a Richtwerte für den Nährstoffanfall bei Mutterkuhkälbern *Agrarforsch. Schweiz* **11** 68–75
Schlegel P, Willi C, Vollenweider O and Morel I 2020b Richtwerte für den Nährstoffanfall aus der Rindviehmast *Agrarforsch. Schweiz* **11** 26–33
Schoumans O F, Chardon W J, Bechmann M E, Gascuel-Odoux C, Hofman G, Kronvang B, Rubæk G H, Ulén B and Dorioz J-M 2014 Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: a review *Sci. Total Environ.* **468–469** 1255–66

Seppelt R, Dormann C F, Eppink F V, Lautenbach S and Schmidt S 2011 A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead *J. Appl. Ecol.* **48** 630–6
Sharpley A 2016 Managing agricultural phosphorus to minimize water quality impacts *Sci. Agric.* **73** 1–8
Sharpley A, Jarvie H P, Buda A, May L, Spears B and Kleinman P 2013 Phosphorus legacy: overcoming the effects of past management practices to mitigate future water quality impairment *J. Environ. Qual.* **42** 1308–26
Sinaj S, Charles R, A Baux, Dupuis B, Hiltbrunner J, Levy L, Pellet D, Blanchet G and Jeangros B 2017 8/ Düngung von Ackerkulturen *Grundlagen für die Düngung landwirtschaftlicher Kulturen in der Schweiz (GRUD 2017)* vol 8, ed W Richner and S Sinaj (Agrarforschung Schweiz, Spezialpublikation) (available at: www.grud.ch)
SRF 2023 Schädliche Gülle: amtlich tolerierte Umweltverschmutzung. Die Gülle des sehr hohen Tierbestandes schädigt Seen, den Wald und die Menschen *Die Behörden vollziehen die Umweltgesetze nicht. SRF 1* (available at: www.srf.ch/sendungen/dok/schaedliche-guelle-amtlich-tolerierte-umweltverschmutzung)
SRF 2024 Bundesgericht bestätigt—Güllegesetz: bundesgericht erteilt Luzerner Bauern eine Absage. Seit 2021 müssen Luzerner Bauern die Gülle reduzieren. Dagegen wehrten sie sich (Nun scheitern sie vor Bundesgericht. Regionaljournal Zentralschweiz (available at: www.srf.ch/news/schweiz/bundesgericht-bestaetigt-guellegesetz-bundesgericht-erteilt-luzerner-bauern-eine-absage)
SRG.D (ed) 2024 Dossier Nr 9670 ff,—«DOK» «Unser täglich Fleisch—Von Gülle, Jobs und Umweltschäden» und Online-Artikel (App SRF News) vom 14. December 2023 *Ombudsstelle SRG Deutschschweiz* (available at: www.srgd.ch/media/cabinet/2024/01/9670ff_OMB_SB_DOK_Unser_t%C3%A4glich_Fleisch_Web.pdf)
Stadelmann F—personal communication (2023): share of farms participating in Seevertrag (Lake Sempach) *Email to Anja Heidenreich. Fachbereichsleiter Natürliche Ressourcen, Landwirtschaft und Wald (lawa)* (Accessed 5 June 2023)
Stettler A and Probst S 2023 Wie viele Nutztiere braucht die Schweiz zur optimalen Landnutzung? *Agrarforsch. Schweiz* **14** 236–42
Stoll S, Arb C V, Jörg C, Kopp S and Prasuhn V 2019 Evaluation der stark zur Phosphor-Belastung des Baldeggersees beitragenden Flächen. Agroscope (available at: https://ira.agroscope.ch/en-US/Page/Publikation/Index/41029)
Strock J S, Johnson J M F, Tollefson D and Ranaivoson A 2022 Rapid change in soil properties after converting grasslands to crop production *Agron. J.* **114** 1642–54
Swiss Federal Council 2025 Tierschutzverordnung *TSchV, SR* vol 455 (available at: www.fedlex.admin.ch/eli/cc/2008/416/de) (Accessed 2 January 2025)
swisstopo (ed) 2017 swissALTI3D multidirectional Hillshade. Federal Office of Topography (available at: https://opendata.swiss/en/dataset/swissalti3d-reliefschattierung-multidirektional) (Accessed 5 May 2025)
swisstopo (ed) 2022 DHM. Digital height model DHM25. Federal office of topography (available at: www.swisstopo.admin.ch/en/height-model-dhm25) (Accessed 6 May 2025)
swisstopo (ed) 2024 swissBOUNDARIES3D. Federal office of topography (available at: www.swisstopo.admin.ch/de/landschaftsmodell-swissboundaries3d#swissBOUNDARIES3D—Download) (Accessed May 2025)
Tirado R, Thompson K F, Miller K A and Johnston P: 2018 Less is more: reducing meat and dairy for a healthier life and planet *Technical Report* (Greenpeace Research Laboratories)03–2018 (ISBN: 978-1-9999978-1-6)
Universität Zürich, Agroscope 2011-2016 FEEDBASE (available at: www.feedbase.ch/index.php#)
UWE; AfU 2023 Jahresbericht Zustand der Mittellandseen 2022. Zuhanden der ASSAN und des Geschäftsberichts der Gemeindeverbände. Edited by Bau-, Umwelt- und Wirtschaftsdepartement—Umwelt und Energie (uwe), Kanton Luzern and Department Bau, Verkehr und Umwelt—Abteilung für Umwelt (Afu) Kanton Aargau (available at: https://sempachersee.ch/wp-content/uploads/2023/08/20230411_Jahresbericht_ASSAN_2022-1.pdf)
van Zanten H H E, Herrero M , van Hal O, Röös E, Muller A and Garnett T 2018 Defining a land boundary for sustainable livestock consumption *Glob. Change Biol.* **24** 4185–94
van Zanten H H E, van Ittersum M K and De Boer I J M 2019 The role of farm animals in a circular food system *Glob. Food Secur.* **21** 18–22
Wang H, Long W, Chadwick D, Velthof G L, Oenema O, Ma W, Wang J, Qin W, Hou Y and Zhang F 2020 Can dietary manipulations improve the productivity of pigs with lower environmental and economic cost? A global meta-analysis *Agric. Ecosyst. Environ.* **289** 106748
Willett W, Rockström J, Loken B, Springmann M, Lang T and Vermeulen S 2019 Food in the Anthropocene: the EAT–Lancet commission on healthy diets from sustainable food systems *Lancet* **393** 447–92
Yerly-Brault F and Jakob S 2022 Ammoniak: die Situation in ausgewählten Schweizer Kantonen. Edited by Politikwerkstatt GmbH, commissioned by WWF Schweiz, Pro Natura, BirdLife Schweiz, Ärztinnen und Ärzte für (available at: www.wwf.ch/sites/default/files/doc-2022-05/Analyse_Ammoniak_D_2022.pdf)
Zimmermann A, Nemecek T and Waldvogel T 2017 Umwelt- und ressourcenschonende Ernährung: detaillierte Analyse für die Schweiz. Edited by Agroscope *Agroscope Science,* vol 55 (available at: https://ira.agroscope.ch/en-US/Page/Publikation/Index/37058)
Zorn A and Zimmert F 2022 Structural change in the dairy sector: exit from farming and farm type change *Agric. Econ.* **10** 7
Zou T, Zhang X and Davidson E A 2022 Global trends of cropland phosphorus use and sustainability challenges *Nature* **611** 81–87