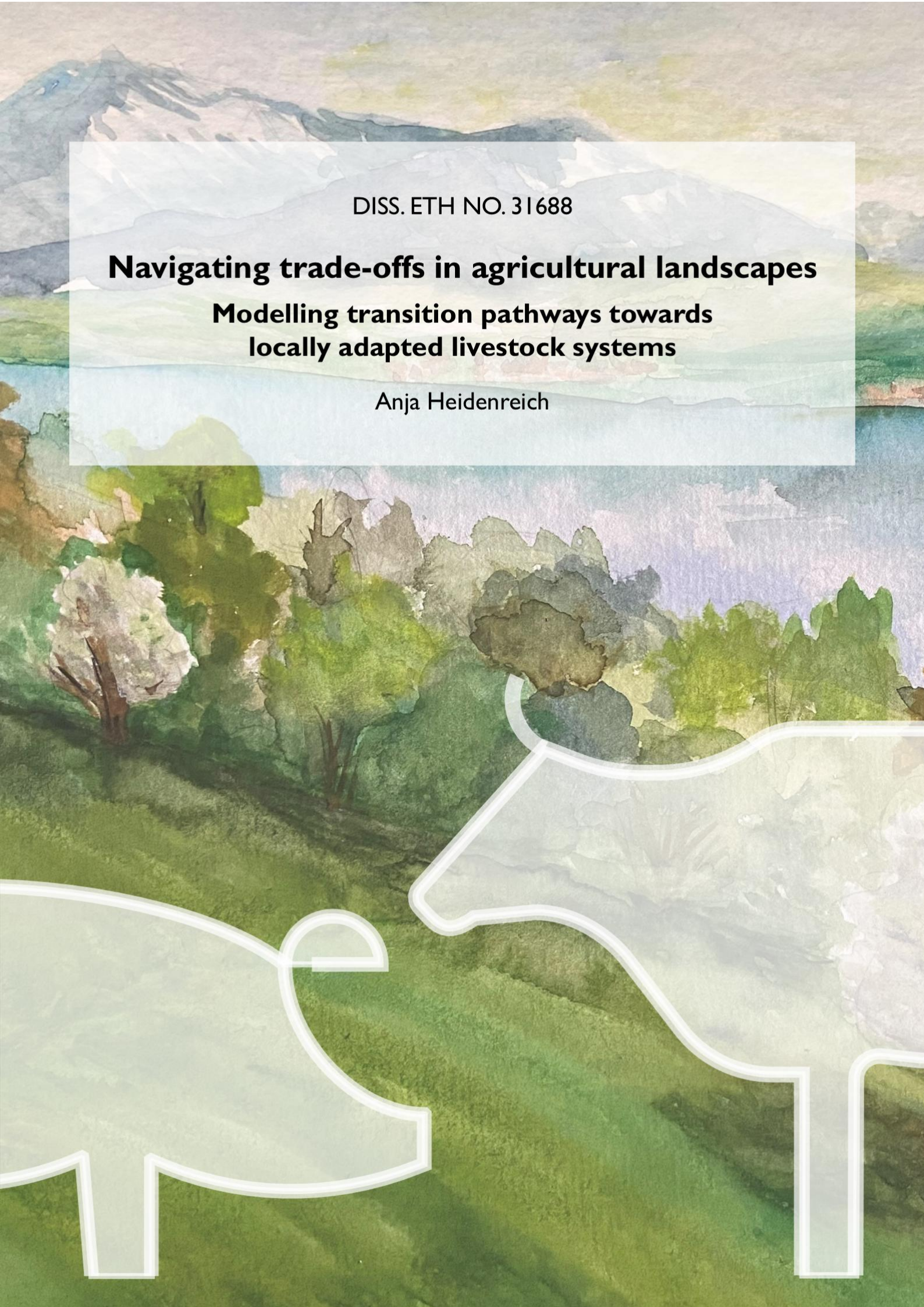




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Navigating trade-offs in agricultural landscapes

Modelling transition pathways towards locally adapted livestock systems

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Navigating trade-offs in agricultural landscapes: Modelling transition pathways towards locally adapted livestock systems

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Cover image: Watercolour painting of Lake Sempach, Switzerland. Artwork by Lisa Scharf.

For Liara Emilie.

Abstract

Current agricultural systems face profound ecological imbalances, including soil degradation, biodiversity loss, water pollution, and disrupted nutrient cycles, all of which are intensified by climate change. Many of these imbalances are region-specific, shaped by local biophysical, socio-economic, and institutional contexts, such as watersheds, ecosystem-based units, or sub-national landscape units. As multifunctional and spatially heterogeneous systems, agricultural landscapes therefore represent critical leverage points for understanding these challenges and for developing targeted, context-specific solutions. Among disrupted nutrient cycles, phosphorus (P) exemplifies the challenge of managing a finite yet essential resource: excess P drives eutrophication and ecosystem degradation, while deficiencies constrain productivity in vulnerable regions. Beyond changes in consumption patterns, such as dietary shifts and reducing food waste, addressing these challenges calls for coordinated, landscape-level strategies, including water restoration, land use optimization, and improved soil, crop, and livestock management to balance P levels and enhance nutrient recycling. Livestock production is a major contributor to P surpluses in agricultural landscapes, especially in high-income economies such as Europe. While these surpluses pose risks to soil and water quality, livestock production also contributes to broader environmental pressures such as greenhouse gas emissions, water use, and biodiversity loss. At the same time, livestock provides essential functions in food production, rural livelihoods, and nutrient cycling. Ensuring the sustainability of livestock systems therefore requires balancing environmental, nutritional, and socio-economic objectives.

In this context, models play a vital role in guiding these sustainable transitions in agriculture by supporting the generation of systems, target, and transformation knowledge. They help to assess current landscape functions and trade-offs (systems knowledge), explore desirable futures through scenario analysis (target knowledge), and inform actionable pathways to achieve these futures (transformation knowledge). From field-level biophysical simulations to global food system models, a wide range of modelling approaches assist to generate this knowledge. Their integrative capacity makes them indispensable tools for assessing trade-offs, envisioning alternatives, and shaping transitions in agricultural landscapes.

Yet current modelling approaches for assessing agricultural landscapes face limitations in capturing their multifunctionality, integrating agronomic with other landscape functions, and representing linkages both within the landscape and to the broader food system. However, a comprehensive synthesis of these approaches is still lacking, leaving open which functions are typically assessed and how food system connections are incorporated. Furthermore, although reducing P surpluses in intensive livestock systems is recognized as a priority, the full range of viable reduction strategies, that balance environmental goals with production needs and farmer acceptance, remains poorly understood. Finally, practical, locally adapted pathways for transforming livestock systems over time to achieve significant P reductions in intensive livestock production

are largely unexplored. This dissertation addresses these gaps by advancing model-based approaches for designing locally adapted agricultural systems and by illustrating pathways towards these desirable future states. In doing so, it contributes essential systems, target, and transformation knowledge to guide the future development of agricultural systems. The dissertation is structured as a cumulative thesis comprising three research articles.

The first article presents a systematic literature review of spatially explicit models used to assess agricultural landscapes. To structure the analysis, a theoretical framework defining key elements of agricultural landscape assessments was developed, enabling a systematic comparison of modelling approaches across studies. The analysis reveals that while biodiversity and ecosystem services such as *Water conditions* and *Atmospheric composition/conditions* are widely covered, they are rarely used in combination. Other services, like *Pest and disease control*, are largely absent. Moreover, most models lack a representation of return flows from the food system and rarely combine crop–livestock dynamics, limiting their ability to capture synergies or trade-offs comprehensively. This review thus identifies critical blind spots and highlights the need for more integrative modelling approaches to adequately support decision-making in multifunctional agricultural landscapes. Additionally, the proposed framework of key elements for agricultural landscape assessments offers a structured starting point for achieving a more comprehensive system understanding in future assessments.

The second article introduces LEAF.livestock, a novel dynamic livestock model developed to overcome some of these limitations. The model is applied to the livestock-intense catchment of Lake Sempach in Switzerland, where nutrient imbalances driven by high livestock densities and feed imports have led to excessive P accumulation. Nearly five million combinations of herd structures and management practices are simulated, covering changes in livestock density and composition, feed sourcing, and rearing pathways. Thereby, the analysis focuses on the consequences of these changes for P excretion, animal-sourced protein output, land use, and feed–food competition. No single scenario meets all environmental and production constraints, but when land-use restrictions are relaxed, over 514'000 viable and 7'174 Pareto-optimal scenarios emerge, each with distinct trade-offs: Pig-dominated scenarios achieve stronger P reduction and protein output but rely on more arable land and imports, while dairy-oriented scenarios are less productive but better align with regional land availability. These findings highlight the potential of multiple, locally adapted solutions rather than one global optimum.

Building on these results, the third article simulates transition pathways from the current livestock system to two contrasting target scenarios. Using a resistance-weighted optimization approach combined with the dynamic LEAF.livestock model, farm type and management changes were simulated from 2020 to 2060. Both transition pathways achieve the P reduction targets, but through different restructuring processes: the pathway towards the pig-dominated target scenario relies on farm exits and specialization, whereas the pathway towards

the dairy-dominated target scenario emphasizes feeding plan changes with fewer exits. These findings highlight that while multiple routes can meet the same environmental and productivity objectives, each carries distinct social, structural, and policy implications, underlining the need for targeted support to ensure feasible and acceptable transitions.

Together, the three articles demonstrate how locally adapted modelling can inform livestock management and policy design by making trade-offs visible, identifying synergies, and supporting evidence-based planning. Focusing on the catchment of Lake Sempach, this dissertation contributes to the design of livestock transition pathways that reduce P excretion while maintaining food production. While the catchment serves as a detailed case study, the modelling approach developed in this dissertation offers broader relevance for agricultural landscapes facing similar challenges, providing a foundation for locally adapted decision-making and policy design.

Zusammenfassung

Das derzeitige Agrarsystem ist von tiefgreifenden ökologischen Ungleichgewichten geprägt, wie Bodendegradation, Biodiversitätsverlust, Gewässerverschmutzung und beeinträchtigte Nährstoffkreisläufe, die durch den Klimawandel zusätzlich verschärft werden. Viele dieser Ungleichgewichte sind regionsspezifisch und werden durch lokale biophysikalische, sozioökonomische und institutionelle Rahmenbedingungen beeinflusst, wie sie beispielsweise in Wassereinzugsgebieten, ökosystembasierten Einheiten oder subnationalen Landschaftseinheiten auftreten. Als multifunktionale und räumlich heterogene Systeme stellen Agrarlandschaften daher einen entscheidenden Ansatzpunkt dar, um diese Herausforderungen zu verstehen und um gezielte, kontextspezifische Lösungsansätze zu entwickeln. Unter den beeinträchtigten Nährstoffkreisläufen steht Phosphor (P) exemplarisch für die Schwierigkeit, mit einer endlichen, aber unverzichtbaren Ressource umzugehen: Ein Überschuss an P führt zu Eutrophierung und einer Degradierung von Ökosystemen, während Defizite die Produktivität besonders in vulnerablen Regionen einschränken. Neben Veränderungen im Konsumverhalten, wie Ernährungsumstellungen und der Reduktion von Lebensmittelabfällen, erfordert die Bewältigung dieser Herausforderungen koordinierte Strategien auf Landschaftsebene. Dazu zählen die Wiederherstellung von Gewässern, die Optimierung der Landnutzung sowie verbesserte Boden-, Pflanzen- und Tierhaltungspraktiken, um P-Bilanzen auszugleichen und das Nährstoffrecycling zu fördern. Die Nutztierhaltung ist ein wesentlicher Treiber von P-Überschüssen in Agrarlandschaften, insbesondere in Ländern mit hohem Einkommen wie Europa. Während diese Überschüsse Risiken für Boden- und Wasserqualität bergen, trägt die Tierproduktion zugleich zu weiteren Umweltbelastungen wie Treibhausgasemissionen, Wasserverbrauch und Biodiversitätsverlust bei. Gleichzeitig erfüllt sie jedoch zentrale Funktionen in der Nahrungsmittelproduktion, für ländliche Existenzen und im Nährstoffkreislauf. Die Sicherung der Nachhaltigkeit von Tierhaltungssystemen erfordert daher eine Balance zwischen ökologischen, ernährungsbezogenen und sozioökonomischen Zielsetzungen.

Bei der Unterstützung dieser Transformationen hin zu einer nachhaltigen Landwirtschaft spielen Modelle eine zentrale Rolle, indem sie die Generierung von System-, Ziel- und Transformationswissen ermöglichen. Sie helfen, erbrachte Landschaftsfunktionen und Zielkonflikte zu bewerten (Systemwissen), wünschenswerte Zukunftsperspektiven mithilfe von Szenarien zu erkunden (Zielwissen) und handlungsorientierte Pfade zu deren Erreichung aufzuzeigen (Transformationswissen). Von biophysikalischen Simulationen auf Feldebene bis hin zu globalen Modellen des Ernährungssystems trägt eine Vielzahl an Modellierungsansätzen dazu bei, dieses Wissen zu generieren. Ihre integrative Fähigkeit macht sie zu unverzichtbaren Werkzeugen, um Zielkonflikte zu bewerten, Alternativen zu entwerfen und Transformationen in Agrarlandschaften zu gestalten.

Die derzeitigen Modellierungsansätze zur Bewertung von Agrarlandschaften stoßen jedoch an Grenzen, wenn es darum geht, ihre Multifunktionalität abzubilden, agronomische Funktionen mit anderen

Landschaftsfunktionen zu integrieren und sowohl die Verflechtungen innerhalb der Landschaft als auch deren Einbettung in das Ernährungssystem darzustellen. Eine umfassende Synthese dieser Ansätze fehlt bislang, sodass offenbleibt, welche Funktionen typischerweise untersucht werden und wie die Verbindungen zum Ernährungssystem berücksichtigt werden. Zudem ist zwar die Reduktion von P-Überschüssen in intensiven Tierhaltungssystemen als Priorität anerkannt, doch der gesamte Handlungsspielraum praktikabler Reduktionsstrategien, die ökologische Ziele mit Produktionsanforderungen und der Akzeptanz seitens der Landwirt:innen in Einklang bringen, ist bislang nur unzureichend verstanden. Schließlich sind praxisnahe, standortangepasste angepasste Transformationspfade zur Umgestaltung von Tierhaltungssystemen, mit dem Ziel einer deutlichen Reduktion von P-Emissionen in der intensiven Tierhaltung, weitgehend unerforscht. Diese Dissertation adressiert diese Forschungslücken, indem sie modellbasierte Ansätze zur Entwicklung standortangepasster Agrarsysteme weiterentwickelt und Wege hin zu wünschenswerten Zukunftsszenarien aufzeigt. Damit liefert sie wichtige Erkenntnisse zu Systemen, Zielen und Transformationen, die als Orientierungshilfe für die zukünftige Entwicklung von Agrarsystemen dienen können. Diese Dissertation ist als kumulative Arbeit aufgebaut, die drei Forschungsartikel umfasst.

Der erste Artikel präsentiert eine systematische Literaturrecherche zu räumlich expliziten Modellen, die zur Bewertung von Agrarlandschaften eingesetzt werden. Um die Analyse zu strukturieren, wurde ein theoretisches Rahmenkonzept entwickelt, das zentrale Elemente von Agrarlandschaftsbewertungen definiert und eine systematische Vergleichbarkeit von Modellierungsansätzen über Studien hinweg ermöglicht. Die Analyse zeigt, dass Biodiversität und Ökosystemleistungen wie *Wasserqualität* und *Atmosphärische Zusammensetzung und -bedingungen* zwar häufig berücksichtigt werden, jedoch nur selten in Kombination. Andere Leistungen, wie etwa die *Schädlingsregulation*, fehlen weitgehend. Darüber hinaus fehlt in den meisten Modellen eine Darstellung der Nährstoffrückflüsse aus dem Ernährungssystem, und sie kombinieren selten die Dynamik zwischen Ackerbau und Nutztierhaltung, wodurch ihre Fähigkeit, Synergien oder Kompromisse umfassend zu erfassen, eingeschränkt ist. Diese Arbeit identifiziert somit kritische blinde Flecken und unterstreicht die Notwendigkeit integrativerer Modellierungsansätze, um die Entscheidungsfindung in multifunktionalen Agrarlandschaften angemessen zu unterstützen. Darüber hinaus bietet das vorgeschlagene Rahmenkonzept zentraler Elemente von Agrarlandschaftsbewertungen einen strukturierten Ausgangspunkt für ein umfassenderes Systemverständnis in zukünftigen Bewertungen.

Der zweite Artikel präsentiert LEAF.livestock, ein dynamisches Tiermodell, das entwickelt wurde, um einige der genannten Einschränkungen zu überwinden. Das Modell wird auf das Nutztier-intensive Einzugsgebiet des Sempachersees in der Schweiz angewandt, wo Nährstoffungleichgewichte infolge hoher Tierdichten und Futtermittelimporte zu einer übermäßigen P-Anreicherung geführt haben. Nahezu fünf Millionen Kombinationen von Herdenstrukturen und Managementpraktiken werden simuliert, darunter Veränderungen in Tierdichte und -zusammensetzung, Futterherkunft sowie Aufzuchtstrategien. Die Analyse konzentriert sich

auf die Folgen dieser Veränderungen für die P-Ausscheidung, die Produktion tierischer Proteine, die Landnutzung sowie die Konkurrenz zwischen Futter- und Nahrungsmittelproduktion. Kein einzelnes Szenario erfüllt alle ökologischen und produktionstechnischen Anforderungen gleichzeitig. Werden jedoch Landnutzungsrestriktionen gelockert, ergeben sich über 514'000 realisierbare und 7'174 Pareto-optimale Szenarien, die jeweils spezifische Zielkonflikte aufzeigen: Schweinedominierte Szenarien ermöglichen eine stärkere Reduktion der P-Ausscheidungen und eine höhere Proteinproduktion, sind jedoch auf mehr Ackerland und Importe angewiesen. Milchviehbasierte Szenarien sind zwar weniger produktiv, aber besser auf die regionale Landverfügbarkeit abgestimmt sind. Diese Ergebnisse unterstreichen das Potenzial mehrerer, lokal angepasster Lösungen anstelle eines globalen Optimums.

Aufbauend auf diesen Ergebnissen simuliert der dritte Artikel Transformationspfade vom aktuellen Nutztierhaltungssystem hin zu zwei kontrastierenden Zielszenarien. Mithilfe eines widerstandsgewichteten Optimierungsansatzes in Kombination mit dem dynamischen LEAF.livestock-Modell wurden Veränderungen in Betriebstypen und Managementpraktiken für den Zeitraum von 2020 bis 2060 simuliert. Beide Transformationspfade erreichen die Ziele zur Reduktion der P-Ausscheidungen, jedoch über unterschiedliche Umstrukturierungsprozesse: der Pfad in Richtung des schweinedominierten Zielszenarios basiert auf Betriebsaufgaben und Spezialisierung, während der Pfad in Richtung des milchviehdominierten Zielszenarios den Schwerpunkt auf Änderungen der Fütterungspläne mit weniger Betriebsaufgaben legt. Diese Ergebnisse verdeutlichen, dass zwar mehrere Wege zu denselben Umwelt- und Produktivitätszielen führen können, jeder einzelne jedoch mit spezifischen sozialen, strukturellen und politischen Implikationen verbunden ist. Dies unterstreicht die Notwendigkeit gezielter Unterstützungsmaßnahmen, um Übergänge zugleich praktikabel und gesellschaftlich anschlussfähig zu gestalten.

Zusammen zeigen die drei Artikel, wie standortangepasster Modellierung das Management von Nutztieren und die Politikgestaltung unterstützen kann, indem sie Zielkonflikte sichtbar macht, Synergien identifiziert und eine evidenzbasierte Planung unterstützt. Am Beispiel des Einzugsgebiets des Sempachersees leistet diese Dissertation einen Beitrag zur Entwicklung von Transformationspfaden in der Nutztierhaltung, die eine Reduktion der P-Ausscheidungen mit der Aufrechterhaltung der Nahrungsmittelproduktion verbinden. Während das Einzugsgebiet als detaillierte Fallstudie dient, bietet der in dieser Dissertation entwickelte Modellierungsansatz eine breitere Relevanz für Agrarlandschaften, die vor ähnlichen Herausforderungen stehen, und liefert eine Grundlage für standortangepasste Entscheidungsfindung und Politikgestaltung.

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Chapter I

General introduction

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I / I. Agricultural landscapes, representatives of levers for change

I / I.1. The state of agriculture landscapes

The global agricultural system faces immense challenges. It must ensure nutritious and secure food supplies for a growing and more food demanding population in the midst of a changing climate (FAO 2018; Willett et al. 2019). At the same time, prevailing agricultural practices exert substantial pressure on biogeophysical Earth systems, contributing to the crossing of planetary boundaries related to climate change, biodiversity, land use, water quality, and nutrient cycling (Rockström et al. 2020; Richardson et al. 2023; Campbell et al. 2017).

While the planetary boundaries are defined at the global level, their transgression is often rooted in processes that play out in local ecosystems. Nutrient surpluses, biodiversity loss, and soil degradation emerge when the carrying capacities of individual ecosystems are exceeded. Zooming into agricultural landscapes makes these ecological and structural imbalances even more tangible: In parts of southern Spain or the Brazilian Cerrado, for example, intensive farming has caused severe soil degradation, diminishing both soil fertility and long-term productivity (Rodríguez-Berbel et al. 2023; Hunke et al. 2015). In Eastern Germany and the US Midwest, intensification, landscape simplification, and habitat loss have led to significant declines in biodiversity (Landis 2017; Batáry et al. 2017). Water overuse and pollution from fertilizers and pesticides are widespread in regions such as Italy's Po Valley and India's Punjab, posing serious risks to both human health and agricultural viability (Aulakh et al. 2009; Lasagna et al. 2016). Disrupted nutrient cycles are also widespread, leading to eutrophication in the Baltic Sea and eutrophication-induced acidification in the Gulf of Mexico; this is mostly driven by nutrient runoff from the heavily fertilized catchment areas (Murray et al. 2019; Laurent et al. 2017). Finally, the effects of climate change are already evident in regions such as drought-stricken south-eastern Australia, flood-affected Indian river basins, and water-stressed California (Chiew et al. 2011; Ali et al. 2019; Mirchi et al. 2013). All examples of places where climate change undermines agricultural productivity, while prevailing farming practices further amplify ecological stress.

I / I.2. The role of agricultural landscapes

The diverse and region-specific challenges outlined above underscore the need for spatially differentiated responses. Agricultural landscapes, defined as spatial units shaped by both biophysical context and human decision making (Nitschelm et al. 2016; Mirschel et al. 2020), play a pivotal role in this regard. These landscapes are where the impacts of global pressures, such as climate change, biodiversity loss and nutrient imbalances, play out locally, and where solutions must ultimately be implemented. Focusing on the landscape level reveals local heterogeneity and context-specific challenges that often remain hidden when considering only national or global scales (Kok et al. 2017; Bennett et al. 2021). At the same time, the landscape level makes ecological processes and constraints, such as nutrient retention or habitat connectivity, visible, which are often difficult to

detect at the field or farm level (Lasseur et al. 2018; Jeanneret et al. 2021b). The landscape level offers therefore critical advantages for analysis and for the design of targeted interventions. It thus represents a key entry point for implementing effective and context-sensitive solutions to environmental challenges. At the same time, focusing on the landscape level also entails difficulties, as agricultural landscapes are complex, strongly embedded in broader systems, and are often not the level at which decisions are made. Aspects that are outlined in more detail in the following section.

I / 1.3. The complexity of agricultural landscapes

To develop and implement spatially differentiated responses to environmental challenges, it is essential to acknowledge the inherent complexity of agricultural landscapes. Agricultural landscapes are often primarily viewed as spaces of food production, reflecting the visibility and dominance of farming activities in these regions. Yet, they are inherently multifunctional systems that provide diverse ecosystem structures and support a range of ecological processes, including carbon sequestration, nutrient cycling, water regulation, and habitat provision (Fry 2001; O'Farrell and Anderson 2010). The capacity to deliver these landscape functions, however, varies widely across regions. It is shaped by a complex interplay of factors, including climatic and topographic conditions, soil characteristics, historical land-use trajectories, the intensity of crop and livestock management, landscape structures, and the socio-economic context (Pfeifer et al. 2009; Hölting et al. 2019b; Bürgi et al. 2005). Additionally, agricultural landscapes are rarely isolated systems. Instead, they are often strongly embedded within broader food systems, shaped by flows of external inputs, such as fertilizer and energy, and by the export of agricultural products for processing, trade, and consumption elsewhere (Liu et al. 2013). Some landscapes maintain integrated crop-livestock systems with localized nutrient cycling, while others are highly telecoupled, relying on feed grown elsewhere and global trade flows (Garrett et al. 2020). These interdependencies influence both the environmental impacts of agricultural landscapes and the scope for adopting more sustainable practices.

At the same time, governance at the landscape level remains challenging as it is complicated by fragmented responsibilities: while some decisions are made at regional level, many remain at the farm level and are influenced by national and international policy frameworks, leading to scale mismatches (Cumming et al. 2006). To realize the potential of landscape-level interventions, stronger coordination mechanisms are needed, such as targeted incentives or collaborative governance schemes that promote joint action among stakeholders (Dale et al. 2013; Wu 2021). For this, tailored strategies are required, including context-specific solutions to improve agricultural practices that address both regional contributions to and vulnerabilities from climate change, biodiversity loss, soil and water degradation, and nutrient cycle disruption (Kazanski et al. 2025; Diogo et al. 2022).

BOX 1. Under the magnifying glass

The agricultural landscape around Lake Sempach, Switzerland

The catchment of Lake Sempach, located in the Swiss Central Plateau in the canton of Lucerne (Figure 1/1), illustrates a striking example of a multifunctional agricultural landscapes. Covering 75 km², of which approximately 70% is agricultural land, the area plays a significant role in national food production (rawi 2019). It features one of Switzerland's highest livestock densities (2.39 LSU/ha compared to the national average of 1.24 (Federal Statistical Office 2025; Kanton Luzern 2021), and simultaneously provides essential ecosystem services, including water regulation and biodiversity conservation (Kanton Luzern 2020). However, the high productivity level comes at an ecological cost: within the catchment, decades of intensive farming have led to a substantial accumulation of phosphorus in soils, with over half of the land now falling into the highest phosphorus supply classes (Hirte, J. - personal communication 9/22/2023). The resulting nutrient surpluses have degraded the water quality, contributing to eutrophication and oxygen depletion in the lake (Scharrer 2013). To counteract this, the lake has been artificially aerated since 1982.

While crop and livestock production in the region are closely integrated and much of the land is used for feed production, the system remains embedded in broader food and trade networks. It is dependent on imported feed, and the surplus manure generated by the intensive livestock production is redistributed beyond the catchment, potentially amplifying nutrient pressures elsewhere. This imbalance highlights the importance of the landscape level for identifying both ecological thresholds and leverage points for intervention, as the cumulative impact of nutrient flows are hidden at farm level. While farm-level efforts like the “Phosphorus Project” (running since 1999), have reduced inputs, phosphorus levels in Lake Sempach remain above ecological targets (UWE and AfU 2023; Kanton Luzern 2021). At the same time, national regulations, such as livestock density limits, often fail to reflect regional conditions, and fragmented responsibilities and the region's strong agricultural identity further complicate structural change. Tailored, landscape-level strategies are therefore needed to reduce nutrient surpluses while maintaining productive system.

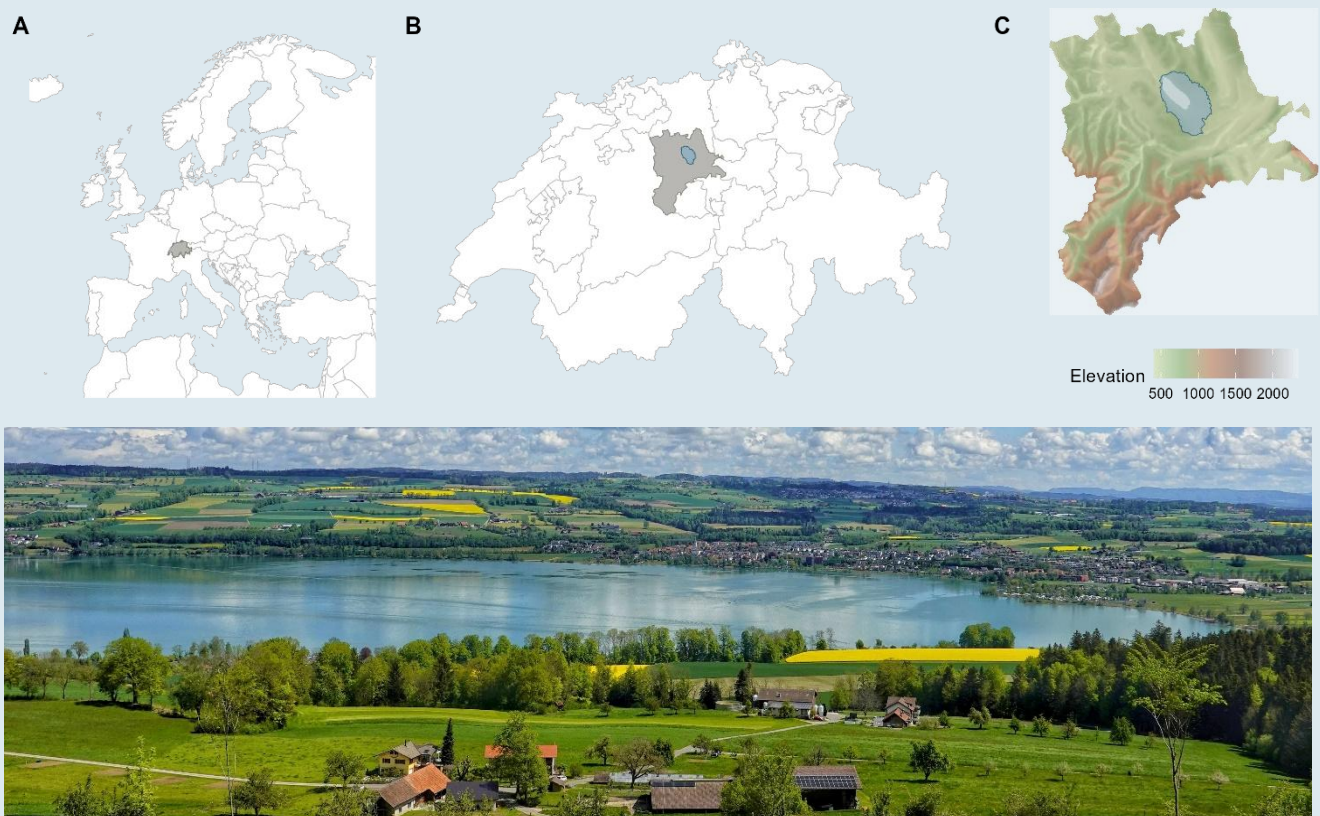


Figure 1/1: Upper panel: A) Location of Switzerland within Europe; B) Location of the canton of Lucerne and the catchment of Lake Sempach within Switzerland; C) Location of Lake Sempach and its catchment area within the canton of Lucerne. **Lower panel:** View of Lake Sempacher (Sempachersee), Switzerland. **Sources:** Photo reproduced with permission from the municipal administration of Neuenkirch. Topographical catchment areas of Swiss waterbodies (FOEN 2019), Lake boundaries (FOEN 2023), National and cantonal borders (swisstopo 2024), Hillshaded relief (swisstopo 2017; Grossenbacher und Zehr 2021), Digital height model (swisstopo 2022).

I / 2. Phosphorus, a representative for disrupted nutrient cycles

As an essential macronutrient alongside nitrogen and potassium, phosphorus (P) is crucial for plant growth and was a key driver of agricultural productivity over the past century. Unlike nitrogen, however, P cannot be synthesized and relies on finite, geopolitically sensitive reserves, leading the European Commission to classify it as a critical raw material (European Commission 2017). As illustrated above (cf. Box 1), the agricultural landscape surrounding Lake Sempach, Switzerland, exemplifies P's critical yet challenging role in food systems: while essential for maintaining crop yields, excessive P inputs lead to its accumulation in soils and the pollution of surface waters, a pattern observed from small ponds to large ecosystems like the Baltic Sea (Strokal and Kroeze 2013). These surpluses contribute to eutrophication, biodiversity loss, and the degradation of water-related ecosystem services (Smith et al. 1999; Ansari et al. 2011).

Historically, industrial sources, such as phosphate-based detergents and insufficient wastewater treatment, contributed substantially to P surpluses, but regulations have largely mitigated these emissions (Ashley et al. 2011; Köhler 2006). In contrast, P use in agriculture remains a persistent challenge with complex spatial and temporal dynamics. On a global scale, P deficits are most acute in sub-Saharan Africa, where P budgets are often negative or fluctuate around zero, indicating long-term depletion of soil P reserves (Bouwman et al. 2017; Ludemann et al. 2024). In contrast, countries like China and India have accumulated substantial P surpluses since the 1990s, resulting in the build-up of significant soil P reserves (Bouwman et al. 2017). High-income countries, particularly in Europe, followed a different trajectory: after being the global hotspot of P fertilizer input prior to the 1980s, they have seen a steady decline in P surpluses, approaching a small deficit in recent years (Lu and Tian 2017; Ludemann et al. 2024). However, despite continental-level improvements, regional disparities remain; certain areas in Europe still exhibit considerable P surpluses, often linked to local imbalances in livestock density and manure management (Muntwyler et al., 2025).

While reduced fertilizer inputs in Europe represent an important achievement, they have not eliminated the legacy of past over-application. The decades of surplus inputs, particularly in intensive livestock and crop production systems, led to the accumulation of P in soils, often referred to as legacy P or residual P. These soil reserves continue to influence ecosystem functioning as of today (Sharpley et al. 2013; Davies 2025). Even with reduced application rates, accumulated legacy P can remain a driver of surface-water pollution, reducing the gains from nutrient-reduction measures or delaying their impact (Sharpley et al. 2013; Zou et al. 2022). Furthermore, the process of reducing excessive soil P levels through reduced application alone may take decades, influenced by the magnitude of prior accumulation (Sharpley et al. 2013; Dodd et al. 2012).

To address the persistent and regionally variable P surplus, a range of technical, policy, and behavioural solutions have been proposed at multiple scales. Globally, scholars and policymakers increasingly call for coordinated P governance. Over 500 scientists have signed a call for international action on P, urging

governments to develop strategies that cut across agriculture, food, waste, and water sectors (European Sustainable Phosphorus Platform 2020; Brownlie et al. 2021). The *Our Phosphorus Future* report outlines ten key actions, including increasing the use of recycled P in fertilisers and chemical industries, optimising P inputs to soils and animal diets, enhancing global monitoring of P emissions and their impacts, restoring freshwater and coastal ecosystems, and ensuring equitable access to P fertilisers (Brownlie et al. 2022). The report also calls for broader systemic changes, such as shifting toward low-P diets via reducing meat consumption, and reducing food waste, to significantly lower P losses across the entire food system (Brownlie et al. 2022).

Concrete mitigation options to reduce P losses from agriculture can be broadly categorized into four interrelated domains: (1) surface water management, (2) water, land use, and landscape management, (3) soil and crop management, and (4) nutrient and livestock management (Schoumans et al. 2014). Measures related to *surface water management* aim at retaining sediment and P transported to aquatic ecosystems from land through e.g. river, lake, or wetland restoration (Schoumans et al. 2014). *Water, land use, and landscape management* addresses the spatial organization of agricultural landscapes and their hydrological connectivity. Strategies involve redirecting runoff flows, optimizing land use patterns to improve the location of P sources and sinks, collecting farmyard runoff, and preventing livestock access to surface waters (Schoumans et al. 2014). *Soil and crop management* centers around agricultural practices, including improving fertilizer application using the 4R principle: right rate, right time, right source, and right placement of fertilizers (Sharpley 2016), as well as converting arable land to grassland, growing deep-rooted crops, or temporarily setting land aside (Schoumans et al. 2014). Targeted P mining, in which no P is applied on soils with high reserves and cultivating P-demanding crops such as maize, can help deplete legacy P over time (Davies 2025). Legumes may also be incorporated, as they efficiently utilize soil P without the need for additional nitrogen inputs. Additional measures involve improving soil structure through reduced tillage or the use of chemical amendments to immobilize soluble P (Sharpley 2016; Schoumans et al. 2014). *Nutrient and livestock management* targets the upstream causes of P surpluses. This involves optimizing animal feed formulations by adjusting P content, using additives like phytase, and aligning diets with animal growth stages to reduce P excretion. Managing manure more effectively by separating it into liquid fractions with a high nitrogen and low P content and solid fractions with a high P and low nitrogen content, and/or redistributing it to areas deficient in P, can further reduce local surpluses (Schoumans et al. 2014; Bouwman et al. 2013). In some cases, regulatory measures such as capping livestock densities have been introduced to limit P loads, although these remain socially and politically sensitive (Schoumans et al. 2014).

I / 3. Livestock production, a representative for challenges within food systems

As highlighted in Section 1/2. and illustrated by the agricultural landscape surrounding Lake Sempach, Switzerland (cf. Box 1), livestock production is a key factor in P losses to surface waters. Agricultural landscapes with high livestock densities often experience elevated nutrient surpluses, which increases the risk of P runoff and water pollution (Schoumans et al. 2014). In Europe, for instance, the livestock sector is responsible for around 73% of the total contribution of agriculture to water pollution from P and nitrogen (Leip et al. 2015). In addition to P losses, livestock production is also associated with a variety of other challenges. Globally, the sector is responsible for around 12% to 20% of greenhouse gas emissions (Gerber 2013; FAO 2023; Xu et al. 2021), and contributes significantly to air pollution, high water consumption, and biodiversity loss (Scanes 2018; Heinke et al. 2020; Godfray et al. 2018; Ball et al. 2025). Beyond environmental impacts, livestock production also raises public health concerns. Excessive consumption of animal-sourced products, especially in the form of red and processed meats, has been associated with greater risk of chronic diseases (Okello et al. 2022; Ma et al. 2025; Herrero et al. 2023). Moreover, the widespread use of antibiotics in livestock production contributes to the growing threat of antibiotic resistance (Woolhouse et al. 2015; Ardakani et al. 2023). Much like in other areas of agriculture, labor conditions in the livestock sector often involve hazardous, low-wage, and precarious work environments, raising questions about worker health, safety, and rights (Kelly 2024; Okello et al. 2022). Finally, concerns about animal welfare continue to prompt ethical questions regarding the treatment and living conditions of farmed animals (European Union 2023). As a result, calls to reduce meat consumption and livestock farming, particularly in regions where dietary habits exceed established health recommendations, are growing louder (Tirado et al.; Bajželj et al. 2014; Ipsos UK 2024; Rööß et al. 2017; Willett et al. 2019; Clark et al. 2020; van Zanten et al. 2018).

At the same time, livestock production and animal-sourced products can, in specific contexts, make important contributions to nutrition, livelihoods, nutrient cycling, land use efficiency, and other agroecological services. Animal-sourced products are sources for high-quality protein, containing all nine essential amino acids and essential micronutrients such as vitamin B12. At certain life stages, such as early childhood, female adolescence, and during pregnancy or nursing, as well as for population groups at risk of undernutrition, the intake of these products may be particularly important (Herrero et al. 2023; Nordhagen 2025). Furthermore, livestock production generates income and employment worldwide, playing a vital role in shaping livelihoods (Thornton 2010). For vulnerable communities, it also serves as an important buffer against economic and food insecurity (Herrero et al. 2009; Herrero et al. 2013; Varijakshapanicker et al. 2019), and the production and consumption of animal-sourced products are deeply embedded in many cultural traditions (Leroy and Praet 2015). Furthermore, animal production systems can play an integral role in advancing circular agriculture, as in mixed crop-livestock systems, manure serves as a valuable source of organic fertiliser, helping to close nutrient cycles

(Herrero et al. 2023; Garrett et al. 2020). Certain livestock production systems are furthermore particularly well-suited to utilise biomass inedible or undesirable for direct human consumption, such as grassland biomass and leftovers (van Zanten et al. 2018). Ruminants, for instance, can convert grassland biomass into milk, meat, and manure. Monogastric animals, such as pigs and poultry, can make use of losses and waste occurring throughout the food system, and also leftovers including by-products from food processing industries and crop residues remaining after harvest are valuable resources suitable as animal feed. By recycling these otherwise unusable resources back into the food system, livestock can help reduce feed-food competition and enhance the overall system efficiency (van Zanten et al. 2018). Depending on the context, livestock can also provide other valuable agroecological services. In well-managed systems, for example, grazing animals can help to maintain landscapes, control weeds, and support biodiversity conservation (Herrero et al. 2023).

These benefits and negative impacts of livestock production represent two sides of the same coin, underscoring the complexity of the ongoing debate about the role of livestock in sustainable food systems. Livestock can support sustainable food systems, but only if managed in ways that reduce trade-offs and strengthen synergies across environmental, health, and equity objectives. The potential of livestock systems depends fundamentally on how, where, and why animals are raised (Kazanski et al. 2025). A transition toward more sustainable livestock systems is necessary, but should be guided by diverse, region-specific strategies: in some agricultural landscapes, livestock is essential for livelihoods and nutrition, while in others, lowering the production and consumption of animal-sourced foods is key to mitigating environmental pressure.

I / 4. The role of models for assessments, visioning, and transitions

In order to address the challenges outlined in Sections 1/2. and 1/3. and to move towards agricultural practices that are better aligned with local ecosystems, and consequently towards more sustainable food systems, it is necessary to identify an appropriate balance between the competing goals. This, in turn, requires a clear understanding of the functions that agricultural landscapes provide and their inherent trade-offs and synergies (*systems knowledge*), clarity about the desired future conditions (*target knowledge*), and insight into how these can be achieved (*transformation knowledge*) (Ejderyan et al. 2023; Hadorn et al. 2008). In contexts where primary or secondary data is lacking, models play a central role in generating the necessary insights (Kanter et al. 2018; Poggi et al. 2021).

For example, models such as the biophysical Environmental Policy Integrated Climate (EPIC) model, which simulates agricultural management at the field level, or the hydrological Soil and Water Assessment Tool (SWAT) model, which operates at the watershed to river basin scale, enable trade-off analyses between agricultural productivity, soil erosion, and water quality (Arnold et al. 2012; Jones et al. 2021). These models help to quantify trade-offs and synergies between production and environmental outcomes. In doing so, they

contribute to the development of *systems knowledge*, an analytical and descriptive understanding of the current state of a system, including its structures, processes, and variability (ProClim 1997; Buser and Schneider 2021).

Furthermore, models also support the comparison of a range of plausible and internally coherent future developments, often structured as scenarios. These scenarios may be based on specific interventions or predefined changes in key influencing factors, such as climatic conditions (Kanter et al. 2018). They can be evaluated against one another or in comparison to the current system state. For example, the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) modeling tool was used by Polasky et al. (2011) to assess carbon storage, water quality, habitat quality, and agricultural production under various land-use change scenarios in the state of Minnesota, USA. Similarly, the global food system model, SOLm, was applied by Muller et al. (2017) to evaluate global scenarios that combined different rates of conversion to organic agriculture, reductions in food waste, and reductions in the use of food-competing feed from arable land, all under varying climate change impacts on crop yields. Optimization approaches further expand this potential. For example, Groot et al. (2018) used spatially explicit optimization to generate a wide range of land-use and management options, enabling the assessment of trade-offs and synergies among ecosystem services across agricultural landscapes. Similarly, the Circular Food System (CiFoS) model minimizes agricultural land use while considering greenhouse gas emissions and dietary demands at the continental level (van Zanten et al. 2023). Through such applications, models contribute to the development of *target knowledge* by enabling the evaluation of current conditions, scenarios, and projections, and by helping to identify desirable future conditions, including normative goals, guiding visions, or sustainability thresholds (ProClim 1997; Pohl et al. 2008; Hadorn et al. 2008).

Additionally, models are used to identify pathways towards these desirable futures. An example at the regional level is the application of a backcasting approach by Brunner et al. (2016), who developed land-use policy strategies for a Swiss region and simulated their influence on ecosystem service supply. The type, combination, and timing of policy measures resulted in multiple possible transition pathways. Soergel et al. (2024), on the other hand, used integrated assessment and sector models to calculate how different societal strategies, referred to as sustainable development pathways (SDPs), influence progress toward achieving both the UN Sustainable Development Goals and the Paris Climate Goals at the global level. These SDPs were developed as target-seeking scenarios and illustrate alternative pathways toward the desirable future defined by these international objectives. With this, the application of models is an essential part in the generation of *transformation knowledge*. This refers to knowledge about how to design and realize the transition from the current state to a desired future state, including technical, social, legal, and cultural means of action (ProClim 1997; Hadorn et al. 2008).

It is worth noting that the three types of knowledge (i.e., systems, target, and transformation knowledge) are closely interconnected and mutual dependent. Rather than being addressed in isolation or in a fixed sequence,

they form a dynamic triangle in which progress in one area often requires insights from the others (Hadorn et al. 2008; Pohl and Hirsch Hadorn 2007). In model-based research, this interplay becomes particularly evident, as models have the capability to describe current system dynamics, explore future visions, and identify feasible transition pathways.

Furthermore, the model applications above are not intended to be exhaustive, but serve to illustrate the diversity of modeling approaches available. They vary in complexity, ranging from empirical models to more detailed process-based simulations, and span a wide range of disciplines, including environmental sciences, hydrology, agricultural sciences, nutritional sciences, animal sciences, plant sciences, and economics. These models operate across multiple spatial scales, from farm to global level, and address different jurisdictional levels, from municipal to national and international contexts. In addition, they are applied at various sectoral levels and across different supply chains and supply chain stages, from primary production to consumption and waste management (Kanter et al. 2018; Jones et al. 2017b, 2017c; IPBES 2016a; Peters and Thilmany 2022).

I / 5. Knowledge gaps and related research questions

1st knowledge gap Capabilities and blind spots of existing modelling approaches

As demonstrated in Section 1/4., model-based approaches are widely used to describe the current state of agricultural and food systems, assist in identifying desirable future conditions, and generate knowledge about how to transition from the current to the target state. In addition, Section 1/1. highlighted that agricultural landscapes are a key entry point for implementing effective and context-sensitive solutions to environmental challenges. However, fully capturing the multiple functions of agricultural landscapes, together with their trade-offs and synergies, depends on modelling approaches that can account for the inherent heterogeneity of these systems. Spatially explicit models are particularly valuable in this regard, as they can reflect variation in biophysical and management conditions across space. For example, water quality assessments improve when differences in slope, soil, and land use within a catchment are considered. Spatially explicit models capture such processes at fine resolution and aggregate them to provide results at the landscape level.

Existing modelling approaches for agricultural landscape assessments, however, appear to miss several crucial aspects. One important gap is the absence of integrated assessments that connect agronomic perspectives with other landscape functions (Hossard and Chopin, 2019; Seppelt et al., 2020; TEEB, 2018). At the same time, provisioning, regulating, and cultural ecosystem services are rarely analysed together, which risks neglecting the multifunctional character of agricultural landscapes (Zabala et al. 2020; Seppelt et al. 2011). In addition, previous work has pointed out that local processes can also affect other, distant regions, calling for better integration of cross-scale interactions and telecoupling effects (Lautenbach et al. 2019; Seppelt et al. 2011). While several reviews have examined agricultural landscapes and landscape multifunctionality (Hölting et al. 2019a; Hossard and Chopin 2019; Huang et al. 2015; Eichler Inwood et al. 2018; Loiseau et al. 2012; Englund et al. 2017),

a systematic overview remains lacking. In particular, the extent to which landscape functions are typically assessed, how the linkages to the wider food system are represented, and whether existing blind spots constrain comprehensive assessments of multifunctionality remains insufficiently understood. I therefore investigate the following question:

Research question 1. How are landscape functions assessed through spatially explicit model-based approaches, and to what extent do these models capture the linkages between agricultural components within the landscape and with the wider food system?

2nd knowledge gap Option space for phosphorus reduction in livestock systems in agricultural landscapes

Although reducing P surpluses in livestock systems is widely acknowledged as necessary (cf. Section 1/2. and 1/3.), the full range of viable system adjustments to better align them with the respective local ecosystem context remains insufficiently explored. While reducing livestock numbers is one possible response, it risks undermining food production and rural economies. Therefore, additional strategies for lowering P excretion from livestock production need to be considered. These include adjusting the composition of livestock herds to reduce P emissions per unit of protein output (Poore and Nemecek 2018b) and prioritizing locally sourced feed to limit external P inputs and close nutrient cycles. In addition, feeding regimes, production intensity, and calf-rearing pathways influence nutrient balances, with shorter cycles such as veal production leading to lower accumulation than longer beef-fattening systems. Such strategies, however, affect not only nutrient excretion but also the amount and type of animal-sourced products. Some approaches reduce output substantially, while others allow production to remain closer to current levels. The key challenge is therefore to identify combinations that lower environmental pressures while maintaining viable production and farmer acceptance. Assessing the quantitative potential of these strategies and their interactions is essential for defining realistic target scenarios. Consequently, the following question emerges:

Research question 2. What is the option space for reducing phosphorus emissions from livestock production in agricultural landscapes, while maintaining protein production for human consumption and staying within ecological limits?

3rd knowledge gap Phosphorus reduction pathways in livestock systems in agricultural landscapes

Designing future-oriented livestock systems requires more than identifying desirable endpoints – it also demands a clear understanding of how to achieve them. Yet, the transition from current regional systems to those capable of meeting P reduction targets remains insufficiently explored. In particular, there is limited

insight into how such transitions can be realized in practice, including concrete steps, feasible timeframes, and implementation under real-world constraints. Dynamic perspectives that account for the complexity of change over time are especially lacking. This is particularly crucial for livestock systems, which are inherently shaped by both interannual and intra-annual variabilities, already in the absence of broader system transformations. Temporal variability arises, for example, at the level of the animal through lifetime and seasonal performance fluctuations (Puillet et al. 2011), at the herd level through seasonal calving patterns or the practice of alpine summer pasturing (Ferreira et al. 2020), or through variations in feed availability (Casasús et al. 2002; Mudavadi et al. 2020). Incorporating these inherent temporal dynamics together with the broader transformation required to align livestock production with local ecosystems is key to identifying realistic pathways of change. Bridging this gap calls for a dynamic, regionally grounded approach that accounts for implementation sequences, trade-offs, and feasibility. Consequently, the following research question emerges:

Research question 3. What transition pathways can facilitate a transition from the current livestock system to scenarios that achieve significant phosphorus excretion reductions?

I / 6. Aim and structure of the dissertation

With this dissertation, I aim to advance model-based approaches for designing locally adapted agricultural systems¹ and to demonstrate pathways towards these desirable future states. In doing so, I contribute to the urgently needed systems, target, and transformation knowledge. Figure 1/2 illustrates visually how this aim is pursued throughout the dissertation, and the following paragraphs provide a summary of how the individual chapters address the identified knowledge gaps.

¹ **Note:** Locally adapted agricultural systems are understood here as systems that utilise location-specific agronomic, economic, and ecological potential for food production while taking into account the ecological carrying capacities of ecosystems (Swiss Federal Council (2020). Dispatch on the Further Development of Agricultural Policy from 2022 (AP22+), Federal Gazette (BBl) 2020 3955, Section 4.2.3.1. Decision of 12 February 2020, published 5 May 2020. Fedlex: <https://www.fedlex.admin.ch/eli/fga/2020/881/de>).

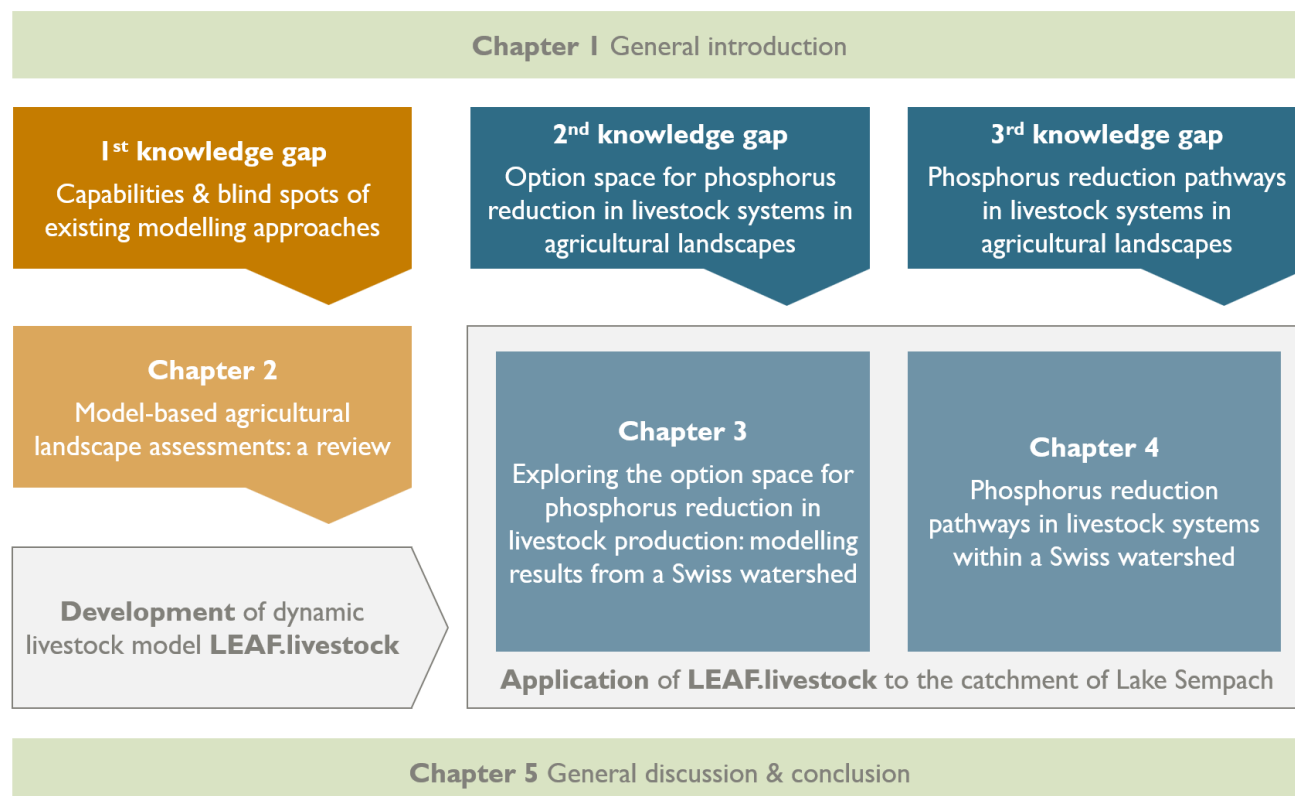


Figure 1/2: Framed by Chapter I (General Introduction) and Chapter 5 (General Discussion and Conclusion, both in green), the figure outlines the structure of the thesis: the first knowledge gap and the corresponding Chapter 2 (in orange), the resulting development of the LEAF.livestock model and its application in the case study of the catchment of Lake Sempach (both in grey), as well as the subsequent second and third knowledge gaps and the associated Chapters 3 and 4 (in blue).

Chapter 2: Model-based agricultural landscape assessments: a review

As a first step toward this aim, and to address the first knowledge gap (Figure 1/2, dark orange box), I conducted a comprehensive review of spatially explicit modelling approaches. To analyse these approaches, I developed a framework that captures the key elements of agricultural landscape assessments, including the range of landscape functions provided and their driving factors, the linkages between crop and livestock production, and the integration into the wider food system. This review revealed both the capabilities and blind spots of existing modelling approach, thereby revealing areas for improvement.

Chapter 3: Exploring the option space for phosphorus reduction in livestock production: insights from a dynamic modeling approach applied to a Swiss watershed

Building on these insights, I developed the novel dynamic livestock model LEAF.livestock, specifically designed to address the limitations of existing modelling approaches and to particularly tackle the challenges associated with ecosystems characterized by intensive livestock production and P surpluses. To address the second knowledge gap (Figure 1/2, dark blue box), I applied this model to the watershed of Lake Sempach (see Box 1) to explore the option space for reducing P excretion from livestock production in agricultural landscapes, while maintaining protein production for human consumption and staying within ecological limits. In doing

so, I offered region-specific recommendations that are adapted to local conditions and contributed therefore to the systems and target knowledge required to inform the necessary societal transformation of agricultural production.

Chapter 4: Phosphorus reduction pathways in livestock systems within a Swiss watershed

To fill the third knowledge gap on how livestock systems in agricultural landscapes can be transformed to achieve P reduction targets (Figure 1/2, dark blue box), I investigated steps for implementing desirable system adjustments that align with local ecological conditions. For this purpose, I selected a subset of two contrasting target system configurations developed in Chapter 3 for the watershed of Lake Sempach in Switzerland. Using the dynamic LEAF.livestock model, I simulated and analyzed transition pathways from the current system to these target states across a 30-year transition period. In doing so, I explored the speed, sequence, and feasibility of these changes within the specific landscape context, thereby generating the transformation knowledge needed to support locally adapted, sustainable livestock system transitions.

Focusing on the catchment of Lake Sempach, I thus contribute with this dissertation to designing ecologically sound and socially acceptable livestock transition pathways, highlighting region-specific trade-offs and actionable strategies to reduce P excretion from livestock production while maintaining food production within the environmental limits. Beyond this specific case study, the overarching goal of this dissertation is however to develop a detailed modeling approach, which is also applicable to other agricultural landscapes and their crop-livestock systems, thereby offering a foundation for informed decision-making and locally adapted policy making in diverse regional contexts.

I / 7. References

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Chapter 2

Model-based agricultural landscape assessments: a review

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2 / 1. Abstract

Agricultural landscapes are multifunctional and closely connected to the much wider food system. In our review, we explore three specific aspects of modelling approaches for agricultural landscape assessments: a) how multifunctionality is commonly analysed to support decision-making for sustainable agricultural land management; b) how the modelling approaches relate to the wider food systems; and c) how gaps in the existing modelling approaches might be addressed. For this, we identified key elements of agricultural landscape assessments, including ecosystem services (ESS) provided, driving factors, and linkages between crop and livestock production, and to the wider food system. We reviewed 238 publications with respect to these elements. While biodiversity and the ESS 'water conditions' and 'atmospheric composition/conditions' are widely covered, they are rarely used in combination. Other ESS, such as 'pest and disease control', are largely missing. Our results further indicate strong differences between individual approaches regarding model parameterisation and consideration of abiotic, biotic, and management driving factors. Our analysis also shows that the interconnectedness of crop and livestock production is rarely considered and that return flows from the food system are not considered. Furthermore, impacts from the production of external inputs and off-site effects are not considered. Consequently, existing models might overlook trade-offs and synergies between landscape functions. Failure to consider variations in relevant driving factors and food system linkages likely results in studying incorrect levers for change and failing to show decision-makers the full scope of available action. We thus suggest adopting more encompassing modelling approaches to ensure coverage of the full scope of potential actions, whilst hedging against overly costly data requirements by, e.g. employing well-designed sensitivity analyses. In this way, the most relevant components and thus the most important leverage points for interventions can be identified.

2 / 2. Introduction

The global agricultural and food system is facing immense challenges. It has to provide a growing population with nutritious and secure food, whilst facing the impacts of climate change (Willett et al. 2019; FAO 2018). However, the current forms of agriculture also directly exert pressure on many biophysical earth systems and contribute significantly to crossing planetary boundaries in the areas of climate change, biodiversity loss, soil erosion, water quality, and nutrient cycles (Campbell et al. 2017; FAO 2019; Steffen et al. 2015). Consequently, strategies are required to transform the agricultural and food system in order to balance their impacts on nutrition, livelihoods, and the environment (OECD 2021). Here, assessments based on scenarios and models can contribute significantly to the design of interventions and related decision support processes, as they can effectively address the relationships between food provision and ecosystem functioning (El Benni et al. 2023). Scenarios can illustrate drivers of change and possible interventions, and models in turn allow an assessment of their consequences and related trade-offs and synergies (IPBES 2016b).

On a spatial scale, landscapes provide a highly relevant level for developing and applying these scenarios and models (Denier et al. 2015; Pörtner et al. 2023). When addressing agriculture at a landscape level, the notion "agricultural landscapes" is often used. These are spatially limited areas, shaped by natural landscape features, where most land use and land management is related to agriculture (Mirschel et al. 2020; Nitschelm et al. 2016). Agricultural landscapes are multifunctional because, in addition to providing food, they also offer functions such as carbon sequestration, nutrient cycling or water supply (Fry 2001; O'Farrell und Anderson 2010). Contrary to focusing on the field or farm level, assessments at the landscape level provide an overview of the relevant ecosystem dynamics and potential constraints that may result, such as ecosystem carrying capacities for nutrient inputs (Lasseur et al. 2018; Jeanneret et al. 2021a). At the same time, and opposed to the national and global level, a focus on landscapes enables the assessment of local dissimilarities, values, and challenges (Bennett et al. 2021; Kok et al. 2017).

Assessing the multiple functions provided by agricultural landscapes requires the availability and use of an appropriate set of modelling approaches. In this context of inherently heterogeneous landscapes, spatially explicit models are valuable tools as they can account for spatial differences in abiotic, biotic and management driving factors. For example, water quantity and quality assessments can be conducted more appropriately by considering the different slopes and different spatial locations of land use and management activities within the catchment. Spatially explicit models can provide this capability through simulating processes at a finer resolution, such as the nutrient runoff from the individual fields in the catchment and aggregating the individual results at the landscape level.

The currently available modelling approaches for agricultural landscape assessments, however, seem to lack certain central aspects. There is, for example, a lack of integrated assessments that combine agronomic with other functions (Hossard and Chopin, 2019; Seppelt et al., 2020; TEEB, 2018). Similarly, provisioning, regulating, and cultural ecosystem services (ESS) are rarely considered simultaneously, thus disregarding the multifunctionality of agricultural landscapes (Zabala et al. 2020; Seppelt et al. 2011). Furthermore, earlier studies have highlighted the failure to consider that local processes can also affect other, distant regions, and have thus called for the consideration and quantification of trade-offs across different scales (Lautenbach et al. 2019; Seppelt et al. 2011).

Various reviews have approached the topic of assessing agricultural landscapes and landscape multifunctionality (Hölting et al. 2019a; Hossard and Chopin 2019; Huang et al. 2015; Eichler Inwood et al. 2018; Loiseau et al. 2012; Englund et al. 2017; Medeiros et al. 2021). Nonetheless, there is no systematic overview of which and how landscape functions are commonly accounted for in the context of agricultural landscapes and how the linkages to the wider food system are assessed. Furthermore, there is no comprehensive assessment of whether the gaps in existing approaches are key barriers to the comprehensive analysis of multifunctionality at

the landscape level, and how these approaches might potentially be improved. We therefore aim to answer the following three research questions: [RQ1] Which landscape functions are commonly analysed? [RQ2] Which spatially explicit model-based approaches are used to assess these agricultural landscape functions? [RQ3] To what extent are the linkages between agricultural components within the landscape and between the agricultural landscape and the wider food system components assessed by these modelling approaches? To achieve this, we develop a framework, that illustrates the key elements of agricultural landscape assessments, the interactions between the components of agricultural production and ecosystem services, and their integration into the wider food system. Using this framework, we analyse the model-based approaches. From the answers to the research questions, we then derive recommendations and strategies for improving model-based agricultural landscape assessments, taking into account the different objectives pursued by such assessments. These range from the scientific investigation of certain specific ecosystem dynamics to the provision of inputs for improved land management and the design of policy instruments, e.g. in the context of locally adapted policies. This allows us to contribute to closing critical knowledge gaps and identify important pathways for future research. In view of the required transformations in agriculture and food system, we ultimately contribute to ensuring that landscape multifunctionality is assessed appropriately when analysing agricultural landscapes and the relevant ecosystem dynamics.

2 / 3. Material and methods

2 / 3.1. Literature search

To identify spatially explicit model-based approaches that analyse landscape functions in agricultural landscapes, we developed four selection criteria and related search terms for the Web of Science (WoS) search in publications published until the 31st of October 2021: (1) spatially explicit models were presented, (2) the spatial unit of analysis was at least the landscape level, (3) agricultural production was one of the landscape functions assessed and (4) at least one additional ecosystem service or environmental impact was evaluated. We validated the comprehensiveness of the WoS search terms (Table 2/1) with a test-list of articles of known relevance², as recommended by Haddaway et al. (2015) and Livoreil et al. (2017). Specifically, we translated the second criterion into a set of synonyms of *landscape** in the sense of a delimited geographical area. Note that the term *ecosystem** as a spatial boundary is omitted here since it is considered through criterion four. To avoid limiting ourselves to the ecosystem service literature, we additionally searched for publications measuring environmental impacts in general (*envir** AND *impact** as well as potential synonyms) as part of the fourth

² Groot et al. 2007; Nelson et al. 2009; Schönhart et al. 2011; Jackson et al. 2013; Kennedy et al. 2016; Nitschelm et al. 2016; Pennington et al. 2017; Verhagen et al. 2018; Fernandez-Mena et al. 2020.

criterion. Finally, we would like to acknowledge a selection bias, as we only considered peer-reviewed publications written in English.

Table 2/1: Selection criteria and related WoS search terms. TS: Search for topic terms in the following fields: title, abstract, author, keywords, keywords plus. AND statements are used to link the four criteria.

Criteria		WoS search terms
[1]	A model, framework or approach is presented, and the presented approach must be spatially explicit.	TS = (approach* OR model* OR framework* OR method* OR tool*) AND TS = (spatial* OR GIS*)
[2]	The spatial unit of analysis is at least a landscape (beyond the field and individual farm level).	TS = (landscape* OR territor* OR watershed* OR catchment* OR regional-scale OR local-scale)
[3]	Agricultural production/Food provision is covered as one landscape function by including agricultural outputs in one of the metrics used.	TS = (agri* OR agro* OR food-pro* OR commodity-prod*)
[4]	At least one environmental impact or ESS is assessed.	TS = (envir* OR ecosystem*) AND TS = (impact* OR objective* OR indicat* OR assess* OR performance* OR benefit* OR service* OR function* OR evaluat*)
		AND LA=(English) AND DT=(Article OR Review)) Timespan: 2001-10-31 to 2021-10-31

The WoS search resulted in 4'593 identified publications (Figure 2/1). The abstract review resulted in the exclusion of 4'210 articles that did not meet the four criteria listed above, leaving 383 articles for a full-text review, of which a further 145 publications were excluded during the full-text screening for the same reason. The results presented in Section 2/4. are consequently based on 238 articles. A full list of these publications and further details can be found in the online supplementary material (available at <https://iopscience.iop.org/article/10.1088/1748-9326/ad57d3/data>).

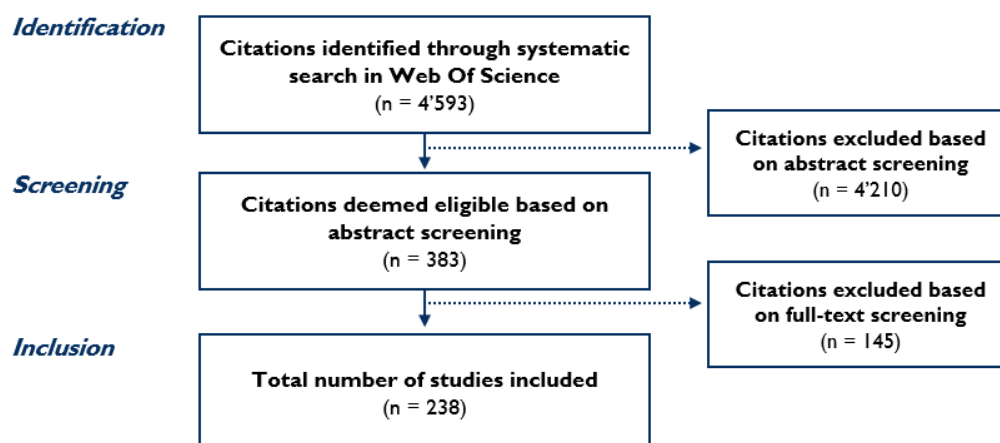


Figure 2/1: PRISMA flow diagram illustrating the stages of the literature selection (based on BMJ et al. (2021)).

2 / 3.2. Theoretical framework: key elements of agricultural landscape assessments

To facilitate the analysis of which and how landscape functions have been commonly assessed, and the extent to which linkages between the agricultural landscape and other components of the food system have been accounted for, we have defined key elements of agricultural landscape assessments (Figure 2/2). These key elements represent the components of agricultural production at the landscape level and their integration into the wider food system. They cover the agricultural system as part of the ecosystem and landscape, the ecosystem services and pressures it generates, extended by the linkages to the food system, and the driving factors that affect all components. Within this framework, we build on existing work, such as from DeClerck et al. (2016), Power (2010) and Zhang et al. (2007), as well as on established concepts, like the ecosystem services framework (Haines-Young and Potschin 2018), and further adapt it to the specific circumstances of agricultural landscapes, as described below.

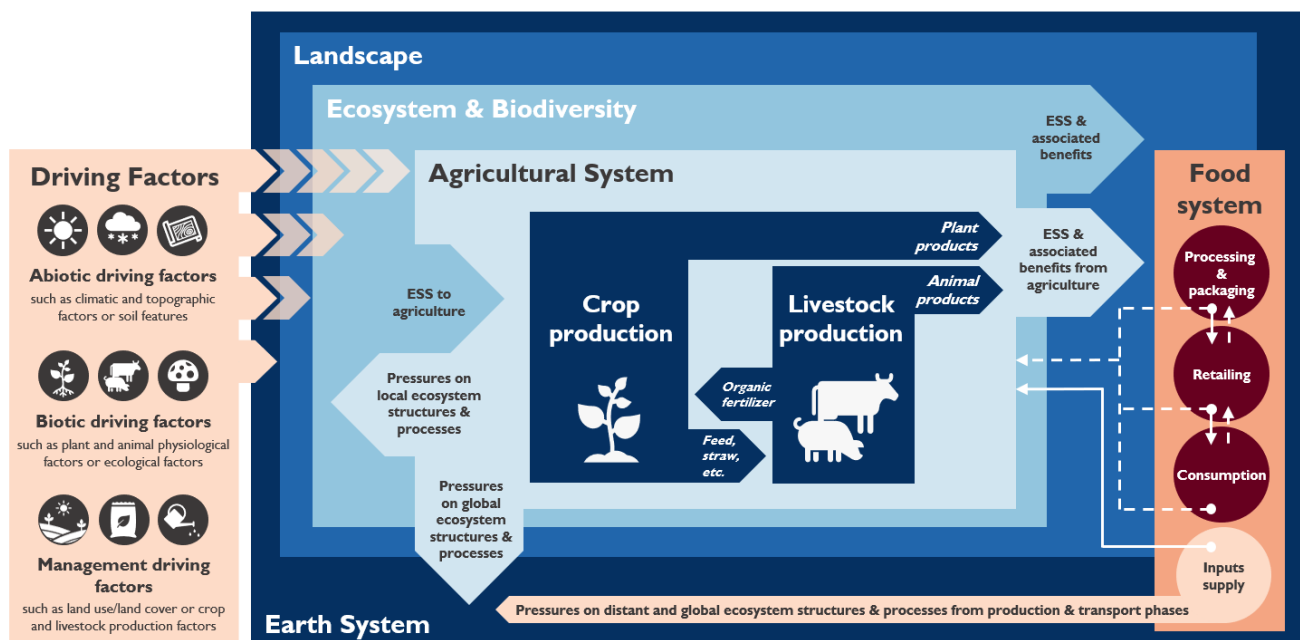


Figure 2/2: Key elements of agricultural landscape assessments. Ecosystem services is abbreviated as ESS.

Ecosystem services: Agricultural landscapes are multifunctional (Fry 2001; O'Farrell and Anderson 2010) by not only providing food, but also offering functions such as carbon sequestration, pest and disease control, soil formation, nutrient cycling, pollination, biodiversity support, water provision and recreational values, part of which are central for agricultural production (DeClerck et al. 2016; Zhang et al. 2007; Power 2010; Du Preez et al. 2020). Assessing agricultural landscapes requires understanding that in any given landscape, ecosystems and biodiversity provide the ecosystem structures and processes and thus landscape functions, creating potential for ecosystem services (Bicking et al. 2020). Here, the ESS framework offers a widely applied concept to capture these landscape functions (Hölting et al. 2020; Mastrangelo et al. 2014; Mandle et al. 2020). Understanding which landscape functions are or are not covered, and consequently which trade-offs and

synergies may be considered or overlooked, has important implications for the completeness of the assessments and how they can be further used.

Pressures on ecosystem structures and processes: In addition to providing beneficial services, agricultural activities also cause pressures on ecosystem structures and associated physical, chemical, and biological processes through emissions to water, air, and soil (Power 2010; Zhang et al. 2007). These pressures can have effects within the landscape or on distant parts of the Earth system and negatively affect their capacity to provide ESS (Zabala et al. 2020).

Driving factors: Scenarios and models for agricultural landscape assessment must acknowledge that ESS and pressures on ecosystem structures and processes depend on and can be influenced by abiotic, biotic, and management driving factors. Abiotic driving factors summarise climatic, soil, and topographic features. Biotic factors refer to plant physiological characteristics (such as nutrient uptake), physiological characteristics of livestock (like feed balances), or ecological information (such as habitat and species distributions). Furthermore, management factors include the multitude of anthropogenic decisions on land use and land management, animal husbandry, and socio-economic factors. The interplay of abiotic, biotic, and management factors can, for instance, be observed in the case of crop production. Here, various factors, including food demand and the policy context influences the crop choice, and then crop characteristics, temperature, CO₂ concentration, planting dates and density determine crop yields and the ESS provided. Yields might be limited through water and nutrient availability or through weeds, pests, or diseases (Jones et al. 2017c). The pressures of the agricultural production on water, air, and soil also depend on abiotic factors (like soil type, slope, and precipitation) or management factors (such as drainage, fertilisation, tillage techniques and timing, or the specific landscape configuration) (Foley et al. 2005; Hong et al. 2021). Similarly, the same three driving factors can influence all other ESS and their associated benefits (Lavorel et al. 2017). Consequently, if scenarios and models are unable to reflect variations in relevant abiotic, biotic, and management driving factors, i.e., if they are unable to account for different values of these factors in a spatially explicit way, the studies will lack central aspects of agricultural landscape assessments.

Interlinkages: While DeClerck et al. (2016) present the agricultural system as a black box in their ESS and resilience framework for agricultural landscapes, we explicitly include crop and livestock production and their interactions (cf. Figure 2/2). This enables us to account for nutrient flows between crop and livestock production in terms of feed, straw, and manure. It also allows a distinction to be made between the underlying causes of pressures on local and global ecosystems (Garrett et al. 2020; Homann-Kee Tui et al. 2020; Martin et al. 2016). To accurately represent possible trade-offs, it is crucial to consider that most agricultural landscapes are not self-sufficient, but rely on external material and energy. These include remotely produced feed, fertiliser, seed, and machinery inputs. While the use phase of those external inputs occurs within the landscape's boundaries,

the extraction, production, and transport phases often exert pressures on distant and global ecosystem structures and processes (Dijkman et al. 2018; Marston et al. 2015; Gumidyala et al. 2020). Similarly, this also applies to the outputs of agricultural production systems, which are often consumed outside the landscape boundaries, and to the associated emissions and other environmental impacts that may leak from the landscape boundaries. However, several flows from outside the landscape boundaries back into the local systems can also occur, e.g. in recycling by-products and waste from processing or sewage sludge as fertilisers to the fields (van Loon et al. 2023; Muscat et al. 2021; Du Preez et al. 2020). Lastly, changes in the production in one location might affect activities in other distant regions and cause geographical shifts of environmental burden in another location via tele-coupling, leading to unintentional off-site effects (Meyfroidt et al. 2013; Friis and Nielsen 2019). To account for the linkages of agricultural landscapes to wider food system components, it is therefore necessary to explicitly acknowledge those linkages in scenarios and models (Pascual et al. 2017; Schröter et al. 2018).

2 / 3.3. Data coding and analysis

We coded and analysed the publications with respect to the above-illustrated key elements of agricultural landscape assessments (cf. Figure 2/2 and Figure 2/3). The data were compiled and preliminarily analysed in a literature review matrix in MS Excel (Microsoft Corporation 2019), followed by further data curation, cleaning and visualisation in R and Rstudio (R Core Team 2022; RStudio Team 2020). A visualization of the structure of the literature review matrix, including the different drop-down menus and an illustrative example can be seen in Figure SM2/1.

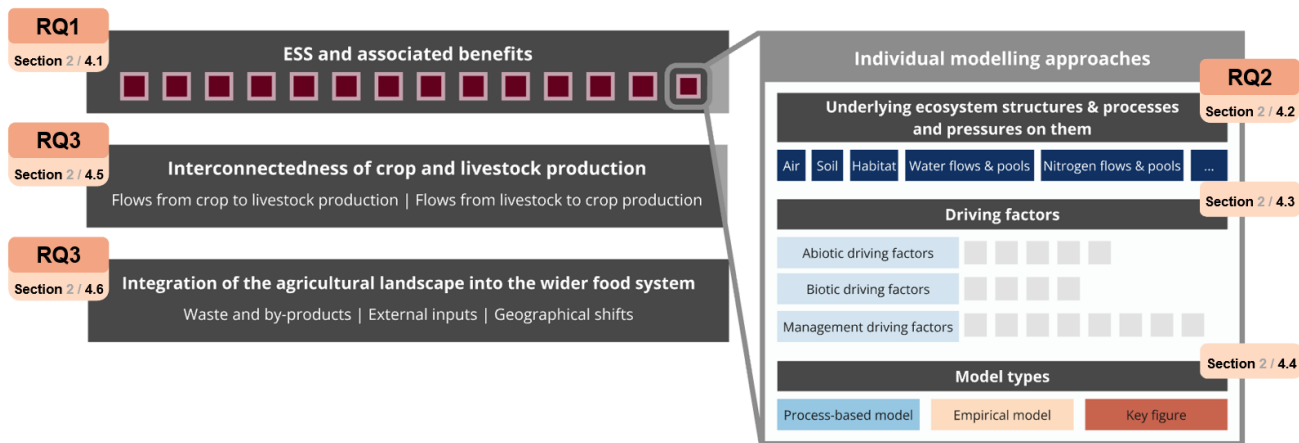


Figure 2/3: Review framework for coding and analysing each individual publication. The dark grey boxes correspond to the five main areas of analysis derived from the theoretical framework plus the information on the model type (cf. details on the modelling approaches given below). The small red squares on the left side represent the different individual ESS assessed in a given publication. Each individual ESS assessment is associated with a specific modelling approach. The elements displayed in the light grey framed box on the right side were analysed for each individual ESS modelling approach. The corresponding research questions (RQ) and results sections are shown accordingly. The colour codes are reflected in the corresponding figures in the results sections.

For each publication, we first identified and classified the ESS assessed and the landscape functions included (Figure 2/3: RQ 1). We predominantly follow the Common International Classification of Ecosystem Services (CICES), which structures ESS and provides a classification against which models for landscape-level assessments can be compared (Haines-Young and Potschin 2018). A list of these ESS and the corresponding CICES V5.1 classes can be found in Table SM2/1.

For each ESS assessed, we analysed the underlying individual spatially explicit modelling approach in more detail (Figure 2/3: RQ 2). It was possible for an ESS to be analysed more than once within a publication using one or more modelling approaches. For each individual modelling approach, we identified the underlying ecosystem structures and processes used to assess the respective ESS. In doing so, we followed the ecosystem integrity framework, which systematically divides the ecosystem structures into atmosphere/air, biotic diversity, habitat, soil, and water, and the ecosystem processes into water, energy, and matter flows and pools (Müller et al. 2000; Burkhard and Maes 2017; Haase et al. 2018). To account for the agricultural production context, we adjusted the framework and further subdivided the ecosystem process category 'matter flows and pools' into carbon, nitrogen, phosphorus, sediment, and biomass flows and pools.

For each modelling approach, we recorded the abiotic, biotic, and management driving factors used to parameterise the model. These included climatic and topographic factors, soil features, plant physiological factors, crop and animal production factors and information on landscape structure. The full list of driving factors can be seen in Figure SM2/1.

Furthermore, we categorised the modelling approaches into three basic model types of increasing complexity: key figures, empirical models, and process-based models. Under the term 'key figures', we summarised indices and metrics based on expert knowledge, coarse statistical associations, or simple functions of the underlying processes. Examples include the direct linking of ecosystem structures and processes to land cover types via look-up tables, or to landscape structures such as patch sizes, or the use of generic emission factors (Rotz et al. 2020; Lavorel et al. 2017). Data-driven statistical or empirical models also presuppose no in-depth knowledge of physical, biological, and chemical processes. Instead, they describe ecological structures and processes as statistical functions, e.g. by correlating inputs like soil or weather information to state variables (Rotz et al. 2020; Ascough et al. 2008). The observed statistical relationships are extrapolated based on historical data sets of the same or similar systems and system responses (Cuddington *et al* 2013). In this way, empirical models implicitly account for the processes inherent in the data generating process. These are then embedded in the estimated relationships. Mechanistic or process-based models, on the other hand, explicitly describe process interactions between system components based on physical, biological, and chemical relationships using mathematical formulations (Lavorel et al. 2017; Ascough et al. 2008). This requires a theoretical understanding of those ecological processes, and assumptions behind those models are based on ecological theory (Cuddington et al.

2013). Furthermore, we categorised hybrid models based on the module with the highest level of complexity and process understanding (Karydas et al. 2014). We would like to acknowledge that the division into the respective model types is somewhat subjective. Differences between models might be more of a continuum than a clear cut grouping, and all models are empirical at a certain level (Dourado-Neto et al. 1998). However, the categorisation helps to address the issue of simplicity versus complexity of modelling approaches, including data requirements.

We further investigated which ESS, ecosystem structures and processes, and abiotic, biotic, and management driving factors were likely to be covered together by conducting a contingency analysis. Here, we calculated the odds ratios by conditional maximum likelihood estimation and the corresponding confidence intervals and p-values using the Fisher's exact test (Fisher 1934; Jewell 2003). The ratio represents the odds of e.g. an ESS being assessed given that another ESS is also rated ($P(D|E)$) and compared this to the odds of the first ESS being assessed without an assessment of the second ESS ($P(D|\text{not } E)$). The Fisher's exact test is used to test statistical significance when analysing contingency tables with small sample sizes and calculates the probability of obtaining the observed data under the null hypothesis that the proportions are equal and that the probability of obtaining deviations is as observed.

We also analysed for each publication how interactions between crop and livestock production and between the agricultural landscape and the wider food system were integrated (Figure 2/3: RQ 3). We thus documented whether the publications considered specific nutrient flows from crop to livestock production and vice versa. Finally, we examined the extent to which the linkages between agricultural landscapes and the wider food system components were assessed. For this, we considered (1) how flows of by-products and waste have been included as nutrient sources as well as in which manner impacts of (2) external inputs and (3) geographical shifts of environmental burden via tele-coupling were considered.

2 / 4. Results

2 / 4.1. ESS coverage and numbers

We found that 87% of the publications analysed at least one ESS within the ESS section 'regulation & maintenance' (see Figure 2/4). Furthermore, when excluding the provisioning ESS 'terrestrial plants', which was inherently included in the search, 49% of the reviewed publications considered provisioning ESS, 41% assessed biodiversity, and 32% assessed cultural ESS. Some specific ESS were covered more frequently than others, which was evident for the regulating functions 'atmospheric composition/conditions', 'water conditions', and 'biodiversity' (see Figure 2/5-A³). These ESS were each considered by around half of the studies. In contrast, other ESS, such as 'pest and disease control', were rarely considered (4%). Through the selected search terms,

³ The ESS named in Figure 2/5-A are described shortly in Table SM2/1 and in more detail in Haines-Young and Potschin 2018.

the provision of terrestrial plants was inherently included as one landscape function. In contrast, livestock production (ESS group 'terrestrial animals for nutrition, materials or energy') was considered by only 25% of the publications. Studies also differed with respect to the number of ESS covered in each analysis. In addition to the provision of terrestrial plants, an average of 4.4 ESS were taken simultaneously into account, with individual studies considering up to 23 ESS (see Figure SM2/2).

We further quantified the odds ratios to investigate which ESS were likely to be covered together (Table 2/2). Values above one indicate a positive association between the respective ESS, and values below one imply a negative association. Thus, we found a significant negative association between the assessment of 'water conditions' and 'biodiversity' as well as with 'other cultural ESS'. For example, for every publication that assessed 'water conditions' and 'biodiversity', we found two publications⁴ that assessed only one or the other. Furthermore, we found a significant positive correlation between assessments of 'atmospheric composition and conditions' and most other ESS. At the same time, ESS addressed in less than 30% of the publications (see Figure 2/5-A) tended to be considered together as a cluster. This was the case for cultural ESS and some regulation and maintenance ESS such as 'regulation of baseline flows and extreme events', 'mediation of waste, toxics and other nuisances', and 'pest and disease control'.

⁴ The odds ratio of 0.47 for assessing 'water conditions' and 'biodiversity' translates to $\frac{1}{2.116}$.

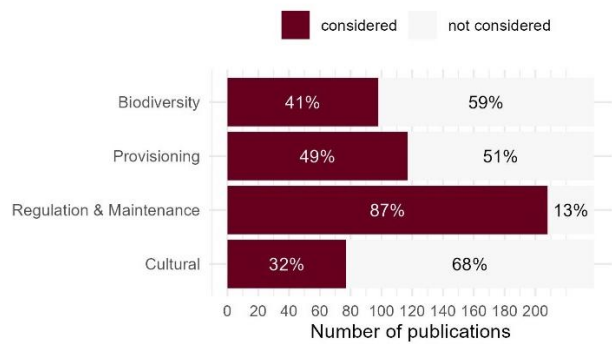


Figure 2/4: Shares of reviewed publications considering ESS sections and biodiversity (excluding the provisioning ESS 'terrestrial plants for nutrition, materials or energy').

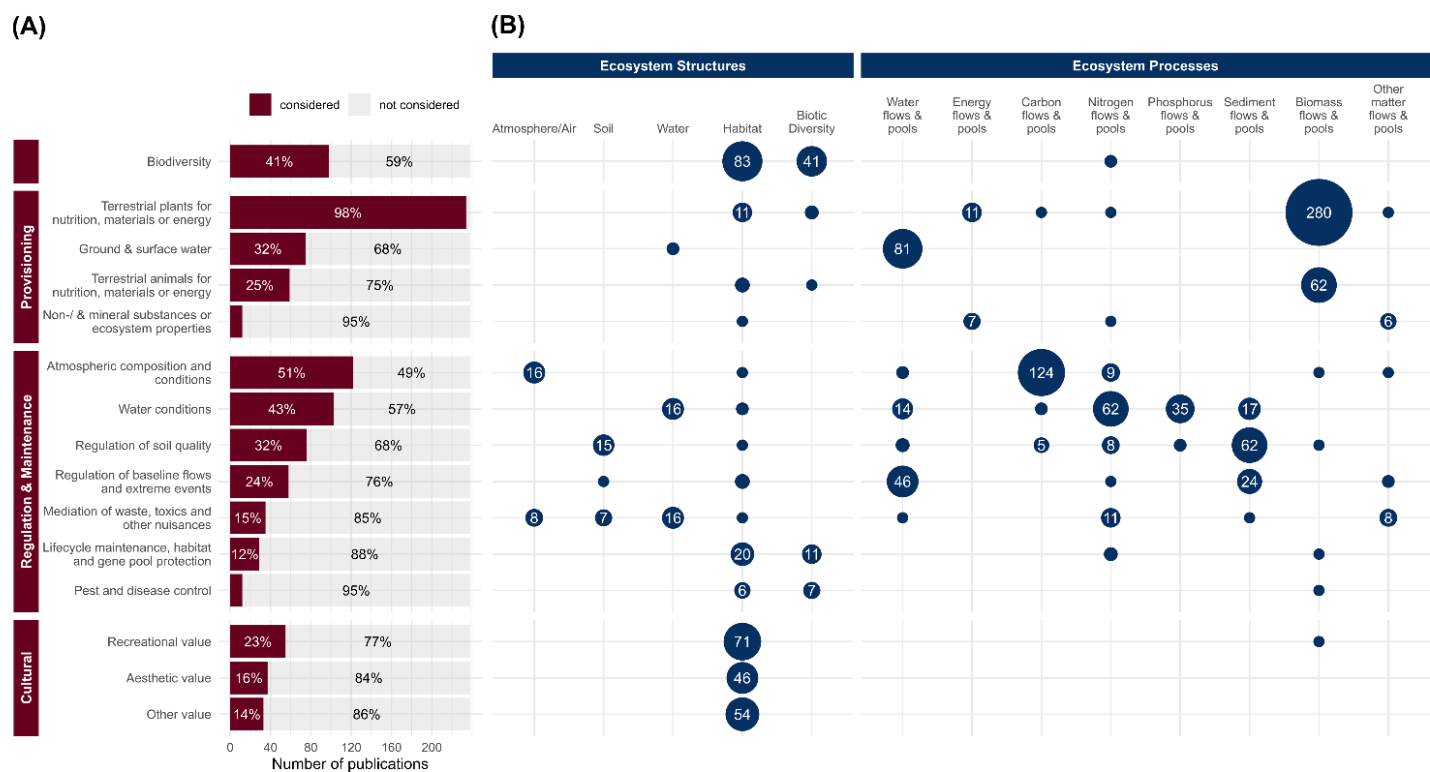


Figure 2/5: The bar chart (A) illustrates the shares of reviewed publications considering specific ESS and biodiversity. The scatterplot (B) displays the ecosystem structure and process variables computed per ESS. The size of and number in the bubbles relates to the number of individual modelling approaches. **Note:** It was possible for an ESS and/or ecosystem structure and process to be analysed more than once within a publication using one or more modelling approaches.

Table 2/2: Estimated odds ratios including significance level based on the Fisher's exact test. Values above (below) one indicate a positive (negative) association between the respective ESS. Significant values are highlighted in bold and coloured in blue (positive association) or red (negative association).

		Biodiversity	Provisioning			Regulation & Maintenance							Cultural	
			Reared animals	Ground & surface water	Non-/ & mineral substances or ecosystem properties	Atmospheric composition and conditions	Water conditions	Regulation of soil quality	Regulation of baseline flows and extreme events	Mediation of waste, toxics and other nuisances	Lifecycle maintenance, habitat and gene pool protection	Pest and disease control	Recreational value	Aesthetic value
Provisioning	Animals for nutrition, materials or energy	2.22 ***												
	Ground & surface water	0.86	1.16											
	Non-/ & mineral substances or ecosystem properties	1.02	4.65 *	2.27										
Regulation & Maintenance	Atmospheric composition and conditions	2.13 ***	4.23 ***	1.67 .	2.99									
	Water conditions	0.47 ***	1.37	0.76	1.89	0.77								
	Regulation of soil quality	0.77	1.52	1.43	0.7	1.88 *	1.18							
	Regulation of baseline flows and extreme events	1.61	1.9 .	1.96 *	4.76 *	2.64 ***	0.99	1.16						
	Mediation of waste, toxics and other nuisances	1.86 .	2.7 *	1.78	6.7 ***	2.72 *	0.98	1.13	1.78					
	Lifecycle maintenance, habitat and gene pool protection	1.62	1.18	1.38	3.98 .	1.65	1.07	1.14	2.94 *	3.84 ***				
	Pest and disease control	1.45	2.27	1.59	13.23 ***	1.35	1.33	3.17 .	3.33 .	9.74 ***	3.98 .			
Cultural	Recreational value	2.23 *	2.92 ***	1.47	11.58 ***	3.27 ***	0.93	0.94	8.3 ***	3.04 ***	7.52 ***	7.53 ***		
	Aesthetic value	2.75 ***	3.2 ***	1.05	4.29 *	2.58 *	1.29	1.56	3.3 ***	5.17 ***	2.89 *	6.21 ***	11.69 ***	
	Other value	2.9 ***	1.63	0.94	7.27 ***	1.8	0.44 *	1.26	4.91 ***	3.11 *	1.34	10.58 ***	10.27 ***	8.13 ***

Note: Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1.

2 / 4.2. Underlying ecosystem structures and processes

Although ESS are a relevant level for e.g. policy makers (Mandle et al. 2020), we found that the examined modelling approaches operated rather on the level of ecosystem structures and processes. Here, we found both '*many to one*' relationships, where different ecosystem structures and processes were used to predict a particular ESS, and '*one to many*' relationships, where single ecosystem structures and processes were calculated to predict a variety of different ESS (Figure 2/5-B). Table 2/3 illustrates which ecosystem structures and processes were more or less likely to be assessed together. There, the negative association identified in Table 2/2 between the assessment of the ESS 'water conditions', mainly quantified by nitrogen and phosphorus flows and pools (see Figure 2/5), and other ESS was reflected again: publications assessing these flows and pools were significantly less likely to consider other ecosystem structures and processes. At the same time, publications assessing nitrogen flows and pools were 6 times more likely to consider phosphorus than publications not assessing nitrogen flows and pools.

Table 2/3: Estimated odds ratios including significance level based on the Fisher's exact test. Values above (below) one indicate a positive (negative) association between the respective ecosystem structures and processes. Significant values are highlighted in bold and coloured in blue (red).

		Ecosystem Structures					Ecosystem Processes						
		Atmosphere/Air	Soil	Water	Habitat	Biotic Diversity	Water flows & pools	Energy flows & pools	Carbon flows & pools	Nitrogen flows & pools	Phosphorus flows & pools	Sediment flows & pools	Biomass flows & pools (Livestock)
Ecosystem Structures	Soil	5.78 ***											
	Water	14.82 ***	10.09 ***										
	Habitat	17.19 ***	1.73	2.97 ***									
	Biotic Diversity	4.88 ***	1.04	0.92	2.33 ***								
Ecosystem Processes	Water flows & pools	2.67 .	1.97	2.1 .	1.6 .	0.64							
	Energy flows & pools	8.56 ***	1.52	6.05 ***	2.36	1.12	2.67 .						
	Carbon flows & pools	1.11	1.9	1.12	2.11 ***	2.12 *	1.76 *	0.85					
	Nitrogen flows & pools	2.72 .	0.44	0.62	0.38 ***	0.61	0.62 .	2.08	0.86				
	Phosphorus flows & pools	0.79	1.36	0.78	0.34 ***	0.78	0.39 *	1.32	1.28	6.02 ***			
	Sediment flows & pools	1.7	0.81	1.15	1.82 *	0.75	1.91 *	0.99	2.25 ***	1.7 .	2.35 *		
	Biomass flows & pools (Livestock)	5.54 ***	1.51	3.05 ***	2.65 ***	2.73 ***	1.49	5.54 ***	2.98 ***	1.27	0.96	1.09	
	Other matter flows & pools	26.85 ***	5.37 *	4.54 *	13.36 ***	3.06 .	6.83 ***	7.75 ***	2.61	2.42	1.02	1.99	3.67 *

Note: Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1. Biomass flows and pools were divided into crop and livestock biomass to reflect the complexity of the agricultural system (cf. Figure 2/2).

2 / 4.3. Driving factors

The state and quality of the different ecosystem structures and processes, and consequently the provision of associated ESS, varies due to differences in abiotic, biotic, and management driving factors (cf. Figure 2/2). It is possible to include these factors explicitly in the analysis by parameterising models. For instance, the endogenous consideration of variations in fertiliser intensities can be used to estimate the impacts of management changes on ecosystem processes such as biomass or nitrogen pools and flows.

When we clustered all identified driving factors into abiotic, biotic, and management factors, we found that 48% of the individual ecosystem structure or process computations included at least one abiotic, 29% at least one biotic, and 94% at least one management factor (see Table 2/4-C). The most common driving factors were land use/land cover information (considered by 79% of the modelling approaches), soil features (37%), climatic factors (31%), crop production factors (35%), and topographic factors (30%). However, the data showed great differences between the individual ecosystem structures and processes in terms of which specific factors were included in each modelling approach (see Table 2/4-D). Crop production factors such as fertilisation, tillage, or irrigation regimes were mainly included in the quantification of nitrogen and phosphorus flows and pools (74% and 76%, respectively), but only in 52% of the quantifications of plant biomass, despite the strong biological connection. The same applies to soil features, climatic factors, and topographic factors, which were predominantly incorporated in the modelling approaches for nitrogen, phosphorus, and sediment flows and pools, but to a much lesser extent in other ecosystem structure and process calculations. Furthermore, no strong patterns emerged when investigating which driving factors were included simultaneously in the modelling approaches. For most factor combinations, we found neither positive nor negative relationships (see Table SM2/2).

Table 2/4: Number of publications **(A)** and individual modelling approaches **(B)** considering the respective ecosystem structures and processes. Percentage of modelling approaches integrating **(C)** abiotic, biotic, and management driving factors and **(D)** the specific driving factors in their ecosystem structure and process modelling approaches. The total percentage of modelling approaches, considering the various driving factors at least once, is shown in the last column **(E)**.

						Ecosystem Structures					Ecosystem Processes									(E)
						Atmospher e /Air	Soil	Water	Habitat	Biotic Diversity	Water flows & pools	Energy flows & pools	Carbon flows & pools	Nitrogen flows & pools	Phosphoru s flows & pools	Sediment flows & pools	Biomass flows & pools (Plants)	Biomass flows & pools (Livestock)	Other matter flows & pools	Total
(A)	Number of publications considering respective ecosystem structure/process					16	21	32	118	55	111	16	113	80	36	90	234	61	13	202
(B)	Number of individual modelling approaches considering respective ecosystem					24	23	34	293	62	147	18	132	98	37	104	291	69	18	1350
(C)	Abiotic driving factors					17%	70%	59%	14%	21%	75%	28%	68%	78%	86%	85%	51%	10%	6%	48%
	Biotic driving factors					17%	13%	24%	17%	63%	29%	11%	45%	33%	32%	13%	37%	25%	11%	29%
	Management driving factors					100%	87%	100%	99%	79%	85%	100%	86%	96%	97%	96%	96%	96%	100%	94%
(D)	Abiotic driving factors	Climatic factors	17%	22%	24%	2%	13%	56%	11%	39%	59%	70%	66%	33%	9%	0%	31%			
		Soil features	4%	61%	44%	3%	6%	59%	22%	54%	66%	78%	79%	42%	3%	0%	37%			
		Topographic factors	0%	39%	47%	11%	15%	43%	28%	23%	48%	73%	75%	27%	6%	6%	30%			
		Risk factors	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	4%			
		Other abiotic factors	0%	0%	0%	0%	2%	0%	0%	0%	3%	1%	0%	0%	0%	0%	0%			
	Biotic driving factors	Plant physiological ecology	8%	4%	21%	3%	13%	28%	11%	43%	29%	30%	13%	35%	9%	0%	21%			
		Animal physiological ecology	8%	9%	6%	1%	0%	1%	0%	3%	4%	5%	0%	1%	17%	11%	3%			
		Ecological factors	0%	4%	0%	16%	56%	0%	0%	1%	1%	3%	1%	3%	0%	6%	7%			
		Other biotic factors	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%			
	Management driving factors	Land use/land cover	100%	87%	85%	79%	71%	76%	78%	74%	70%	86%	87%	84%	61%	94%	79%			
		Crop production factors	13%	39%	50%	6%	13%	31%	50%	35%	74%	76%	53%	52%	13%	22%	35%			
		Animal production factors	8%	13%	18%	2%	2%	1%	0%	8%	13%	8%	0%	2%	55%	6%	7%			
		Landscape structure	0%	9%	15%	30%	19%	4%	6%	4%	3%	3%	9%	9%	4%	0%	12%			
		Built environment/infrastructure	21%	17%	15%	17%	8%	10%	22%	4%	5%	8%	3%	4%	6%	22%	9%			
		Risk factors	4%	17%	21%	2%	2%	6%	6%	3%	5%	5%	3%	2%	0%	0%	4%			
		Socio-economic factors	33%	22%	24%	26%	10%	16%	22%	8%	7%	5%	10%	36%	48%	11%	22%			
		Other management factors	0%	0%	3%	1%	2%	1%	6%	4%	1%	0%	1%	0%	0%	0%	1%			

2 / 4.4. Model types

The utilised model type can explain part of the variation in the number of considered driving factors. Overall, we found that all three model types (key figures, empirical models, and process-based models) were used to compute most ecosystem structures and processes (see Figure 2/7-A). However, the share depended on the specific ecosystem structure and process. While 'Biomass flows and pools (Plants)' were approximately evenly approached by key figures, empirical models, and process-based models, 'Phosphorous flows and pools' were mainly assessed through process-based models.

The data showed further strong differences between the model types regarding which driving factors were specifically incorporated (Figure 2/6-B). Abiotic factors were mainly considered by process-based models (95%), followed by empirical models (66%), but were only incorporated by 20% of all key figures. In contrast, management factors were widely used and integrated by more than 90% of all approaches in the three model categories. This picture is also evident at the level of ecosystem structures and processes (Figure 2/7-C). Generally, process-based models were more likely to include these three categories of driving factors than empirical models and key factors. However, the specific parameterisation of the models varied between the ecosystem structures and processes.

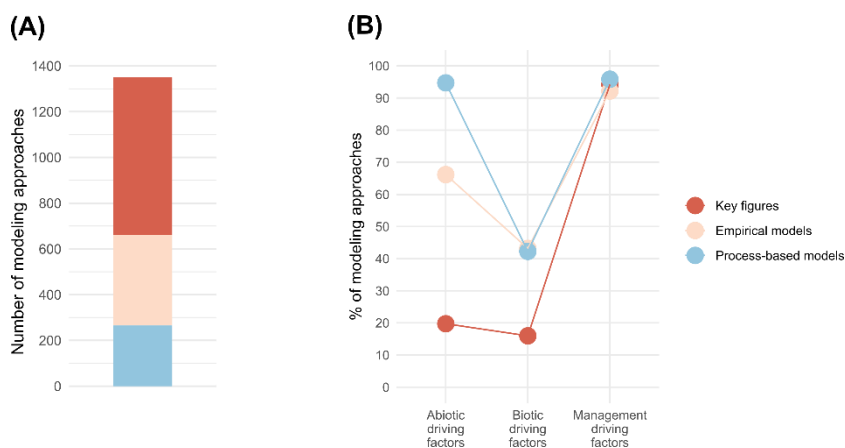


Figure 2/6: (A) Number of modelling approaches per model type. **(B)** Percentage of modelling approaches considering at least one abiotic, biotic, or management driving factor per model type.

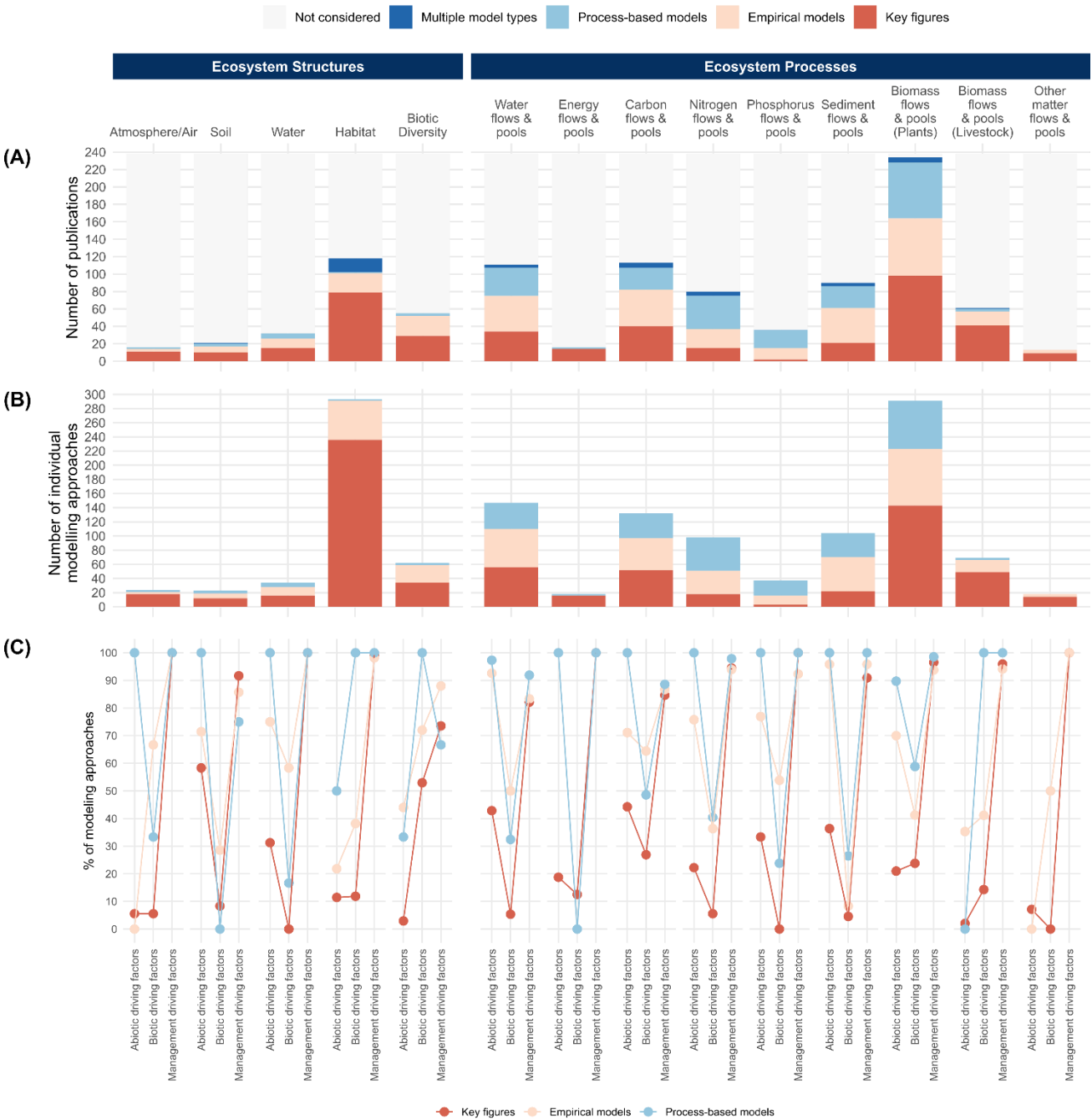


Figure 2/7: (A) Model types per ecosystem structure/process. Publications in which individual ecosystem structures/processes were assessed several times with different model types were categorised as 'multiple model types'. **(B)** The number of individual modelling approaches per model type and ecosystem structure/process. **(C)** Percentage of modelling approaches considering at least one abiotic, biotic, or management driving factor per model type and per ecosystem structure/process.

2 / 4.5. The interconnectedness of crop and livestock production at the landscape level

Our analysis showed that about 25% of the publications considered livestock production (Figure 2/5-A). Of these, only 32% (19 out of 59) incorporated flows from crop to livestock production. These flows were mainly included in the form of feed, either via produced fodder (e.g. Leip et al. (2008), Münier et al. (2004), Lusiana et al. (2012), or Vries et al. (2015)) or via the available area for grazing (e.g. Gassman et al. (2009), Verhagen et al. (2018), Jiang et al. (2013)). However, in addition to feed, flows in the form of crop residues and by-products for

bedding or feeding were not explicitly considered. Flows from livestock to crop production were even less frequently considered than flows from crop to livestock production. Only 22% (13 out of 59) of the publications accounting for livestock production incorporated such flows in the form of manure (e.g. Gassman et al. (2009), Kros et al. (2015), Vries et al. (2015), Schönhart et al. (2011)).

2 / 4.6. The integration of the agricultural landscape into the wider food system

Despite the widespread use of external inputs in agricultural production, only nine reviewed publications considered some of the corresponding external impacts (Egbenewe-Mondzozo et al.; Ding et al. 2021; Ding et al. 2020 (2011), Chopin et al. (2017), Nitschelm et al. (2016), Sinistore et al. (2015), Mishra et al. (2019), Jones et al. (2017a), Vries et al. (2015)). Egbenewe-Mondzozo et al. (2011) assessed the ESS 'atmospheric composition and condition' by explicitly considering the impacts of the production, distribution and use of pesticides, fertilisers, seeds and water. Similarly, Nitschelm et al. (2016) and Sinistore et al. (2015) accounted for the human activities required to produce the inputs used within the boundaries of the landscape by incorporating impact values taken from life cycle assessments. Furthermore, only one of the 238 reviewed publications considered flows of by-products and waste as nutrient sources (Fernandez-Mena et al. 2020). Impacts on distant and global ecosystem structures and processes occur not only due to external inputs; they might also be caused by changed production patterns and thus trade-flows, which can result in geographical shifts in environmental impacts through tele-coupling (Meyfroidt et al. 2013; Friis and Nielsen 2019). Despite their high relevance, these off-site effects and spatial cross-level interactions beyond the respective landscape were rarely considered. Chen et al. (2019) analysed these tele-connections, and thus how urban land use in one region can lead to ESS degradation in another. Jiang et al. (2021) examined the balance between ESS supply and demand as well as spillover effects. In addition to the ESS supply, eight publications included the demand side and the associated spatial mismatches (Fu et al. 2020; Zhang et al. 2017; Sun et al. 2018; Lorilla et al. 2019; He et al. 2021; Meng et al. 2021; Zhang et al. 2020; Del Río-Mena et al. 2020).

2 / 5. Discussion

2 / 5.1. Blind spots in the coverage of key elements of agricultural landscape assessments

Incomplete coverage of multifunctionality: Our review shows strong biases regarding which landscape functions are commonly analysed and which spatially explicit model-based approaches are used to do so. We found that whilst certain ESS are widely included, others are largely missing, confirming similar conclusions by Seppelt et al. (2011), Lautenbach et al. (2019), Hossard and Chopin (2019), Englund et al. (2017) or Medeiros et al. (2021). Most importantly, we identified a lack of consideration of 'pest and disease control', which is an essential service for agriculture. This aligns with other studies like Hossard and Chopin (2019). They found

'water quality', 'water quantity', and 'biodiversity' among the main topics in studies that modelled impacts of agricultural changes at the landscape level, while topics like pesticides or diversification were not included. Englund et al. (2017) also found 'pest and disease control' and 'ground and surface water' to be among the least commonly assessed ESS. Furthermore, while about half of the publications assessed biodiversity and water conditions, these assessments appear to be mutually exclusive. Again, this lack of combined assessment is particularly relevant for agriculturally dominated landscapes, as farming activities have an immense impact on both. There are several reasons why there may be an uneven distribution of assessed ESS. These include the perceived importance of individual ESS within national research and policy programs, researchers with different focuses, and financial, logistical, and methodological challenges in measuring some ESS, as in the case of models for natural pest control (Alexandridis et al. 2021; Englund et al. 2017; Lautenbach et al. 2019).

Our results on the overall coverage of ESS imply that existing models have a bias towards certain ESS and that using these models therefore entails the risk of not adequately considering multifunctionality. Hence, trade-offs and synergies between landscape functions that might be relevant for a specific geographical context are most likely overlooked. Alternative agricultural production systems that strongly rely on natural plant protection measures, such as organic agriculture, can only be properly assessed and compared with other systems, if these services are included.

Insufficient consideration of driving factors: Although the choice of the most appropriate modelling approach depends on the research question, the purpose of the study, and the available competences and data, our results show that key elements of agricultural landscape assessments were not fully covered by the modelling approaches used. This was particularly evident when considering the different abiotic, biotic, and management driving factors included in the models. Our results also indicate strong differences between individual approaches in terms of model types and their parameterisation. Here, a high level of simplification was observed in many modelling approaches which is in line with earlier studies (Seppelt et al. 2011). However, these key figure-approaches cannot adequately predict non-linear feedbacks in ecosystem and social processes (Lautenbach et al. 2019; Eigenbrod et al. 2010). For instance, our results show that various crop biomass assessments did not account for relevant factors and based their calculations exclusively on land use/land cover maps. However, the provision of plant biomass depends on an interplay of abiotic, biotic, and management factors, where for instance, crop characteristics, temperature, planting dates, as well as water and nutrient availability define crop yields (Jones et al. 2017c; White et al. 2002; Schröter et al. 2021). Similarly, using the correct fertiliser source at the correct rate, time, and place are key in sustainable nutrient management (Fixen 2020), but were often not considered when quantifying nitrogen and phosphorous flows and pools in agricultural landscapes. The same situation prevails for the quantification of biodiversity in agricultural landscapes. Recent literature (Felipe-Lucia et al. 2020; Le Provost et al.; Seppelt et al. 2020; Dullinger et al. 2021;

Estrada-Carmona et al. 2022) highlights the importance of how available land is used (an aspect often covered in the reviewed publications), secondly, how intensively agricultural land is used (an aspect hardly covered in the reviewed publications), and, thirdly, how the landscape is structured (an aspect only partly covered in the reviewed publications). However, if scenarios and models do not reflect variations in abiotic, biotic, and management factors relevant to the ecosystem structures and processes, it is likely that the studies will misidentify the levers for change and fail to show the full potential of action.

Missing crop-livestock integration: In agricultural landscapes that encompass both crop and livestock production, these two parts of the agricultural system are often closely linked (cf. Figure 2/2). It is therefore relevant to account for the nutrient flows, their related dynamics and the interdependencies between them. Our analysis indicates that the interconnectedness of crop and livestock production is rarely considered in agricultural landscape assessments. This applies both to product and nutrient flows from crop to livestock production, such as feed or by-products for bedding, as well as to flows from livestock to crop production, such as manure or slurry. Although integrated crop-livestock systems are declining in most agricultural areas (Garrett et al. 2020), this is still a highly relevant aspect in agricultural landscape assessments, as the crop-livestock integration at the farm or landscape level has the potential to enhance ESS in sustainable food systems (Garrett et al. 2020; Homann-Kee Tui et al. 2020; Martin et al. 2016). An explicit analysis of these product and nutrient flows would therefore allow a differentiation of the underlying causes of pressures on local and global ecosystems.

Missing food-system level linkages: Our results show that linkages between agricultural landscapes and the wider food system components are not considered in the reviewed literature. This absence concerns various aspects of such food-system level components. First, our results show that return flows from the food system in the form of by-products or waste from processing, retailing, and consuming food commodities are rarely considered. Since these flows can be rich in nutrients (especially for ruminants), they should be considered as a return to the agricultural landscapes in the form of organic fertiliser or feed. Their explicit incorporation into agricultural landscape assessments would help identify their potential role in a more circular food system (Basso et al. 2021; Muscat et al. 2021; van Loon et al. 2023). Our analysis also shows that the distant pressures from the production of external inputs are not well considered. Agricultural activities within a defined landscape often rely on external material and energy inputs, such as remotely produced feed, fertiliser, seed, and machinery inputs. While the use phase of those external inputs occurs within the landscape's boundaries, the extraction, production, or transport phases exert pressures on distant and global ecosystem structures and processes. As Ding et al. (2021) highlighted, these off-territorial impacts might be substantial and therefore need to be factored into agricultural landscape assessments, such as part of a trade-off analysis comparing local and global impacts. Neglecting the environmental burden of these externally produced inputs can otherwise lead

to the unjustified favouring of scenarios based on external inputs over scenarios with agricultural activities depending on locally produced inputs.

Finally, the results indicate that off-site effects were neglected in most of the reviewed agricultural landscape assessments. Consider a hypothetical case, where the demand for agricultural products remains constant and landscape-level improvements are achieved by reducing the intensity of agricultural land use. This would lead to more imports and thus to a geographical shift in production and the associated environmental impacts. Therefore, an exclusive focus on landscape solutions entails the risk of overlooking such off-site effects and off-stage ecosystem service burdens. These findings align with earlier studies (Seppelt et al. 2011; Pascual et al. 2017; Breure et al. 2024). Agricultural landscape assessments therefore need to better account for these transfers of environmental impacts. This can, for example, be achieved by integrating other analytical approaches, such as life cycle analysis and risk-based approaches, which are more effective in dealing with uncertainty (Pascual et al. 2017).

2 / 5.2. Recommendations and strategies for future model-based agricultural landscape assessments

Overall, our results show blind spots in the coverage of the key elements of agricultural landscape assessments. They range from incomplete coverage of landscape multifunctionality to insufficient consideration of abiotic, biotic, and management driving factors in model parameterisation to neglecting crop-livestock interlinkages as well as connections to the broader food system. Agricultural landscape assessments are pursued for a broad range of goals. Examples are specific detailed scientific investigation of certain ecosystem dynamics, assessments to analyse the consequences of different land management options, or also inputs to landscape-level decision-making processes and policy design. The blind spots identified can ultimately affect how well the assessments can contribute to these goals.

Based on our findings, we deduce the following suggestions for conducting future agricultural landscape assessments to better ensure that they can contribute to achieving the goals pursued. We recommend starting with a comprehensive system understanding, which can subsequently be simplified in the parts not relevant to the context focused on and the goals pursued. The framework presented in Figure 2/2 can be used as a starting point because it summarises key elements of agricultural landscape assessments. Consequently, relevant ESS and the most appropriate ecosystem structures and processes to quantify those, need to be identified. Concepts and frameworks such as CICES (Haines-Young and Potschin 2018), the ecosystem integrity framework (Müller 2005; Haase et al. 2018) or similar are widely applied and studied (Czúcz et al. 2018; Mafongoya and Sileshi 2020; Verhagen et al. 2015; TEEB 2018). They offer a holistic basis to structure decision-making and ensure that no relevant aspects are overlooked. Constant transparency and a thorough justification of the selection process

should be ensured. Criteria such as credibility, saliency, legitimacy, and feasibility can guide the development and selection of appropriate indicators (Cash et al. 2003; van Oudenhoven et al. 2018).

When assessing the state and quality of the selected ecosystem structures and processes, considering the following three aspects might further improve the evaluations: [1] *Consideration of all relevant components depending on the respective ES structure or process.* For instance, when quantifying carbon flows and pools, it is highly relevant for the conclusions to consider the share of greenhouse gas emissions created by producing external inputs such as fertilisers or pesticides. [2] *Selection of relevant driving factors to include in the modelling approach.* Start with the biophysical processes and transparently justify why certain factors are included in the model parameterisation and what assumptions are made to exclude factors. In the case of crop yields, fertiliser use intensity and land suitability explain a large part of the variations in yields (Schröter et al. 2021). Therefore, their inclusion or omission might strongly influence the results and consequently any suggestions for improvements derived from them. This is where the advantage of interdisciplinary modelling groups, which bring in-depth knowledge of the respective processes, becomes apparent. [3] *Decision for the most appropriate modelling approaches.* Including modelling approaches outside the disciplinary realm might, for instance, help to account for the connections to the broader food system. To recognize the environmental burden of using external inputs, life cycle assessment approaches can be used. They address energy and material flows and the environmental impacts of these for a single production or area unit (ISO 2006; Poore and Nemecek 2018b). Similarly, off-site effects could be made visible through global food system models. Next to the production, these also consider the consumption side by integrating dietary scenarios (Erb et al. 2016; Muller et al. 2017; Popp et al. 2010). In general, it should be noted that ESS quantifications are affected by spatial and system complexity with associated data and modelling issues (Antle and Stoorvogel 2006), and that strategies are needed to account for and deal with different types of uncertainty (Geary et al. 2020). To further improve the assessment of agricultural landscapes, more research is needed, such as a comparison of indicators at different levels of complexity, similar to Roesch et al. (2023) who evaluated simple, medium or detailed indicators for the assessment of different environmental impacts at farm level.

Overall, therefore, the general recommendation for improving the modelling of agricultural landscapes is to include more aspects of the key elements of agricultural landscape assessments, and to include those in more detail than is currently the case. However, this might pose challenges about data availability and modelling requirements. Therefore, we need strategies to avoid such costly requirements while at the same time assuring coverage of all relevant aspects of the framework. Sensitivity analyses, such as Monte-Carlo, represent one promising strategy in this development (e.g. Schouten et al. (2014)), paired with a clear statement of what the modelling approach can and cannot do (Geary et al. 2020). A clear specification of the goals allows a selection of which ecosystem structures and processes need to be modelled in detail and which do not. As outlined above,

such a 'maximal' model can then be analysed through various sensitivity analyses to identify the abiotic, biotic, and management driving factors that are most important in terms of their influence on the outcome indicators of interest and their sensitivity to parameter choices⁵. Driving factors that are not influential can be modelled simplistically without large requirements for better data. Influential factors sensitive to parameter choices should, however, be focused on and modelled with a higher level of detail. For these factors, investments in additional data collection or model development are most warranted. In particular, the Monte-Carlo simulation approach to sensitivity analysis allows interactions and nonlinearities between different parameters and variables to be captured (Schouten et al. 2014). Although these simulations can be demanding in terms of computational requirements, computing power is becoming increasingly cheap and accessible, and methodological advances in Monte-Carlo simulations can also help to reduce these requirements (e.g. Zhang (2021)), while improvements in data quantity and quality are often only possible at high cost. Furthermore, process-based models can aid in mitigating the demand for computing power by excluding parameter combinations that are biophysically impossible from the onset. Sensitivity analysis can also be valuable when, for example, land use/land cover data sets are based on different extrapolation methods (Sieber et al. 2021). Also, combining results from different models, thus creating a model ensemble, can help reduce uncertainties (Hooftman et al. 2022; Willcock et al. 2023). Finally, attention should be paid to potential 'unknown unknowns' at the first stage, i.e., when deciding what the model needs to achieve the stated goals. Naturally, this cannot be addressed by sensitivity analysis, but, e.g. by a broad review of the suggested modelling approach by a diverse expert panel to assure coverage of the broadest possible knowledge basis.

2 / 6. Conclusion

Our review shows that there is a rich body of knowledge and tools available for spatially explicit model-based agricultural landscape assessments, but that there are important gaps that may hinder them to effectively achieve the goals pursued. Most notably, the incomplete coverage of landscape multifunctionality, the insufficient consideration of abiotic, biotic, and management driving factors while parameterising the modelling approaches, and the neglect of crop-livestock interlinkages as well as missing connections to the broader food system. Through the development and use of the "Key elements of agricultural landscape assessments", we [1] demonstrate the importance of ensuring that relevant ESS are captured and that the selection of ESS is not influenced by the perceived importance of ESS or the difficulty of assessing certain ESS; [2] highlight that the range of possible scenarios, and consequently of recommendations, depends on the quantified ecosystem structures and processes, the abiotic, biotic and management driving factors considered, and the type of model used; and [3] emphasise the importance of considering agronomic aspects in the

⁵ With 'parameters' we here refer to individual values and constants, such as methane conversion factors of feed to determine the emissions of enteric fermentation, which again introduce a certain amount of uncertainty.

assessment of agricultural landscapes, such as interactions between crop and livestock production, feedbacks from the food system to the agricultural system, and impacts of external inputs and off-site effects.

In order to optimally address these gaps and to make the assumptions underlying each modelling approach transparent, we recommend starting with a comprehensive understanding of the system, which can then be simplified in those parts that are not relevant to the particular context. This can be undertaken, for example, by using the theoretical framework developed in this publication. We further propose to use sensitivity analysis where detailed, good quality data is lacking or expensive. This allows an option space of what might happen under different conditions to be built up, trying to identify conclusions that may not depend on good data being available. If these are sufficient, then the model has met its objectives and can provide clear recommendations on how or how not to reach a specific goal. However, if such robustness is lacking, a clear statement should be made of the additional data requirements, as without it, the consequences of an intervention cannot be determined at the level of detail needed for effective advice. Moreover, assessing the sensitivity of different factors also identifies which factors are central leverage points and which are less important. This allows further refinement of where to focus the request for additional data: only on the relevant factors that are sensitive to the choice of parameters. These central leverage points are also where measures should focus on to achieve change.

2 / 7. Acknowledgements

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2 / 8. References

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Chapter 3

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

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3 / 1. Abstract

Livestock production is a major driver of phosphorus (P) surpluses, threatening eutrophication-prone 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 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, animal-source protein 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 animal-source protein (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 $\geq$ 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.

3 / 2. 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 stricter measures are needed. Reducing P balances to below 80% 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 12/10/2018; SRF 1/23/2024, 12/14/2023; 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 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 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, animal-source protein (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; Rööß 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 localised production systems but allow for flows in feed, manure and animals to closer relate to current practices.

3 / 3. Material and methods

3 / 3.1. Case study

The watershed of Lake Sempach is located in the Swiss Central Plateau in the canton of Lucerne (Figure 3/1). It covers 75.38 km², 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%. Eighty-five percent of the catchment area are classified as agricultural "valley zone," the remaining 15% falls within the "hilly zone". About 69% of the catchment's terrestrial area is agricultural land, including arable land (33%, of which 44% are temporary grassland) and permanent grassland (33%) (rawi 2019). 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)). In Lippenrütibach, a sub-catchment of the Lake Sempach watershed, cattle account for 52 to 66% of livestock P excretion, pigs for 32 to 47%, and other livestock for only 1 to 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) (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 (Scharer 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).

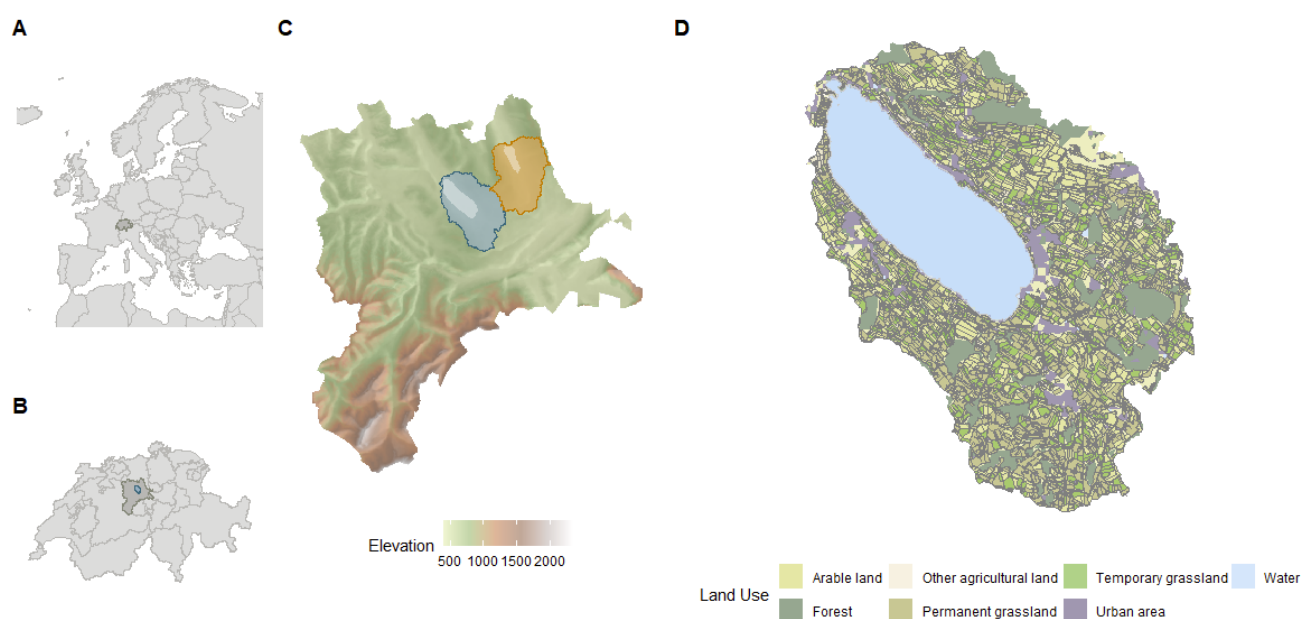


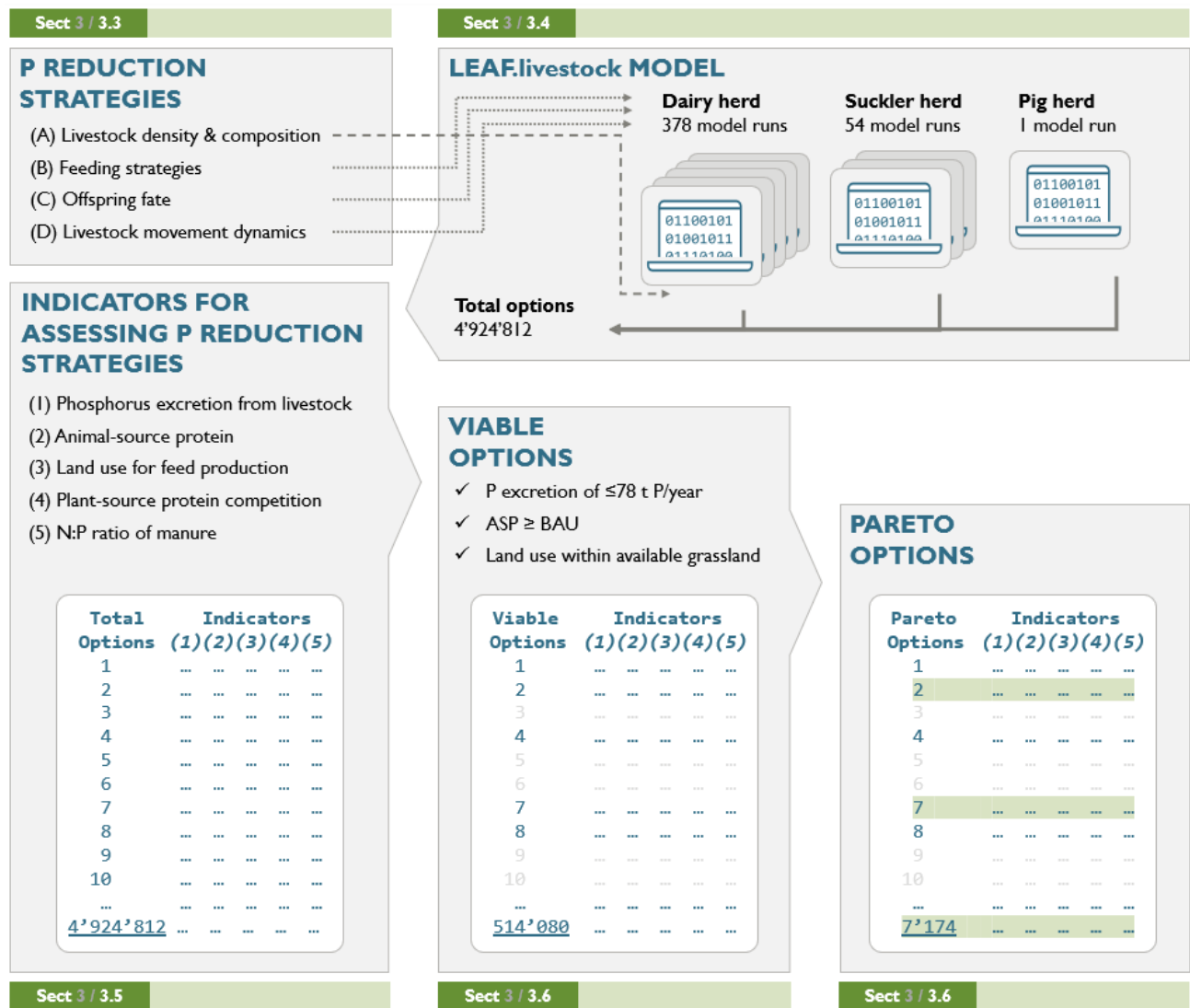
Figure 3/1: **A)** Location of Switzerland within Europe; **B)** Location of the canton of Lucerne and the catchment of Lake Sempach within Switzerland; **C)** Location of Lake Sempach and its catchment area (blue), shown alongside the catchment of Lake Baldeg for comparison (orange), within the canton 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* (© Geoinformaton Kanton Luzern / Raumdatenpool - Dienststelle Raum und Wirtschaft, 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).

3 / 3.2. Research approach

We systematically explored the option space for strategies to reduce P excretion from livestock production (Figure 3/2). For this, we selected a diverse set of P reduction strategies across three livestock herds (dairy, suckler, and pigs⁶) encompassing adjustments of livestock density and composition (A), feeding strategies (B), offspring management (C), and movement dynamics (D) (Section 3/3.3.). The P reduction strategy (A) was implemented as an overarching constraint, with all herd-level results subsequently combined. To generate these

⁶ 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

herd-level results, the LEAF.livestock model (Section 3/3.4.) 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 analyzed 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 3/3.5.). To define the viable options in the option space, we applied three constraints: (1) P excretion of lower or equal to 78 t P/year, (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 3/3.6.1.). From this subset of viable scenarios, Pareto-optimal scenarios were identified (Section 3/3.6.2.).



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. The selection of parameter step sizes is guided by the need to balance computational feasibility and the level of granularity required to adequately represent the option space. A brief reasoning for each intervention is given in Section SM3/1.

Table 3/I: 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

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 (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.

3 / 3.4. 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. 2025a).

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 3/3). 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.

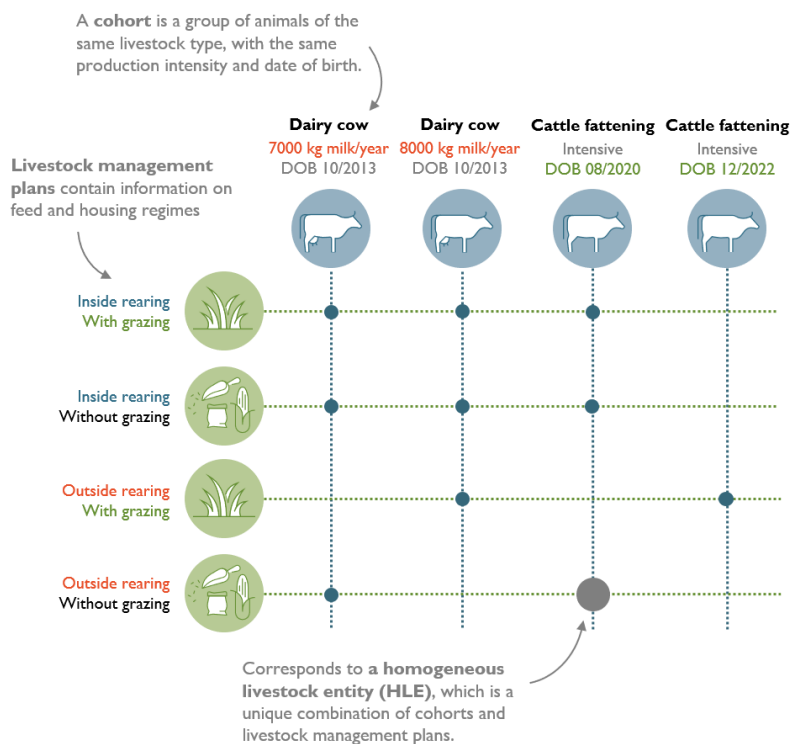


Figure 3/3: Conceptual framework of the LEAF.livestock model illustrating and defining livestock cohorts, livestock management plans, and homogeneous livestock entities (HLE). DOB – Date of birth.

Model sequences. The model runs through sequential phases – growth, production, movement, and feeding – at each time step (Figure 3/4 – 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, 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 Section SM3/2.1.

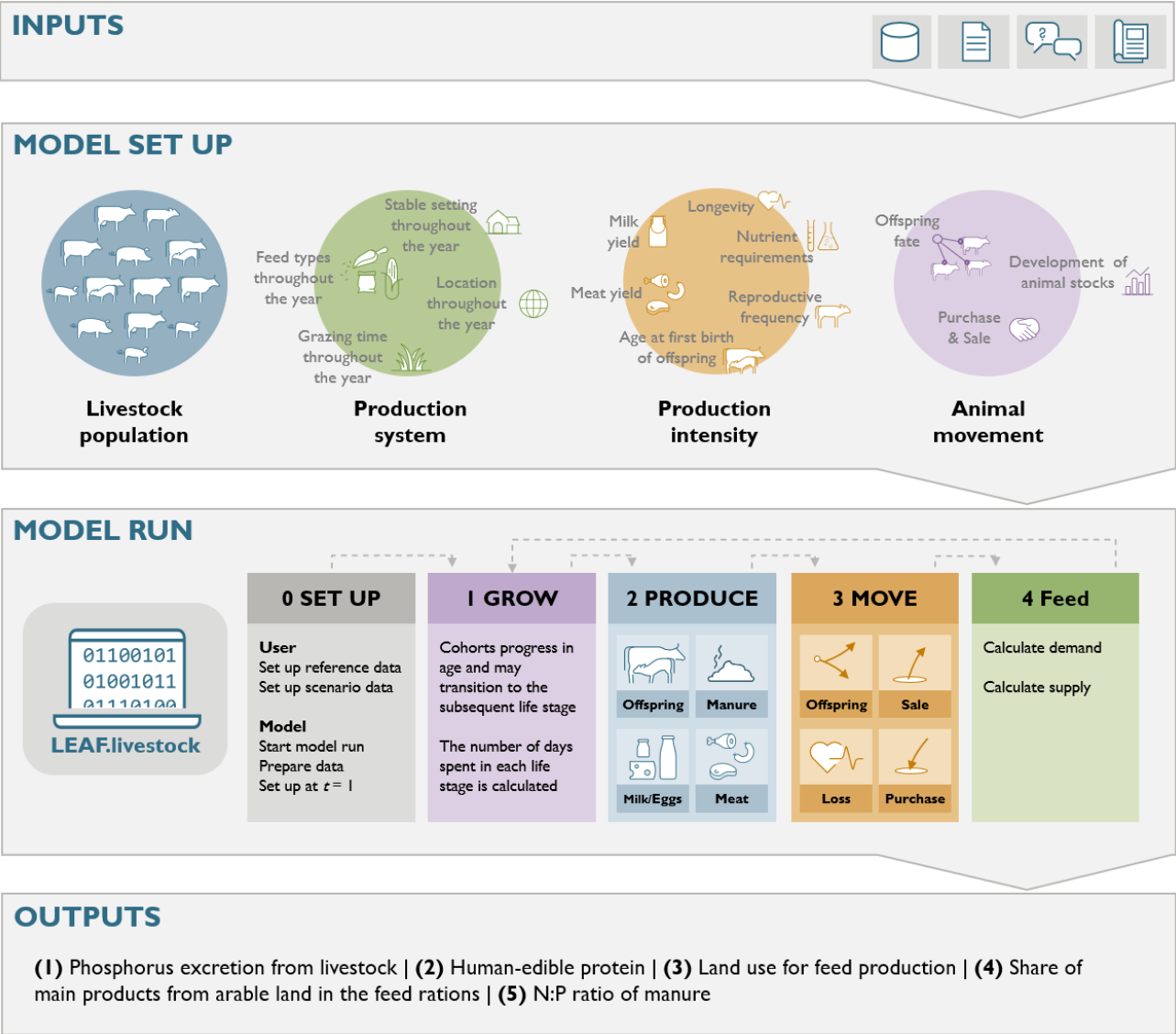


Figure 3/4: Flowchart illustrating the overall model structure, from data inputs through model setup and execution to output generation. During model setup, key components such as livestock population, production systems, production intensities, and animal movement patterns are defined. The model run proceeds through the sequential phases: set up, grow, produce, move, and feed.

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 3/2), were prepared to represent the livestock population, reflecting the production systems, production intensities, and animal movements (Figure 3/4 – 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 3/3; additional information is available in Section SM3/2.2.1. 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 (Section SM3/2.2.2.). 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 (Section SM3/2.2.3.). The model setup furthermore included the identification of detailed animal movement patterns, purchase and sales dynamics, and offspring fates (Section SM3/2.2.4.). 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 Section SM3/4.

Table 3/2: Data and sources used in model setup.

Source	Usage									
	Livestock population		Production intensity			Production system		Animal movement		
	Livestock types	Animal numbers	Yield	Nutrient requirements	Reproduction	Feeding plans	Housing plans	Offspring fate	Temporary absences	Sales/Purchases
AMD (2023) ⁷	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.I, 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

⁷ 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.

Table 3/3. 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	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

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

3 / 3.5. Indicators for assessing P reduction strategies

To assess the P reduction strategies (cf. Section 3/3.3.) and, explore the option space for reducing P excretion from livestock production while maintaining animal-source protein 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/year) 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 **animal-source protein** (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) (FAO 2025; Zimmermann A. et al. 2017). 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 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 plant-source protein (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).

$$PSP \text{ competition} = \frac{\text{Alternative } PSP_{\text{arable land}} + \text{Alternative } PSP_{\text{convertible perm.grassland}} + \text{Additional } PSP_{\text{unutilized arable land}} + \text{Additional } PSP_{\text{unutilized convertible perm.grassland}}}{ASP} \quad (1)$$

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 two thirds of it being cropped with wheat and one third with peas. We assume national average yields (FAO 2025) and human-edible protein contents from FSVO (2023). 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 Section SM3/3.). 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. 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 (Flisch R. et al. 2017; Hirte, J. - personal communication 9/22/2023). This resulted in an overall desirable N:P ratio for the catchment of 5.33, with a range of 3.76 to 8.43, depending on the crop type and area.

3 / 3.6. Narrowing the option space

3 / 3.6.1. 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/year (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/year 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 feed area of 4'050 ha in the region.

3 / 3.6.2. 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 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 3/5).

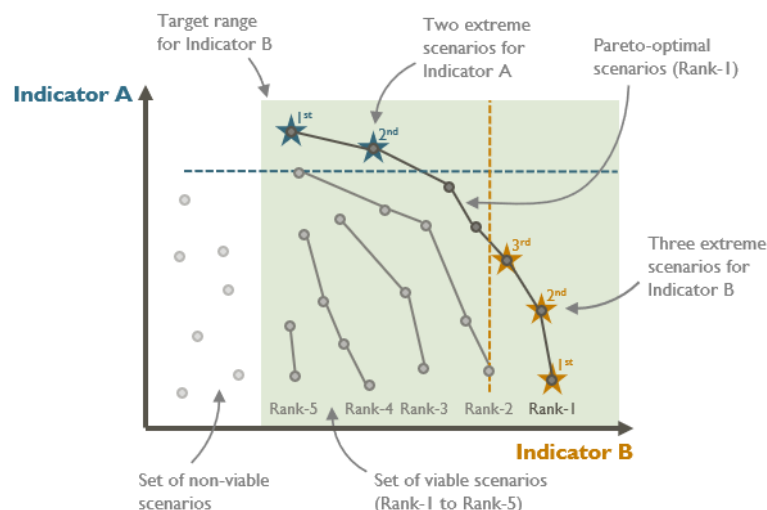


Figure 3/5: Conceptual 2D plot of non-viable, viable, Pareto-optimal, and extreme scenarios for two illustrative indicators. The target range for Indicator B is indicated by a transparent green box. Dark grey points represent rank-1 (Pareto-optimal) scenarios; medium grey points represent viable (aka 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.

3 / 4. Results

3 / 4.1. Reference scenario: Business-as-usual (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 Section SM3/5.1.). 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 (Section SM3/5.2.). 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 (Section SM3/5.3.).

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 3/4). 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.

Table 3/4: 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			

3 / 4.2. Assessment of P reduction strategies

3 / 4.2.1. 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 3/6, col. A, row 2; Table SM3/15), 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 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 $\geq 60\%$ pigs), dairy-dominated scenarios (with an LSU composition of $\geq 60\%$ dairy cattle), suckler-dominated scenarios (with an LSU composition of $\geq 60\%$ suckler cattle), and mixed scenarios ($\leq 60\%$ dairy, $\leq 60\%$ suckler, $\leq 60\%$ pigs). Across all groups, most scenarios resulted in lower P excretion than BAU, with many meeting the P excretion target of ≤ 78 t P/year (Figure 3/6, col. D; Table SM3/15). 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/year), followed by mixed (914.7 t/year) and dairy-dominated (881.2 t/year), while suckler-dominated scenarios produced the least (476.2 t/year, range: 75.3-978 t/year). No suckler-dominated scenario reached the BAU ASP production. Arable land use was on average highest in pig-dominated systems (3'988 ha/year) and lowest in suckler-dominated (776.9 ha/year). 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).

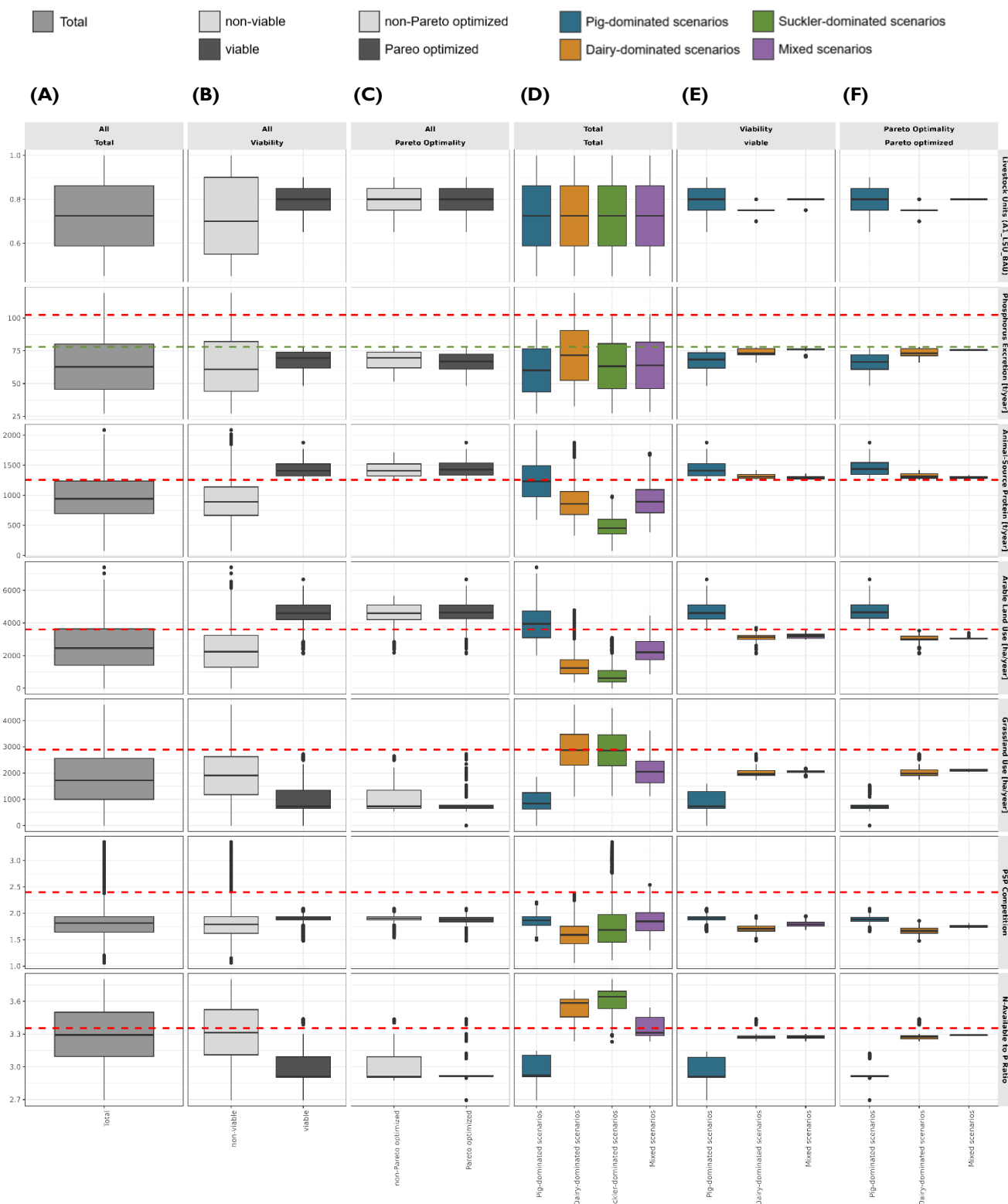


Figure 3/6: Performance of scenarios across all indicators for assessing P reduction strategies (horizontal rows) plus share of LSU compared to BAU. The columns (A) and (D) show the results for all scenarios, (B) and (E) show viable and (C) and (F) Pareto optimized scenarios. (D), (E), and (F) divide the scenarios into pig-dominated scenarios, dairy-dominated scenarios, suckler-dominated scenarios (with an LSU composition of $\geq 60\%$ 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/year. 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.

3 / 4.2.2. Defining the viable option space

To identify a viable option space for P reduction in livestock production, we applied the following constraints (cf. Section 3/3.6.1.): P excretion ≤ 78 t P/year; produced ASP $\geq$ BAU; using $\leq 4'050$ ha total land (arable plus temporary and permanent grassland) to produce the necessary feed. Figure 3/7 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/year) 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).

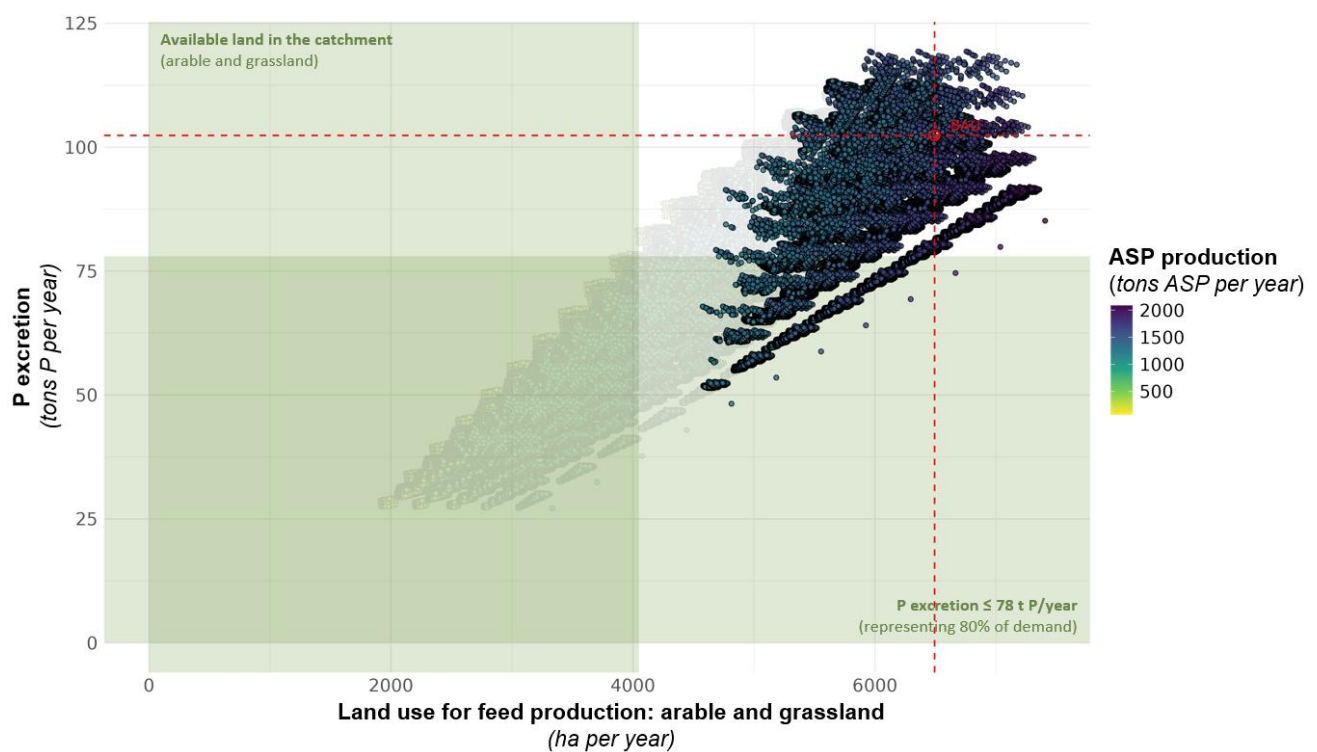


Figure 3/7: Relationship between phosphorus (P) excretion (y-axis), agricultural land use for feed production (x-axis), and animal-source protein (ASP) production (dot colour). Each dot represents one scenario; BAU is marked by a red dot and red dashed lines. Scenarios not meeting the ASP constraint (i.e., lower ASP than BAU) are shown with reduced opacity. The target range for P excretion (≤ 78 t P/year) and the available agricultural land in the catchment (4'050 ha) are indicated by transparent green boxes.

Figure 3/7 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 green box in Figure 3/8). The diagonal clusters of points in Figure 3/8 illustrate the influence of P reduction strategy A2, which varies the share of cattle versus pigs (Section SM3/6.2.). 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.

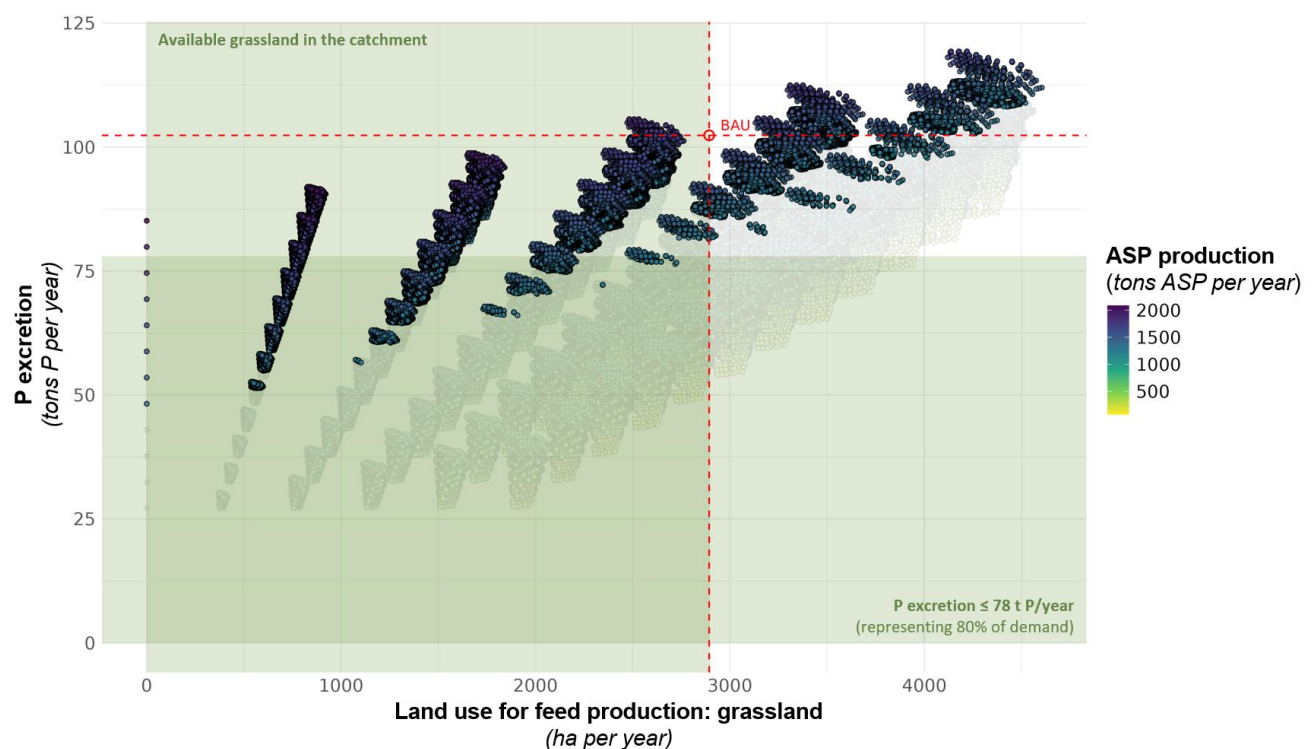


Figure 3/8: Relationship between phosphorus (P) excretion (y-axis), grassland use for feed production (x-axis), and animal-source protein (ASP) (dot colour). Each dot represents one scenario; BAU is marked by a red dot and red dashed lines. Scenarios not meeting the ASP constraint (i.e., lower ASP than BAU) are shown with reduced opacity. The target range for P excretion (≤ 78 t P/year) and the available grassland in the catchment (2'898 ha) are indicated by transparent green boxes.

3 / 4.2.3. 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/year, (2) ASP production $\geq$ BAU, and (3) land use within the available grassland. Such

scenarios were categorised as viable (Figure 3/6, col. B; Table SM3/16). Within this viable option space, 7'174 scenarios had Pareto rank-1 (0.15% of all scenarios, 1.4% of viable ones) (Figure 3/6, cols. C/F; Table SM3/17). 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 3/6, 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/year, 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 / 4.2.4. 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 (Figure SM3/73-75).

Livestock density and composition (A1 to 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 $\geq 40\%$ 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 to 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. 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 / 4.2.5. 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 (Table 3/5). For the indicator P excretion, two Pareto-optimal scenarios (rank-1) were identified before the selection process (cf. Section 3/3.6.2.) 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 3/9 illustrates the performance of the selected scenarios and their LSU levels relative to BAU. Scenarios with the lowest P excretion (Figure 3/9 – 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 3/9 – 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 (Table 3/5). 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 (Figure 3/9 – C to E). Nevertheless, all of these scenarios outperformed the BAU baseline across the evaluated indicators.

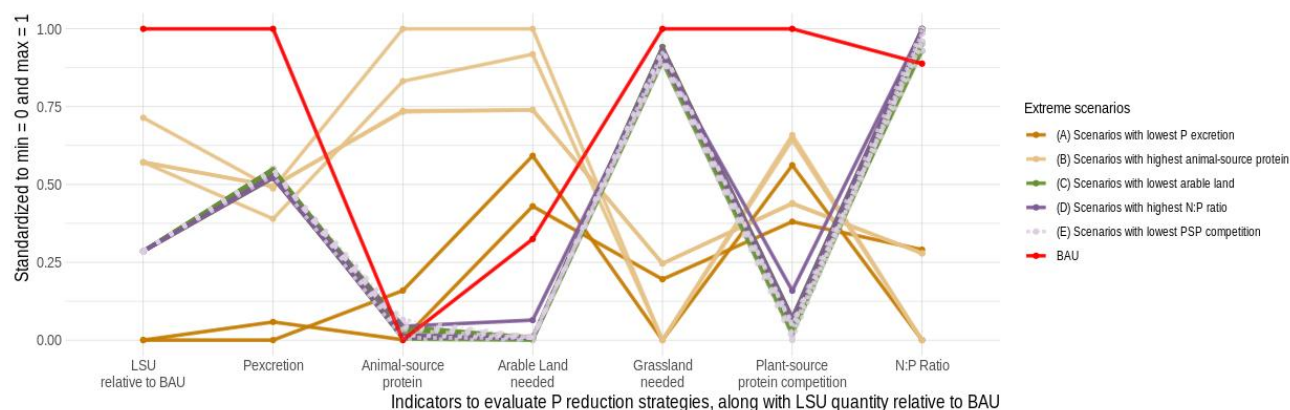


Figure 3/9: Performance of extreme scenarios across indicators used to evaluate P reduction strategies, together with livestock units (LSU) relative to BAU. For comparison, the BAU scenario is also shown. All indicators were rescaled to a 0–1 scale.

When examining the P reduction strategies behind the extreme and intermediate scenarios, several general patterns emerged (Table 3/5). 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 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 ($\geq 60\%$ pigs in LSU composition). In these scenarios, total LSU (A1) were reduced to 65% to 90% of BAU levels. As a result, these scenarios correspond to pig LSU levels approximately 1.5 to 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 ($\geq 80\%$ 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.

Table 3/5: P reduction strategies (rows) underlying extreme scenarios (columns). Note: Several scenarios are optimal across multiple indicators (A to E), as indicated in the second row.

[illegible]

3 / 5. Discussion

3 / 5.1. 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 ≤ 78 t/year, (2) ASP production $\geq$ 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 as 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 to 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 a soil-health conserving and sustainable manner that minimizes erosion and nutrient runoff. 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 all plant foods contain the full spectrum of essential amino acids and that mixed plant-based diets are sufficient to achieve protein adequacy in adults (Mariotti and Gardner 2019; Sarathy et al. 2025).

3 / 5.2. 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 Bielza et al. 2025; Stettler and Probst 2023). 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 (Identitas 2025; Mutterkuh Schweiz 2024). 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 ($\geq 60\%$ 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 2018a), 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 ($\geq 60\%$ 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.

3 / 5.3. 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 to 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).

3 / 5.4. 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.

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.

3 / 6. Conclusion

Using the novel LEAF.livestock model, we systematically explored over 4.9 million scenarios to identify viable pathways for reducing P excretion from livestock production within the Lake Sempach catchment. The option space analysis revealed multiple optima, showing that similar results can be achieved through different strategies. This underscores the importance of identifying local optima rather than relying on a single global solution from optimization models. Several conclusions regarding viable pathways can be drawn from our results. First, a consistent result across all Pareto-optimal scenarios was the need to reduce livestock density to 65% to 90% of current levels, emphasizing the urgency for structural change in regional livestock management. Second, in all scenarios, more PSP could be produced than ASP if the same land were used directly for food production rather than for feed, and maintaining the current ASP production. Third, leakage effects will play a central role: all viable scenarios depend on external land for feed production, manure export, or off-site rearing, which shift environmental burdens beyond the catchment. While these measures relieve local pressures, strengthen current practice and thus may increase acceptance and also economic viability of the strategies, they raise concerns about nutrient leakage and sustainability elsewhere. Future assessments should therefore move beyond territorial boundaries and include food-system-wide perspectives, integrating land use strategies, feed–food competition, and emissions beyond P, such as methane and ammonia.

The LEAF.livestock model provides a strong foundation for such integrative approaches, and this study already demonstrates its potential to support evidence-based policy design: it delivers actionable insights into reducing

nutrient outputs from livestock systems by systematically evaluating strategies and the trade-offs and synergies between environmental and nutritional outcomes. Moving beyond simplistic solutions like blanket reductions in livestock numbers, the results highlight region-specific recommendations. Ultimately, recognising the trade-offs and synergies between environmental goals and production demands is key to designing socially acceptable and ecologically sound transition pathways. This study provides a solid basis for stakeholder dialogue and policy planning to adapt livestock systems to operate within ecological limits, locally and beyond.

3 / 7. Acknowledgements

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Chapter 4

Phosphorus reduction pathways in livestock systems within a Swiss watershed

This chapter will be submitted to *Agricultural Systems* as Heidenreich, Anja; Pfeifer, Catherine; Six, Johan; Muller, Adrian: Phosphorus reduction pathways in livestock systems within a Swiss watershed.

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4 / 1. Abstract

Livestock-intensive regions face persistent phosphorus (P) surpluses that threaten water quality and biodiversity. Reducing P excretion requires not only defining long-term targets but also identifying concrete pathways for how such transformations could be realized in practice. This study explores how catchment-level P reduction targets can be translated into farm-level transition pathways, explicitly considering structural resistances, tolerance constraints, and temporal dynamics. We analysed two contrasting target scenarios for the livestock-intensive catchment of Lake Sempach in Switzerland derived from Heidenreich et al. (submitted): one dairy-dominated and one pig-dominated. Transition dynamics were determined using a resistance-weighted optimization approach to define plausible farm type and management changes, which were then simulated with the dynamic LEAF.livestock model from 2020 to 2060, producing monthly time series of herd dynamics, production outputs, and nutrient flows. Both pathways achieved the defined P reduction targets, but through fundamentally different restructuring processes. The pathway towards the pig-dominated target scenario relied heavily on farm exits and specialization into pig-only systems, while the pathway towards the dairy-dominated target scenario involved fewer exits and farm-type changes, but centred on changes of feeding strategies. Importantly, the analysis revealed that while both strategies were feasible, they implied very different social, structural, and policy requirements. By bridging abstract sustainability targets with implementable change processes, this approach delivers transformation knowledge urgently needed for regional planning and policy-making. The findings demonstrate that solving the P excretion problem will require far-reaching adjustments, but also that, with timely action and supportive policies, such transitions are both possible and manageable.

4 / 2. Introduction

The need to transform livestock production systems towards more sustainable forms is widely acknowledged in both scientific and policy circles (Leip et al. 2015; Godfray et al. 2018; Springmann et al. 2018; Willett et al. 2019). Such a transformation is essential not only for mitigating greenhouse gas emissions, improving water quality, and promoting healthier diets, but also for addressing persistent nutrient imbalances with corresponding adverse environmental impacts in agricultural landscapes (Scanes 2018). Among these, the over-accumulation of phosphorus (P) has emerged as a particularly pressing challenge, particularly in regions characterized by high animal densities, substantial feed imports, and limited nutrient recycling (Leip et al. 2015). The resulting P surplus leads to eutrophication of water bodies, long-term legacy loads in soils, and biodiversity loss, highlighting the urgency for change (Smith et al. 1999; Ansari et al. 2011). However, addressing this challenge requires more than incremental efficiency gains; it demands a fundamental realignment of livestock production with the ecological limits of local environments (Röös et al. 2017; van Zanten et al. 2018; Kazanski et al. 2025). Achieving such alignment calls for a comprehensive redesign of livestock systems, involving a

reconsideration of production volumes, a shift in management practices, and a reorganization of livestock distribution across agricultural landscapes.

In the context of an intensively managed agricultural region in Switzerland with a persistent P surplus, previous research has identified alternative livestock system configurations that could substantially reduce P excretion while maintaining, or even increasing, the production of animal-source protein (Heidenreich et al. submitted). These desirable states demonstrate that it is technically feasible to align livestock production with regional sustainability boundaries. However, while desirable endpoints have been defined, the transition pathways to get there are still underexplored. Existing approaches rarely capture the complexity of dynamic change, nor do they offer implementation-oriented guidance for farmers and policymakers. To bridge this gap, a dynamic, target-seeking perspective is required, which explicitly considers the feasibility, sequencing, and speed of change within a specific regional context. To close this gap, we therefore address the following question in this study: *What transition pathways can facilitate a transition from the current livestock system to scenarios that achieve significant P excretion reductions?* To investigate this, we selected two desirable yet contrasting system configurations that met three criteria: reducing the P balance to 80% (following Stoll et al. (2019)) with a correspondingly derived reduction of P excretion to 80%, animal-source protein production equal to or greater than the status quo, and roughage use within the local grassland area available (Heidenreich et al. submitted). Based on typical farm types in the catchment, we defined plausible transition pathways towards these targets. We applied the dynamic LEAF.livestock model to simulate these transitions over 30-year timeframe, assessing the different transition pathways in terms of speed, implementation sequence, associated trade-offs, and compatibility with the specific regional landscape context. With this approach, we do not merely explore theoretical options, but provide practical guidance on how change can be realized.

4 / 3. Material and methods

4 / 3.1. Case study

This study focuses on the Lake Sempach watershed, a P-impacted agricultural region in the Swiss Central Plateau, located in the canton of Lucerne (Figure 4/1). The 75 km² catchment is dominated by intensive livestock farming, with approximately 69% of the terrestrial area under agricultural use, split nearly evenly between arable land and permanent grassland. Livestock densities in the region are among the highest in Switzerland, reaching 2.39 LSU/ha in 2019; nearly double the national average (Kanton Luzern 2021; Federal Statistical Office 2025). Cattle and pigs account for the majority of P excretion in the area, a trend consistent with comparable nearby catchments (Stoll et al. 2019; Heidenreich et al. submitted). Decades of intensive production have led to substantial P accumulation in agricultural soils, with the majority of both arable and grassland areas now classified in the highest P supply categories (Hirte, J. - personal communication 9/22/2023). Despite long-

standing mitigation efforts, including artificial lake aeration and the implementation of the “Phosphorus Project” with broad farmer participation (63%, Stadelmann, F. - personal communication (6/5/2023), Kanton Luzern (2021)), target values for P inputs and lake concentrations are not met (UWE and AfU 2023). This persistent surplus highlights the need for a more systemic transformation of livestock production in the region – one that moves beyond incremental adjustments and aligns with the ecological capacity of the local landscape.



Figure 4/1: 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 within the canton of Lucerne. Sources: 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).

4 / 3.2. From status quo to targets: deriving transition pathways

To develop transition pathways from the 2020 status quo to the 2050 target animal numbers and management, we followed a stepwise process illustrated in Figure 4/2. We first specified the current situation in the catchment, detailing farm types and their respective numbers (Section 4/3.2.1.). We then described the two contrasting target scenarios for 2050, outlining future animal numbers and management strategies (Section 4/3.2.2.). Based on this, we defined possible farm type shifts, considering potential resistances (Section 4/3.2.3.). At the catchment level, transition pathways were then derived through an optimization approach that minimized the number of affected farms while respecting farm type-specific resistances and, finally, by adding a temporal dimension to represent stepwise changes from 2020 to 2050 (Section 4/3.2.4.). Each of these steps is described in detail in the following subsections.

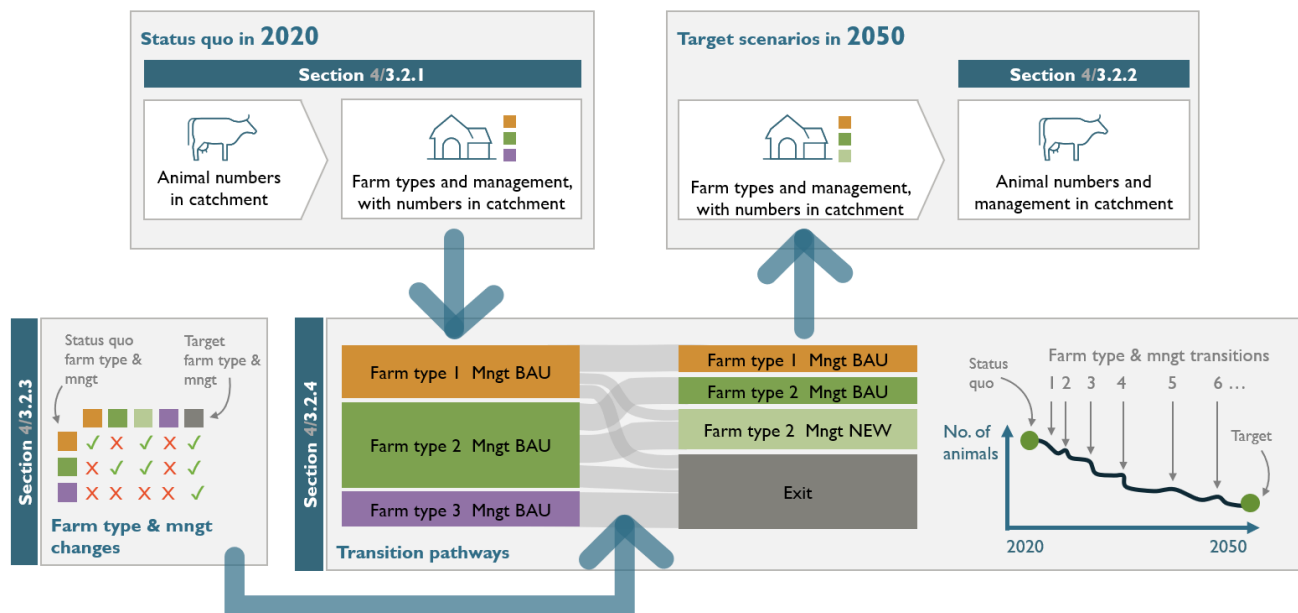


Figure 4/2: Overview of the process used to develop transition pathways from the 2020 status quo (farm types, management practices, and animal numbers) to the 2050 target scenarios. The process consists of four main steps: specifying the status quo, describing the target animal numbers and management for 2050, defining changes at the farm level under potential resistance, and deriving stepwise transition pathways at the catchment level.

4 / 3.2.1. Status quo in 2020: farm types and their characteristics

We first identified representative farm types and their characteristics for the catchment for the year 2020, thereby establishing the status quo. This step was based on 2020 AGIS data, restricted to conventional farms receiving direct payments in municipalities where at least 70% of the area lies within the catchment (and with this covering 75% of the catchment area and 61% of the farms in the catchment, Figure SM4/1). To better reflect actual farming practices and due to similarities in animal numbers, the AGIS farm types *Pigs* and *Combined finishing* were combined and reclassified into three distinct types: *Pig finishing*, *Pig breeding*, and *Combined pig breeding and finishing*. Each of these was further subdivided into variants with and without cattle. Finally, ten distinct farm types were selected, while all others were grouped under the category *Remaining farms combined*.

For each farm type, we derived the number of farms and calculated the average agricultural area and the average number of animals per farm. Outlier exclusion was applied to the latter, where farms with animal numbers exceeding 1.5 times the interquartile range were removed. Using the distribution of farm types and the average number of animals per farm, we then scaled the data to match the total number of conventional farms receiving direct payments in the catchment in 2020 ($n = 241$; Stadelmann, F. - personal communication (6/5/2023)). The resulting livestock numbers were validated against catchment-level animal population data from the same year, obtained from the Swiss Animal Movement Database (AMD 2023), a mandatory nationwide registry of individual cattle and their movements. This comparison revealed gaps in the coverage of certain livestock categories, particularly an underrepresentation of suckler cows and fattening cattle. To address these gaps, we examined also the AGIS data from the remaining municipalities and refined the

classification of farm types accordingly. Specifically, the farm type *Mixed cattle* was disaggregated into *rearing*, *beef*, and *veal*, and the farm type *Suckler cows* was subdivided into *average-scale* and *large-scale farms*. The refined farm type structure was again scaled to the entire catchment based on the 241 reference farms and cross-validated with AMD data. Finally, for each livestock type, animal numbers across all farm types were adjusted using a correction factor to match catchment-level totals reported in the AMD (2023) (Table SM4/2). The final number of animals per livestock and farm type, as well as the number of farms per type in the catchment, are presented in Table 4/1 and Figure SM4/4.

Table 4/1: Number of animals per livestock and farm type, as well as the number of farms per type. Animal numbers per farm type may include fractional values, as they represent averages of the respective farm types. In the model simulations, however, only whole animals are assigned and moved between farm types⁸. Highlighted cells indicate animals up to 160 days of age in the case of cattle, and up to weaned piglets in the case of pigs. All other animal numbers are reported across all life stages and reflect the intended production fate of each animal⁹.

Farm type	Number of farms	Average agricultural area (in ha)	Number of animals per farm								
			Dairy herd					Suckler herd		Pig herd	
			Dairy cow	Calf fattening	Bull fattening	Ox fattening	Cattle fattening	Suckler cow	Suckler cow husbandry	Finishing pig	Breeding sow
Dairy production with rearing/fattening	33	56.1	37.3	1.9	0.8	0.2	1.5	-	-	-	-
Dairy production without rearing/fattening	11	40.4	26.2	1.2	0.5	0.1	0.9	-	-	-	-
Mixed cattle - rearing	8	40.5	28.7	-	-	-	-	-	-	-	-
Mixed cattle fattening - beef	2	23.0	-	-	139.4	92.5	159.4	-	-	-	-
Mixed cattle fattening - veal	2	3.9	1.5	88.4	-	-	-	-	-	-	-
Suckler cows (average-scale)	19	38.4	-	-	-	-	-	24.8	11.9	-	-
Suckler cows (large-scale)	6	33.7	-	-	-	-	-	103.7	42.0	-	-
Pig finishing	44	74.5	25.6	2.4	1.9	0.8	5.4	-	-	100.2	-
Pig finishing (without cattle)	5	11.9	-	-	-	-	-	-	-	216.4	-
Pig breeding	36	59.8	23.8	1.6	0.5	0.1	1.4	-	-	143.4	36.7
Pig breeding (without cattle)	13	16.6	-	-	-	-	-	-	-	262.1	75.1
Combined pig breeding and finishing	24	57.3	31.2	2.3	1.0	0.3	1.7	-	-	125.3	7.9
Combined pig breeding and finishing (without cattle)	3	20.8	-	-	-	-	-	-	-	522.7	93.8
Remaining farms combined	36	69.7	19.9	1.5	1.2	0.6	2.6	1.4	1.2	1.4	0.3
Total	241		5'197	491	421	225	733	1'172	533	18'600	2'771

4 / 3.2.2. Target scenarios for 2050: animal numbers and management strategies

In Heidenreich et al. (submitted), we investigated regionally adapted strategies for the Lake Sempach catchment to reduce livestock-related P excretion while maintaining animal-source protein production. Using the LEAF.livestock model, we simulated nearly five million combinations of herd structures and management practices, evaluating each scenario across five key indicators: P excretion, animal-source protein output, land use, food-feed competition, and the fertilizing potential of manure. Ecological and production constraints were applied, including limits on P excretion, maintenance of animal-sourced protein output, and adherence to

⁸ **Note:** For example, if 0.1 cows are shown for a given farm type, then in the simulation one cow is moved only for every tenth farm of this type that undergoes a shift.

⁹ **Note:** For example, animals listed under "Dairy cow" include all individuals from birth onward that are destined for dairy production, regardless of their current age or production status.

available land resources. Although no scenario simultaneously fulfilled all constraints, relaxing the land-use constraint revealed a subset of viable and Pareto-optimal system configurations. From this subset, we selected two desirable yet contrasting Pareto-optimal configurations that exemplify the divergent strategies revealed in the analysis. Figure 4/3 illustrates the target number of animals per livestock type in the catchment for these two contrasting scenarios, alongside the status quo values.

The selected **pig-dominated target scenario** is characterized by a livestock density reduced to 65% of the baseline, with pigs contributing 80% of total LSU, dairy 16%, and suckler herds 4% (Table 4/2). 50% of the dairy herd is fed with the baseline and 50% with a grassland-based feed, while the suckler herd relies entirely on locally sourced grassland-based feed. This configuration results in a P excretion of 51 tons per year and animal-source protein production of 1,257 tons per year. It relies on 4'078 ha of arable land and only 565 ha of grassland, leaving 2'008 ha of permanent and 325 ha of temporary grassland unused. The plant-source protein competition score is relatively high, indicating that 1.83 as much plant-source protein could be produced if the same land were used directly for food production rather than for livestock feed.

While both target scenarios apply consistent strategies for offspring management and livestock movement (all calves are sold at two months and all cattle undergo seasonal or rearing movements), the **dairy-dominated target scenario**, in contrast, features a livestock density reduced to 75% of the baseline. In this configuration, dairy cattle make up 80% of the LSU, pigs 20%, and no suckler herd is present. Dairy cows receive a 50:50 mix of maximized locally producible forage-and-feed plan and grassland-based feed. This target scenario achieves a slightly higher ASP output (1'261 tons per year), has a higher P excretion (77 tons per year) and requires less arable land (2'159 ha). It also uses 2'646 ha of grassland, leaving only 252 ha of permanent grassland unused. Additionally, it features a slightly lower plant-source protein competition score (1.53) and more favourable N:P ratio in manure (3.44).

Table 4/2: Performance of key indicators and P reduction strategies (A) to (D) behind the two contrasting target scenarios. First column represents the pig-dominated target scenario, and the second column the dairy-dominated target scenario.

			Pig-dominated scenario	Dairy-dominated scenario
LSU (perYear)			5'336	6'156
Pexcretion (tons P per year)			51	77
Animal-source protein (tons ASP per year)			1'257	1'261
Arable land needed (ha per year)			4'078	2'159
Grassland needed (ha per year)			565	2'646
Unused temporary grassland (ha per year)			325	-
Unused permanent grassland (ha per year)			2'008	252
Plant-source protein competition (score)			1.83	1.53
N _{available} :P ratio of FYM			2.91	3.44
Across all herd types	(A) Livestock density and composition	A1 Livestock density (% of BAU LSU/ha)	65%	75%
		% LSU pig herd	80%	20%
		% LSU dairy herd	16%	80%
		% LSU suckler herd	4%	
Dairy herd	(B) Feeding strategy	B1 BAU feeding (% of cattle)	50%	
		B2 Maximized locally producible forage and feed utilization (% of cattle)		50%
		B3 Maximized locally producible grassland-based feed utilization (% of cattle)	50%	50%
	(C) Offspring fate	C1 Dairy offspring sold at 2 months (% of dairy offspring)	100%	100%
		C2 Remaining dairy offspring into calf fattening (% of remaining dairy offspring)		
	(D) Livestock movement dynamics	D1 Dairy/suckler cows leaving for rearing phase (% of dairy cows)	100%	100%
Suckler herd	(B) Feeding strategy	D2 Cattle seasonally absent (Jul-Oct) (% of cattle)	100%	100%
		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		
	(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%	

Pig-dominated target scenario Dairy-dominated target scenario

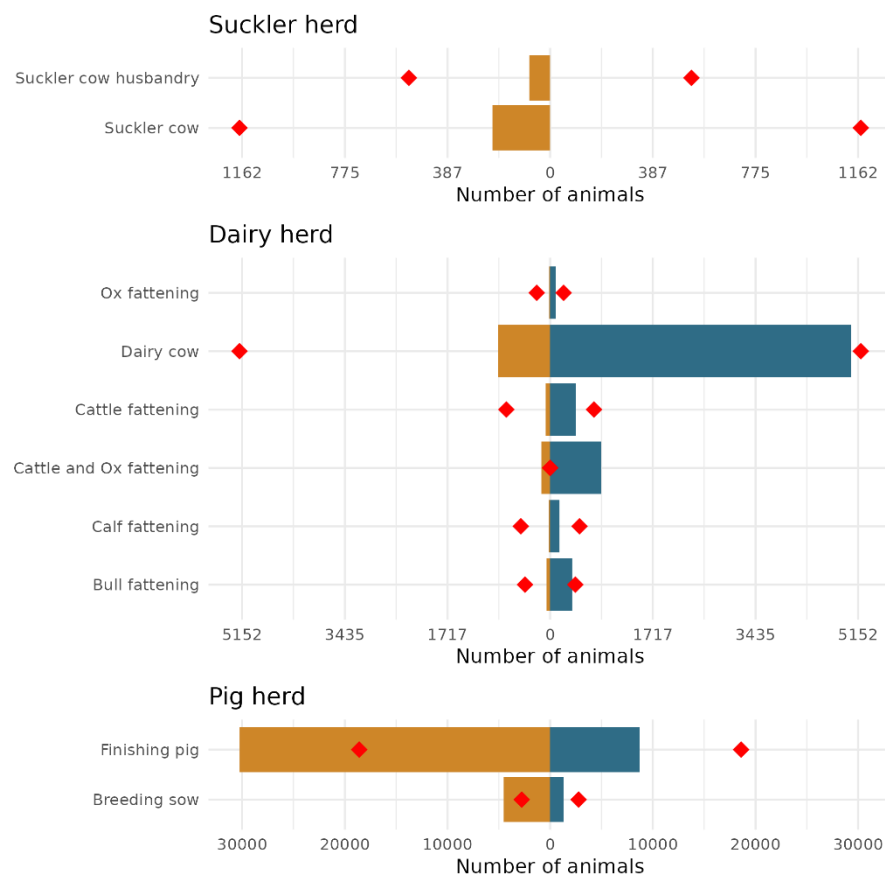


Figure 4/3: Target number of animals per livestock type in the catchment for 2050, shown for the two contrasting target scenarios. Orange bars represent the pig-dominated target scenario, and blue bars the dairy-dominated target scenario. Red diamonds indicate the number of animals in December 2020, representing the status quo (BAU).

4 / 3.2.3. Farm-level: changes in farm type and management under potential resistance

Based on the representative farm types identified in Section 4/3.2.1, we defined potential farm type shifts from each status quo farm type to one or more alternative farm types. These included:

- (a) a complete switch to another farm type that is broadly compatible with existing practices and likely to be acceptable to farmers,
- (b) extensification through full-farm conversion to organic production, either as a switch to an organic variant of the same farm type or as a switch to another farm type under organic production¹⁰, and
- (c) complete exit of livestock production.

The range of possible from-to shifts was determined using a resistance matrix, which indicates the relative difficulty of moving from one farm type to another (Table 4/3). The matrix was developed based on the expert judgment of a livestock science specialist and informed by case study-specific literature. The expert’s input guided the definition of the matrix structure, including the selection and categorization of relevant resistance criteria. The resistance scores capture barriers to change, including the need for infrastructure adjustments, implications for labour and workload, challenges related to animal health and management, and regulatory or market constraints. In this way, the matrix accounts for example for the high resistance associated with shifts into farm types that differ substantially from the original, as such transitions would require fundamental changes in the underlying knowledge system. Previous research in this region has identified this, along with farmers’ stable investments and corresponding debts, as key barriers to change (Bartel-Kratochvil et al. 2020). In addition to the resistance matrix, target scenario-specific constraints were applied, such as requirements for offspring management and the requirement that all replacement heifers for dairy and suckler herds must be reared outside the catchment. As a result, shifts to certain farm types were restricted.

Table 4/3: Resistance matrix, indicating resistance against shifts between farm types (rows: current farm type; columns: target farm type). Resistance is rated on a scale from 0 to 3, where 0 = No resistance, 1 = Low resistance, 2 = Medium resistance, and 3 = High resistance. Note: The matrix reflects resistance only against (a) complete switches to another farm type, (b) shifts to the organic variant

¹⁰ **Note:** Extensification through full-farm conversion to organic production was represented by assuming livestock densities of 81% for cattle and 21% for pigs relative to conventional farms. These values were derived from Federal Statistical Office (2025) and weighted according to the catchment’s composition of 85% valley zone and 15% hilly zone.

of the same farm type, and (c) complete exits from livestock production. The table therefore provides an illustrative excerpt; for the full resistance matrix is available see Table SM4/3.

From farm type ↓ to farm type →	Dairy production with rearing/fattening	Dairy production without rearing/fattening	Mixed cattle - rearing	Mixed cattle fattening - beef	Mixed cattle fattening - veal	Suckler cows (average-scale)	Suckler cows (large-scale)	Pig finishing	Pig finishing (without cattle)	Pig breeding	Pig breeding (without cattle)	Combined pig breeding and finishing	Combined pig breeding and finishing (without cattle)	Remaining farms combined	Extensification through full-farm conversion to organic production	Exit of livestock production
Dairy production with rearing/fattening	0	0	1	1	1	2	3	3	3	3	3	3	3	0	1	2
Dairy production without rearing/fattening	0	0	1	2	2	2	3	3	3	3	3	3	3	0	1	2
Mixed cattle - rearing	2	2	0	2	2	2	3	2	3	3	3	3	3	2	3	1
Mixed cattle fattening - beef	3	3	2	0	2	2	3	2	3	3	3	3	3	3	3	1
Mixed cattle fattening - veal	2	2	2	2	0	2	3	2	3	3	3	3	3	2	3	1
Suckler cows (average-scale)	3	3	1	2	3	0	1	3	3	3	3	3	3	3	1	1
Suckler cows (large-scale)	3	3	1	2	3	0	0	3	3	3	3	3	3	3	1	1
Pig finishing	2	1	2	2	3	3	3	0	1	2	3	2	3	2	3	2
Pig finishing (without cattle)	3	3	3	3	3	3	3	3	0	3	3	3	2	3	3	2
Pig breeding	2	1	3	3	3	3	3	2	2	0	1	1	2	2	3	2
Pig breeding (without cattle)	3	3	3	3	3	3	3	3	2	3	0	3	2	3	3	2
Combined pig breeding and finishing	2	1	3	3	3	3	3	1	1	2	2	0	1	2	3	2
Combined pig breeding and finishing (without cattle)	3	3	3	3	3	3	3	3	1	3	2	3	0	3	3	2
Remaining farms combined	0	0	1	1	1	2	3	3	3	3	3	3	3	0	1	2

4 / 3.2.4. Catchment-level: stepwise transition pathways from 2020 to 2050

The potential farm type shifts defined in Section 4/3.2.3 were subsequently combined into catchment-level transition pathways. These pathways describe the overall restructuring of livestock production required to achieve the livestock density, composition, and feeding strategies specified by the 2050 target scenarios. The process involved two steps: first, an optimization to identify the set of farm type shifts needed to reach the targets; and second, the addition of a temporal dimension to derive stepwise pathways from 2020 to 2050.

4 / 3.2.4.1. Optimizing farm type changes towards targets

The goal of the optimization was to identify, for each target scenario, a single optimal configuration of farm-type changes required to meet the catchment-level targets. To achieve this, we solved a mixed-integer programming model that minimized the resistance-weighted number of farm shifts, with higher resistance values reflecting more difficult transitions. The optimization was subject to three conditions: (i) farms were treated as indivisible units, so only whole-farm shifts were possible, (ii) target changes in livestock numbers had to stay within defined tolerance ranges, and (iii) farm availability constraints ensured that the number of transitions from each *from* farm type did not exceed the initial number of farms.

Because farms could only transition as whole units rather than fractions, it was not possible to exactly reproduce the target livestock numbers. We therefore introduced tolerance levels, specifying how close the solution had to come to the targets for each livestock type. To ensure feasibility, we first manually identified the lowest global tolerance level at which all livestock-specific targets could still be met (see Section SM4 for more details). We

then applied a stepwise tolerance reduction procedure to minimize individual tolerances per livestock type while preserving model feasibility. The resulting livestock-type-specific tolerances were used in the final optimization run.

After determining the set of farm type changes, feeding strategies were assigned according to the specifications of each target scenario. In this step, the scenario-defined target shares were operationalized at the farm level by first assigning up to 50% of dairy cows to the local grass-based feeding plan (B3). The remaining farms were then allocated to the scenario-specific alternatives, namely the status quo feeding plan (B1) or the local forage-and-feed plan (B2), to ensure consistency with the scenario-specific shares.

4 / 3.2.4.2. Adding a temporal dimension

Building on the optimized configuration of farm type changes identified in Section 4/3.2.4.1, we simulated the timing of these shifts by generating a transition date per farm using a biased random sampling approach. Transition dates were spread over 30 years in monthly intervals (2021–2050), with the distribution skewed toward earlier dates depending on the resistance of the farm type change: shifts with lower resistance values occurred earlier, reflecting their higher likelihood, whereas transitions with higher resistance values tended to occur later. In this sense, the temporal allocation of farm changes can be interpreted as a stylized innovation diffusion process, where lower-resistance changes occur earlier and higher-resistance ones later. This temporal allocation transformed the optimized static configuration of farm type changes into stepwise transition pathways, providing a dynamic representation of how the catchment could evolve from 2020 to 2050. To capture stochastic variability, we repeated this procedure ten times for each target scenario, resulting in ten distinct time series of transition pathways.

4 / 3.3. Model description and set-up

This study builds on the LEAF.livestock model, a dynamic livestock model that simulates herd structures, production outputs, and feed requirements at monthly time steps (Heidenreich et al. submitted). Livestock populations are represented as homogeneous livestock entities (HLEs), which combine cohorts with defined life stages and management plans. At each time step, growth, production, movement, and feeding are simulated sequentially, generating time series of animal numbers, outputs, and nutrient flows.

For this analysis, the model was set up and calibrated for the Swiss livestock population in the Lake Sempach catchment using data from the AMD (2023), literature sources, and expert knowledge, as detailed in Heidenreich et al. (submitted). The calibrated baseline (01/2011 to 01/2021) captured herd dynamics, production intensities, feeding regimes, and animal movements, with December 2020 serving as the reference state (timestep 0) from which alternative pathways were initiated. The model then simulated the period 2020 to 2060, with farm type changes occurring between 2020 and 2050. The subsequent ten years were included in order to

account for lagged adjustments in herd composition and management. For instance, when transitioning from the status quo feeding plan to the grass-based plan (B3), existing animals remain under the status quo regime, and only offspring or newly purchased animals are gradually integrated under the B3 feeding plan. Model runs were then conducted separately for each herd type (dairy, suckler, pigs), each pathway (dairy-dominated vs. pig-dominated target scenario), and each of ten simulated time series of transition dates, resulting in a total of 60 runs.

To ensure stable baseline herd dynamics, transition pathways were implemented under balancing rules. Positive slaughter–offspring balances were offset by additional purchases of animals (after correcting for incoming animals among slaughtered stock and for outgoing animals among offspring), while negative balances were compensated by selling additional offspring. In this way, animal numbers remained stable over time, and changes were driven exclusively by farm-level transitions.

These *farm type changes* were executed as follows: (i) in the case of farm exits, the respective animals were sold at the transition date; (ii) for farm type changes, herd sizes were adjusted to match the composition of the target farm type, with surplus animals sold and deficits filled by purchases. These adjustments were calculated at the individual farm level and then aggregated per livestock type and timestep, assuming that animals were reallocated within the catchment before external sales or purchases took place. *Management adjustments*, such as the share of dairy offspring sold at two months, the proportion of replacement heifers for dairy and suckler cows leaving the catchment for rearing, or the share of cattle experiencing seasonal absences (see Table 4/2), were implemented at the transition dates of the individual farms. *Changes in feeding strategies* were applied as follows: for dairy cattle, additional animals resulting from farm transitions were allocated directly to the local forage-and-feed plan (B2) or the local grass-based feeding plan (B3). Animals already present in the catchment were treated differently depending on the transition: shifts from business-as-usual (BAU) to B2 involved an immediate reassignment, while a direct shift from BAU to B3 was considered agronomically infeasible for the intensively kept dairy cattle. In such cases, animals remained under BAU until the end of their productive cycle, but new offspring or purchased animals entered directly into B3. For suckler cattle, by contrast, both new animals and those already present in the catchment were immediately reassigned to the local grass-based feeding plan (B3) once their farm was affected by a transition at a given time step.

4 / 4. Results

4 / 4.1. Pathways towards target scenarios

4 / 4.1.1. Achieving target scenarios under tolerance constraints

Because farms could only transition as whole units, exact reproduction of target livestock numbers was not feasible. To address this, the optimization introduced tolerance levels specifying the allowable deviation

between realized and target animal numbers. The lowest feasible global tolerance was similar between the two target scenarios, but livestock-type specific values varied (Table 4/4).

Table 4/4: Comparison between **2020 status quo animal numbers**, the **2050 targeted numbers**, and the **realized numbers** obtained through optimization, shown separately for the pig- and dairy-dominated target scenarios. The table also reports the lowest feasible tolerance levels and realized-to-target ratios per livestock type. The **lowest feasible tolerance level** reflects the minimum deviation from target values required to maintain model feasibility. The **realized-to-target ratio** indicates how closely the final animal numbers aligned with the targets (a ratio of 1 indicates a perfect match, values above 1 indicate overshoots, and values below 1 indicate shortfalls). **Note:** Calf fattening and suckler cow calves were excluded from direct optimization constraints.

		Dairy herd					Suckler herd		Pig herd		
		Dairy cow	Calf fattening	Bull fattening	Ox fattening	Cattle fattening	Cattle and Ox fattening	Suckler cow	Suckler cow husbandry	Finishing pig	Breeding sow
2020 status quo animal numbers		5'197	'491	'421	'225	'733	'0	1'172	'533	18'600	2'771
Pig-dominated scenario	Targeted change of animal numbers	-4'324	n/a	-382	-213	-676	102	-954	n/a	11'661	1'737
	Lowest feasible tolerance level	5%	n/a	-2%	-11%	9%	1%	4%	n/a	-5%	4%
	Realized change of animal numbers	-4'116	n/a	-391	-236	-615	101	-920	n/a	12'239	1'664
	Targeted number of animal	873	14	39	12	57	102	218	78	30'261	4'508
	Realized number of animals	1'081	42	16	8	34	101	223	127	30'927	4'445
	Realized-to-target ratio	1.24	3.03	0.40	0.64	0.59	0.99	1.02	1.63	1.02	0.99
Dairy-dominated scenario	Targeted change of animal numbers	-160	n/a	-198	-153	-402	587	-1'172	n/a	-9'871	-1'471
	Lowest feasible tolerance level	4%	n/a	-13%	14%	8%	3%	5%	n/a	4%	3%
	Realized change of animal numbers	-153	n/a	-224	-132	-368	568	-1'114	n/a	-9'427	-1'430
	Targeted number of animal	5'037	82	223	72	331	587	-	-	8'729	1'300
	Realized number of animals	5'044	11	183	112	281	568	29	26	9'261	1'351
	Realized-to-target ratio	1.00	0.14	0.82	1.55	0.85	0.97	#DIV/0!	#DIV/0!	1.06	1.04

To reach the pig-dominated target scenario, moderate tolerance levels were sufficient for most livestock types, with the highest values observed for ox fattening (-11%), and cattle fattening (9%). The pig herd was reproduced closely, with finishing pigs slightly above target (realized-to-target ratio 1.02, meaning that 102% of the target was achieved) and breeding sows nearly identical (0.99). Larger deviations occurred in livestock types within the dairy herd: calf fattening substantially exceeded its target (3.03) and suckler cow husbandry also overshoot (1.63). These very high ratios are largely explained by the small absolute target numbers for these groups (42, and 127 animals, respectively), where even minor deviations resulted in large proportional effects.

To reach the dairy-dominated target scenario, tolerances were generally comparable or slightly higher, though most remained below 10%. Major livestock groups aligned well with their targets: dairy cows (1.0), finishing pigs (1.06), breeding sows (1.04), and cattle and ox fattening (0.97) were all close to 1.0. Notable deviations nevertheless remained, including an overshoot in ox fattening (1.55) and lower-than-target values for calf fattening (0.14), bull fattening (0.82), and cattle fattening (0.85). As in the pig-dominated pathway, calf fattening and suckler cow calves were not directly constrained in the optimization, as suckler cow calves are inherently linked to suckler cow numbers, and calf fattening was subsequently adjusted manually through the *Mixed cattle fattening – veal* farm type.

4 / 4.1.2. Catchment-level transitions: farm type and management changes

Farm type changes. Farm type restructuring differed markedly between the two target scenarios (Figure 4/4). To reach the pig-dominated target scenario, the most prominent transition was the dismantling of mixed pig–cattle systems. In total, 100 farms originally classified as *Pig finishing* (n = 40), *Pig breeding* (n = 36), or *Combined pig breeding and finishing* (n = 24) were affected. The optimization reassigned many of these farms to simplified pig-only structures such as *Pig finishing (without cattle)* or *Pig breeding (without cattle)*. Exits from livestock production affected 65 farms in total, with *Dairy production with rearing/fattening* (n = 31), *Suckler cows* farms (n = 18), and various cattle-specialized types accounting for the largest share. These exits contributed to a substantial reduction in livestock density and a streamlining of the production base toward pig specialization. In contrast, to reach the dairy-dominated target scenario, the restructuring relied more on internal reorganization, rather than exits. A notable share of farm type changes involved structural consolidation combined with an extensification through a conversion to organic production. For example, *Pig finishing* (n=12), *Pig breeding* (n=26), and *Combined pig breeding and finishing* farms (n=23) were reassigned to *Organic dairy production without rearing/fattening*. Exits were less frequent than in the pig-dominated scenario (11% versus 27%) and were concentrated among suckler cow and fattening farms.

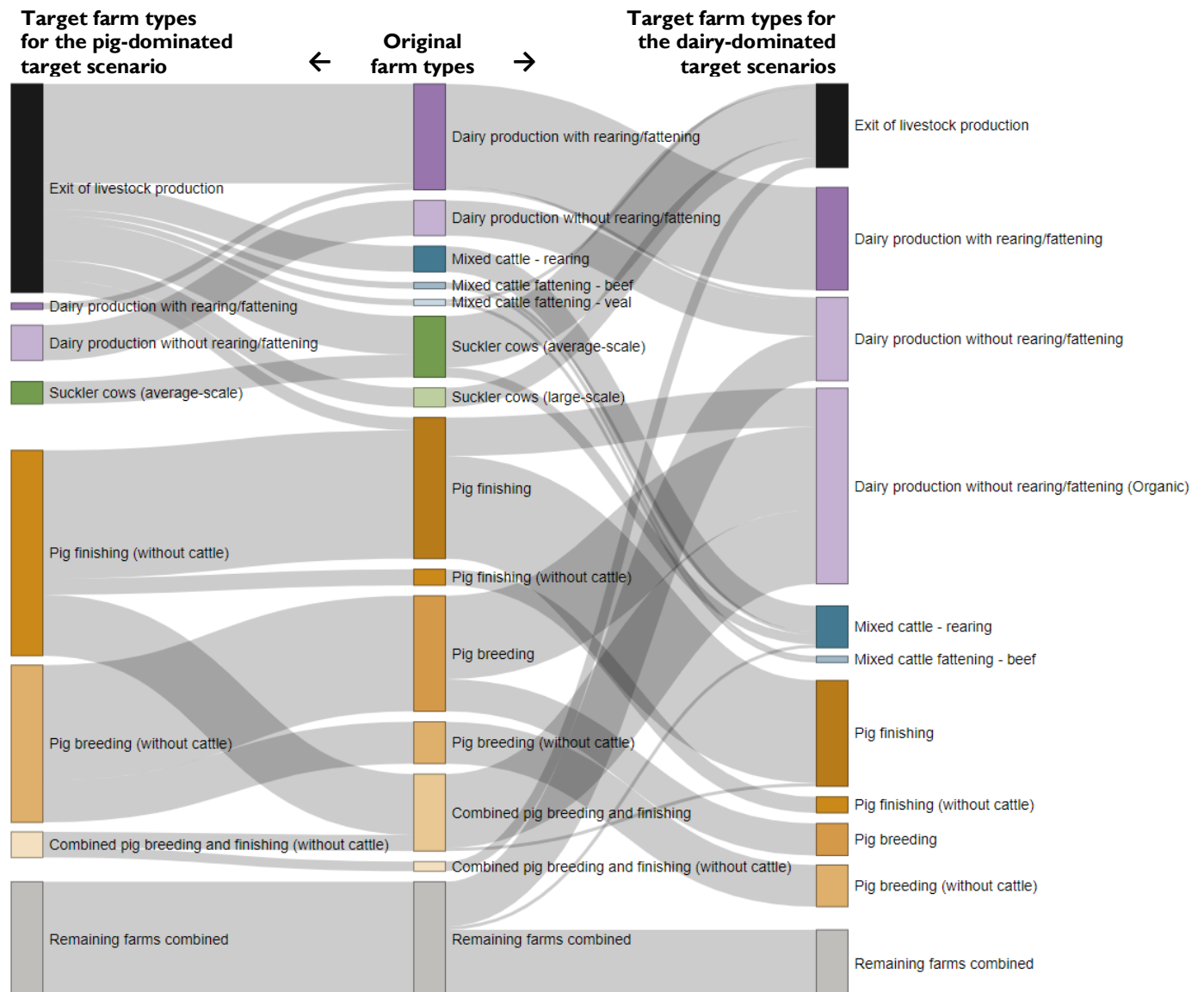


Figure 4/4: Farm type changes towards contrasting target scenarios. This Sankey diagram illustrates how current livestock farms (centre) are transformed towards the pig-dominated target scenario (left) and towards the dairy-dominated scenario (right). Each flow represents a group of structurally identical farms changing their current farm type (centre) to an alternative farm type under the respective scenario. Node colours indicate farm types and are consistent across the diagram to highlight shared categories.

Management changes. Beyond structural farm-type shifts, we also assigned management changes. All farms with dairy or suckler herds were required to implement the target settings for offspring fate, outside rearing, and seasonal absences (Table 4/2). The most prominent adjustments concerned feeding strategies (Figure 4/5). To achieve the pig-dominated target scenario, these adjustments played only a secondary role: 19% of farms were affected by feeding strategy changes, reflecting the dominance of exits and farm type simplification. To realize the dairy-dominated target scenario, feeding adjustments were central. 34% of farms underwent both a farm type change and a feeding strategy change, while 48% were reconfigured solely through feeding adjustments, with 39% via dairy herd feeding strategies and 9% through combined changes across dairy and suckler herds. Thus, whereas the pig-dominated pathway achieved its targets largely through structural

reduction and simplification, the dairy-dominated pathway relied more heavily on management level adaptation within the existing farm type structure.

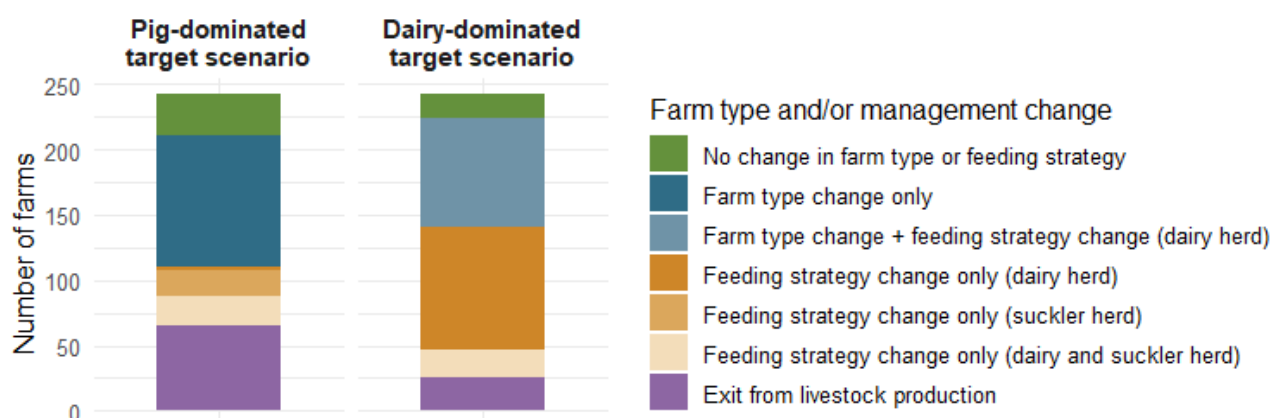


Figure 4/5: Distribution of farm type and/or feeding strategy changes towards the pig-dominated target scenario (left) and towards the dairy-dominated target scenario (right).

4 / 4.1.3. Temporal dynamics of transition pathways

Adding a temporal dimension highlighted contrasting dynamics between the two pathways (Figure 4/6). The timing of farm type and management changes reflected their resistance levels, with low-resistance changes realized earlier and high-resistance changes postponed to later years. When pooling results across the ten simulated time series, restructuring toward the dairy-dominated scenario generally occurred earlier (on average 11 years after the start of the simulation), while achieving the pig-dominated target scenario involved more gradual and prolonged adjustments (mean of 12 years), reflecting the higher resistance of the required changes. In the pathways towards the dairy-dominated scenario, feeding strategy adjustments in dairy herds appeared first, on average after 9.8 years (median of 7.3 years), followed by broader feeding changes across dairy and suckler herds (mean of 9.7 years, median of 7.3 years). Farm type changes and combined feeding–farm type adjustments took place somewhat later (mean of 12.5 years, median of 10.9 years), while exits from livestock production were centred around 12.5 years (median of 11.6 years). In contrast, pathways toward the pig-dominated scenario unfolded more gradually and with a wider spread. Feeding strategy changes in dairy herds occurred earliest (mean of 9.3 years, median of 4.8 years), followed by feeding changes in both dairy and suckler herds (mean of 9.6 years, median of 8.3 years) and suckler-only herds (mean $\approx$ 10.5 years, median 8.8 years). Farm type changes were realized later (mean of 12.1 years, median of 10.8 years), while exits from livestock production were the most delayed (mean of 13.3 years, median of 12.8 years).

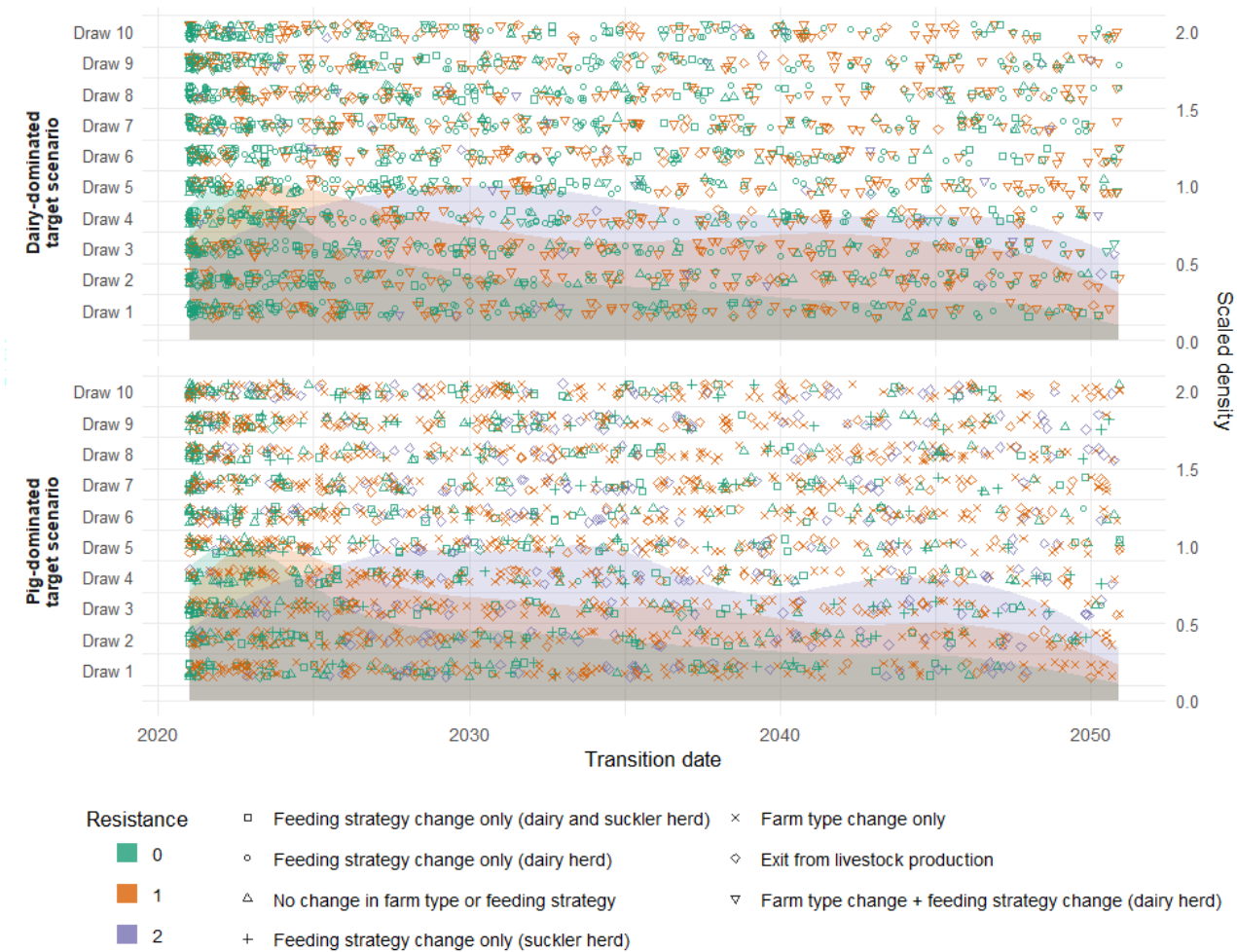


Figure 4/6: Simulated farm-level transition timelines under contrasting target scenarios. Each point represents a simulated transition date for an individual farm and time series (Draw), where colours indicate transition resistance and shapes denote type of farm transition pathway. Background density curves reflect the distribution of transition timings by resistance level.

4 / 4.2. Assessment of pathways towards targets

4 / 4.2.1. Phosphorus excretion along pathways

Development of P excretion over time revealed minor differences between the two transition pathways (Figure 4/7). Under the baseline (red line), monthly P excretion remained stable at around 9–10 t P per month until the end of 2020. At the onset of farm type and management changes, P excretion temporarily increased, as the expansion of the pig herd in pathways toward the pig-dominated target scenario (or of the dairy herd in pathways toward the dairy-dominated target scenario) began right at the start of the transition pathways, whereas the corresponding reduction of the other herd type occurred only later. Following this brief increase, both target scenarios showed a marked decline, but with distinct dynamics. Pathways toward the dairy-dominated scenario (blue lines) reached the target range by around 2038 at an average reduction rate of -1.1 t P per year and then stabilizing near 8.3 t/month, i.e. near the upper boundary of the target range. Pathways toward the pig-dominated scenario (orange lines) showed a much steeper and earlier decline, reaching the

target by 2028 with an average reduction rate of -2.5 t P per year and stabilizing close to 6.3 t/month. While individual time series varied slightly in timing and slope, the overall patterns were robust: both pathways converged toward the target within the same timeframe, with only marginal differences in long-term stabilization levels.

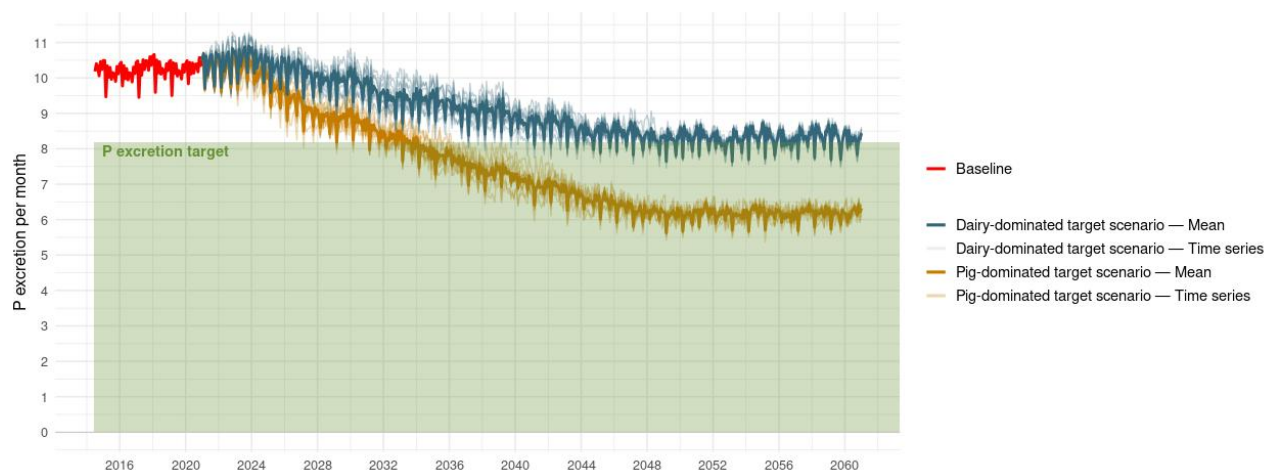


Figure 4/7: Development of P excretion over time under two different pathways. The red line represents the baseline until 12/2020. Lighter orange lines show individual transition pathways (time series 1 to 10) toward the pig-dominated target scenario, with the thicker orange line indicating the mean. Lighter blue lines show individual transition pathways toward the dairy-dominated target scenario, with the thicker blue line indicating the mean. The transparent green boxes mark the target range for P excretion (78 t P/year plus 20.3 t P/year exported via farmyard manure).

The overall reduction dynamics also shaped how P accumulated above the target level over the full simulation period (Figure 4/8). Clear differences emerged between the two pathways: cumulative P surpluses were substantially higher under the pathways towards the dairy-dominated target scenario, with interquartile values ranging from 380 to 460 t P, whereas pathways towards the pig-dominated target scenario accumulated much lower surpluses (IQR = 160 to 190 t P). Thus, while both scenarios eventually reached the target range, their long-term cumulative impacts differed markedly.

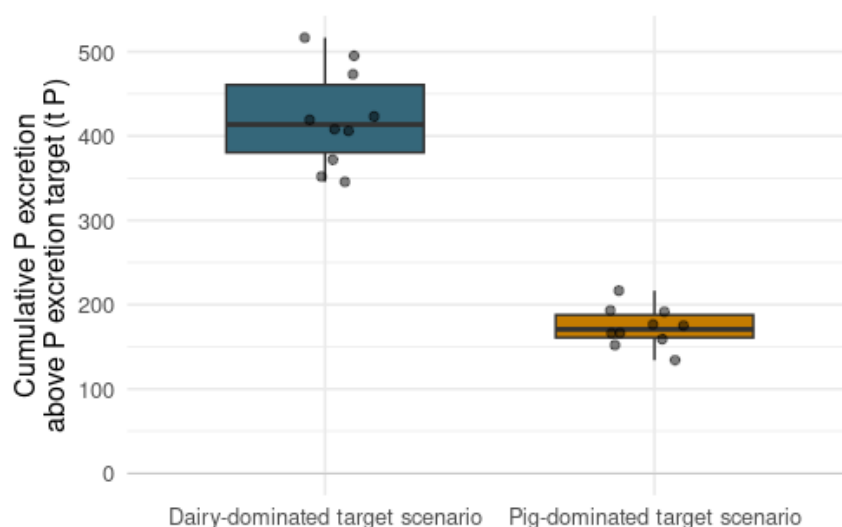


Figure 4/8: Cumulative P excretion above P excretion target across the full simulation period. Boxplots show the distribution of cumulative P excretion across time series, with individual points representing single time series.

4 / 4.2.2. Livestock and management restructuring along pathways

While Section 4/4.2.1. highlighted how P excretion developed under the two pathways, Figure 4/9 and Figure SM4/5 and SM4/6 illustrate the underlying restructuring of livestock herds and management strategies. The following subsections illustrate how the farm type changes and resistance-based timing rules translated into dynamic herd and management trajectories.

Herd-level restructuring. Figure 4/9 shows how the resistance-weighted timing of farm type changes translated into changes at the herd-level. Because different farm types carry distinct herd compositions, earlier transitions of low-resistance farm types resulted in earlier adjustments of their associated herds, while shifts in higher-resistance farm types occur later and thus delay changes in the corresponding herds. This produced the stepwise evolution of dairy, pig, and suckler herds toward their scenario-specific compositions.

Livestock-type-specific adjustments. Disaggregating further into livestock types illustrates how simulated animal numbers gradually approached both the targeted and realized values over time (Figure SM4/5). The *targeted numbers* were directly derived from the specifications of the 2050 target scenarios, while the *realized numbers* resulted from the optimization procedure, which translated farm type changes into herd adjustments under the constraint of whole-farm transitions and predefined tolerances. The gradual reduction of the gap between simulated animal numbers and these reference values reflects how the system moved stepwise toward the scenario goals.

Management strategy allocation within herds. Management strategy dynamics show how BAU management gradually declined, while target-specific strategies, such as the local forage-and-feed plan (B2) or the local grass-

based feeding plan (B3), gain importance over time (Figure SM4/6). Beyond feeding, other target-specific adjustments are reflected, including the sale of all calves at two months (C1), the rearing of all replacement heifers for dairy and suckler cows outside the catchment (D1), and the seasonal absence of all cattle (D2). These shifts follow directly from the scenario design and allocation procedure but provide a clear picture of how management changes are phased in within herds.

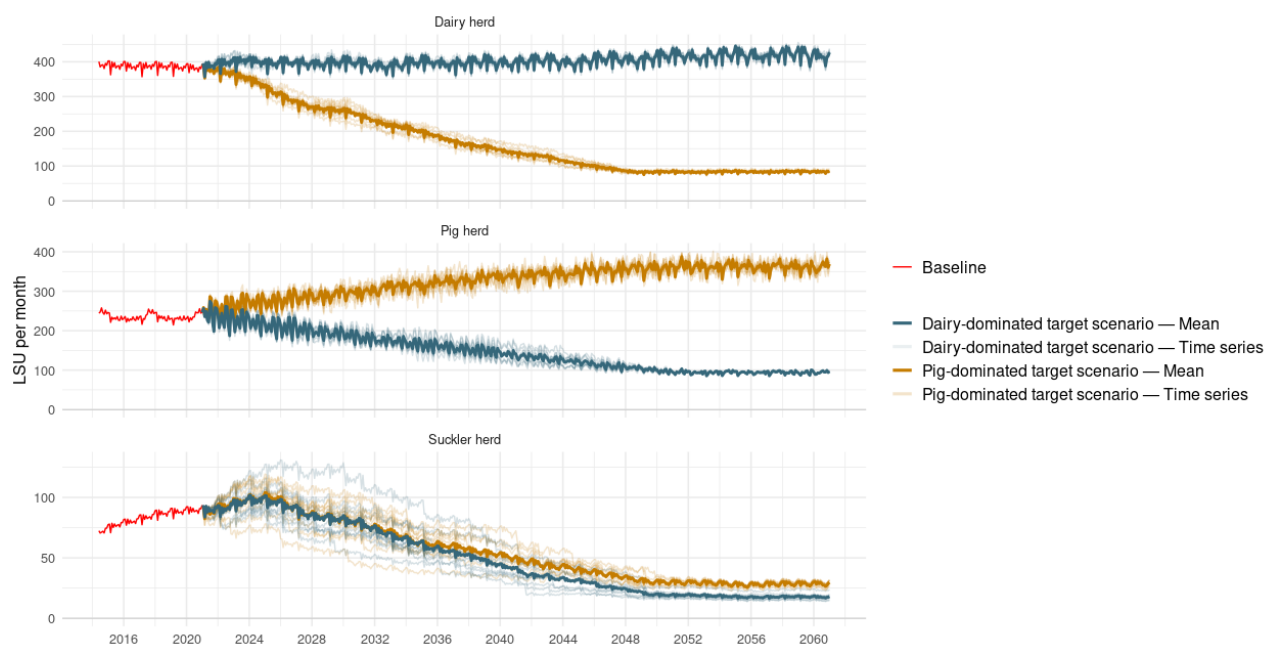


Figure 4/9: Development of livestock units (LSU per month) over time under two different pathways for different livestock herds, displayed in vertically arranged panels. The red lines represent the baseline until 12/2020. Lighter orange lines show individual transition pathways (time series 1 to 10) toward the pig-dominated target scenario, with the thicker orange lines indicating the respective mean. Lighter blue lines show individual transition pathways toward the dairy-dominated target scenario, with the thicker blue lines indicating the respective mean.

4 / 5. Discussion

4 / 5.1. Linking catchment-level targets with farm-level change processes

This study applied a back-casting/target-seeking approach to connect long-term reduction targets with possible pathways for achieving them (IPBES 2016a). Building on Heidenreich et al. (submitted), which outlined alternative futures for the Lake Sempach catchment, we derived concrete transition pathways that show how livestock restructuring could unfold towards these targets. In doing so, the study bridges target knowledge with transformation knowledge, shifting the emphasis from abstract targets to implementable change processes that can inform practice and policy. A key contribution is thus the attempt to close existing *transformation gaps* by linking scenario-based target setting with concrete pathways of change (Duygan et al. 2025).

A key innovation of our framework is the explicit linkage between catchment-level targets and farm-level decision-making. By applying a resistance-weighted optimization approach under tolerance constraints, we derived whole-farm transition pathways toward catchment-level P reduction targets while maintaining

structural detail at herd and management level. In doing so, the framework addresses a common scale mismatch in social-ecological systems (Cumming et al. 2006): the catchment of Lake Sempach is a suitable unit for setting environmental targets, yet it does not align with existing decision-making structures at farm levels. By bridging these scales, the analysis improves the relevance and applicability of catchment-level solutions. Adding a temporal dimension further enhanced realism. Resistance-weighted timing rules transformed a static optimization into dynamic trajectories, showing how restructuring might evolve stepwise over three decades. While simplified, our resistance concept captured important barriers to change (infrastructure, labour and workload, animal health and management, and regulatory or market issues). This made the simulated pathways more credible than those based solely on technical feasibility. Moreover, simulating farm type and management changes along a temporal axis revealed that such transitions may even entail short-term increases in P excretion. In the simulated pathways, this temporary rise resulted from the early expansion of the pig herd in pathways toward the pig-dominated target scenario (or of the dairy herd in pathways toward the dairy-dominated target scenario), while the corresponding reduction of the other herd type occurred only later. These transitional effects became visible only when the temporal dimension was explicitly considered, highlighting the importance of such dynamic perspectives for informed decision-making in practice.

4 / 5.2. Pathway-specific restructuring dynamics

The two selected target scenarios share the objectives of reducing P excretion in the catchment while maintaining or increasing animal-source protein production and respecting local grassland resources. However, they pursue these goals through different strategies, representing contrasting ends of the option space. This contrast is mirrored in the pathways toward them, which differ in which farm types are most affected, the types of transitions required, and the degree of structural disruption. Pathways toward the pig-dominated target scenario required a large number of farm type changes and exits from livestock production, reflecting the need for stronger structural adjustments. In contrast, pathways toward the dairy-dominated target scenario involved considerably fewer farm exits and fewer farm type changes. Here, most farms were primarily affected by changes in the feeding regimes of their cattle herds rather than by structural reorganization. The following sections discuss in more detail three key aspects of these restructuring processes: (i) farm exits, (ii) specialization dynamics, and (iii) feeding plan changes.

4 / 5.2.1. Farm exits

Both pathways required certain farm types to leave livestock production altogether. Farms specialized in *Mixed cattle – rearing* or *Mixed cattle – fattening (beef and veal)* were assigned to exit in both scenarios. *Suckler cow* farms exited entirely under the dairy-dominated pathway, while under the pig-dominated pathway only part of this

farm type exited. For the pathway towards pig-dominated target scenario, additional farm types had to leave livestock production, implying a stronger reliance on farm exits as a restructuring mechanism.

In Switzerland, the ongoing generational turnover in agriculture may offer a window of opportunity to incentivize such exits, as almost one-third of farmers are expected to reach retirement age between 2020 and 2030, increasing the probability of farm exits (Zorn 2020; Ferjani et al. 2015). Specifically for dairy farms, studies confirm the same trend: older farmers are more likely to exit (Zorn and Zimmermann 2022). At the same time, exits are associated with smaller herd sizes, averaging around twelve dairy cows, whereas larger farms measured by number of cows or employees appear less likely to leave livestock production. Policy could therefore prioritize the stabilization of viable dairy farms through targeted growth support, while at the same time offering tailored exit options for older farmers nearing retirement (Zorn and Zimmermann 2022). Facilitating such exits will therefore require targeted policy support. Government-run decommissioning schemes may be one relevant instrument to support these transitions: evidence from Germany suggests strong farmer interest in such programs when adequate compensation and conditions are provided (Thiermann et al. 2023). By contrast, implementation attempts in the Netherlands triggered strong farmer resistance and mobilization (Upham et al. 2025), highlighting the importance of scheme design and legitimacy. Exits may also reflect broader transition pathways identified elsewhere, where farmers leaving intensive livestock systems transitioned to horticulture, agritourism, or even animal sanctuaries, depending on motivations and available support structures (Salliou 2023).

4 / 5.2.2. Specialization

Restructuring toward the pig-dominated target scenario required a large number of farm type changes, affecting 42% of all farms, many of which involved transitions into specialized systems. For example, farms categorized as *pig breeding* or *pig finishing* typically also keep around 22 and 29 dairy cows, respectively. Under this pathway, however, the dairy branch was discontinued and pig numbers doubled, reflecting also broader structural trends in Swiss agriculture toward specialization and growth (Zorn 2020; El Benni et al. 2012). Similar, though less pronounced, specialization processes also occurred under the pathway towards the dairy-dominated target scenario, for instance when mixed pig–dairy farms transitioned into dairy-only systems or when replacement heifer rearing was outsourced. The latter could be facilitated through inter-regional contract rearing, which has been shown to increase income potential for lowland farms while reducing workload for the mountain counterparts, though without corresponding income benefits in those regions (Marton et al. 2016). Such arrangements would therefore require tailored support measures. At the same time, specialization is not without risks. Evidence shows that specialized farms may be less resilient because they rely on fewer outputs and face higher income volatility (El Benni et al. 2012; Pfeifer et al. 2022). Off-farm income can help buffer these risks, as studies indicate it reduces household income instability, particularly in valley and hill regions, even

though it may increase revenue risks in some contexts (El Benni et al. 2012). For dairy farms, diversification through agritourism has also proven to be an advantageous strategy, providing both additional income and increased resilience (Hochuli et al. 2021).

4 / 5.2.3. Feeding plan changes

In contrast to structural reorganization, the pathway towards the dairy-dominated target scenario was characterized mainly by changes in feeding strategies, affecting the majority of cattle farms. These shifts included among others transitions toward grassland-based milk and meat production, supported in practice e.g. by Switzerland's voluntary GMF program¹¹ introduced in 2014. Studies show that participation in GMF reduces concentrate use and increases reliance on grass feeds, while additional price premiums can make grass-fed production cost-efficient, particularly when only minor system adjustments are required (Hoop 2021; Mack and Kohler 2019). However, more substantial adaptations, such as changes in herd genetics or the repurposing of infrastructure, may be less economically viable. In our pathways, feeding strategy changes thus represent a lower resistance but still transformative adjustment that could be scaled with the right policy incentives. Beyond feeding, other management measures were phased in across both pathways, such as selling calves at two months, and seasonal cattle absences. These measures illustrate that even without major farm type changes, significant adjustments in herd management practices are involved.

4 / 5.3. Limitations & Outlook

We would like to acknowledge that this study applied a “social-planner” perspective, with pathways designed by researchers based on targets, resistance scores, and optimization rules, guided by literature and expert judgment. While this approach provides structural clarity, it does not capture the full diversity of farmer behaviour and agency. Farmers may not follow optimized transitions in practice, and human decision-making is not explicitly represented. This study should therefore be understood as an illustration of possible pathways. By integrating structural and management detail at the required resolution, it provides an initial foundation for subsequent extensions that could more explicitly incorporate behavioural diversity and participatory elements. Future research can address these limitations in several ways. Stakeholder engagement could enrich the resistance matrix and refine transition pathways, for instance through participatory backcasting (Duygan et al. 2025) or analytical frameworks for co-designing target-seeking scenarios (Aguiar et al. 2020). Agent-based modelling could further capture heterogeneity in farmer decision-making and explicitly integrate economic

¹¹ **Note:** The GMF (Graslandbasierte Milch- und Fleischproduktion) program is a national production system contribution to promote locally adapted milk and meat production. Aimed at farms that cover their feed requirements primarily with grass, hay, and grass silage.

considerations. Furthermore, linking the framework with policy simulations (e.g. subsidies, regulations) would allow testing how different incentive structures shape the feasibility and timing of pathways.

Finally, situating the framework within broader transition theories could sharpen the interpretation of the empirical findings. The observed reliance on farm exits, specialization processes, and feeding plan changes can be understood through the lens of niche–regime dynamics: while some transitions align with existing structural trends (e.g., specialization in pig production), others require regime-level adjustments (e.g., decommissioning schemes or support for grassland-based milk production) (Geels 2002, 2004). Concepts such as leverage points help to highlight where policy interventions, such as targeting older farmers nearing retirement, or incentivizing low-resistance feeding adjustments, could accelerate change (Meadows 1999; Magliocca et al. 2025). In addition, insights from diffusion of innovation theory (Rogers 1983) could help identify possible tipping points, where early change by a subset of farms might trigger wider uptake of new practices. By linking farm-level restructuring to these broader perspectives, the framework offers not only a tool for assessing transition pathways but also an entry point for understanding how transition processes in Swiss livestock production could be governed more effectively.

4 / 6. Conclusion

Overall, this study demonstrated that catchment-level P reduction targets can be translated into concrete farm-level transition pathways, by explicitly accounting for resistance and tolerance. In doing so, we generated transformation knowledge that can inform both policy and practice, because trade-offs and synergies of individual targets can only be fully understood when the implementation pathways are also examined. These pathways may differ substantially from one another and, in some cases, reveal that a particular target is not viable given the challenges of implementation. The two contrasting target pathways illustrate this point clearly: while both pursue the same objectives, but the routes to achieve them differed fundamentally. The pig-dominated pathway relied heavily on specialization and farm exits, whereas the dairy-dominated pathway centred more on changes in feeding strategies, with comparatively fewer farm-type transitions and exits.

The findings highlight that solving the problem will inevitably require far-reaching structural adjustments, whether through specialization, farm exits, or changes in management. The scenarios presented here are therefore not optional add-ons to current practice but necessary strategies if the environmental challenges are to be solved. With timely action and supportive policies, however, the transition is both possible and manageable. Thus, our approach provides a concrete support tool for regional planning and policy-making, moving the debate from abstract goals toward implementable change processes.

Finally, the catchment of Lake Sempach reflects challenges shared by many regions with high livestock densities, nutrient surpluses, and ageing farmer populations. While this study focused on livestock

restructuring in a livestock-intensive watershed, even more drastic measures, such as reducing or phasing out livestock altogether, are being discussed in other contexts. By connecting environmental targets with feasible farm-level pathways, the framework contributes not only to the Swiss debate but also to broader discussions on how sustainability transitions in agriculture can be governed effectively.

4 / 7. Acknowledgements

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With this dissertation, I aimed to **advance model-based approaches for designing locally adapted agricultural systems and to explore pathways toward these desirable future states**. In this chapter, I synthesise the key findings from the three preceding chapters, discuss their scientific and practical implications, and show how they contribute to the essential systems, target, and transformation knowledge required for agricultural sustainability transitions (Section 5/1.). I then critically reflect on the approach taken, outlining its main limitations, and conclude with an outlook on promising directions for future research (Section 5/2.).

5 / 1. Main findings and their scientific and practical implications

The findings presented in this section progress from identifying limitations in current modelling approaches for agricultural landscape assessments (Section 5/1.1.), through addressing one of these gaps via the development of the LEAF.livestock model (Section 5/1.2.), to insights gained from its application to the pilot case study (Section 5/1.3.). Finally, I take a broader perspective by reconsidering the role of animal- versus plant-source protein in livestock-focused agricultural landscape, emphasizing the tension between environmental ambition and social feasibility (Section 5/1.4.). The scientific and practical implications of each finding are discussed in the respective subsections.

5 / 1.1. Limitations in existing modelling approaches for agricultural landscape assessments

Finding 1. The identified limitations in existing modelling approaches for agricultural landscape assessments can lead to a reduced system understanding, potentially resulting in biased conclusions and suboptimal decisions.

As highlighted in the introduction of this dissertation, agricultural landscapes are a highly relevant spatial level to move towards agricultural practices that are better aligned with local ecosystems. Models are central to this task, as they help to generate the urgently necessary systems, target, and transformation knowledge. However, in Chapter 2, I showed that existing modelling approaches for agricultural landscape assessments exhibit several blind spots. These range from an incomplete representation of landscape multifunctionality, to insufficient inclusion of abiotic, biotic, and management-related driving factors, as well as a lack of crop–livestock integration and limited attention to food-system-level linkages such as by-product flows or off-site effects.

It should be acknowledged that the review presented in Chapter 2 covered publications up to 10/2021. However, even though it is a rapidly evolving research field, several more recent review studies, drawing on extended publication periods up to 2023/2024, largely corroborate the conclusions of Chapter 2. These reviews identify a recurring set of widely used modelling frameworks (e.g. InVEST, SWAT, APEX), but similarly highlight persistent limitations, including an incomplete representation of ecosystem services such as pest control, a continued reliance on proxy-based approaches, and the challenge of balancing model simplicity with

meaningful, context-specific results (Inácio et al. 2025; Mukhopadhyay et al. 2025; Li and Goslee 2025). Notably, they confirm that livestock production remains weakly integrated into landscape-level ecosystem service assessments, with animal production either marginally represented or entirely absent, and explicitly call for improved modelling of integrated crop–livestock systems (Inácio et al. 2025; Mukhopadhyay et al. 2025).

These limitations have important implications for both practice and research. If modelling practices fail to capture key processes and relationships, assessments risk leading to biased or incomplete decisions while overlooking critical dynamics that are essential for identifying robust levers of change and revealing the full potential of action. Policymakers and practitioners should therefore be aware not only of what is included in a model, but also of what is omitted, especially when such assessments guide long-term transitions. For researchers and modellers, this underlines the need to begin with a comprehensive systems understanding of the landscape to ensure that all relevant components and driving factors that influence the ecosystem structures and services are included, and then strategically simplify models according to the context. The framework of *“Key elements of agricultural landscape assessments”*, which was introduced in Chapter 2 (Figure 2/2), can support both groups in critically evaluating model scope and outputs, guiding appropriate choices, and ensuring more transparent, credible, and practically relevant outcomes.

5 / 1.2. Extending modelling approaches for agricultural landscape assessments with LEAF.livestock

Finding 2. The LEAF.livestock model developed in this thesis addresses the identified limitations by offering a comprehensive representation of livestock systems and enabling their integration into established modelling approaches for agricultural landscape assessments.

As identified in Chapter 2, the majority of modelling approaches for agricultural landscape assessments do not consider livestock production. Among those that do, most rely on simplified indices or metrics, with only a few accounting for bidirectional flows between crop and livestock systems, such as manure-based nutrient cycling or the use of crop-derived feed and by-products. This is a significant gap, given the important role livestock systems play in shaping land use, nutrient cycles, and food system sustainability as illustrated in the introduction of this dissertation. To address this gap, I developed and presented the dynamic livestock model LEAF.livestock, which was designed to enhance the representation of livestock systems within broader agricultural landscape assessments.

From a modelling and research perspective, the LEAF.livestock model demonstrates several key strengths: (1) connectivity, (2) flexibility and adaptability, (3) multiplicity of solutions, and (4) temporal dynamics, which together highlight its potential to enhance agricultural landscape assessments and to support more comprehensive analyses of livestock systems. These strengths are illustrated in the following sections.

(1) Connectivity: The LEAF.livestock model contributes directly to addressing the shortcomings identified in Chapter 2. Its modular design facilitates coupling with widely used process-based models such as SWAT, EPIC/APEX, or DayCent, which provide detailed spatio-temporal representations of hydrological processes, soils, and land management, but lack adequate livestock representation (Arnold et al. 2012; Jones et al. 2021; Muntwyler et al. 2024). With the LEAF.livestock model, agricultural landscape assessments are no longer limited to crop management variations, but can now meaningfully include livestock management strategies, herd structure transformations, and feeding system reconfigurations. Through such couplings, researchers can capture nutrient and product flows between crop and livestock systems more comprehensively, including the implications for nutrient budgets, emissions, and circularity.

(2) Flexibility and adaptability: The model code and documentation are openly available on Zenodo (Heidenreich et al. 2025b), and although it was parameterized based on Swiss and European reference data, the structure is sufficiently flexible for adaptation to other contexts. This flexibility is essential, as context is key to understanding and improving livestock production systems (Kazanski et al. 2025). Moreover, the model's structure allows both future expansions (e.g. additional livestock types or management options) and simplifications (e.g. fewer life stages per livestock type), depending on the research question and data availability, while still capturing spatio-temporal detail equivalent to that of the above-mentioned models, thereby facilitating their coupling. As such, the LEAF.livestock model provides a robust foundation for future applications aiming to better integrate livestock systems into agricultural landscape modelling.

(3) Multiplicity of solutions: A further strength of the LEAF.livestock model is in being able to create a broad option space for scenario exploration, rather than limiting the analysis to a single global optimum. This supports a more nuanced understanding of trade-offs and synergies between livestock system goals. Compared to classical optimisation models, which typically converge on a single optimal solution depending on the initial conditions or model setup, my approach allows the identification of multiple local optima. For example, the analysis revealed several Pareto rank 1 scenarios, but based on distinctly different P reduction strategies. This illustrates that the same performance outcome can emerge from fundamentally different configurations, emphasising the value of exploring a diverse option space rather than relying on one “best” pathway.

(4) Temporal dynamics: The analysis of P reduction pathways in Chapter 4 demonstrates how agricultural landscape modelling can be extended to include transformation knowledge, a dimension often overlooked in existing approaches, leading to so-called “transformation gaps” (Duygan et al. 2025). This extension is made possible by the model's ability to account for the temporal dynamics of livestock production systems. In doing so, it becomes possible to incorporate concrete interventions and capture the broader transformations required to align livestock production with local ecosystems, while also reflecting inherent interannual and intra-annual variabilities, such as lifetime and seasonal performance fluctuations, or calving and movement patterns, including purchases, sales, and temporary absences.

5 / 1.3. Application of LEAF.livestock to explore transition pathways for phosphorus reduction in livestock production

Finding 3. The first application of the LEAF.livestock model demonstrated its capacity to generate both target and transformation knowledge by identifying region-specific P reduction strategies and simulating multiple transition pathways, thereby supporting decision-making towards more locally adapted agricultural systems.

The first application focused on a catchment in Central Switzerland facing persistent P pollution, providing a valuable opportunity to test the model in a real-world setting characterised by disrupted nutrient cycles from intensive livestock production. In Chapter 3, I used the model to generate target knowledge by identifying herd structures and management practices that could meet region-specific environmental and production constraints and with this to lead to a locally adapted agricultural system. The analysis showed that no single strategy could satisfy all constraints simultaneously, but relaxing the land-use constraint opened up a broad range of viable and Pareto-optimal scenarios. These differed substantially in their underlying configurations, such as livestock composition (highlighting the role of livestock type specific P emissions per protein output), feeding strategies (highlighting the role of feed origin), and other management factors (highlighting the role of offspring fate and temporary absences during unproductive life stages). In Chapter 4, I extended the analysis to also generate transformation knowledge by simulating transition pathways while accounting for the resistance against shifts between farm types. This made it possible not only to identify desirable system states but also to explore the structural and management changes required to reach them, thereby linking environmental targets with real-world transition pathways.

These findings carry several implications for the case study region and for practice and policy more broadly. Most notably, the model results can enable a more nuanced discussion in a case study context where debates have often been polarised: some actors have called for blanket reductions in animal numbers, livestock producers have defended current practices, and public debates have tended to lack differentiated, actionable alternatives (Luzerner Zeitung 12/10/2018; SRF 1/23/2024, 12/14/2023; SRG.D 2024). At the same time, past research and monitoring has largely focused on water quality, hydrology, and land management, leaving the complexity of livestock production underexplored (Stoll et al. 2019; UWE and AfU 2023; Prasuhn and Lazzarotto 2005). In this context, the application of the LEAF.livestock model proves highly valuable, as it systematically links livestock diverse P reduction strategies, ranging from herd restructuring to feeding system adaptations, and thereby broadens the scope of options considered. This provides a more comprehensive assessment of livestock production as a core component of agricultural landscapes. The results therefore highlight both the magnitude of change required and the diversity of feasible options, offering a valuable starting point for stakeholder dialogues, not only about environmental targets but also about the underlying values and priorities, that ultimately shape transition strategies. In doing so, the model provides a foundation

for building consensus around shared goals, while recognising the diversity of pathways and the trade-offs they entail.

While the results in Chapters 3 and 4 illustrate viable target scenarios and transition pathways towards them, they also raise the crucial question of how such locally adapted systems can be implemented in practice. As already outlined in the introduction of this dissertation, governance at the landscape level remains challenging due to scale mismatches (Cumming et al. 2006): while the catchment of Lake Sempach proved suitable for assessing environmental challenges, it does not align with existing decision-making structures at farm, cantonal, or national levels. Current policy instruments, such as livestock density limits per hectare, apply uniform rules across farms and are therefore well suited to enforcing simple reductions in animal numbers. Yet, the analysis demonstrated that viable transition pathways extend far beyond animal number reductions, involving shifts in livestock composition, feeding strategies, and management practices, with differentiated adoption across farms. This raises the need for market and policy instruments that can facilitate such differentiated transitions. Key questions include how to support a subset of farmers in exiting livestock production or undertaking major structural changes, thereby enabling others to continue operating at current levels without triggering large-scale protest, as seen in the Netherlands (Upham et al. 2025); how to incentivise shifts in feeding regimes by certain farmers; or how to enable widespread contract rearing arrangements, which would even require inter-regional cooperation and involve farms in e.g. mountain regions (Marton et al. 2016). These examples highlight that policy innovations must move beyond uniform, one-size-fits-all approaches towards regionally tailored frameworks that foster cooperation and collective action among farms and balance responsibilities across regions. Addressing these challenges requires therefore carefully designed policy mixes that combine regulatory, economic, and informational instruments in ways that build on their respective strengths while avoiding unintended trade-offs (Grohmann and Feindt 2024; Acciai and Capano 2021). Such mixes need to be calibrated to diverse regional contexts, with participatory co-design processes, such as those tested in Brandenburg's pig sector transformation, showing promise for enhancing their legitimacy and effectiveness (Grohmann and Feindt 2024; Grohmann et al. 2025). In parallel, forms of collective action among farmers offers another promising avenue (Velten et al. 2021; Reichenspurner et al. 2024), provided that structures for inclusive dialogues, regional facilitators, and mechanisms to manage expectations are in place (Schüler et al. 2025). Importantly, the challenge of designing effective instruments extends beyond the case of the catchment of Lake Sempach and is central to advancing locally adapted agricultural systems more broadly.

5 / 1.4. Plant- versus animal-source protein: balancing environmental ambition and social feasibility

Finding 4. In all P-reduction scenarios, more plant- than animal-source protein could be produced if the same land were used directly for food production, highlighting both the advantages of plant-source protein and the tension between the transformations required and those likely to be feasible in livestock-focused regions.

Although the results in Chapter 3 demonstrate that substantial reductions in P excretion from livestock production, and thereby a shift towards a more locally adapted agricultural system, are achievable, they also reveal that in all analysed P-reduction scenarios, more plant-source than animal-source protein could be produced if the same land were used directly for food production rather than for feed. This aligns with a substantial body of literature from the feed-no-food debate, which consistently highlights the environmental advantages of plant- over animal-source protein production (Tirado et al.; Bajželj et al. 2014; Ipsos UK 2024; Rööß et al. 2017; Willett et al. 2019; Clark et al. 2020; van Zanten et al. 2018). At the same time, the transition pathways towards target scenarios that maintained or increased animal-source protein production, as shown in Chapter 4, already required substantial structural and management changes, including farm exits, farm type conversions, and adjustments in livestock management. Moving towards scenarios with minimal or no livestock production would entail considerably more profound changes in the livestock-focused case study region, with far-reaching implications for farmers, rural communities, and the regional economy.

For practice and policy, these findings raise important questions about transition pathways, targets, and timelines. One critical consideration concerns path dependencies, lock-ins and the political and social feasibility of change (Rønningen et al. 2021; Nair and Howlett 2016). Such dependencies are also evident in the catchment of Lake Sempach, where infrastructure, financial, market, and knowledge-related factors constrain the scope and pace of change (Frick 2020). Given these constraints, the following questions arise: Should policies aim directly for the most ambitious goal, for example, a near-complete shift to plant-source protein production, with the risk of losing social acceptance and political support (Craft and Pitt 2024), thereby jeopardising progress altogether? Or should they target a transition pathway that stays closer to the current system to maintain stakeholder buy-in, while accepting the risk of insufficient environmental improvements? Such questions underline the need for open and inclusive debates on how ambitious environmental goals can be met, while making visible the magnitude of change these transitions will require. The results presented here can enrich these debates, offering a quantitative basis for weighing trade-offs between environmental ambition and social acceptance.

From a modelling and research perspective, the findings highlight the importance of system boundaries in modelling exercises. In this case, comparing protein production from livestock – the core focus of the study – with a simplified estimate of potential plant-source protein production was essential for arriving at this insight.

Without such cross-comparisons, important opportunities or trade-offs may remain invisible. Furthermore, modelling efforts that explicitly map transition pathways can make abstract targets more tangible. By showing the structural and management changes required to achieve different goals, such modelling outputs can inform and stimulate public debate, providing stakeholders with a clearer picture of the practical implications of ambitious environmental targets.

5 / 2. Limitations and further research

The limitations illustrated in this section point to three overarching areas where further research is needed. First, the analytical scope could be broadened by more closely connecting crop and livestock production, extending the range of ecosystem structures and processes considered, and linking landscape-scale dynamics to the wider food system (Section 5/2.1.). Second, a stronger integration of human decision-making processes is required to better capture the social, economic, and behavioural drivers and barriers of transitions (Section 5/2.2.). Third, future studies should explicitly analyse and address uncertainties in data, model structure, and scenario outcomes to enhance the robustness and credibility of results (Section 5/2.3.).

5 / 2.1. The need to broaden the analytical scope

While this dissertation and the developed LEAF.livestock model addressed several of the blind spots in key elements of agricultural landscape assessments identified in Chapter 2 (see Section 5/1.1.), others were only partially covered or remained unaddressed. The following subsections highlight these limitations, discuss their implications, and propose directions for future research to broaden the analytical scope.

5 / 2.1.1. Connect crop and livestock production at the landscape level

While I discussed the potential of coupling LEAF.livestock with established crop or hydrological models such as SWAT in Section 5/1.2., this was not implemented in the current study. Future research could address this by developing a detailed two-way integration, for example through a loose coupling where SWAT (Arnold et al. 2012) provides feed supply estimates and LEAF.livestock returns manure quantities. Such integration would allow more accurate representation of feed production–consumption balances, temporal lags in feed availability, nutrient recycling via manure, and the dependence of livestock systems on local crop yields. Further research could therefore usefully examine questions such as **how seasonal feed supply constraints livestock productivity and nutrient surpluses, or how changes in manure management affect crop yields and nutrient leaching at the landscape level**. Incorporating these linkages would also enable modelling of related systemic feedbacks, such as whether feed shortages trigger external imports that, in turn, influence nutrient budgets and environmental impacts. By representing crop production through e.g. process-based models, future agricultural landscape assessments could better capture circularity potentials and provide more robust evidence for policy measures aimed at integrated land–livestock management.

5 / 2.1.2. Expand the coverage of ecosystem structures and processes

Another challenge lies in the limited coverage of ecosystem structures and processes represented in this dissertation. While P flows were central to the analysis, livestock production also affects carbon and nitrogen cycles, as well as economic outcomes and non-environmental aspects such as animal welfare. The LEAF.livestock model already incorporates nitrogen alongside P and has a flexible structure that allows additional indicators to be added at the livestock-type or life-stage level. Future research could build on this flexibility to broaden the scope by adding further impact categories directly within LEAF.livestock or via integration with complementary modelling frameworks, such as life cycle assessment (LCA) approaches. This would make it possible to explore questions such as **how different livestock management strategies influence greenhouse gas emissions or nitrogen excretion**, and **how production system changes interact with ecosystem services beyond nutrient regulation, such as biodiversity and animal welfare**. Expanding the range of processes considered would make it possible to identify further trade-offs and synergies across multiple sustainability dimensions, thereby enhancing the utility of agricultural landscape assessments for designing interventions towards locally adapted agricultural systems.

5 / 2.1.3. Integrate the agricultural landscape into the wider food system

Environmental impacts of external inputs in agricultural production. While I accounted in Chapter 3 for the total land use (both inside and outside the catchment) for producing feed consumed in the watershed, other environmental impacts of these feed sources were not considered. Feed production outside the catchment can entail substantial greenhouse gas emissions, nutrient losses, biodiversity impacts, and water use. Similarly, feed produced within the catchment often relies on external inputs such as synthetic fertilizers, whose production and transport also carry environmental burdens. Such telecoupled impacts can be substantial (Ding et al. 2021) and should be explicitly included in agricultural landscape assessments. Neglecting the environmental burdens of externally produced inputs risks unjustifiably favouring scenarios that rely on external inputs over those based on locally sourced resources. Future research could address this by quantifying the full environmental footprint of external inputs, drawing on e.g. LCA approaches, which are widely used to evaluate energy and material flows and their associated environmental impacts (ISO 2006; Poore and Nemecek 2018b). Relevant questions could include: **How do the upstream impacts of imported feed or fertilizers compare with those of locally produced inputs? How might alternative sourcing strategies or input substitution influence the overall environmental performance of the system?** Incorporating these dimensions would help identify potential burden-shifting between regions and support the design of interventions that improve environmental outcomes both within the landscape and across the wider food system. This, in turn, would strengthen the capacity of agricultural landscape assessments to inform policies that balance local environmental goals with global sustainability considerations.

Effects of landscape optimization on the environmental impacts of national food consumption. In Chapter 3, I found that when adapting livestock production in the Lake Sempach watershed to local ecosystem boundaries, total animal-source protein production could be maintained. However, the relative contributions of pig meat, beef, and milk differed from the business-as-usual levels. If national demand for specific types of animal-source protein remains constant, this mismatch could shift production and the associated environmental impacts to other regions (Bystricky et al. 2017; Seppelt et al. 2011). Focusing solely on landscape-level solutions therefore risks overlooking such off-site effects. Studies are therefore needed to assess research questions like **how locally adapted agricultural systems affect national production and its environmental performance, and where such impacts might relocate, for instance through changes in trade or imports**. Such analyses will help quantify cross-scale trade-offs and address one of the blind spots in current agricultural landscape modelling identified in Chapter 2. At the same time, extending the geographical boundaries of landscape-scale models to the broader food system remains challenging, particularly with respect to imports and exports that cross national borders, where data availability, attribution of environmental impacts, and the consistency of system boundaries pose key limitations. Mass-flow models such as SOLm (Schader et al. 2015) can be used to evaluate how the target landscape scenarios influence national agricultural production, environmental indicators, and dietary outcomes. By replacing coarse FAOSTAT country-level data with the scenario-specific inputs from Chapter 3, SOLm can quantify the impacts of both business-as-usual and alternative scenarios on indicators such as energy use, greenhouse gas emissions, nutrient eutrophication, land occupation, deforestation, and toxicity. This would allow systematic assessment of trade-offs and synergies between landscape optimisation and national food consumption impacts, providing valuable evidence for policy-making.

5 / 2.1.4. Extend the geographical system boundaries

While the focus on the catchment of Lake Sempach provided a clear and well-defined case study area, the analysis also showed that agricultural systems are rarely confined to single watersheds. They are embedded in wider networks of resource flows, particularly through the exchange of feed and manure. Future research could therefore broaden the geographical system boundaries by analysing additional watersheds or by considering networks of multiple landscapes connected through nutrient and product flows. Research questions could include: **Where is excess manure from the catchment of Lake Sempach transported to, and do these imports contribute to nutrient surpluses or integrate well into local nutrient balances? How do such nutrient flows reshape the sustainability performance of both exporting and importing landscapes, and what governance frameworks could support more balanced recycling at regional and national level?** Concepts such as manuresheds, i.e., regions surrounding animal feeding operations where manure nutrients are applied (Spiegel et al. 2020), provide a promising framework as it can support circular agriculture by making nutrient

management more dynamic and by reducing spatial nutrient imbalances (Haque et al. 2025). A concrete step would be to use the Swiss HODUFLU dataset (Möhring 2023; HODUFLU) to trace where excess manure from Lake Sempach is relocated and link this to fertilizer use data in recipient landscapes to assess whether inflows contribute to overfertilization or close nutrient gaps. Expanding the analysis beyond single catchments would make it possible to capture cross-regional feedbacks, avoid burden-shifting, and identify synergies for more efficient nutrient recycling. This would enhance the robustness of agricultural landscape assessments and strengthen their policy relevance by connecting local interventions to regional and national sustainability strategies.

5 / 2.2. The need to integrate human decision-making

Much of the work presented in Chapters 3 and 4, including the choice of P-reduction strategies, the selection of target scenarios, and the exploration of pathways toward them, was framed from a “social-planner” perspective, designed by researchers based on literature and expert judgment, but without direct input from stakeholders. However, human decision-making is essential for designing locally adapted agricultural systems as people play a dual role in the people–landscape interaction: they are embedded in the biosphere but, as reflective and acting beings, they also shape landscapes through perceptions, choices, and actions that feed back into future developments (Tress and Tress 2001; DeClerck et al. 2016). Capturing these dynamics more explicitly would therefore strengthen the relevance and realism of agricultural landscape assessments.

In Chapter 3, both the P-reduction strategies and the indicators for evaluating them, including their weights, were defined without stakeholder involvement. A valuable next step would be to validate these P reduction strategies and evaluation criteria together with stakeholders, taking into account their diverse priorities and trade-offs. Beyond such validation, the existing results can still serve as a basis to actively support decision-making. For example, visualizing the preferences of different stakeholder groups, such as farmers, environmental NGOs, or policy makers, within the option space for P reduction in livestock production, as demonstrated by King et al. (2015), could help identify zones of mutual acceptability. Participatory modelling approaches, such as companion modelling, go a step further by explicitly engaging stakeholders in co-developing and testing pathways (Poggi et al. 2021; Étienne 2014). Serious games can build on this role by turning the model into an interactive learning environment. In this context, the model can act as a boundary object: an object flexible enough to be understood differently by various actors, yet structured enough to visualize their inputs in a comparable format and thereby facilitate dialogue and knowledge exchange (Morris et al. 2021; Stanitsas et al. 2019). For instance, a web-based interface could allow users to select and combine P-reduction strategies at different intensities and immediately observe their impacts on key indicators, drawing on the pre-calculated five million simulated scenarios as a data foundation. Such real-time feedback can make trade-offs tangible, foster mutual learning, and support collective decision-making.

In Chapter 4, farmer behaviour was approximated through resistance scores against farm type changes based on expert judgement. While useful as a first step, this approach remains a strong simplification of real decision processes. Future research could refine the development of transition pathways by applying backcasting approaches in collaboration with stakeholders, guided by frameworks such as the one proposed by Duygan et al. (2025), which combines e.g. actor and network analysis with stakeholder workshops to jointly generate systems and transformation knowledge. Another promising avenue is to couple LEAF.livestock with agent-based models that simulate farmer decision-making, thereby creating more realistic transition pathways. And more generally, the developed pathways would also benefit from being embedded in broader target-seeking sustainability scenarios, such as Sustainable Development Pathways (SDPs), Food System Development Pathways (FSDPs), or Shared Socioeconomic Pathways (SSPs) (van Vuuren et al. 2022; Gaupp et al. 2021; Riahi et al. 2017). The latter is currently being downscaled for Switzerland in the SSP-CH project (WSL 2022).

Embedding farmer behaviour, stakeholder preferences, and governance dynamics more explicitly into the modelling framework would consequently strengthen its role for transformation research: it deepens our understanding of how agricultural systems function, clarifies desirable goals from multiple viewpoints, and generates actionable insights into how transitions can be achieved. In this sense, advancing the integration of human decision-making is key for making model-based research more effective in supporting real-world sustainability transformations.

5 / 2.3. The need to analyse and address uncertainties

Uncertainty is inherent in modelling work, and agricultural landscape assessments are no exception. Models inevitably rely on assumptions and simplifications, which introduce uncertainty at different stages of the process, from defining system boundaries and data inputs via model implementation to their linkages and evaluation (Refsgaard et al. 2007; Kanter et al. 2018). These uncertainties stem from diverse sources, ranging from inexact or incomplete data, conflicting evidence, and limited knowledge about processes and causal relationships, to irreducible variability in natural systems such as weather and ecological dynamics, and human factors such as values, behavioural choices, institutional settings, and technological breakthroughs (Kanter et al. 2018). The overall aim should be to move uncertainties from being hidden and uncontrolled to being explicit, transparent, and, where feasible, quantified and reduced.

Promising directions include the systematic application of an uncertainty matrix to identify and prioritize the most critical uncertainties (Refsgaard et al. 2007; Kanter et al. 2018). This would, for instance, reveal that statistical uncertainties are particularly relevant for input data such as livestock numbers, feed demands, growth rates, or production outputs of milk, meat, and manure. These can be expressed as means with standard deviations and addressed using tools such as error propagation equations, or expert elicitation via e.g. delphi processes, complemented by strict quality assurance procedures (Refsgaard et al. 2007). Similar approaches can

also be applied to dynamic system drivers, such as calving frequencies, replacement rates, or purchase and sales patterns, which strongly influence herd structures over time. Model-related uncertainties, especially those linked to parameter calibration, can be tackled through inverse modelling and further quality assurance. Finally, output-related uncertainties can be further assessed through multiple model simulations or sensitivity analysis, thereby improving understanding of the robustness of the results. Beyond statistical uncertainties, the matrix would also point to the importance of scenario uncertainties, where outcomes are known but probabilities remain undefined (Refsgaard et al. 2007). They are relevant, for example, when exploring alternative feeding plans, housing systems, or the design of P reduction strategies and transition timelines. In such cases, scenario analysis combined with expert elicitation can help explore the plausible range of developments, supported again by quality assurance and systematic data treatment. Developing such methods represents a key avenue for future research, as embedding uncertainties directly into the modelling process not only enhances the robustness of the outcomes but also makes them more transparent and relevant for decision-making.

5 / 3. Conclusion

The presented dissertation provides valuable insights into P reduction pathways in livestock-intensive agricultural landscapes, using the watershed of Lake Sempach in Switzerland as a case study. The findings have demonstrated that, if land currently used for feed production were directly devoted to food crops, substantially more plant-source than animal-source protein could be produced. When animal-source protein production was required to be maintained at or above current levels, the analysis nevertheless identified multiple contrasting P reduction strategies capable of achieving environmental goals. Pig-dominated target scenarios were most effective at lowering P excretion from livestock production while sustaining animal-source protein output, yet they depended strongly on imported feed and required substantial restructuring of current farm types via exists and specialization. By contrast, dairy-dominated target scenarios made more efficient use of arable land and achieved a more favourable nitrogen-to-phosphorus ratio of farmyard manure, though at the cost of lower, but still sufficient, animal-source protein production and only moderate restructuring of farms via feeding plan changes. Importantly, these results contribute to an improved understanding of the trade-offs and synergies inherent in different livestock-oriented strategies for nutrient management.

To enable these analyses, and to extend the scope of existing assessment approaches, I developed the LEAF.livestock model as part of this dissertation. This modelling framework advances our knowledge of how livestock production in agricultural landscapes can be systematically evaluated. It extends the capacity of current approaches by explicitly representing livestock production and thereby addresses one of the blind spots identified in Chapter 2. With this, the dissertation lays the foundation for future work by highlighting key research needs. These include strengthening crop–livestock linkages at the landscape level, expanding the coverage of ecosystem structures and processes, and embedding agricultural systems more firmly within the

wider food system and across broader geographical boundaries. Advancing the integration of human decision-making is equally important, as embedding farmer behaviour, stakeholder preferences, and governance dynamics more explicitly into modelling frameworks would enhance their relevance for supporting real-world transformations. Finally, the need to analyse and address uncertainties calls for shifting them from being hidden and uncontrolled to becoming explicit, transparent, and, where feasible, quantified and reduced.

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Declaration of the use of AI-based tools

During the preparation of this work, I made use of several AI-based tools to support translation, text revision, and model documentation (Table SM1). These tools were used to improve clarity, consistency, and technical accuracy. All AI-generated or AI-assisted content was carefully reviewed, edited, and validated, and I take full responsibility for the final version of the published work.

Table SM1: Summary of AI-assisted tools and their respective applications.

AI-Based Tool	Use Case	Scope	Remarks
DeepL Pro Translator	Translation (English ↔ German)	Entire work	Used for full-text and section-level translations
DeepL Write	Correction of grammatical and stylistic errors; revision for conciseness	Entire work	Used for improving readability and style consistency
Grammarly	Correction of grammatical and stylistic errors	Entire work	Premium plan with Microsoft Word integration
ChatGPT 4o and 5	Correction of grammatical and stylistic errors; revision for conciseness	Entire work	Used for improving readability and style consistency
	Assistance with coding (model development)	Development of LEAF.livestock	Programming language: R
	Assistance with coding (data visualization)	Entire work	Programming language: R
	Summarization of code in descriptive text to outline its purpose and workflow	Model documentation	Used to generate human-readable explanations of R scripts and their logical structure
Claude.ai 3.7 Sonnet	Summarization of code in descriptive text to outline its purpose and workflow	Model documentation	Used to generate human-readable explanations of R scripts and their logical structure

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Supplementary material of chapter 2

Table SM2/I: Description of Ecosystem Services (ESS). For more details Haines-Young and Potschin (2018).

ESS Section	ESS	Corresponding CICES V5.1 Class
Provisioning	Terrestrial plants for nutrition, materials or energy	Cultivated plants (including fungi, algae) grown as a source of energy
		Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes
		Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials)
		Fibres and other materials from wild plants for direct use or processing (excluding genetic materials)
		Wild plants (terrestrial and aquatic, including fungi, algae) used as a source of energy
		Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition
	Terrestrial animals for nutrition, materials or energy	Animals reared for nutritional purposes
		Animals reared to provide energy (including mechanical)
		Fibres and other materials from reared animals for direct use or processing (excluding genetic materials)
		Fibres and other materials from wild animals for direct use or processing (excluding genetic materials)
		Wild animals (terrestrial and aquatic) used as a source of energy
		Wild animals (terrestrial and aquatic) used for nutritional purposes
	Ground & surface water	Ground (and subsurface) water for drinking
		Ground water (and subsurface) used as a material (non-drinking purposes)
		Ground water (and subsurface) used as an energy source
		Coastal and marine water used as energy source
		Freshwater surface water used as an energy source
		Surface water for drinking
	Non-/ & mineral substances or ecosystem properties	Surface water used as a material (non-drinking purposes)
		Mineral substances used for as an energy source
		Mineral substances used for material purposes
		Mineral substances used for nutritional purposes
		Geothermal
		Non-mineral substances or ecosystem properties used for nutritional purposes
Regulation & Maintenance	Atmospheric composition and conditions	Non-mineral substances used for materials
		Solar energy
	Water conditions	Wind energy
		Regulation of chemical composition of atmosphere and oceans
	Regulation of soil quality	Regulation of temperature and humidity, including ventilation and transpiration
		Regulation of the chemical condition of freshwaters by living processes
	Regulation of baseline flows and extreme events	Regulation of the chemical condition of salt waters by living processes
		Decomposition and fixing processes and their effect on soil quality
		Weathering processes and their effect on soil quality
		Buffering and attenuation of mass movement
		Control of erosion rates
		Fire protection
		Gaseous flows
		Hydrological cycle and water flow regulation (Including flood control, and coastal protection)
	Mediation of waste, toxics and other nuisances	Liquid flows
		Mass flows
		Wind protection
		Bio-remediation by micro-organisms, algae, plants, and animals
		Dilution by atmosphere
		Dilution by freshwater and marine ecosystems
		Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals
		Mediation by other chemical or physical means (e.g. via Filtration, sequestration, storage or accumulation)
Cultural	Lifecycle maintenance, habitat and gene pool protection	Mediation of nuisances by abiotic structures or processes
		Noise attenuation
	Pest and disease control	Smell reduction
		Visual screening
	Recreational value	Maintaining nursery populations and habitats (Including gene pool protection)
		Pollination (or 'gamete' dispersal in a marine context)
	Aesthetic value	Seed dispersal
		Disease control
		Pest control (including invasive species)
	Other value	

Contextual information	#	ID 1	ID 2	ID ...	
	Authors	Group of authors 1	Group of authors 2	Group of authors ...	
	Title of publication	Title 1	Title 2	Title ...	
	Year of publication	Year 1	Year 2	Year ...	
	Reviewer				
ESS 1	Review Date				
	Spatial extend				
	Spatial resolution				
	Name (as used in publication)	Food production			
	Unit	t/ha/year			
	Associated ecosystem service	Provisioning - Cultivated terrestrial plants			
	Associated ecosystem structure or process	Ecosystem Processes - Biomass flows & pools (Crop)			
	Model Type	Process-based model			
	Model name (if available)	EPIC model - Crop growth module			
	Abiotic driving factors	Climatic factors	X		
		Soil features	X		
		Topographic factors	X		
		Risk factors	n/i		
		Other abiotic factors	n/i		
	Biotic driving factors	Plant physiological ecology	n/i		
		Animal physiological ecology	n/i		
		Ecological factors	n/i		
		Other biotic factors	n/i		
	Management driving factors	Land use/land cover	X		
		Crop production factors	X		
		Animal production factors	n/i		
		Landscape structure	n/i		
		Built environment/infrastructure	n/i		
		Risk factors	n/i		
		Socio-economic factors	n/i		
		Other management factors	n/i		
ESS 2	...	...			
ESS 3	...	...			
ESS ...	...	...			
Interconnectedness of crop and livestock production at landscape level	Flows 'Crop production' towards 'Livestock production' (Type of flows or n/i)	...			
	Flows 'Livestock production' towards 'Crop production' (Type of flows or n/i)	...			
Integration of the agricultural landscape into the larger food system	By-products & waste along the supply chain, recycled sludge & solid waste, organic fertilizer (Type of flows or n/i)	...			
	Environmental Impacts of external inputs (Type of flows or n/i)	...			
	Spatial cross-level interactions (beyond the case study region) (How?)	...			

Associated ecosystem service

- Biodiversity
- Provisioning - Cultivated terrestrial plants
- Provisioning - Reared animals
- Provisioning - Ground & surface water
- Provisioning - Non-/ & mineral substances or ecosystem properties
- Regulation & Maintenance - Atmospheric composition and conditions
- Regulation & Maintenance - Water conditions
- Regulation & Maintenance - Regulation of soil quality
- Regulation & Maintenance - Regulation of baseline flows and extreme events
- Regulation & Maintenance - Mediation of waste, toxics and other nuisances
- Regulation & Maintenance - Lifecycle maintenance, habitat and gene pool protection
- Regulation & Maintenance - Pest and disease control
- Cultural - Recreational value
- Cultural - Aesthetic value
- Cultural - Other value

Associated ecosystem structure or process

- Atmosphere/Air
- Soil
- Water
- Habitat
- Biotic Diversity
- Water flows & pools
- Energy flows & pools
- Carbon flows & pools
- Nitrogen flows & pools
- Phosphorus flows & pools
- Sediment flows & pools
- Biomass flows & pools (Livestock)
- Biomass flows & pools (Crop)
- Other matter flows & pools

Model Type

- Key figure
- Empirical model
- Process-based model
- Hybrid model - most complex module is key figure
- Hybrid model - most complex module is empirical model
- Hybrid model - most complex module is process-based model

Figure SM2/I: Structure of the literature review matrix (left side) including the different drop down menus (right side) and an illustrative example. One column corresponds to one assessed publication

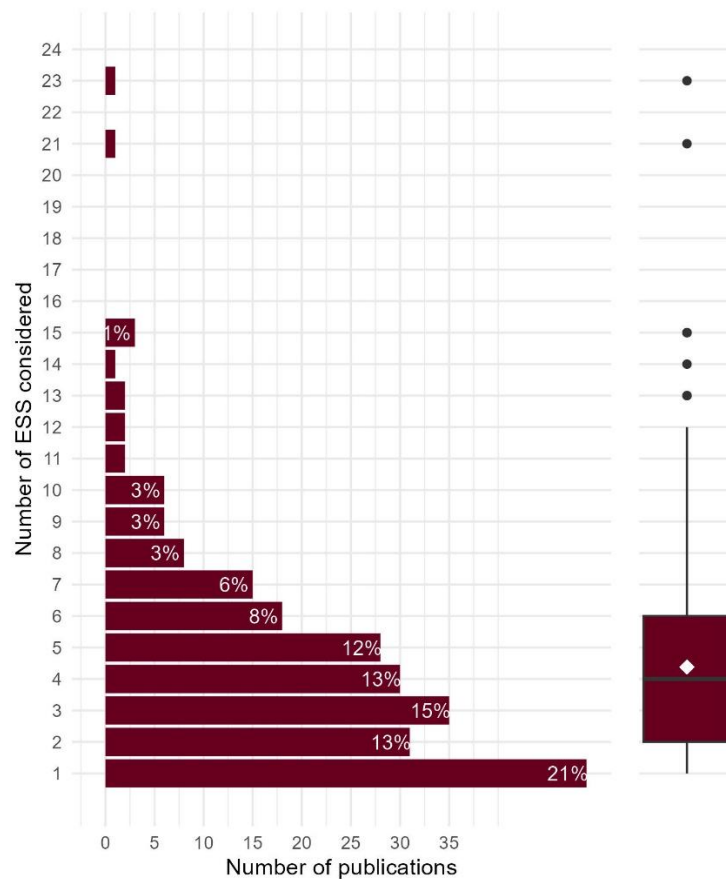


Figure SM2/2: Number of ecosystem services considered per reviewed publication (excluding the provisioning ESS 'terrestrial plants for nutrition, materials or energy'). The white diamond indicates the mean.

Additions to section 2/3.3. Driving factors

Biotic factors were particularly rare in combination with management factors (see Table SM2/2). The inclusion of land use and land cover information was negatively associated with eleven other driving factors. However, this was only evident for some few/a low number of ecosystem structure and process calculations: in the case of plant biomass flows and pools, negative associations were observed between land use and land cover information and crop production factors as well as plant and soil characteristics. In the case of habitat assessments, negative associations were found between land use and land cover information and information on landscape structure and the built environment/infrastructure. Multiple and mostly positive relationships were found between crop production factors, climatic factors, soil features, and topographic factors. This was particularly true for calculating plant biomass, carbon, nitrogen, phosphorus, water flows, and pools.

Table SM2/2: Number of ecosystem structures and processes, where a significant (p -value ≤ 0.1) positive (negative in brackets) association between the respective considered abiotic, biotic and management driving factors were observed (based on the estimated odds ratios and the Fisher's exact test). Blue (red) coloured cells indicate solely positive (negative) relations, whereas orange-coloured cells display cases with simultaneously positive and negative associations.

[illegible]

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Supplementary material of chapter 3

SM3 / I. P reduction strategies: Explanatory notes

A brief reasoning for each intervention is given in below, followed by a detailed overview of the scenario/parameter settings in Table SM3/1.

(A) Livestock density and composition directly impact the nutrient demand and production within the catchment. Adjustments in livestock density and composition offer opportunities to influence overall P excretion, production levels, and feed requirements.

A1 Reducing the overall livestock density. Lowering the number of animals is a commonly proposed measure to reduce nutrient excretion, including phosphorus, and therefore minimize the environmental burden (Maria Bielza et al. 2025). However, this adjustment may result in a decrease in animal sourced protein outputs, as fewer animals may lead to reduced production of meat and other livestock-derived products.

A2 Adjusting the share of cattle versus pigs. Balancing the mix of cattle and pigs can influence manure quantity and composition as well as feed efficiency. While pigs are generally more efficient at converting cropland sourced feed into protein for human consumption, only cattle can convert protein in grass into human-edible protein and have thus the potential to reduce food-feed competition (Brameld and Parr 2016). A well-balanced mix of livestock types can reduce P accumulation and improve feed use efficiency by matching livestock types with available land and feed resources (Schader et al. 2015).

A3 Modifying the share of dairy cows among cattle. The dairy and suckler systems are two common forms of cattle production, each with different feed requirements, manure outputs, and production levels (Estermann et al. 2001). Shifting the balance from dairy towards suckler cows can help reduce feed demand, particularly for concentrates, and may lower nutrient surpluses due to their typically lower productivity and manure output, while focusing on the dairy system can increase protein production, but often requires higher inputs and results in greater nutrient excretion (Poore and Nemecek 2018a).

(B) Feeding strategies are a key factor in influencing the P cycle, as importing external feed adds P to the catchment, creating nutrient imbalances. Adjustments to feeding strategies can minimize the influx of these external nutrients and optimize the nutrient use within the system.

B1 BAU. The “Business-as-usual” approach reflects current feeding practices, which may not prioritize nutrient efficiency or sustainability. While this approach may not optimize P use, it could be the most efficient from the farmer’s perspective in terms of production costs and output.

B2 Maximizing locally sourced forage and feed utilization (grassland and arable land) for cattle. Prioritizing locally producible forage and feed from both grassland and arable land helps align feed resources with land capacity, reducing the need for external inputs. This strategy minimizes

additional nutrients, including P, from entering the catchment, supporting more sustainable nutrient cycling and reducing the risk of phosphorus runoff. Adapting feed rations to local resources can therefore significantly reduce the risk of P accumulation.

B3 *Maximizing locally producible grassland-based feed utilization for cattle.* Focusing on locally producible, grassland-based feed for cattle ensures that nutrients remain within the local ecosystem, preventing additional P from entering the watershed (Wyngaarden et al. 2020). While it leads to reduced production intensities, this approach also frees up arable land, enabling it to be used for growing food for humans or feed for pigs, further optimizing land use and nutrient management across the system.

(C) Offspring fate impacts the number of animals in the system and influences the production channel into which they will go, each with varying lifespans and outputs. Adjusting offspring fate can help optimize phosphorus utilization and nutrient cycling within the system.

C1 *Adjusting the share of dairy offspring sold at an age of 2 months.* Selling offspring at an early age reduces the total number of animals in the system, thereby lowering overall P excretion. This adjustment may help to minimize P build-up in the system and reduce the nutrient load on the land. Although this reduces total meat production, it may offer a way to optimize the balance between livestock numbers and available resources. Bearing in mind that this raises concerns for animal health, as calves and piglets transferred at such a young age often require antibiotic support due to their still-immature immune systems. It may also shift environmental impacts to the regions where the offspring are moved, ideally to areas that are less nutrient-sensitive.

C2 *Varying the share of remaining dairy offspring going into calf fattening.* Fattening systems vary in lifespan and nutrient needs, with calf fattening typically having a shorter duration and different feed requirements than bull/cattle fattening. Adjusting calf pathways, such as focusing on veal production versus longer-term beef fattening, can influence the total P excreted due to differences in feed requirements, manure production, and lifespan. Shorter production cycles, like veal production, tend to reduce nutrient accumulation compared to extended fattening periods, but they also impact total meat output differently.

(D) Livestock movement dynamics affect nutrient cycling, manure management, and the overall phosphorus balance within the system. Adjustments to livestock movement can optimize resource use, complement local nutrient flows, and help align livestock systems with regional ecological conditions. Livestock movements may however also result in some leakage of impacts to the areas where livestock is moved to.

D1 *Adapting the share of animals leaving for the rearing phase.* When animals are sent to external rearing systems, this can temporarily reduce the number of animals in the catchment, which lowers local P

excretion. Strategically integrating external rearing systems can help balance local nutrient flows by redistributing manure production and optimizing resource use across different areas. This adjustment may help to prevent P overload in the local system and improves nutrient cycling.

D2 *Optimizing the share of animals that are seasonally absent.* Seasonal absences, such as those seen with alpine grazing systems, offer opportunities to align livestock systems with regional ecological conditions. During this period, livestock are often moved to higher pastures, which helps to reduce nutrient pressure on lower lands during critical periods. By adapting livestock management to seasonal opportunities, P loading can be better managed, and grazing pressure can be balanced with regional nutrient cycles.

Table SM3/I: P reduction strategies (A to D; vertical) and their model implementation for the three production systems dairy cows, suckler cows and pigs (horizontal). Light grey cells indicate when model parameters are set to BAU, dark grey cells indicate non-applicable cases.

		Dairy herd				Suckler herd		Pig herd		
		Dairy cow	Bull fattening	Ox fattening	Cattle fattening	Calf fattening	Suckler cow	Suckler cow husbandry	Breeding sow	Finishing pig
(A) Livestock density and composition										
A1	Overall livestock density	45% - 50% - 55% - 60% - ... - 100% of BAU LSU/ha								
A2	Share of cattle vs pigs	Cattle contribute to 0% - 20% - 40% - 60% - 80% - 100% of LSU/ha								
A3	Share dairy herd among cattle	Dairy herd contributes to 0% - 20% - 40% - 60% - 80% - 100% of cattle LSU/ha							n/a	n/a
(B) Feeding strategies										
B1	BAU	0% - 50% - 100% of animals				0% - 50% - 100% of animals		100%		
B2	Maximized locally producible forage and feed utilization (grassland and arable land)	0% - 50% - 100% of animals				0% - 50% - 100% of animals		0%		
B3	Maximized locally producible grassland-based feed utilization	0% - 50% - 100% of animals				0% - 50% - 100% of animals		0%		
(C) Offspring fate										
C1	Offspring sold at an age of 2 months	5% sold at 2months 16% sold 40months	0% - 50% - 100% of offspring			26% sold at 2months 75% sold 33months	11%	0%	60%	
C2	Remaining offspring going into calf fattening	Replacement rate: 38%	Ratio 87% bull vs 13% ox fattening	n/a	10% - 50% - 100% of remaining offspring	Replacement rate: 27%	n/a	n/a	n/a	
(D) Livestock movement dynamics										
D1	Animals leaving for the rearing phase	0% - 50% - 100% of animals	n/a	n/a	n/a	n/a	0% - 50% - 100% of animals	n/a	n/a	n/a
D2	Animals that are seasonally absent (Jul to Oct)	0% - 50% - 100% of animals (2nd year of life)	0% - 50% - 100% of animals (1st year of life)			0%	0% - 50% - 100% of animals (2nd year of life)	0% - 50% - 100% of animals (1st year of life)	0%	0%

SM3 / 2. LEAF.livestock model: Explanatory notes

SM3 / 2.1. Model sequences

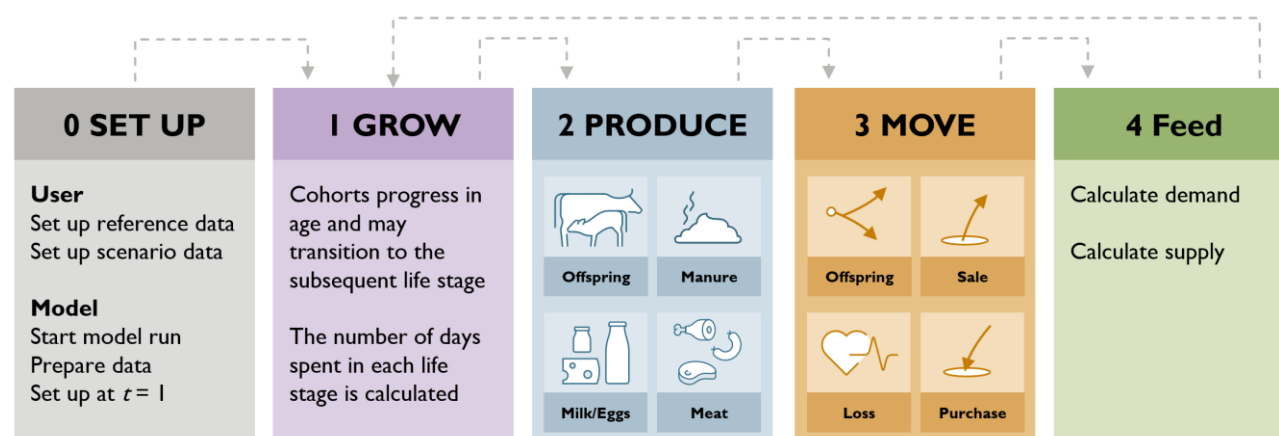


Figure SM3/1: Model sequence of the LEAF.livestock model.

Model Set up: During model set up, the user defines reference data, which includes livestock types with their respective nutrient needs and production levels at different life stages, as well as feed types with their nutritional values. Additionally, the user specifies scenario data, specifying the cohorts at the initial time step ($t=1$), livestock management plans, and their allocation to the cohorts. Once the model run is initiated, the data structure is internally adjusted, and output data is calculated for $t=1$. The phases of update, growth, production, movement, and feeding are then executed and repeated for each subsequent time step.

Growth: At the start of each t , cohorts advance in age and may transition to the following life stage(s). The model then calculates the number of days each cohort spends in each life stage during t . Afterward, it determines how many days each HLE spent in each life stage and livestock management plan sequence.

Production: The model calculates the amount of milk, manure, and offspring produced by each HLE based on the number of days spent in each life stage during t , and the production rates defined for each day and life stage. When a cohort reaches the end of its life, it is slaughtered, producing meat. Using location information from the livestock management plans, the model distinguishes between production quantities that occur inside or outside the landscape.

Movement: During the movement sequence, the number of animals per HLE fluctuates due to [1] losses, [2] market operations, and [3] offspring fate. The life stage specific mortality rate determines how many animals are lost in each HLE. Additionally, the number of animals changes according to the individual sales and purchases per t and HLE. Offspring are furthermore allocated to specific livestock types and livestock management plans according to user-defined or data-driven proportions, resulting in the formation of new HLEs. The user also controls how different livestock types evolve over time. Depending on this setting, animals are finally sold or bought in order to maintain a stable, increasing, or decreasing population.

Feeding: The required feed quantities are calculated for the animals remaining after accounting for new offsprings, slaughter, losses, and market operations at the end of t . Feed demand is assessed for various nutrient parameters, such as crude protein, net energy for growth and lactation, and metabolic energy. The livestock feeding plans specify the types of feed offered. Based on these plans, the quantities needed to meet each nutrient requirement are calculated, and the minimum amount of dry matter (kg DM/day) required to satisfy all nutrient needs is determined. The quantities are finally aggregated across all animals in each HLE and t , which ensures that the total feed requirement reflects the entire population for the time step.

Handling of livestock movements within monthly time steps: The LEAF.livestock model operates with monthly time steps. The required feed quantities are calculated for the animals remaining after accounting for new offsprings, slaughter, losses, and market operations at the end of t . It was assumed that incoming animals (births or purchases) contribute to the feed demand for the entire month, while outgoing animals (sales or slaughter) do not contribute to the feed demand in the month of their departure. This simplification assumes that, across the full herd and over time, early- and late-month events will balance out. It is acknowledged that this approach does not capture the gradual increase in feed demand as animals grow older; for instance, a newborn animal typically has a lower feed requirement than an animal close to slaughter. Nevertheless, this method provides a practical approximation suitable for the aggregated, monthly time step of the model.

SM3 / 2.2. Model setup and data

The input data were prepared to represent the livestock population, reflecting the production systems, intensities, and animal movements (Figure SM3/2).

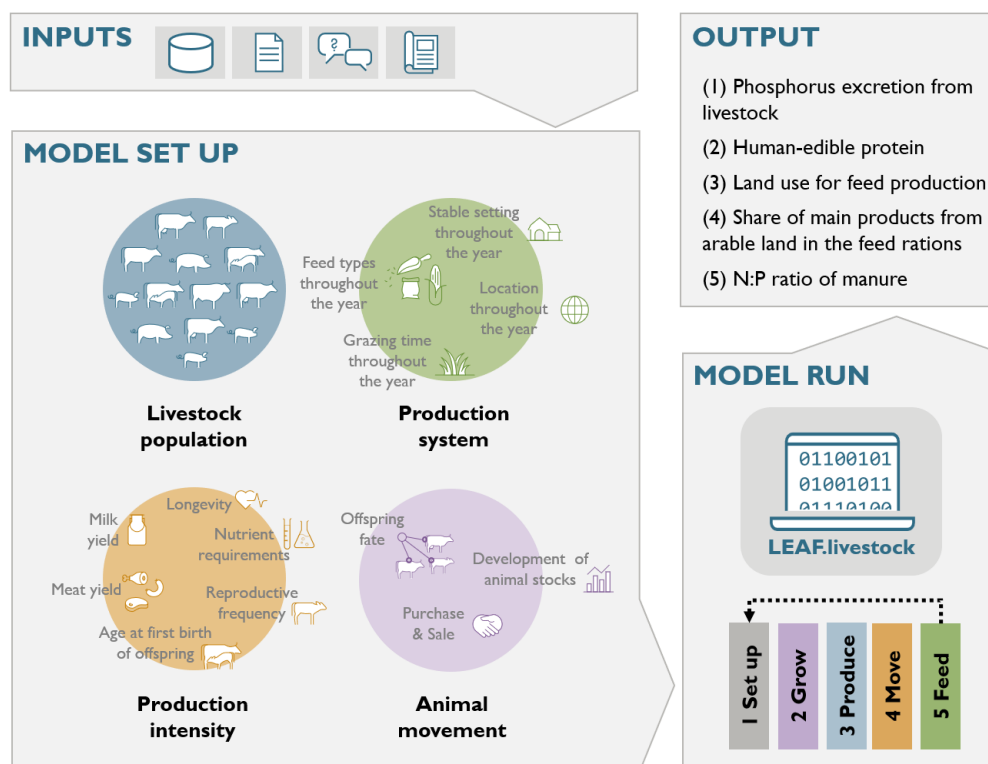


Figure SM3/2: Flow chart showing the data inputs, the model integration, and the model outputs.

SM3 / 2.2.1. Livestock population

For cattle, records of the official Swiss animal movement database (AMD) were used and contained general information and records of the location of each individual animal (within or outside the catchment area) per month from 2010 to 2022 (AMD 2023). Animals were assigned to livestock types based on variables such as type of use, slaughter category, sex, calving status, age at slaughter and slaughter weight (section 0 and 0). These variables were used to describe the livestock population for both the BAU scenario, as well as for the scenario settings *B1 – BAU* and *B2 – Maximizing locally producible forage and feed utilization*. For the scenario setting *B3 – Maximizing grassland-based feed*, the production intensity was reduced in order to increase the proportion of grass in the feed rations. As a result, animals of the livestock types "Bull fattening," "Ox fattening," and "Cattle fattening" were combined into a less intensive production type "Cattle and ox fattening" based on AGRIDEA (2023). For the BAU scenario, the number of animals at $t=0$ for each defined livestock type was then derived from the AMD (2023) (section 0 and 0). The AMD for pigs included data from 2014 to 2022 and details of each group of animals moving in or out of the catchment, as well as information on whether the group consisted of breeding sows or finishing pigs, along with their slaughter weight (AMD 2023). For the BAU scenario, the

number of pigs born within the catchment was calculated based on the number of animals sold or purchased, the number of breeding sows and finishing pigs slaughtered, and literature values for litters per year and piglets per litter cast (AGRIDEA 2023) (section 0). For all scenario settings, the number of animals at $t=0$ was kept the same as for BAU, but its subsequent development was influenced by the settings for *C – Offspring fate* and *D – Livestock movement dynamics*.

SM3 / 2.2.1.1. Cattle herds

In a first step, the data provided by the AMD (2023) was used to identify livestock types (step 1 to step 3). Afterwards, the initial cohorts were formed (step 4).

Step 1

The following decision tree was applied in a first step to categorize the animals into livestock types:

- Dairy cow:** *Sex_firstCalving* == "f - with first calving" & *Type of use* == "Dairy cows"
- Suckler cow:** *Sex_firstCalving* == "f - with first calving" & *Type of use* == "Other cows"
- Calf fattening:** *SlaughterFatteningCategory* == "Calves"
- Cattle:** *SlaughterFatteningCategory* == "Cattle with up to a maximum of 4 permanent incisors" & *Sex* == "f"
- Bull:** *SlaughterFatteningCategory* == "Bull with no permanent incisors" & *Sex* == "m"
- Ox:** *SlaughterFatteningCategory* == "Ox up to a maximum of 4 permanent incisors" & *Sex* == "m"

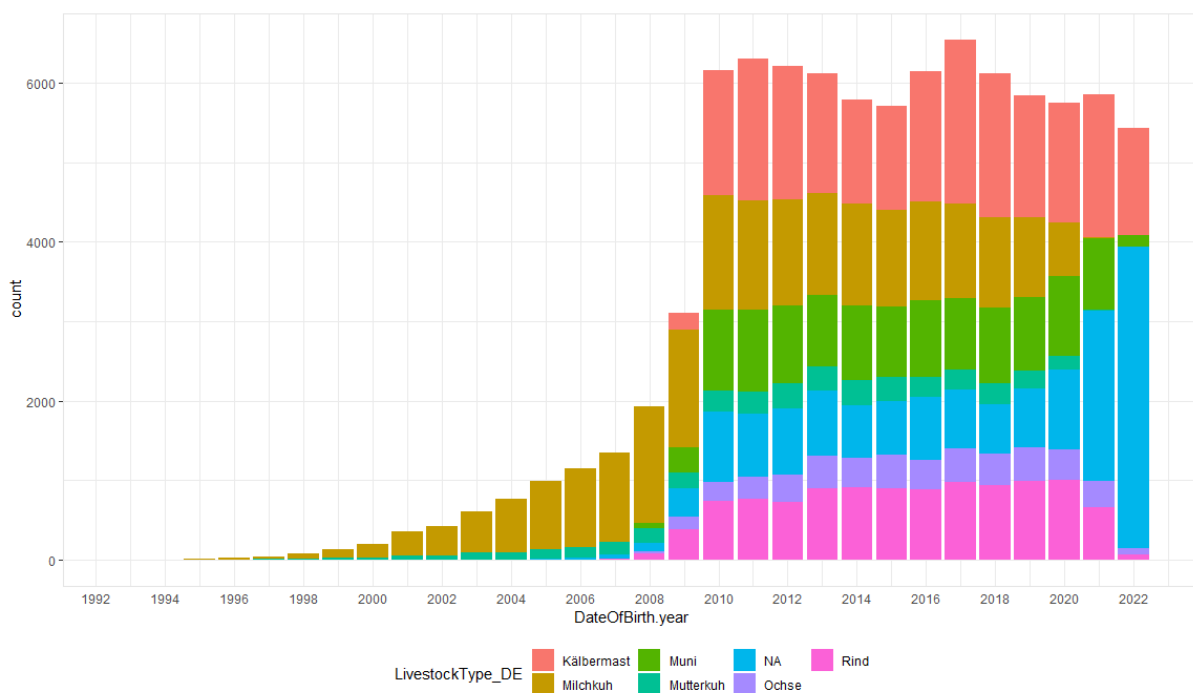


Figure SM3/3: Number of animals born per year by production category. "Kälbermast" refers to calf fattening, "Muni" to bull, "Rind" to cattle, "Milchkuh" to dairy cows, "Mutterkuh" to suckler cows, and "Ochse" to ox.

Step 2

In a second step and based on the age (see Figure SM3/4 and Figure SM3/5), the animals belonging to the categories **Cattle** and **Ox** have been further differentiated into

- a. **Cattle fattening:** *SlaughterFatteningCategory* = "Cattle with up to a maximum of 4 permanent incisors" & *Sex* = "f" AND *Age* $\geq$ 386.2
- a. **Ox fattening:** *SlaughterFatteningCategory* = "Ox up to a maximum of 4 permanent incisors" & *Sex* = "m" AND *Age* $\geq$ 393.8
- b. **Suckler cow husbandry:**
 - o *SlaughterFatteningCategory* = "Cattle with up to a maximum of 4 permanent incisors" & *Sex* = "f" AND *Age* $<$ 386.2
 - o *SlaughterFatteningCategory* = "Ox up to a maximum of 4 permanent incisors" & *Sex* = "m" AND *Age* $<$ 393.8

To identify the respective cut-off points (Cattle fattening 386.2, Ox fattening 393.8), the turning points in the density functions of the variable "*Age*" were calculated (Figure SM3/6). The two peaks of the bimodal distributions calculated in this way have been compared to the modes (Table SM3/2). Furthermore, the category **Bull** was converted to "**Bull fattening**".

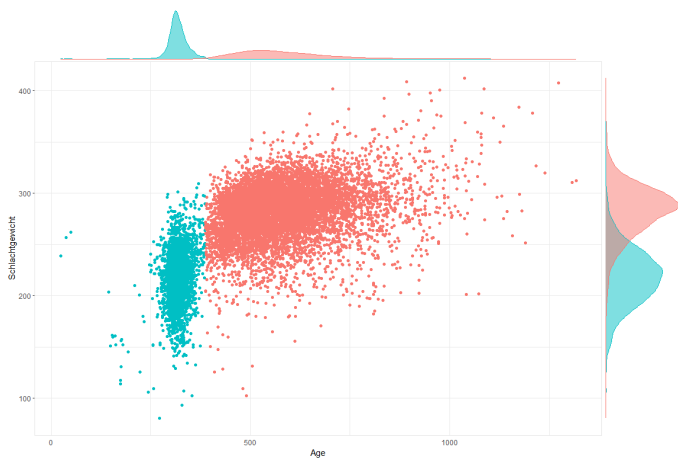


Figure SM3/4: Distribution of ages and slaughterweights for the category "Cattle fattening". Red colored points and density functions refer to the new livestock type "Grossviehmast Cattle fattening", blue colored points and density functions to the new livestock type "Suckler cowhaltung"

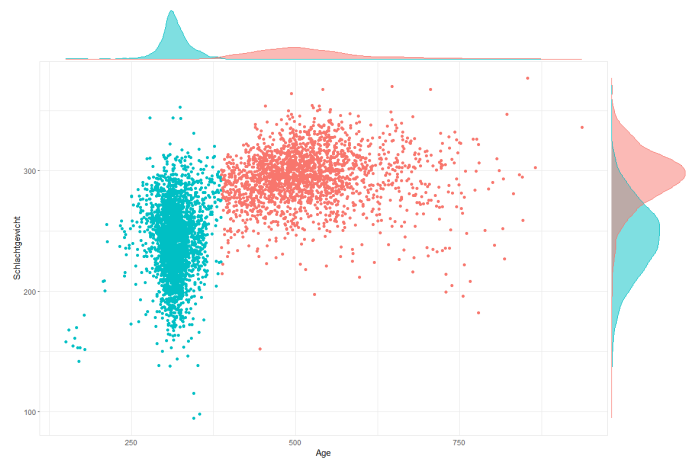
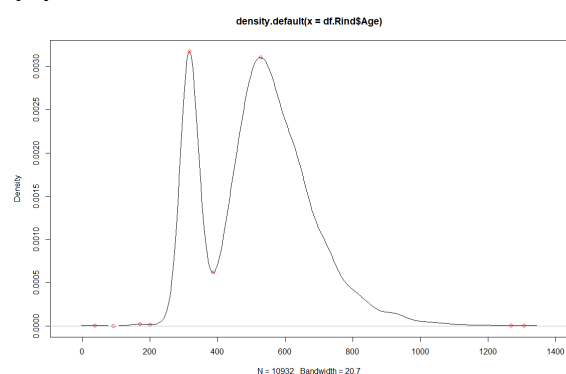


Figure SM3/5: Distribution of ages and slaughterweights for the category "Ox fattening". Red colored points and density functions refer to the new livestock type "Grossviehmast Ox fattening", blue colored points and density functions to the new livestock type "Suckler cowhaltung"

(A)



(B)

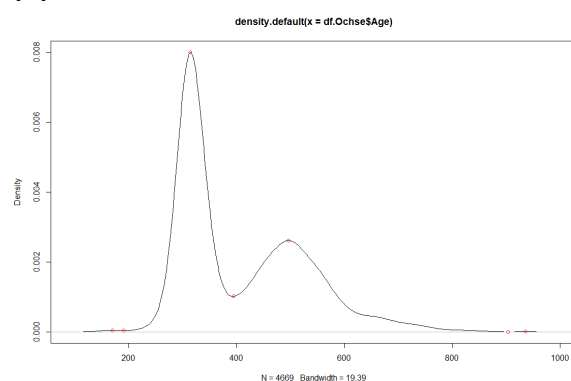


Figure SM3/6: Density functions of the variable “Age” for the livestock types (A) “Cattle fattening” and (B) “Ox fattening” and identified turning points (in red)

Table SM3/2: Comparison of modes and two highest turning points.

Livestock Type	modes	Highest turning points
Cattle fattening	316.8867	316.88674
Cattle fattening	527.6680	527.66798
Ox fattening	314.3192	314.3192
Ox fattening	496.2043	496.2043

Finally, the following main cattle livestock types are derived from this: dairy cow, suckler cow, calf fattening, cattle fattening, bull fattening, ox fattening, and suckler cow husbandry (see Figure SM3/7).

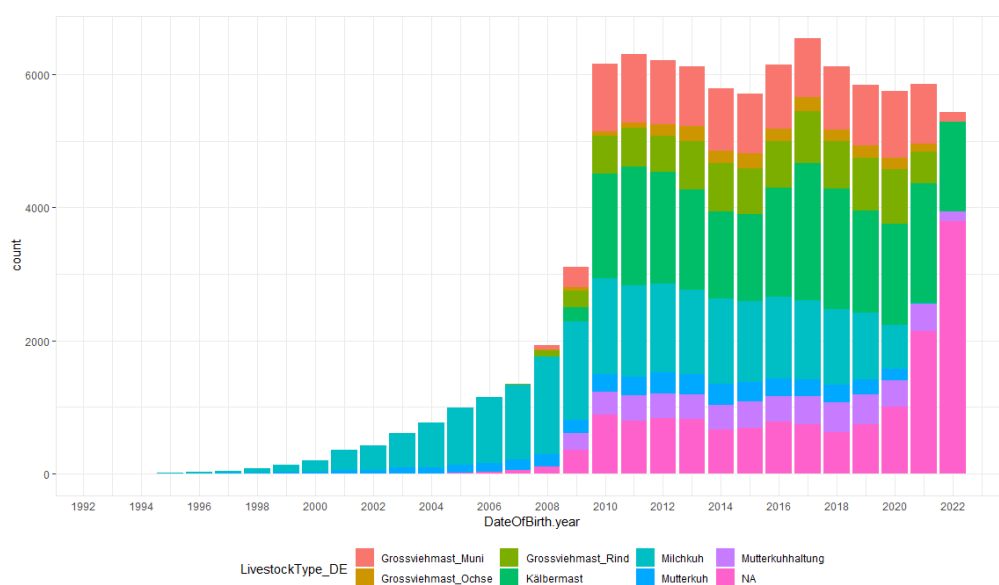


Figure SM3/7: Number of animals born per year by production category. “Grossviehmast_Muni” refers to bull fattening, “Grossviehmast_Rind” to cattle fattening, “Milchkuh” to dairy cow, “Mutterkuhhaltung” to suckler cow husbandry, “Grossviehmast_Ochse” to ox fattening, “Kälbermast” refers to calf fattening, «Mutterkuh» to suckler cow.

Step 3

After the identification of livestock types and the allocation of each animal to one livestock type, a certain number of animals could not be allocated (NA values) (see Figure SM3/8). Those animals were grouped into animals which were “alive” or “dead” at the date of the data extract (31.12.2022). Within the group of **living animals**, NA values occurred mainly in the years 2020 to 2022. These are animals that could not be allocated to a livestock type because they have not yet calved or been slaughtered since. At the date of the data extract they have been too young for any of this. Within the group of **dead animals**, NA values occurred since those animals have not been assigned a slaughter category. This is the case, when the animals were slaughtered in smaller slaughterhouses/privately which did not record these information.

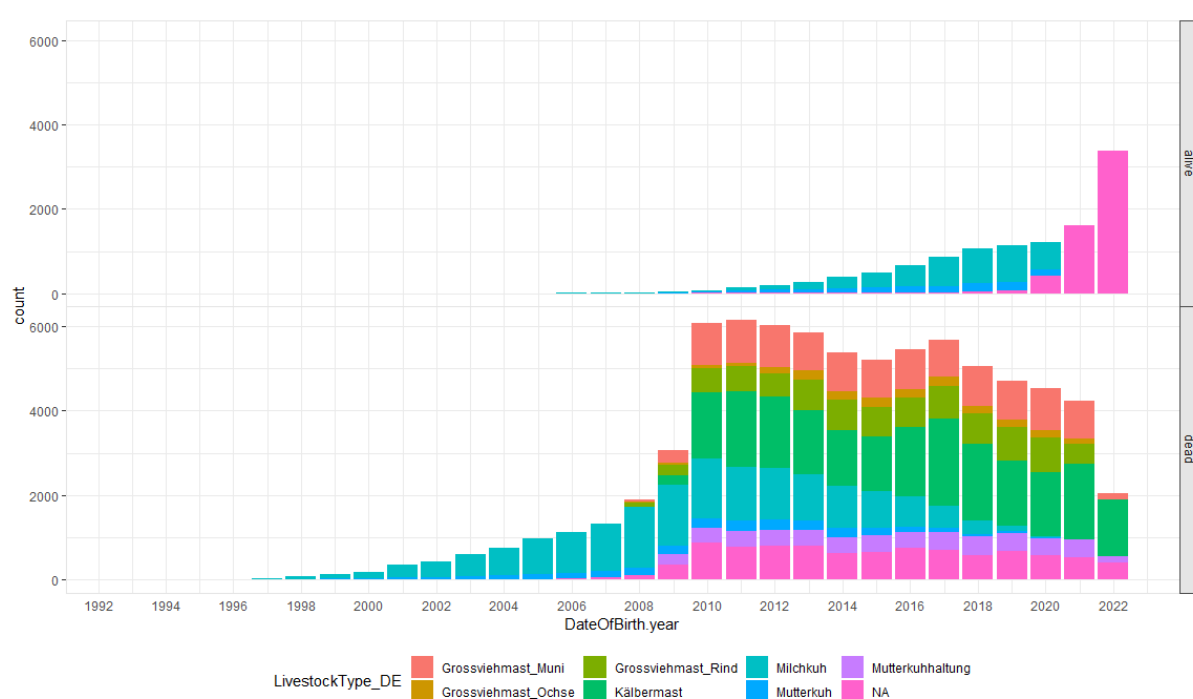


Figure SM3/8: Distribution of animals according to the year of birth. “Grossviehmast_Muni” refers to bull fattening, “Grossviehmast_Rind” to cattle fattening, “Milchkuh” to dairy cow, “Mutterkuhhaltung” to suckler cow husbandry, “Grossviehmast_Ochse” to ox fattening, “Kälbermast” refers to calf fattening, “Mutterkuh» to suckler cow.

- **Procedure for the group of living animals:** To generate the final number of animals in each category, only data between 2011 and 2021 was used. It was assumed, that animals born before or in 2021 which have neither calved nor been slaughtered by the data extract date (31 December 2022), cannot belong to the livestock types 'Calf Fattening' or 'Suckler Cow Management'. Therefore, the number of animals still alive at the time of data extraction, which could not previously be assigned to any livestock type, was distributed among the remaining livestock types based on their respective proportions.

Table SM3/3: Median age at slaughter and likelihood of survival for livestock born before or in 2021, as of the data extract date (31 december 2022), by livestock type.

Livestock type	Median age at slaughter in months	Possibly born before or in 2021 and still alive at the time of the data extract (31.12.2022)?
Dairy cow	68	Yes
Suckler cow	73	Yes
Calf fattening	6	No
Suckler cow husbandry	11	No
Bull fattening	14	Yes, but only if born in Oct/Nov/Dec 2021
Ox fattening	18	Yes, if born in 2021
Cattle fattening	20	Yes, if born in 2021

- **Procedure for the group of dead animals:** These animals have been further differentiated into male and female animals without first calving. Cut-off points were defined based on the 90th quantile of the existing livestock types (step1 & step2). Based on the age (90th quantile) (see Figure SM3/9), the animals have been therefore further differentiated into:

a. **Calf fattening:**

- *Alive* = “dead” & *Sex_firstCalving* = “f – without first calving” & *Age* ≤ 178
- *Alive* = “dead” & *Sex_firstCalving* = “m” & *Age* ≤ 178

b. **Suckler cow husbandry:**

- *Alive* = “dead” & *Sex_firstCalving* = “f – without first calving” & *Age* > 178 & *Age* ≤ 347
- *Alive* = “dead” & *Sex_firstCalving* = “m” & *Age* > 178 & *Age* ≤ 347

b. **Cattle fattening:** *Alive* = “dead” & *Sex_firstCalving* = “f – without first calving” & *Age* > 347

c. **Ox fattening or bull fattening:** *Alive* = “dead” & *Sex_firstCalving* = “m” & *Age* > 347

For the time being, male animals with an age above 347 were not yet split into “Ox fattening” or “Bull fattening”.

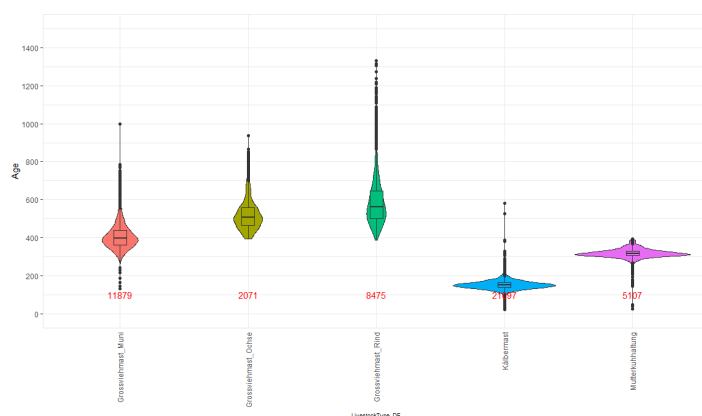


Figure SM3/9: Distribution of age by livestock type, shown using boxplots and violin plots. “Grossviehmast_Muni” refers to bull fattening, “Grossviehmast_Rind” to cattle fattening, “Mutterkuhhaltung” to suckler cow husbandry, “Grossviehmast_Ochse” to ox fattening, and “Kälbermast” refers to calf fattening.

Step 4

Based on the above described livestock types and the information in the AMD (2023), the individual cohorts are formed and the number of animals per cohort is defined. A cohort comprises all animals of the same livestock type born in the same month and year. For the model set up, all animals inside of the catchment at $t=1$ were specified. This included animal which were born before and still alive in 2011 and were in the catchment at $t=1$. Based on the average slaughter ages (AMD 2023) per livestock type, the earliest date of birth was obtained to fulfill these requirements. From the respective earliest date of birth until $t=1$, a cohort was formed for each month.

Based on the above defined livestock types and the data provided in the AMD (2023), individual cohorts were constructed, and the number of animals per cohort was determined. Each cohort represents all animals of a specific livestock type born in the same month and year. For the model initialization ($t = 1$, i.e., January 2011), all animals present in the catchment at that time had to be specified. This included animals that were born before January 2011, still alive at that point, and located within the catchment. Using average slaughter ages (AMD 2023) for each livestock type, the earliest required birth date was calculated to ensure all animals alive at $t = 1$ could be represented. From this earliest birth date up to January 2011, monthly cohorts were created for each livestock type (see Table SM3/4 for the number of cohorts at $t=1$ per livestock type). The number of animals in each cohort was then determined by calculating the average monthly births per livestock type using the AMD (2023) and assigning these values to the corresponding month of birth for each cohort.

Table SM3/4: Number of cohorts at $t=1$ per livestock type.

	Number of cohorts
Bull fattening (Born before $t1$)	13
Ox fattening (Born before $t1$)	17
Cattle fattening (Born before $t1$)	18
Calf fattening (Born before $t1$)	5
Dairy cow (Born before $t1$)	76
Suckler cow (Born before $t1$)	85
Suckler cow husbandry (Born before $t1$)	10
Breeding sow (Born before $t1$)	34

SM3 / 2.2.1.2. Pig herds

The structure of pig-related data in AMD (2023) differs from that of cattle data. While cattle records are available at the individual animal level, pig data are reported at the group level, representing batches of animals entering or leaving the catchment. Consequently, the classification of livestock types and the formation of cohorts required a different approach than that used for cattle herds.

To model the pig production system, two livestock types were defined: **breeding sows** and **finishing pigs**. The input data provided group-level information on (1) the number of finishing pigs entering the region alive (assumed to be weaned at 24 days of age), (2) finishing pigs leaving the region alive (also assumed weaned at 24 days), (3) finishing pigs leaving the region for slaughter (assumed fattened at 186 days of age), and (4) breeding sows leaving the region for slaughter. Based on these data and literature values for litters per year and piglets per litter cast (AGRIDEA 2023), the required number of breeding sows was estimated to produce the recorded monthly number of piglets born, accounting for average litter size, mortality, and reproductive cycles. These values were used to define initial cohorts (Table SM3/5) and their sizes, which served as input for the model starting in 2011.

Table SM3/5: Number of cohorts at $t=1$ per livestock type.

	Number of cohorts
Breeding sow (Born before t_1)	34

SM3 / 2.2.2. Production intensity

For each livestock type, lifespan and life stages are defined, along with production intensity (milk and meat yield, manure quantity) and associated nutrient requirements. For maternal animals, the age at first offspring and reproductive frequency are specified. Life stages and daily nutrient requirements were determined using the last day of life and live weight at slaughter, derived from the AMD (2023) and AGRIDEA (2023). These parameters provided the basis for calculating daily weight gain plans for each life stage using literature values (Agroscope 2021).

Nutrient requirements for cattle and pigs were determined based on life stage, breed, and production system. For cattle, life stages covered calf rearing, dairy and suckler cow rearing, lactation phases, and fattening, using established growth rates and literature values (Morel and Kessler 2021; Münger and Kessler 2021; Gruber et al. 2006). Dairy cow rations were adjusted for the number and phase of lactation as well as the feeding plan and season. Beef production nutrient needs were specified for bull, ox, and cattle fattening at different life stages. For pigs, nutrient requirements per life stage for finishing pigs and breeding sows followed Stoll and Kessler (2016). Further details are provided in section 0.

The average daily milk yield was calculated based on lactation number, lactation phase, and production intensity using a lactation curve. Average milk composition was 4.1% fat, 3.25% protein, and 4.8% lactose, with first lactation yield assumed to be 82% of subsequent lactations (Agroscope 2021). For the BAU and scenario settings *B1 – BAU* and *B2 – Maximizing locally producible forage and feed utilization*, four intensity levels¹²

¹² 15% low intensity and silage-free feeding with 6'000 kg milk, 43% low intensity and silage-based feeding with 7'000 kg milk, 11% high intensity and silage-free feeding with 7'000 kg milk, 31% high intensity and silage-based feeding with 8'000 kg milk.

were implemented for dairy cows, determined by breed share and the proportion of silage-based and silage-free feeding (Gassmann 3/28/2024) (see section 0). *For B3 – Maximizing grassland-based feed*, production intensity was reduced to increase the proportion of grass in the feed rations, with a target production level of 7'000 kg of milk based on a silage-based diet. Values for slaughter yields for cattle and pigs were derived from the AMD (2023) and AGRIDEA (2023). Nutrient excretion, slurry and manure quantities per day were calculated for each livestock type and life stage using Agroscope (2017), Schlegel et al. (2020a), and Schlegel et al. (2020b). Excretion rates for dairy cows were based on milk yield and for fattening cattle on average daily weight gain and final live weight. The rates for suckler cows depend on the live weight, while those for the calves of suckler cows depend on the slaughter age and weight. For pigs, nutrient values were adjusted based on feeding type, considering phytase use and reduced N and P excretion in conventional pig production. Excretion values were derived from AGRIDEA and BLW (2023). The age at first calving was set at 1016 days for dairy cows and 1031 days for suckler cows, with a calving frequency of 390 days for the first calf and 450 days for subsequent lactations for dairy cows, and 390 days for suckler cows, each producing one calf each time. For pigs, the first farrowing was set at 340 days of age, with 168 days between farrowing and an average of 11 piglets per farrowing. A 50% proportion of female offspring was assumed.

SM3 / 2.2.2.1. Nutrient requirements

Cattle

Calf rearing: The recommended daily intake of nutrients for a rearing calf from 1 to 112 days of age was calculated based on Morel and Kessler - Tbl. 5.1 (2021) with an assumed growth intensity corresponding to an ADG of 800 g. These values have been used for the calf rearing life stages of dairy cows, bull fattening, ox fattening and cattle fattening.

Cattle rearing: Depending on the type and breed (early maturing (dairy breeds) or late maturing (mixed breeds)) and the assumed ADG, the recommended daily intake of nutrients was calculated according to Münger and Kessler - Tbl. 6.1 (2021). A distinction was made between the rearing phase for dairy and suckler cows. For dairy cows, the nutrient requirements were calculated from 113 to 953 days of age, the day before first calving, an ADG of 650 g, a starting LW of 125 kg, and a final LW of 589 kg, which corresponds to 93% of the LW. For suckler cows the requirements were calculated from 317 to 1031 days of age, an ADG of 626 g, a starting LW of 421 kg, and a final LW of 584 kg.

Lactating dairy cattle: The calculation of the **total DMI** was based on Gruber et al. (2006) (equation 2) and depends among others on the milk yield, the number of lactations (first versus second and subsequent lactations), the lactation phase (start, production, dry) as well as the feeding plan (a combination of production intensity and silage/silage-free rations), and feeding type (summer-, winter-, transitional feeding). In a

subsequent step, the DMI values for the different feeding types have been aggregated based on the following shares.

Feeding Type	days	shares
Winter feeding	165	0.452
Transitional feeding	20	0.055
Summer feeding	180	0.493

The calculation of the **NEL**, **APD**, and **CP** for each number of lactations, lactation phase, and intensity level was further based on Münger et al. - Tbl. 7.1 (2021). Growth rates during the first lactation of 0.3 (start phase) and 0.1 (production phase) were assumed.

Suckler cow husbandry: As the milk transfer between suckler cows and their calves is treated implicitly in the model, only the nutrient requirements of the suckler calves for supplementary feed were considered. Following Morel et al. - Tbl. 8.2 (2021b), these requirements were calculated for suckler cow offspring from 1 to 316 days of age, with an initial LW of 44 kg and a final LW of 421 kg. An ADG of 1200 g was assumed.

Suckler cow For the calf and cattle rearing phases, see sections “Suckler cow husbandry” and “Cattle rearing”. The requirements of the lactating suckler cow have been calculated according to Morel et al. - Tbl. 8.1 (2021b) and depend on the lactation/ pregnancy phase (lactation month 1, lactation month 2 and following, 7th to 8th gestation month, 9th gestation month).

Calf fattening: The recommended daily intake of dry matter, calf metabolizable energy and digestible protein for the fattening calf from 1 to 150 days of age was calculated using the recommendations in Morel et al. - Tbl. 9.1 (2021a) and an ADG of 1177 g.

Bull fattening, ox fattening, and cattle fattening: The calculations of the nutrient requirements for the beef production were based on Morel et al. - Tbl. 10.4 and 10.5 (2021c). Nutrient requirements for bull fattening were calculated from 113 to 395 days of age, with an initial LW of 125 kg, a final LW of 521 kg, and a corresponding ADG of 1392 g. For ox (and cattle) fattening, these values were calculated from 113 to 507 (653) days of age, a starting LW of 125 kg, a final LW of 570 (551) kg, and a corresponding ADG of 1127 (940) g.

Pigs

Finishing pig: The calculations of the nutrient requirements (DEP, DiLys, and DiMet) for finishing pigs were based on Stoll and Kessler (2016). As the milk transfer between sows and their suckling piglets is treated implicitly in the model, the nutrient requirements during the suckling piglet-phase was not considered. An ADG of 880 g/day was assumed for conventional production and 700 g/day for organic production.

Breeding sow: The calculations of the nutrient requirements (DEP, DiLys, and DiMet) for breeding sows were based on Stoll and Kessler (2016). As the milk transfer between sows and their suckling piglets is treated implicitly in the model, the nutrient requirements during the suckling piglet-phase was not considered.

SM3 / 2.2.2.2. Production

Milk

Intensity levels for dairy cows: Dairy cow intensity levels were categorized based on breed data from AMD (2023), which enabled a division into low- and high-intensity systems (Table SM3/6). To further differentiate feeding types, regional milk volume data from the valley zone of the Canton of Lucerne (Gassmann 3/28/2024), distinguishing between silage-free and silage-based systems, were used to estimate feeding shares (Table SM3/7). This classification resulted in four dairy cow intensity levels: 15% low-intensity silage-free, 43% low-intensity silage-based, 11% high-intensity silage-free, and 31% high-intensity silage-based.

Table SM3/6: Share of low intensity and high intensity breeds in catchment based on AMD (2023) and own classification.

Production intensity	% of dairy cattle
Low intensity (including breeds such as Braunvieh, Rotfleckvieh and Swiss Fleckvieh)	58
High intensity (including breeds such as Holstein and Red Holstein)	42

Table SM3/7: Share of silage-free and silage-based feeding based on Gassmann (3/28/2024).

Feeding	% of dairy cattle
Silage-free	26
Silage-based	74

Dairy cow: The average daily milk yield was calculated as a function of the number of lactations (first versus second and subsequent lactations), the lactation phase (start, production) and the production intensity (annual milk yield of 6'000 to 8'000 kg) as well as a lactation curve. A start phase of 77 days, a production phase of 248 days for the first lactation, and 264 days for subsequent lactations were assumed, along with average milk composition values of 4.1% fat, 3.25% protein, and 4.8% lactose. It was also assumed that the reduced milk yield in the first lactation was 82% of the milk yield in the second and subsequent lactations (Agroscope 2021).

Suckler cow: As the milk of a suckler cow is completely consumed by the suckler calves, this implicit milk transfer was implemented in the model in the following way: No milk production by suckler cows was specified and the nutrient requirements of the suckler calves were reduced accordingly (total requirements minus nutrients covered by milk).

Manure

Nutrient excretion in kg per day (N_{tot}, P_{tot}) was derived for each livestock type and life stage based on Agroscope (2017), Schlegel et al. (2020a), and Schlegel et al. (2020b). The excretion rates for dairy cows depend on the milk yield. The rates for fattening cattle are based on the average daily weight gain and the final live weight. The rates for suckler cows depend on the live weight, while those for suckler cow husbandry depend

on the slaughter age and weight. As the addition of phytase, and thus reduced N and P excretion, is common in conventional pig production in the case study region, the nutrient values of pig manure were adjusted for the type of feeding. For this purpose, values for the calculation of N and P_2O_5 production as a function of feed content based on AGRIDEA and BLW (2023) were used. Furthermore, the **daily produced slurry (in m³) and manure (in t)** quantities were compiled based on Agroscope (2017) and Schlegel et al. (2020b) depending on the milk yield and life stage, and the $N_{tot}:N_{sol}$ and $N_{tot}:N_{avail}$ rates for slurry and manure respectively based on Agroscope - Chapt.4, Tbl. 6 (2017). The $P_{tot}:P_{avail}$ rates have been extracted from AHDB (2023).

SM3 / 2.2.3. Production system

The type of feed, grazing period, location, and stable setting throughout the year are defined in the livestock housing plans and the livestock feeding plans and have been developed for the different combinations of livestock type and movement type. The housing plans specify the location of the animals (inside/outside the catchment), housing/grazing period, and the stable configuration. How many animals are leaving for the rearing phase or are seasonally absent are specified at this point. For the BAU, the shares were derived by the AMD, whereas the scenario settings for *D1 – Adapting the share of animals leaving for the rearing phase* and *D2 – Optimizing the share of animals that are seasonally absent* determined the shares for the individual scenarios. Manure type and place of origin depend on housing/grazing duration and interspersed areas, with slurry produced in non-interspersed areas and solid manure only in interspersed stable areas. For cattle, we assumed that the Swiss Animal Welfare Ordinance (TSchV, SR 455.1, Swiss Federal Council (2/1/2025)) and the Swiss Animal Welfare Programme RAUS (Federal Office for Agriculture FOAG 2022), were implemented, which require that animals have at least 13 days of outdoor access per month (November-April) and at least 26 days of pasture access per month (May-October). Alternatively, permanent access to a partially uncovered exercise yard can replace grazing from May to October for young calves, female fattening cattle, and male cattle. For the pig herd, total grazing time was assumed to be zero hours and IP-Suisse values were used for interspersed lying area and total area per animal.

Feeding plans vary according to livestock type, life stage, production intensity and season. Two feeding strategies were implemented: (a) life stage-based feeding, where rations vary only according to age (e.g. 0-1.5 months, 1.5-4 months); (b) seasonal feeding, where rations are also adjusted for summer, winter and transitional periods¹³. For each feeding plan sequence, the proportion of DM covered by each feed type was specified. For each type of feed used, the individual composition of the feed components was compiled and linked to the nutrient values recorded in the Swiss Feed Database (Universität Zürich and Agroscope 2016). The nutrient

¹³ **Note on suckler and pig herds:** Milk transfer from mother to offspring is implicit in the model - maternal milk production is excluded, while offspring nutrient requirements are reduced accordingly. The remaining nutrient deficiencies are provided by the ration.

composition of the different grass-based roughage types, such as hay or grass silage, was determined based on the management intensity in the catchment (Weber et al. 2023). The BAU feeding plans for the cattle herds follow rations from AGRIDEA (2022), AGRIDEA (2023), and LfL (2024), while the feed components and their proportions in the pig diets were provided by Kamm (11/25/2024) (see section 0 for more details). For the feeding plans of the scenario setting *B2 – Maximizing locally producible forage and feed utilization (grassland and arable land) for cattle*, soybean in the BAU rations was replaced with field beans where possible (LfL 2013) (see section 0 for more details). In addition, Calf-rearing concentrates were substituted with higher milk volumes (Spengler Neff et al. 2019). Feeding plans for calf fattening and suckler herds were adapted to their organic equivalents (AGRIDEA 2023), as their concentrate mixtures contain only locally producible cereals. To increase the proportion of grass in the diets for scenario setting *B3 – Maximizing locally producible grassland-based feed utilization for cattle*, BAU rations for cattle and ox fattening were replaced with organic equivalents, which have higher proportions of grass in the feed plan (AGRIDEA 2023) and soybean was substituted with field beans. Concentrate-free rations were chosen for suckler herds (AGRIDEA 2022) and a ration including silage for dairy cows (AGRIDEA 2023).

SM3 / 2.2.3.1. Livestock feeding plans

Table SM3/8: Overview about implemented feeding plans per livestock type and feeding strategy. References: AGRIDEA (2022), AGRIDEA (2023), Kamm (11/25/2024), Spengler Neff et al. (2019), LfL (2024), and LfL (2013).

Livestock Tye	Feeding Strategy	Feeding Type	Reference Feeding Plan	Reference Source
Breeding sow	B1	Life-stage based feeding	Piglet feed	Kamm, J. (2024)
Breeding sow	B1	Life-stage based feeding	Pre-fattening	Kamm, J. (2024)
Breeding sow	B1	Life-stage based feeding	Fattening	Kamm, J. (2024)
Breeding sow	B1	Life-stage based feeding	Complete feed breeding sows (lactating)	Kamm, J. (2024)
Breeding sow	B1	Life-stage based feeding	Complete feed breeding sows (gilt)	Kamm, J. (2024)
Bull fattening	B1	Life-stage based feeding	0-1.5 Monate (6Wochen)_ Vollmilch	LfL (2024)
Bull fattening	B1	Life-stage based feeding	1.5-4 Monate (10Wochen)_ Milchaustauscher	AGRIDEA (2022)
Bull fattening	B1	Life-stage based feeding	Muni Intensivmast, 1300 g Tageszuwachs bis 325 kg LG	AGRIDEA (2022)
Bull fattening	B1	Life-stage based feeding	Muni Intensivmast, 1300 g Tageszuwachs bis 550 kg (327 Tage)	AGRIDEA (2022)
Bull fattening	B2	Life-stage based feeding	0-1.5 Monate (6Wochen)_ milk and hay only	Spengler Neff et al. (2019)
Bull fattening	B2	Life-stage based feeding	1.5-4 Monate (10Wochen)_ milk and hay only	Spengler Neff et al. (2019)
Bull fattening	B2	Life-stage based feeding	Muni Intensivmast, 1300 g Tageszuwachs bis 325 kg LG_Soy substitute from 200kg LW	AGRIDEA (2022) with soy substitute based on LfL (2013)
Bull fattening	B2	Life-stage based feeding	Muni Intensivmast, 1300 g Tageszuwachs bis 550 kg (327 Tage)_Soy substitute from 200kg LW	AGRIDEA (2022) with soy substitute based on LfL (2013)
Calf fattening	B1	Life-stage based feeding	0-2 Monate (8Wochen)_ Milchaustauscher	LfL (2024)
Calf fattening	B1	Life-stage based feeding	Vollmilchmast ohne Milchablieferung	AGRIDEA (2023)
Calf fattening	B2	Life-stage based feeding	0-2 Monate (8Wochen)_ Vollmilch	LfL (2024)
Calf fattening	B2	Life-stage based feeding	Vollmilchmast ohne Milchablieferung, BIO	AGRIDEA (2023)
Calf fattening	B3	Life-stage based feeding	0-4 Monate (16Wochen)_ milk and hay only	Spengler Neff et al. (2019)
Calf fattening	B3	Life-stage based feeding	Vollmilchmast ohne Milchablieferung, BIO	AGRIDEA (2023)
Cattle and Ox fattening	B3	Life-stage based feeding	0-2 Monate (8Wochen)_ milk and hay only	Spengler Neff et al. (2019)
Cattle and Ox fattening	B3	Seasonal Feeding	BIO-Weide-Beef, Remontenaufzucht	AGRIDEA (2023)

Livestock Tye	Feeding Strategy	Feeding Type	Reference Feeding Plan	Reference Source
Cattle and Ox fattening	B3	Seasonal Feeding	BIO-Weide-Beef, 700 gr Tageszunahme_Soy substitute	AGRIDEA (2023) with soy substitute based on LfL (2013)
Cattle fattening	B1	Life-stage based feeding	0-1.5 Monate (6Wochen)_ Vollmilch	LfL (2024)
Cattle fattening	B1	Life-stage based feeding	1.5-4 Monate (10Wochen)_ Milchaustauscher	AGRIDEA (2022)
Cattle fattening	B1	Life-stage based feeding	Ochsen/Rinder Halbintensivmast, 1000 g Tageszuwachs bis 527 kg (402 Tage)	AGRIDEA (2022)
Cattle fattening	B2	Life-stage based feeding	0-1.5 Monate (6Wochen)_ milk and hay only	Spengler Neff et al. (2019)
Cattle fattening	B2	Life-stage based feeding	1.5-4 Monate (10Wochen)_ Milchaustauscher	AGRIDEA (2022)
Cattle fattening	B2	Life-stage based feeding	Ochsen/Rinder Halbintensivmast, 1000 g Tageszuwachs bis 527 kg (402 Tage)_Soy substitute from 200kg LVV	AGRIDEA (2022) with soy substitute based on LfL (2013)
Dairy cow	B1	Life-stage based feeding	0-4 Monate (16Wochen)_ Vollmilch	LfL (2024)
Dairy cow	B1	Seasonal Feeding	Aufzuchtvertrag ab Alter 5 Mte. (Erstkalbealter 28 Mte)	AGRIDEA (2023)
Dairy cow	B1	Seasonal Feeding	8000 kg, Silozone	AGRIDEA (2023)
Dairy cow	B1	Life-stage based feeding	0-4 Monate (16Wochen)_ Vollmilch	LfL (2024)
Dairy cow	B1	Seasonal Feeding	Aufzuchtvertrag ab Alter 5 Mte. (Erstkalbealter 28 Mte)	AGRIDEA (2023)
Dairy cow	B1	Seasonal Feeding	7000 kg, verkäste Milch	AGRIDEA (2023)
Dairy cow	B1	Life-stage based feeding	0-4 Monate (16Wochen)_ Vollmilch	LfL (2024)
Dairy cow	B1	Seasonal Feeding	Aufzuchtvertrag ab Alter 5 Mte. (Erstkalbealter 28 Mte)	AGRIDEA (2023)
Dairy cow	B1	Seasonal Feeding	7000 kg, Silozone	AGRIDEA (2023)
Dairy cow	B1	Life-stage based feeding	0-4 Monate (16Wochen)_ Vollmilch	LfL (2024)
Dairy cow	B1	Seasonal Feeding	Aufzuchtvertrag ab Alter 5 Mte. (Erstkalbealter 28 Mte)	AGRIDEA (2023)
Dairy cow	B1	Seasonal Feeding	6000 kg, verkäste Milch	AGRIDEA (2023)
Dairy cow	B2	Life-stage based feeding	0-4 Monate (16Wochen)_ milk and hay only	Spengler Neff et al. (2019)
Dairy cow	B2	Seasonal Feeding	Aufzuchtvertrag ab Alter 5 Mte. (Erstkalbealter 28 Mte)	AGRIDEA (2023)
Dairy cow	B2	Seasonal Feeding	6000 kg, verkäste Milch_Soy substitute	AGRIDEA (2023) with soy substitute based on LfL (2013)
Dairy cow	B2	Life-stage based feeding	0-4 Monate (16Wochen)_ milk and hay only	Spengler Neff et al. (2019)
Dairy cow	B2	Seasonal Feeding	Aufzuchtvertrag ab Alter 5 Mte. (Erstkalbealter 28 Mte)	AGRIDEA (2023)
Dairy cow	B2	Seasonal Feeding	7000 kg, Silozone_Soy substitute	AGRIDEA (2023) with soy substitute based on LfL (2013)
Dairy cow	B2/B3	Life-stage based feeding	0-4 Monate (16Wochen)_ milk and hay only	Spengler Neff et al. (2019)
Dairy cow	B2/B3	Seasonal Feeding	Aufzuchtvertrag ab Alter 5 Mte. (Erstkalbealter 28 Mte)	AGRIDEA (2023)
Dairy cow	B2/B3	Seasonal Feeding	7000 kg, verkäste Milch_Soy substitute	AGRIDEA (2023) with soy substitute based on LfL (2013)
Dairy cow	B2	Life-stage based feeding	0-4 Monate (16Wochen)_ milk and hay only	Spengler Neff et al. (2019)
Dairy cow	B2	Seasonal Feeding	Aufzuchtvertrag ab Alter 5 Mte. (Erstkalbealter 28 Mte)	AGRIDEA (2023)
Dairy cow	B2	Seasonal Feeding	8000 kg, Silozone_Soy substitute	AGRIDEA (2023) with soy substitute based on LfL (2013)
Finishing pig	B1	Life-stage based feeding	Piglet feed	Kamm, J. (2024)
Finishing pig	B1	Life-stage based feeding	Pre-fattening and fattening	Kamm, J. (2024)
Ox fattening	B1	Life-stage based feeding	0-1.5 Monate (6Wochen)_ Vollmilch	LfL (2024)
Ox fattening	B1	Life-stage based feeding	1.5-4 Monate (10Wochen)_ Milchaustauscher	AGRIDEA (2022)
Ox fattening	B1	Life-stage based feeding	Ochsen/Rinder Halbintensivmast, 1000 g Tageszuwachs bis 527 kg (402 Tage)	AGRIDEA (2022)
Ox fattening	B2	Life-stage based feeding	0-1.5 Monate (6Wochen)_ milk and hay only	Spengler Neff et al. (2019)
Ox fattening	B2	Life-stage based feeding	1.5-4 Monate (10Wochen)_ Milchaustauscher	AGRIDEA (2022)
Ox fattening	B2	Life-stage based feeding	Ochsen/Rinder Halbintensivmast, 1000 g Tageszuwachs bis 527 kg (402 Tage)_Soy substitute from 200kg LVV	AGRIDEA (2022) with soy substitute based on LfL (2013)
Suckler cow	B1	Seasonal Feeding	Natura-Beef	AGRIDEA (2023)
Suckler cow	B2	Seasonal Feeding	Mutterkuhhaltung BIO Natura-Beef	AGRIDEA (2023)
Suckler cow	B3	Seasonal Feeding	Suckler cow_GrassBased	AGRIDEA (2022)

Livestock Tye	Feeding Strategy	Feeding Type	Reference Feeding Plan	Reference Source
Suckler cow husbandry	B1	Seasonal Feeding	Natura-Beef	AGRIDEA (2023)
Suckler cow husbandry	B2	Seasonal Feeding	Mutterkuhhaltung BIO Natura-Beef	AGRIDEA (2023)
Suckler cow husbandry	B3	Seasonal Feeding	Suckler cow_GrassBased	AGRIDEA (2022)

B2/B3 - Soy replacement: To increase the share of locally available feed, the share of soy in the feeding plans has been reduced to an agronomically feasible minimum. For replacing the soy share, we decided to integrate field beans (Ackerbohnen) and rapeseed meal into the feeding plans. Field beans were selected based on recommendations for the Lake Sempach catchment to reduce the high soil P levels. As legumes, field beans have high P requirements and low N demands, which promotes a reduction in soil P without necessitating additional nutrient inputs (Stoll et al. 2019). The following recommendations were applied during the implementation of the replacement (LfL 2013; Bayerische Landesanstalt für Landwirtschaft 2018; Ettle et al. 2013):

- 1 kg of field beans replaces 0.6 kg of grains and 0.4 kg of soy extraction meal.
- Field beans were mixed in a 50/50 ratio with rapeseed meal and with this, field beans make up a maximum of 50% of the protein carriers.
- Rearing cattle: Field beans make up a maximum of 55% of the concentrated feed.
- Dairy cows: less than 4 kg of field beans per animal per day.
- Fattening cattle/bulls from 200kg live weight onwards: Field beans make up a maximum of 55% of the concentrated feed.
- Remaining soy has been replaced with rapeseed meal (ratio 1:1).

As with these changes the NEL content of the feed rations (as well as the % of roughage, % of hay, % of maize silage, % forage, XP/NEL-relation) changed, we adjusted the DMI requirements of dairy cows accordingly.

SM3 / 2.2.4. Animal movement

Details of purchase and sales activities, the fate of offspring and the general development of animal stocks must be provided when the model is set up. Using individual animal location data at birth and slaughter (AMD 2023), all cattle were classified into four movement types: (1) Stays – born and slaughtered inside the catchment, (2) Outgoings – born inside but slaughtered outside, (3) Incomings – born outside but slaughtered inside, and (4) Pass-throughs – born and slaughtered outside but spending time in the catchment during their lifetime (see section SM3 / 2.2.4.1. for more details). Incomings and Pass-throughs were assumed to be purchased alive, while Outgoings and Pass-throughs were sold alive. The average purchase and sales age and related animal numbers were derived from the data. In total, 37 distinct movement patterns including purchase and sales activities and temporary absences like summer grazing were implemented in the model (see section 0 for more details). The number of finishing pigs purchased and sold was estimated using the monthly median values provided in

AMD (2023). Across all scenario settings, the purchase and sale rates, expressed relative to the number of mother cows, i.e. dairy or suckler cows, remained consistent with those used in the BAU scenario across all settings. However, the allocation of animals to livestock types varied based on the specific scenario settings. The fate of each calf born - whether it enters the fattening sector as veal or beef or is used as a replacement animal—was determined from AMD (2023) for BAU. This was based on the proportions of livestock types born within dairy and suckler herds, respectively. For the scenarios, it was determined by the settings *C1 – Offspring sold at an age of 2 months* and *C2 – Remaining offspring going into calf fattening*. For cattle, replacement rates were derived from AMD (2023) and implemented in both BAU and scenario models. For breeding sows, the model calculated the number of replacement animals needed to maintain a consistent number of fattening pigs as indicated by the data.

Capturing mortality via lightly reduced lifespan and fixed replacement rates

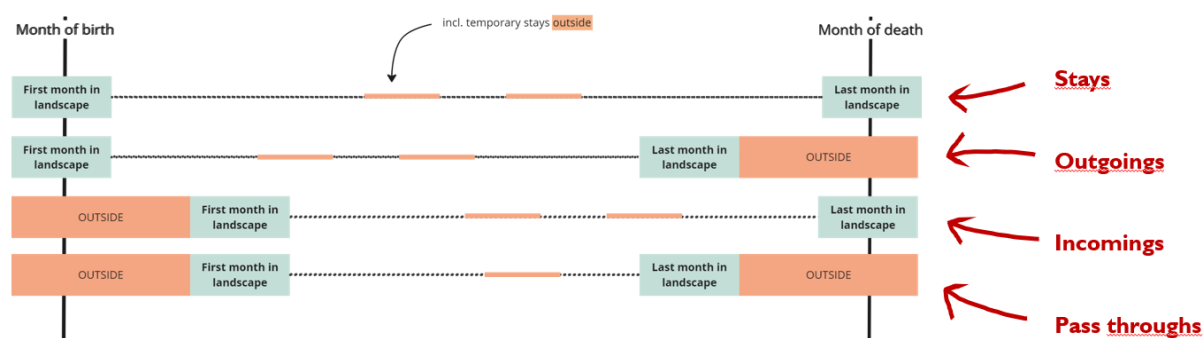
In this study, mortality rates were not explicitly implemented. Instead, mortality was accounted for indirectly by slightly reducing lifespans and applying fixed replacement rates based on the AMD (2023). It was ensured that overall animal numbers matched observed data.

SM3 / 2.2.4.1. Movement types and patterns

Movement Types based on whereabouts at month of birth and death

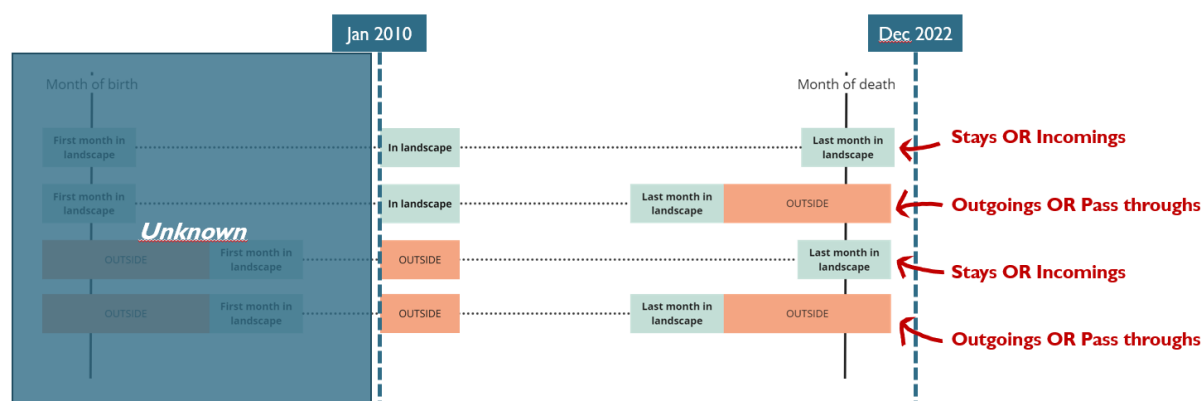
Group A. Animals born after 2010 and slaughtered before Dec 2022

Depending on the location of the individual animal in the month of birth and month of slaughter, four main movement types were defined: “Stays”, “Outgoings”, “Incomings”, and “Pass throughs”. Animals born after 2010 and slaughtered before Dec 2022 have been allocated to these main movement types.



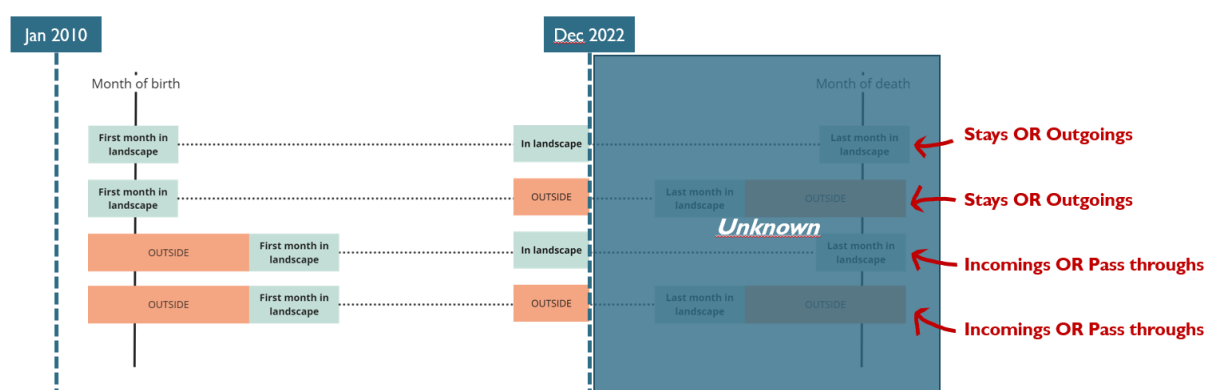
Group B. Animals born before 2010

However, as the movement data is only available from 01/2010 onwards, for animals born before 2010, the information about the place of residence in the month of birth is not known. These animals have been allocated to one of the following two movement types: “Stays or Incomings”, or “Outgoings or Pass throughs”



Group C. Animals that are still alive in Dec 2022

Additionally, for animals that **were still alive in Dec 2022**, the information about the place of residence in the month of slaughter not known at the moment of data extraction. These animals were allocated to one of the following two movement types: “Stays or Outgoings”, or “Incomings or Pass throughs”



The division of animals into these movement types is the basis for A) the design of the movement patterns and consequently B) the generation of the final number of animals per livestock type – movement type – movement pattern combination:

- Only data from group A, comprising the movement types 'Stays', 'Outgoings', 'Incomings', and 'Pass-throughs', served as the basis for **designing the movement patterns**.
- As can be seen in Figure SM3/10, groups B & C were less relevant for the livestock types calf fattening, suckler cow husbandry, bull fattening, cattle fattening, and ox fattening. On the other hand, in the case of the livestock types dairy cow and suckler cow, group B & C animals were also included in the data throughout all years. Therefore, the number of group A animals in the years 2011 to 2021 was the basis for **the generation of the final number of animals per livestock type - movement type - movement pattern combination** for the livestock types calf fattening, suckler cow husbandry, bull fattening, cattle fattening, and ox fattening. Whereas for the livestock types dairy cow and suckler

cow, the number of animals in groups A, B & C in the years 2011 to 2021 was the basis for the generation of the final number of animals per livestock type - movement type - movement pattern combination. The animals of group B & C were allocated to one of the four main movement types (group A) on the basis of the proportions shown in Table SM3/9.

Remark: 118 animals could not be allocated to one of the three groups, as they were born before 2010 and still alive after 12/2022 (mainly livestock type Milchkuh and Mutterkuh). For these animals, there is consequently no information about the whereabouts at the month of birth and death available. These animals have been allocated to the four main movement types (Stays, Outgoings, Incomings, and Pass throughs) based on the shares per livestock type

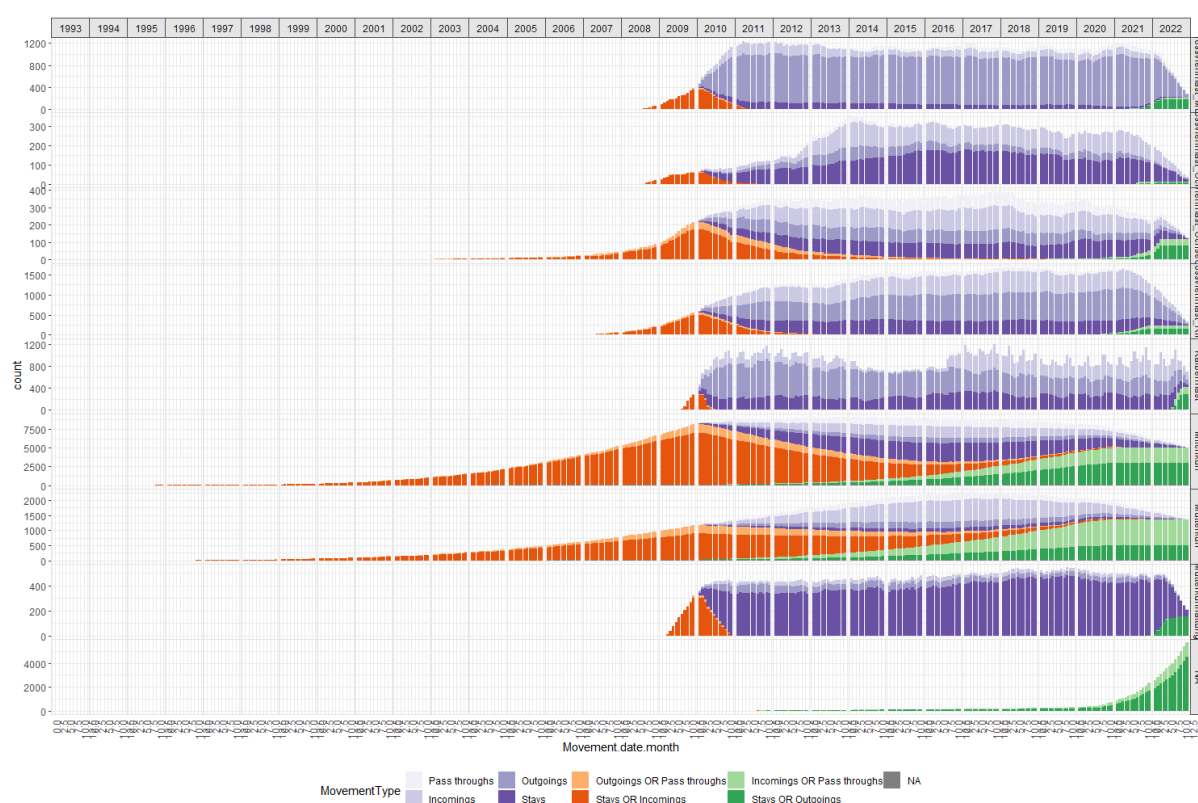


Figure SM3/10: Number of animals (y-axis) per month and year (x-axis and horizontal facets), Livestock Type (vertical facets), and Movement Type (colors). “Grossviehmast_Muni” refers to bull fattening, “Grossviehmast_Rind” to cattle fattening, “Milchkuh” to dairy cow, “Mutterkuhhaltung” to suckler cow husbandry, “Grossviehmast_Ochse” to ox fattening, “Kälbermast” refers to calf fattening, «Mutterkuh» to suckler cow.

Table SM3/9: Share (in %) of the four main movement types in the respective movement types combinations (Group B and Group C) over all years for the livestock types dairy cow and suckler cow.

	Group B				Group C			
	Stays_vs_Incomings		Outgoings_vs_PassThroughs		Stays_vs_Outgoings		Incomings_vs_PassThroughs	
	Stays	Incomings	Outgoings	PassThroughs	Stays	Outgoings	Incomings	PassThroughs
Dairy cow	64.52	35.48	38.64	61.36	79.73	20.27	57.67	42.33
Suckler cow	16.6	83.4	50.94	49.06	36.86	63.14	75.28	24.72

Final movement types and proportions

The above described definition of the four main movement types (group A) resulted in a distribution of animals as presented in Table SM3/10. Those livestock type - movement type combinations were the basis for the definition of the movement pattern.

Table SM3/10: Percentage of animals per livestock and movement type, e.g. 45% of all dairy cows are allocated to the movement type “Stays”. Movement types relevant for less than 10% of the animals of that livestock type have been excluded (grey marked cells). Animals not belonging to any of the final movement types were allocated to these final groups on the basis of proportions.

	Perc				n			
	Stays	Outgoings	Incomings	Pass throughs	Stays	Outgoings	Incomings	Pass throughs
Dairy cow	45	12	25	18	3740	951	2057	1510
Calf fattening	31	46	23	0	7435	11120	5560	73
Suckler cow	11	18	54	18	174	298	874	287
Suckler cow husbandry	83	11	6	1	5181	676	351	36
Bull fattening	8	78	10	5	847	8823	1115	510
Ox fattening	50	14	34	2	996	271	682	43
Cattle fattening	22	43	31	4	2087	4164	2953	407

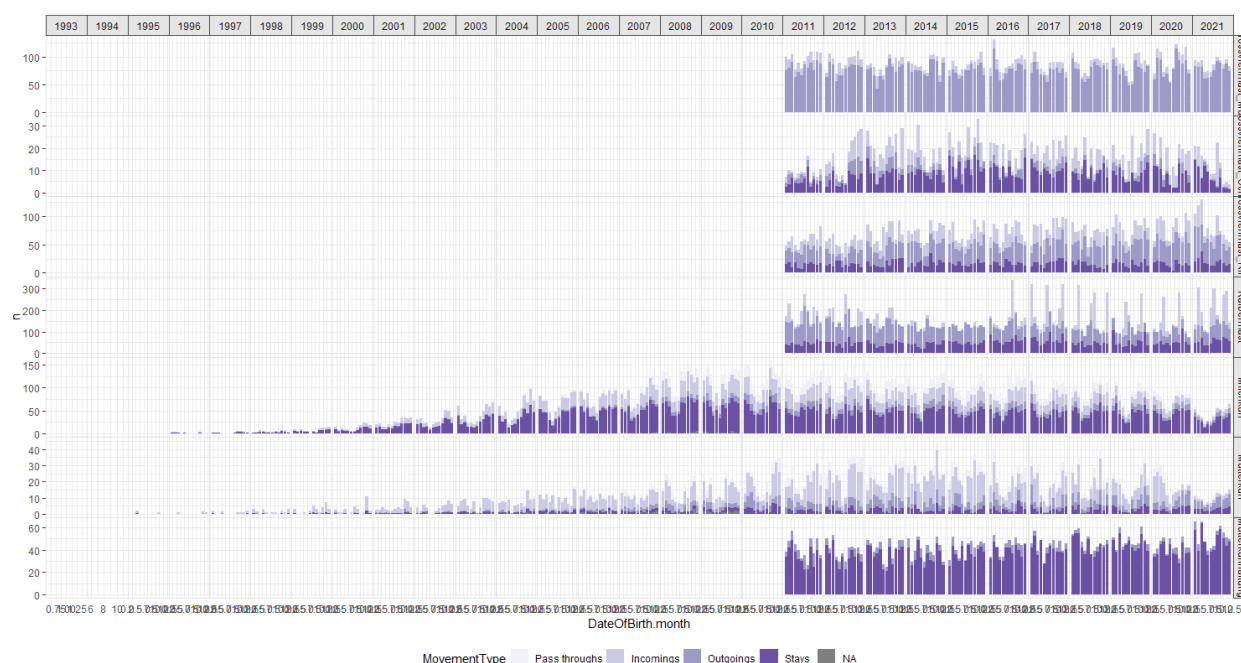


Figure SM3/I I: Final number of animals (y-axis) per month/year of birth (x-axis and horizontal facets), Livestock Type (vertical facets), and Movement Type (colors). “Grossviehmast_Muni” refers to bull fattening, “Grossviehmast_Rind” to cattle fattening, “Milchkuh” to dairy cow, “Mutterkuhhaltung” to suckler cow husbandry, “Grossviehmast_Ochse” to ox fattening, “Kälbermast” refers to calf fattening, “Mutterkuh» to suckler cow.

SM3 / 2.2.4.2. Definition of Movement Patterns and Movement Plans

Table SM3/I I: Overview of movement types and plans for each livestock type, including the respective ages at purchase, sale, and slaughter (in months), along with a graphical representation of these movement patterns throughout the animal's life. EoL = End of life.

LivestockType	MovementType	MovementPlan	Month of life			LivestockHousingPlan
			AgeAtPurchas einMonths	AgeAtSaleIn Months	AgeAtSlaught erInMonths	
Bull fattening	Incomings	Early entry	2		13	LHP1_S to Einside_Type A
Bull fattening	Outgoings	Early exit		2	13	LHP1_S to Einside_Type A
Ox fattening	Incomings	Early entry	2		17	LHP1_S to Einside_Type A
Ox fattening	Outgoings	Early exit		2	17	LHP1_S to Einside_Type A
Ox fattening	Stays	Staying			17	LHP1_S to Einside_Type A
Cattle fattening	Incomings	Early entry	2		18	LHP1_S to Einside_Type A
Cattle fattening	Outgoings	Early exit		2	18	LHP1_S to Einside_Type A
Cattle fattening	Stays	Staying			18	LHP1_S to Einside_Type A
Cattle fattening	Stays	1x Summer grazing (1st year)			18	LHP4_Outside 1st summer_Type A
Cattle fattening	Stays	1x Summer grazing (2nd year)			18	LHP5_Outside 2nd summer_Type A
Calif fattening	Incomings	Early entry	2		5	LHP1_S to Einside_Type A
Calif fattening	Outgoings	Early exit		2	5	LHP1_S to Einside_Type A
Calif fattening	Stays	Staying			5	LHP1_S to Einside_Type A
Dairy cow	Incomings	Late entry	38		76	LHP1_S to Einside_Type B1
Dairy cow	Outgoings	Early exit		3	76	LHP1_S to Einside_Type B1
Dairy cow	Outgoings	Late exit		40	76	LHP1_S to Einside_Type B1
Dairy cow	Outgoings	Outside rearing		41	76	LHP2_Outside 6-28_Type B1
Dairy cow	Outgoings	1x Summer grazing		40	76	LHP5_Outside 2nd summer_Type B1
Dairy cow	Pass throughs	5 months stay	28	33	76	LHP1_S to Einside_Type B1
Dairy cow	Pass throughs	Inside rearing	7	26	76	LHP1_S to Einside_Type B1
Dairy cow	Pass throughs	2 stays	37	53	76	LHP3_Outside 40-48_Type B1
Dairy cow	Stays	Staying			76	LHP1_S to Einside_Type B1
Dairy cow	Stays	Outside rearing			76	LHP2_Outside 6-28_Type B1
Dairy cow	Stays	1x Summer grazing			76	LHP5_Outside 2nd summer_Type B1
Suckler cow	Incomings	Late entry	30		85	LHP1_S to Einside_Type B1
Suckler cow	Outgoings	Early exit		2	85	LHP1_S to Einside_Type B1
Suckler cow	Outgoings	Late exit		27	85	LHP1_S to Einside_Type B1
Suckler cow	Stays	Staying			85	LHP1_S to Einside_Type B1
Suckler cow	Outgoings	Outside rearing		39	85	_Type B1
Suckler cow	Stays	Outside rearing			85	LHP2_Outside 6-27_Type B1
Suckler cow	Outgoings	1x Summer grazing		34	85	LHP5_Outside 2nd summer_Type B1
Suckler cow	Pass throughs	Inside rearing	3	27	85	LHP5_Outside 2nd summer_Type B1
Suckler cow	Stays	1x Summer grazing			85	LHP5_Outside 2nd summer_Type B1
Suckler cow	Pass throughs	5 months stay	2	28	85	LHP6_Inside Oct to Mar_Type B1
Suckler cow husbandry	Outgoings	Early exit		2	10	LHP1_S to Einside_Type B2
Suckler cow husbandry	Stays	Staying			10	LHP1_S to Einside_Type B2
Suckler cow husbandry	Stays	1x Summer grazing			10	LHP4_Outside 1st summer_Type B2

SM3 / 3. Determination of convertible permanent grassland

To calculate the proportion of permanent grassland that could be converted to arable land, we first extracted the agricultural suitability classes for the catchment (FOAG 2000) and categorized them as potentially convertible vs. non-convertible (Table SM3/12). The potentially convertible areas were overlaid with the area of permanent grassland (rawi 2019). Of the total permanent grassland of 2'008 ha, 74% (1'486 ha) could potentially be converted to arable land. We assumed that on the newly created arable land would have a similar crop rotation to the existing arable land, resulting in a temporary grassland share of 44%. This proportion was subtracted from the 1'486 ha, resulting in a maximum of 838 ha of potentially convertible permanent grassland.

We furthermore calculated for each individual scenario the amount of unused temporary and permanent grassland after the grassland requirement had been met, and determined how much of the remaining permanent grassland could potentially be converted to arable land, taking into account suitability (times 74%) and rotation limitations (times 44%). Finally, the remaining arable land requirement was calculated after taking into account the converted grassland area.

Table SM3/12: Possible conversion to arable land of agricultural suitability classes. Suitability classes based on FOAG (2000)

Agricultural suitability class	Distinction made
Cereal cultivation, fodder cultivation: ++, root crop cultivation: +/++	Permanent grassland can potentially be converted to arable land
Fodder cultivation: +/+++; arable farming: +	Permanent grassland can potentially be converted to arable land
Natural fodder cultivation: +; artificial fodder cultivation: +/-	Permanent grassland cannot be converted to arable land
Cereal cultivation: +, fodder cultivation: ++, root crop cultivation: +/-	Permanent grassland can potentially be converted to arable land
Young livestock pasture: ++; natural fodder cultivation: +; large livestock pasture: +/-	Permanent grassland cannot be converted to arable land

SM3 / 4. Model set up

For the BAU model run, the following values were consequently used to represent the baseline against which reduction strategies (A–D) were assessed (see Table SM3/13). Based on the AMD, the livestock composition was derived such that cattle accounted for 69% of the total LSU (A2), with 82% of the cattle LSUs attributed to the dairy herd (A3). For both dairy and suckler herds, feeding strategies followed a 100% B1 feed ration, reflecting current practices. Offspring were sold at different ages (C1). In the dairy herd, 5% of replacement calves for dairy cows were sold at 2 months, and 16% of the remaining replacement calves at 40 months, while the remaining animals stayed within the catchment. Animals in the various fattening production lines of the dairy herd had different selling rates, but all are sold at 2 months of age: 100% of animals in bull fattening, 25% in ox fattening, 67% in cattle fattening, and 60% in calf fattening were sold at this age. In the suckler herd, 26% of replacement calves for suckler cows were sold at 2 months, 75% of the remaining replacement calves at 33

months, and 11% of suckler calves were sold at 2 months. From the total remaining dairy herd offspring, 39% went into calf fattening (C2). Of the replacement heifers, 38% (dairy) and 20% (suckler) left for the rearing phase (D1), while the remainder were reared within the catchment. During the period from July to October, several animals are seasonally absent (D2). In the dairy herd, 26% of replacement heifers for dairy cows in their second year of life are absent, along with 3.9% of cattle fattening animals in their first year and 2.6% in their second year. In the suckler herd, 34% of replacement heifers for suckler cows in their second year of life and 8% of suckler calves in their first year are also absent during this time.

Table SM3/I3: BAU parameter settings.

		Dairy herd					Suckler herd		Pig herd		
		Dairy cow	Bull fattening	Ox fattening	Cattle fattening	Calf fattening	Suckler cow	Suckler cow husbandry	Breeding sow	Finishing pig	
(A) Livestock density and composition											
A1	Overall livestock density	100%									
A2	Share of cattle vs pigs	LSU: 69% FLU: 74%									
A3	Share dairy cows among cattle	LSU 82% FLU 86%							n/a	n/a	
(B) Feeding strategies											
B1	BAU	100%					100%		100%		
B2	Maximized locally sourced forage and feed utilization (grassland and arable land)	0%					0%		0%		
B3	Maximized locally sourced grassland-based feed utilization	0%					0%		0%		
(C) Offspring fate											
C1	Offspring sold at an age of 2 months	5% sold at 2months 16% sold at 40months	100%	25%	67%	60%	26% sold at 2months 75% sold at 33months	11%	0%	60%	
C2	Remaining offspring going into calf fattening	Replacement rate: 38%	Ratio 87% bull vs 13% ox fattening		n/a	39%	Replacement rate: 27%	n/a	n/a	n/a	
(D) Livestock movement dynamics											
D1	Animals leaving for the rearing phase	38%	n/a	n/a	n/a	n/a	20%	n/a	n/a	n/a	
D2	Animals that are seasonally absent (Jul to Oct)	26% 2nd year of life	0%	0%	>> 3.9% 1st year of life >> 2.6% 2nd year of life	0%	34% 2nd year of life	8% 1st year of life	0%	0%	

SM3 / 5. Calibration

SM3 / 5.1. Animal numbers

Comparison of animal numbers per t

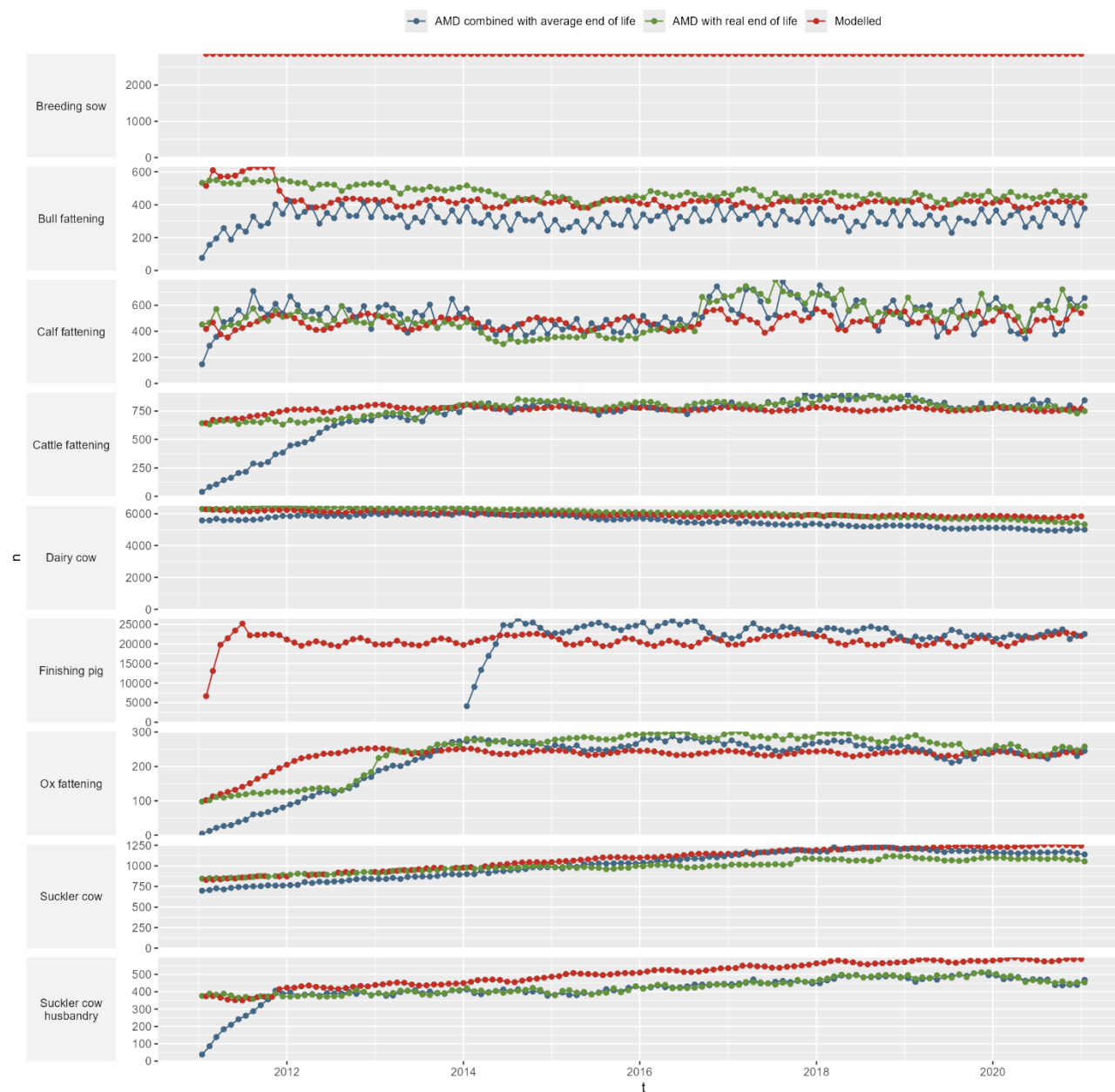


Figure SM3/I2: Development of animal numbers over time by livestock type. The red line shows simulated model results; the green line represents observed animal numbers from AMD (2023); and the blue line is derived from the number of animals born per month (AMD 2023), adjusted using average lifespans per livestock type based on AMD data. Note: AMD data included cattle records from 2010 to 2022 and pig records from 2014 to 2022.

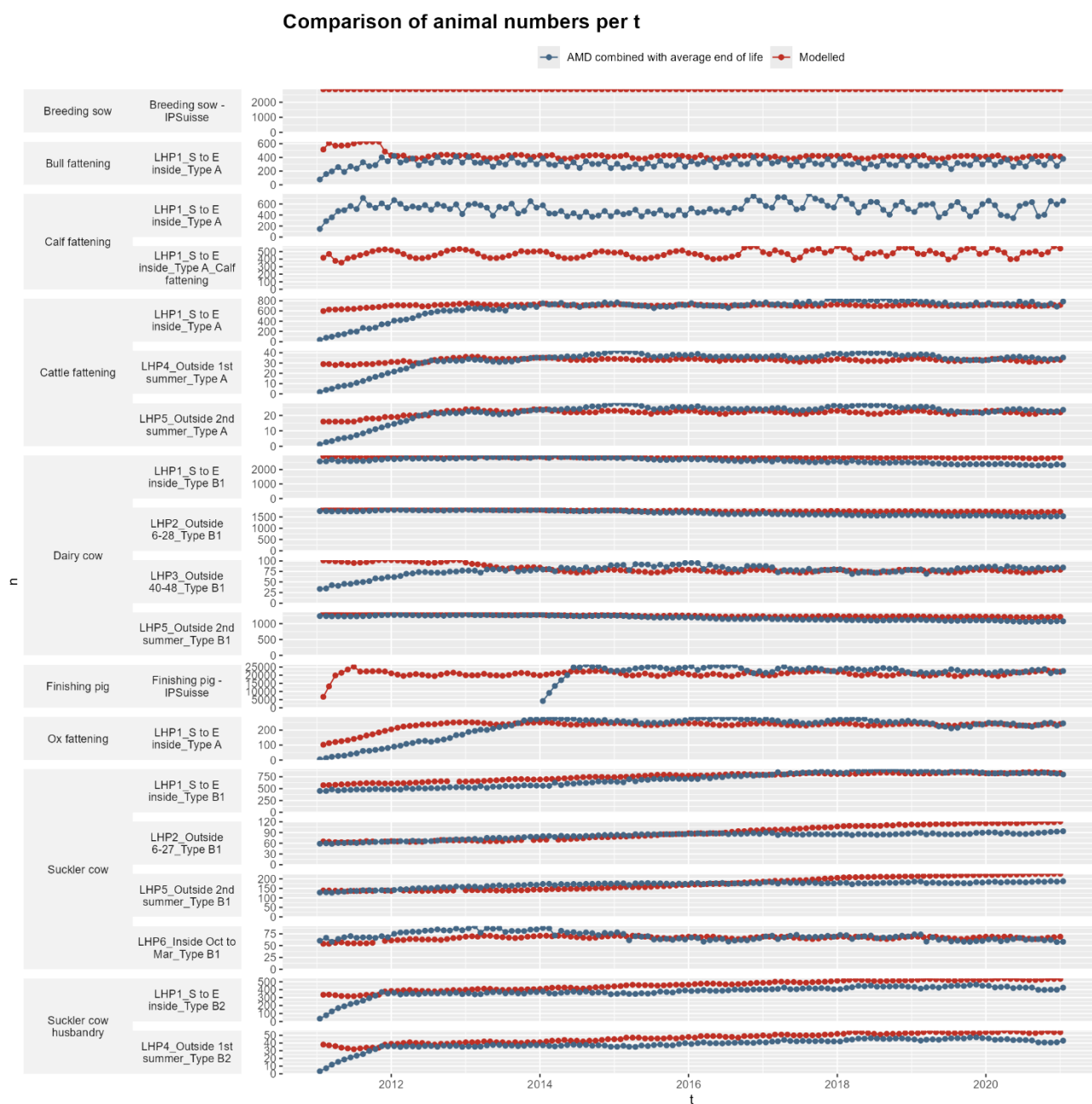


Figure SM3/I3: Development of animal numbers over time by livestock and movement type. The red line shows simulated model results and the blue line is derived from the number of animals born per month (AMD 2023), adjusted using average lifespans per livestock type based on AMD data. Note: AMD data included cattle records from 2010 to 2022 and pig records from 2014 to 2022.

SM3 / 5.2. Production quantities

SM3 / 5.2.1. Milk

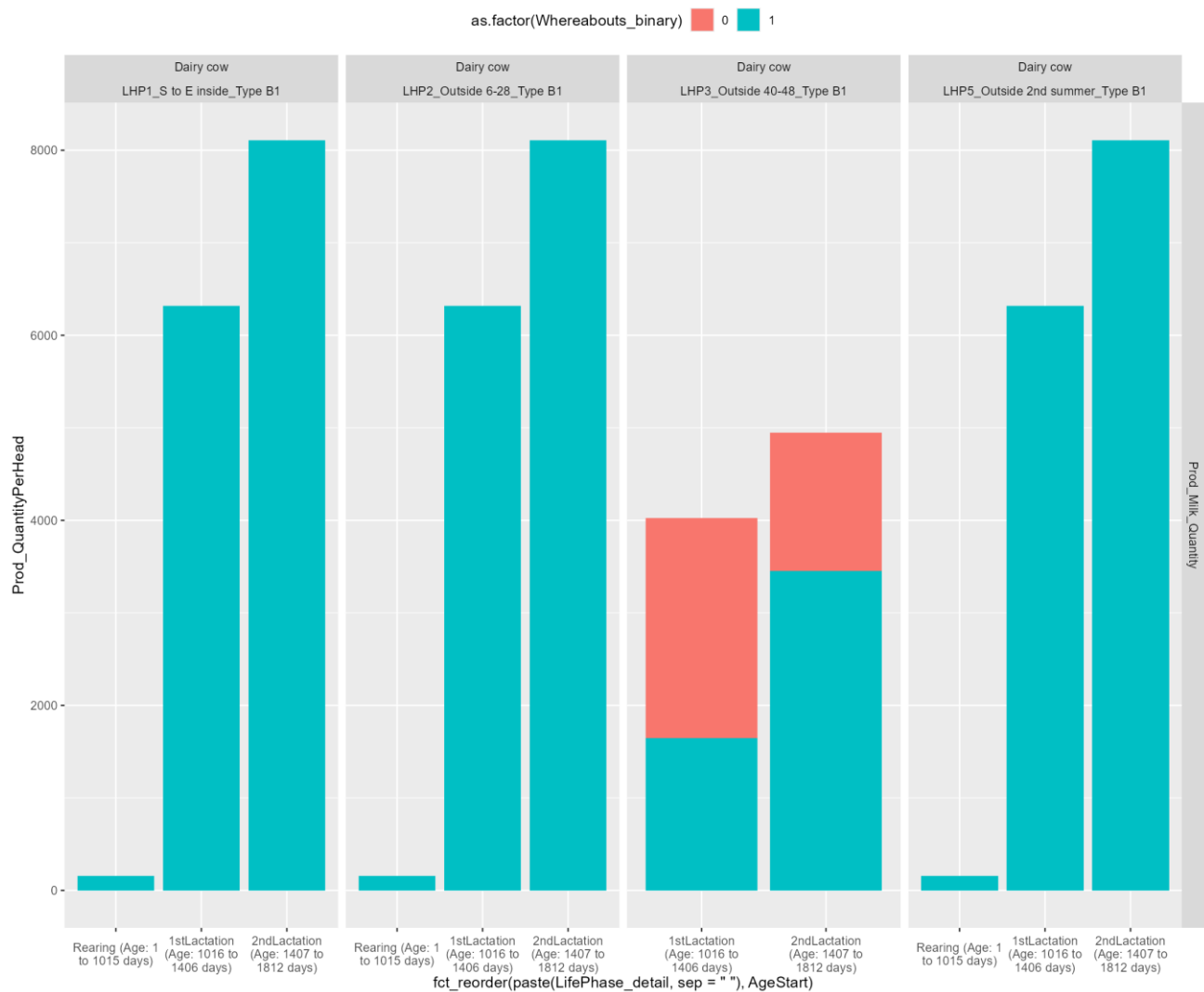


Figure SM3/14: Milk yield per dairy cow and lactation number. Colors indicate whether milk is produced inside (blue) or outside (red) the catchment. Vertical facets represent different movement types. The second lactation is shown as representative for all subsequent lactations. **Note:** animals with the movement type “*LHP3_Outside 40–48_Type B1*” are purchased at 37 months of age (approximately 3.5 months into their first lactation, with that portion of milk not included) and sold at 57 months (around the transition between starting and production phase of the second lactation, with no milk recorded post-sale). These animals are located outside the catchment between 40–48 months, indicated by the red color. Apparent milk yield during the rearing phase is a display-related artifact of the monthly data structure, where one month includes the end of rearing, first calving, and the start of the first lactation.

SM3 / 5.2.2. Manure



Figure SM3/15: Annual quantity of manure and slurry (kg/year) produced per stable space occupied by dairy cows. Vertical facets represent different movement types; horizontal facets distinguish between manure occurring outside (top) and inside (bottom) the catchment. Note the differing y-axis scales. The x-axis shows life stages with corresponding ages in brackets. Colors indicate slurry on pasture (red), slurry in the stable (green), and solid manure in the stable (blue).



Figure SM3/16: Annual quantity of nitrogen (top facet, kg/year) and phosphorus (bottom facet, kg/year) produced per stable space occupied by dairy cows. The x-axis shows life stages with corresponding ages in brackets. Colors indicate nutrients occurring outside (red) and inside (blue) the catchment.

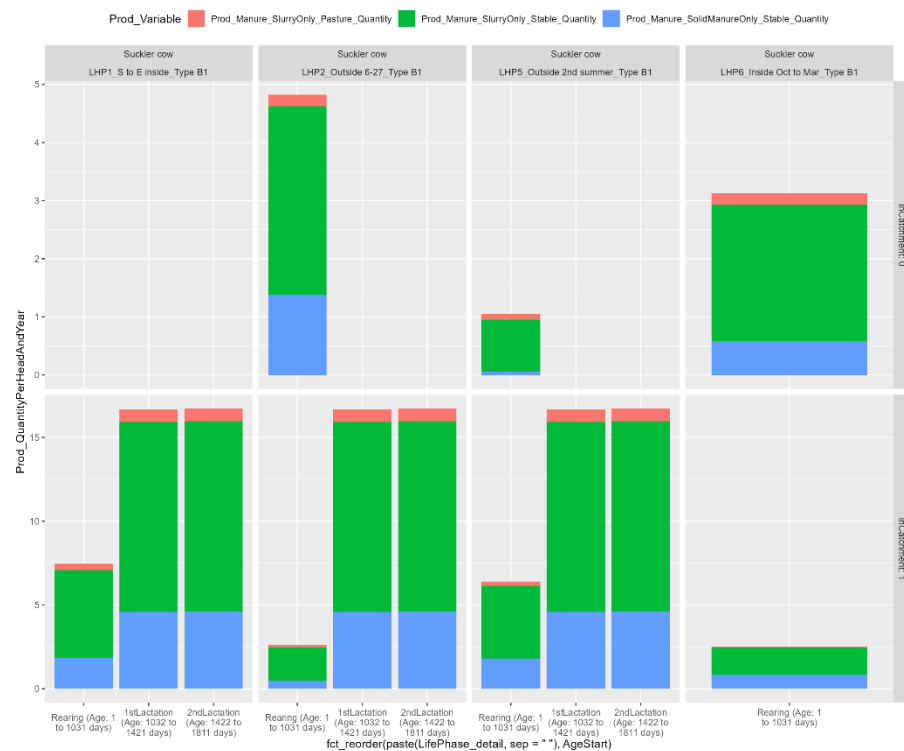


Figure SM3/17: Annual quantity of manure and slurry (kg/year) produced per stable space occupied by suckler cows. Vertical facets represent different movement types; horizontal facets distinguish between manure occurring outside (top) and inside (bottom) the catchment. Note the differing y-axis scales. The x-axis shows life stages with corresponding ages in brackets. Colors indicate slurry on pasture (red), slurry in the stable (green), and solid manure in the stable (blue).

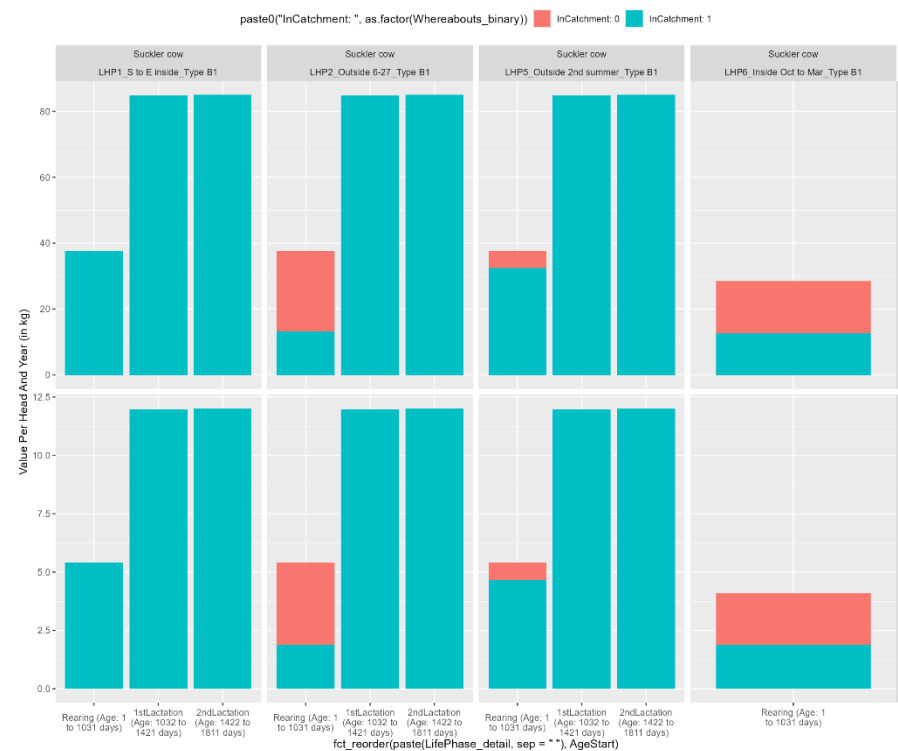


Figure SM3/18: Annual quantity of nitrogen (top facet, kg/year) and phosphorus (bottom facet, kg/year) produced per stable space occupied by suckler cows. The x-axis shows life stages with corresponding ages in brackets. Colors indicate nutrients occurring outside (red) and inside (blue) the catchment.

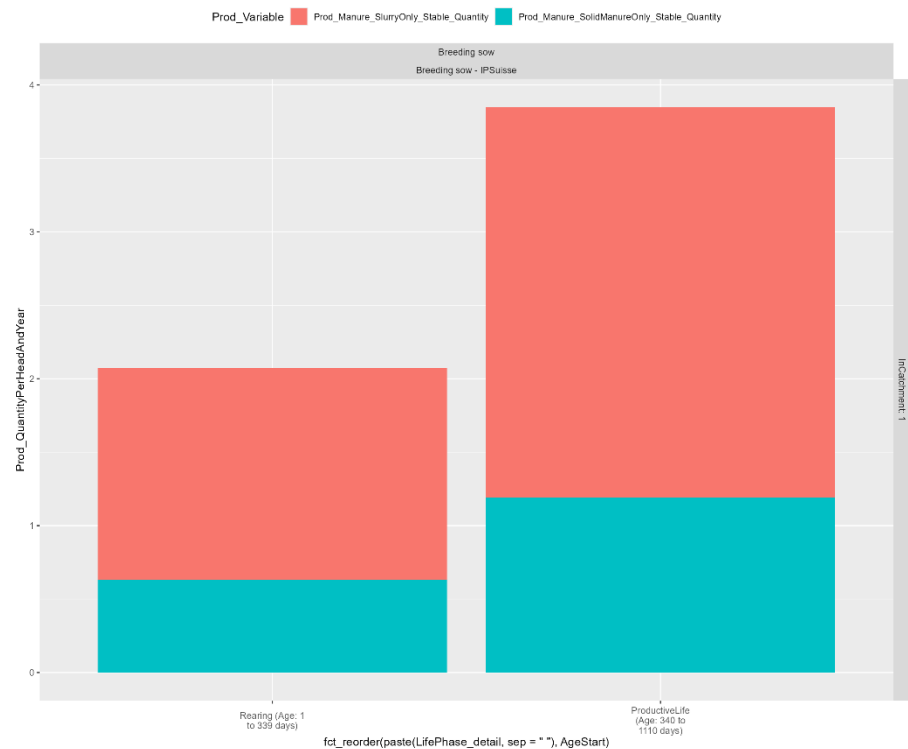


Figure SM3/19: Annual quantity of manure and slurry (kg/year) produced per stable space occupied by breeding sows. Vertical facets represent different movement types; horizontal facet show manure occurring and inside the catchment. Note the differing y-axis scales. The x-axis shows life stages with corresponding ages in brackets. Colors indicate slurry in the stable (red) and solid manure in the stable (blue).



Figure SM3/20: Annual quantity of nitrogen (top facet, kg/year) and phosphorus (bottom facet, kg/year) produced per stable space occupied by breeding sows. The x-axis shows life stages with corresponding ages in brackets. Colors indicate nutrients occurring inside (red) the catchment.

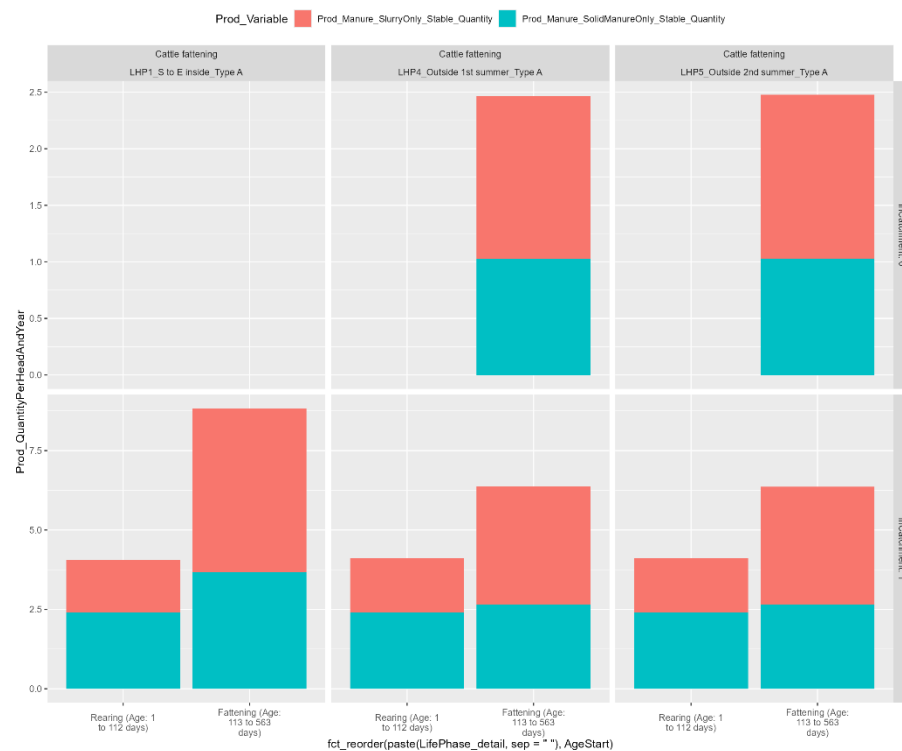


Figure SM3/21: Annual quantity of manure and slurry (kg/year) produced per stable space occupied by cattle (for fattening). Vertical facets represent different movement types; horizontal facets distinguish between manure occurring outside (top) and inside (bottom) the catchment. Note the differing y-axis scales. The x-axis shows life stages with corresponding ages in brackets. Colors indicate slurry in the stable (red) and solid manure in the stable (blue).



Figure SM3/22: Annual quantity of nitrogen (top facet, kg/year) and phosphorus (bottom facet, kg/year) produced per stable space occupied by cattle (for fattening). The x-axis shows life stages with corresponding ages in brackets. Colors indicate nutrients occurring outside (red) and inside (blue) the catchment.



Figure SM3/23: Annual quantity of manure and slurry (kg/year) produced per stable space occupied by oxen (for fattening). Vertical facets represent different movement types; horizontal facet show manure occurring and inside the catchment. Note the differing y-axis scales. The x-axis shows life stages with corresponding ages in brackets. Colors indicate slurry in the stable (red) and solid manure in the stable (blue).



Figure SM3/24: Annual quantity of nitrogen (top facet, kg/year) and phosphorus (bottom facet, kg/year) produced per stable space occupied by oxen (for fattening). The x-axis shows life stages with corresponding ages in brackets. Colors indicate nutrients occurring inside (red) the catchment.



Figure SM3/25: Annual quantity of manure and slurry (kg/year) produced per stable space occupied by bulls (for fattening). Vertical facets represent different movement types; horizontal facet show manure occurring and inside the catchment. Note the differing y-axis scales. The x-axis shows life stages with corresponding ages in brackets. Colors indicate slurry in the stable (red) and solid manure in the stable (blue).

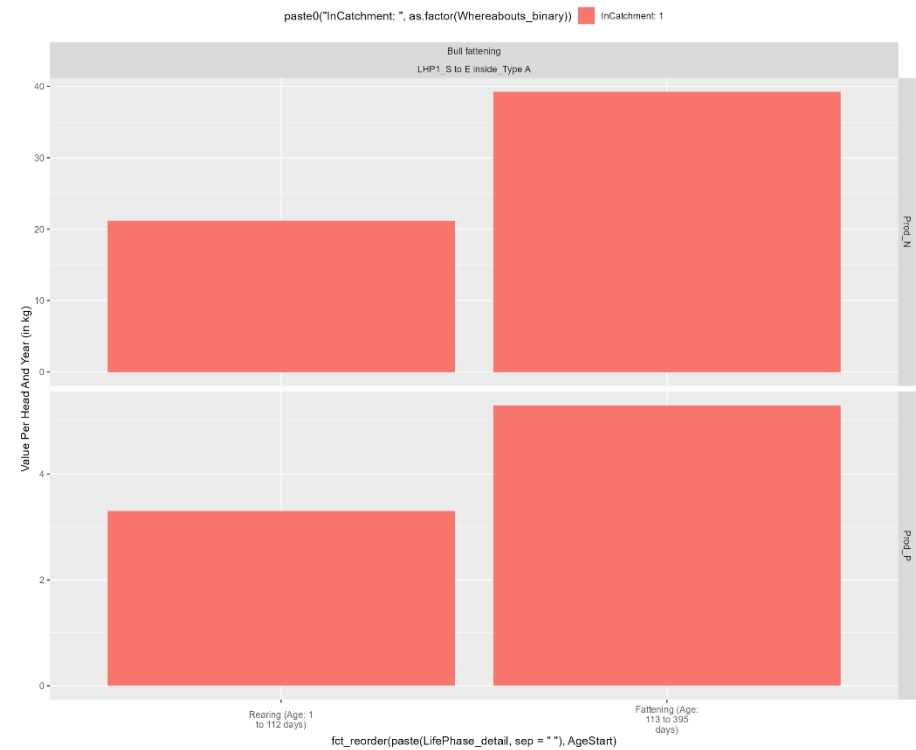


Figure SM3/26: Annual quantity of nitrogen (top facet, kg/year) and phosphorus (bottom facet, kg/year) produced per stable space occupied by bulls (for fattening). The x-axis shows life stages with corresponding ages in brackets. Colors indicate nutrients occurring inside (red) the catchment.

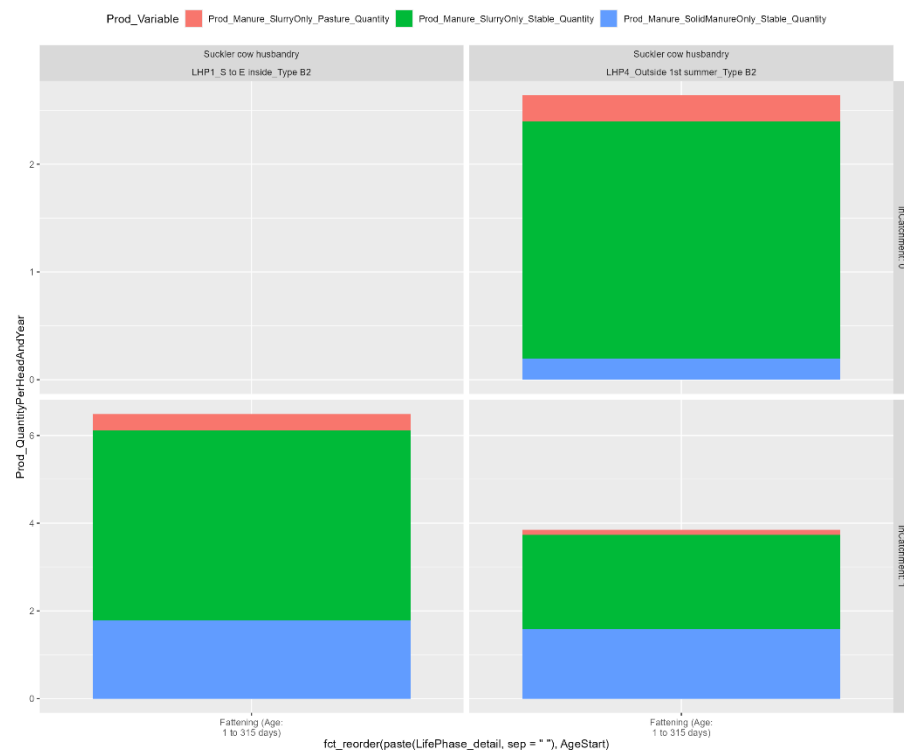


Figure SM3/27: Annual quantity of manure and slurry (kg/year) produced per stable space occupied by suckler cow calves. Vertical facets represent different movement types; horizontal facets distinguish between manure occurring outside (top) and inside (bottom) the catchment. Note the differing y-axis scales. The x-axis shows life stages with corresponding ages in brackets. Colors indicate slurry on pasture (red), slurry in the stable (green), and solid manure in the stable (blue).



Figure SM3/28: Annual quantity of nitrogen (top facet, kg/year) and phosphorus (bottom facet, kg/year) produced per stable space occupied by suckler cow calves. The x-axis shows life stages with corresponding ages in brackets. Colors indicate nutrients occurring outside (red) and inside (blue) the catchment.

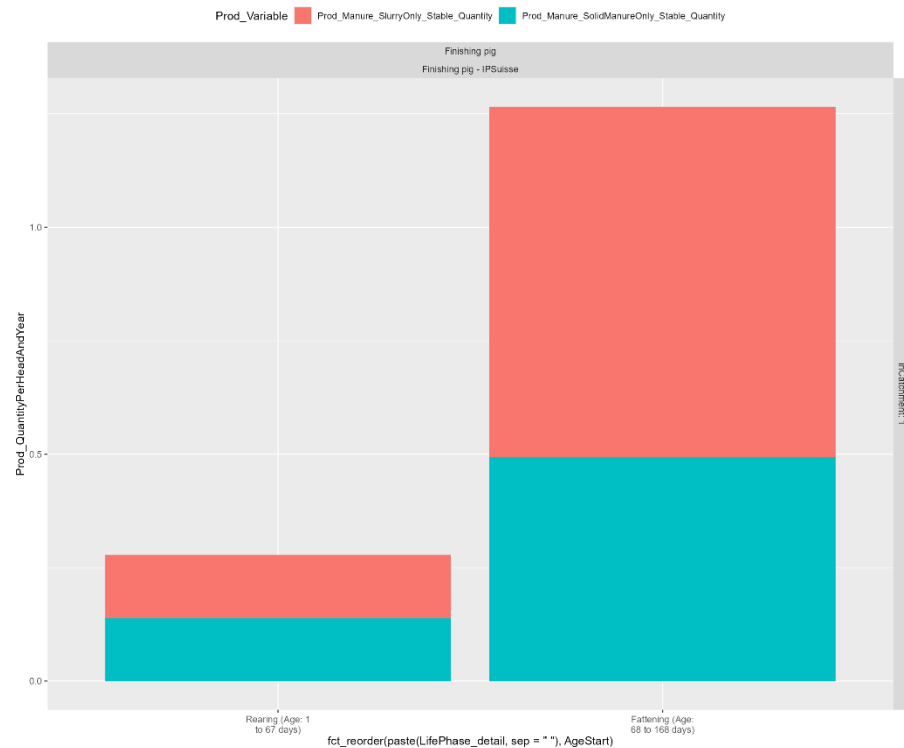


Figure SM3/29: Annual quantity of manure and slurry (kg/year) produced per stable space occupied by finishing pigs. Vertical facets represent different movement types; horizontal facet show manure occurring and inside the catchment. The x-axis shows life stages with corresponding ages in brackets. Colors indicate slurry in the stable (red) and solid manure in the stable (blue).

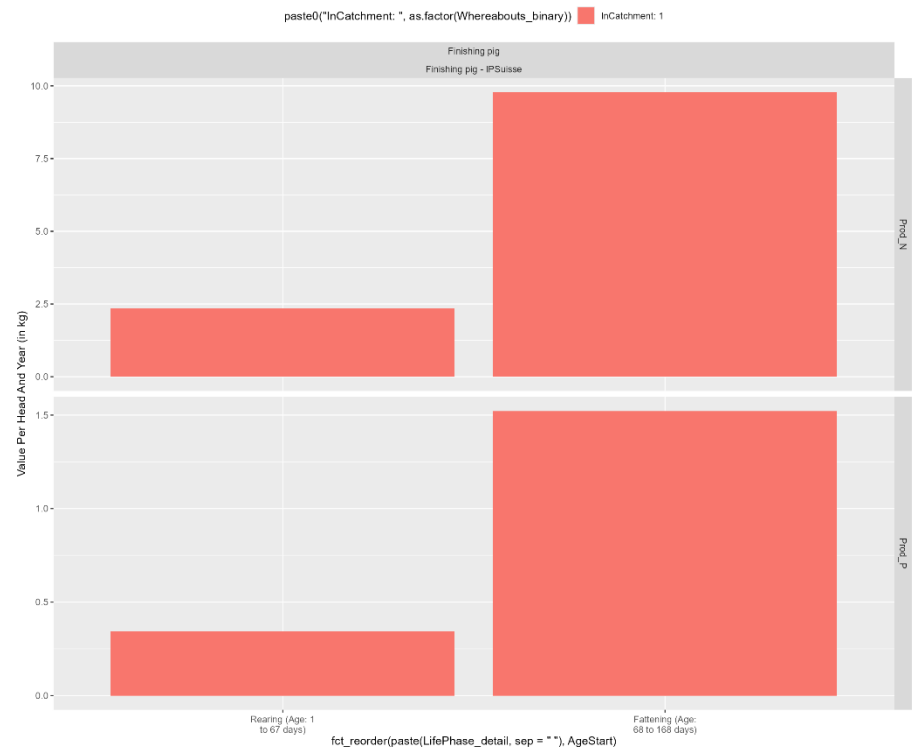


Figure SM3/30: Annual quantity of nitrogen (top facet, kg/year) and phosphorus (bottom facet, kg/year) produced per stable space occupied by finishing pigs. The x-axis shows life stages with corresponding ages in brackets. Colors indicate nutrients occurring inside (red) the catchment.

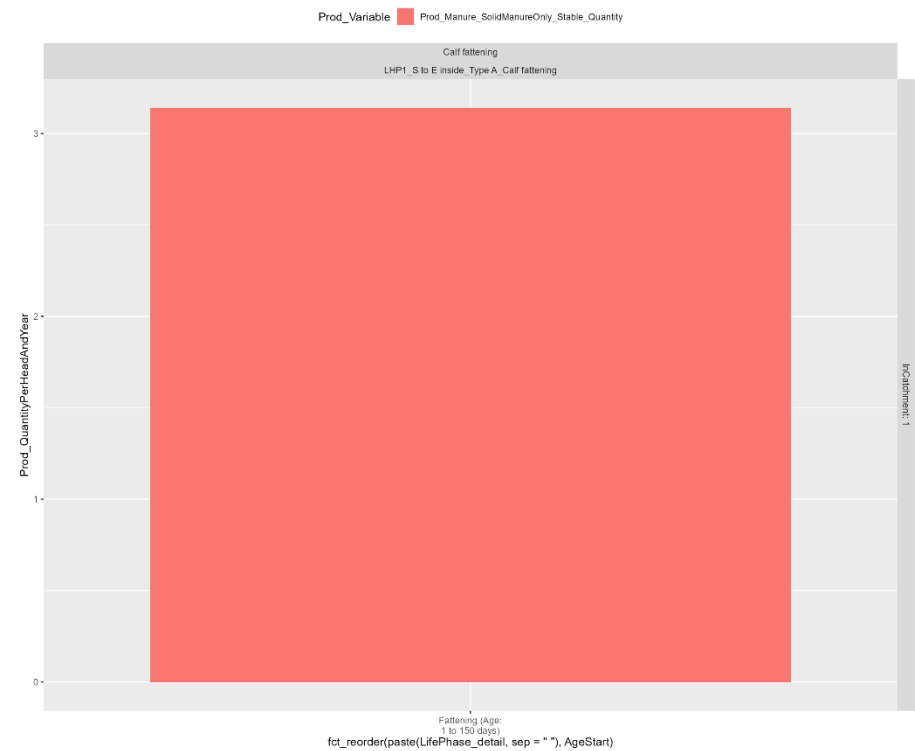


Figure SM3/31: Annual quantity of manure and slurry (kg/year) produced per stable space occupied by calves (for fattening). Vertical facets represent different movement types; horizontal facets distinguish between manure occurring outside (top) and inside (bottom) the catchment. Note the differing y-axis scales. The x-axis shows life stages with corresponding ages in brackets. Colors indicate solid manure in the stable (red).



Figure SM3/32: Annual quantity of nitrogen (top facet, kg/year) and phosphorus (bottom facet, kg/year) produced per stable space occupied by calves (for fattening). The x-axis shows life stages with corresponding ages in brackets. Colors indicate nutrients occurring inside (red) the catchment.

SM3 / 5.2.3. Offspring

Number of produced animals by the producing livestock type

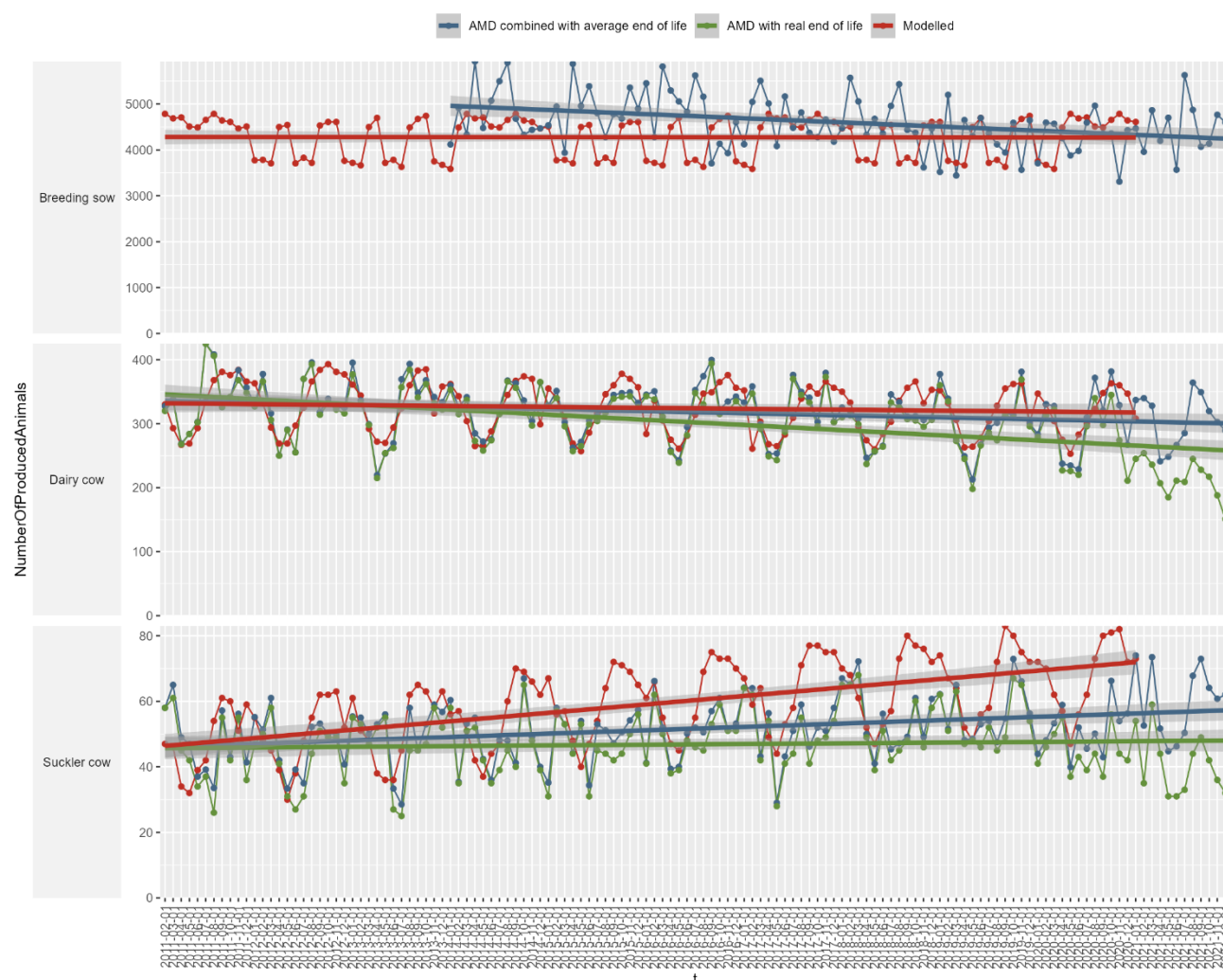


Figure SM3/33: Number of offspring born per month from breeding sows (top horizontal facet), dairy cows (middle horizontal facet), suckler cows (bottom horizontal facet). The red line shows simulated model results; the green line represents observed animal numbers from AMD (2023); and the blue line is derived from the number of animals born per month (AMD 2023), adjusted using average lifespans per livestock type based on AMD data. Note: AMD data included cattle records from 2010 to 2022 and pig records from 2014 to 2022.

SM3 / 5.3. Feed quantities

SM3 / 5.3.1. Feeding plan B1

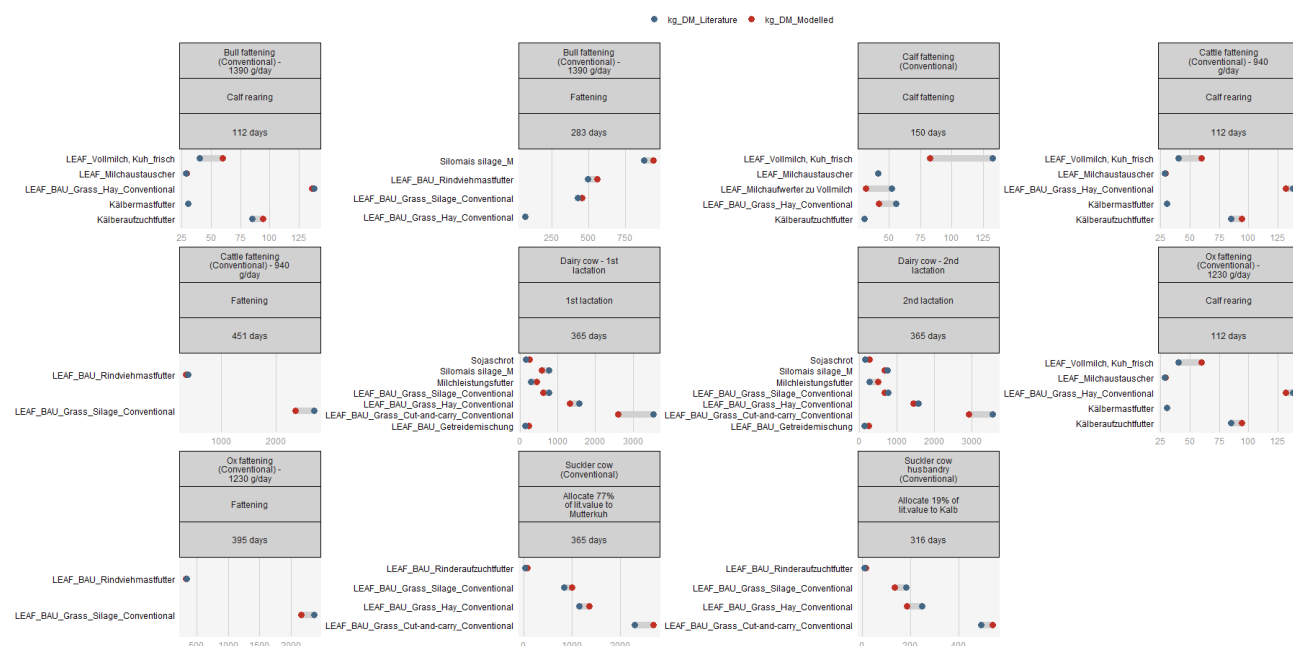


Figure SM3/34: Comparison of simulated feed quantities (kg DM per life stage) with literature values. Each subplot shows the livestock type (top grey box), life stage, and its duration (middle and bottom grey boxes). The y-axis indicates the relevant feed types. Data correspond to feeding plan B1.



Figure SM3/35: Comparison of simulated feed composition (proportion of each feed type in the total ration) with literature values. Each subplot shows the livestock type (top grey box), life stage, and its duration (middle and bottom grey boxes). The y-axis indicates the relevant feed types. Data correspond to feeding plan B1.

Table SM3/I4: Abbreviations of variables used in the subsequent figures

Variable	Nutrient parameter
FeedSup_CP	Crude protein [g/kg DM]
FeedSup_NEL	Net energy lactation [MJ/kg DM]
FeedSup_NEG	Net energy growth [MJ/kg DM]
FeedSup_API	Absorbable protein in intestine, smallest of APDE and APDN [g/kg DM]
FeedSup_ME_calf	Metabolic energy (Fattening calves) [MJ/kg DM]
FeedSup_DCP_calf	Digestible crude protein (Fattening calves) [g/kg DM]
FeedSup_DEP	Digestible energy (pigs)
FeedSup_DiLys[p]	Intestinal digestible lysine (pigs)



Figure SM3/36: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan BI.

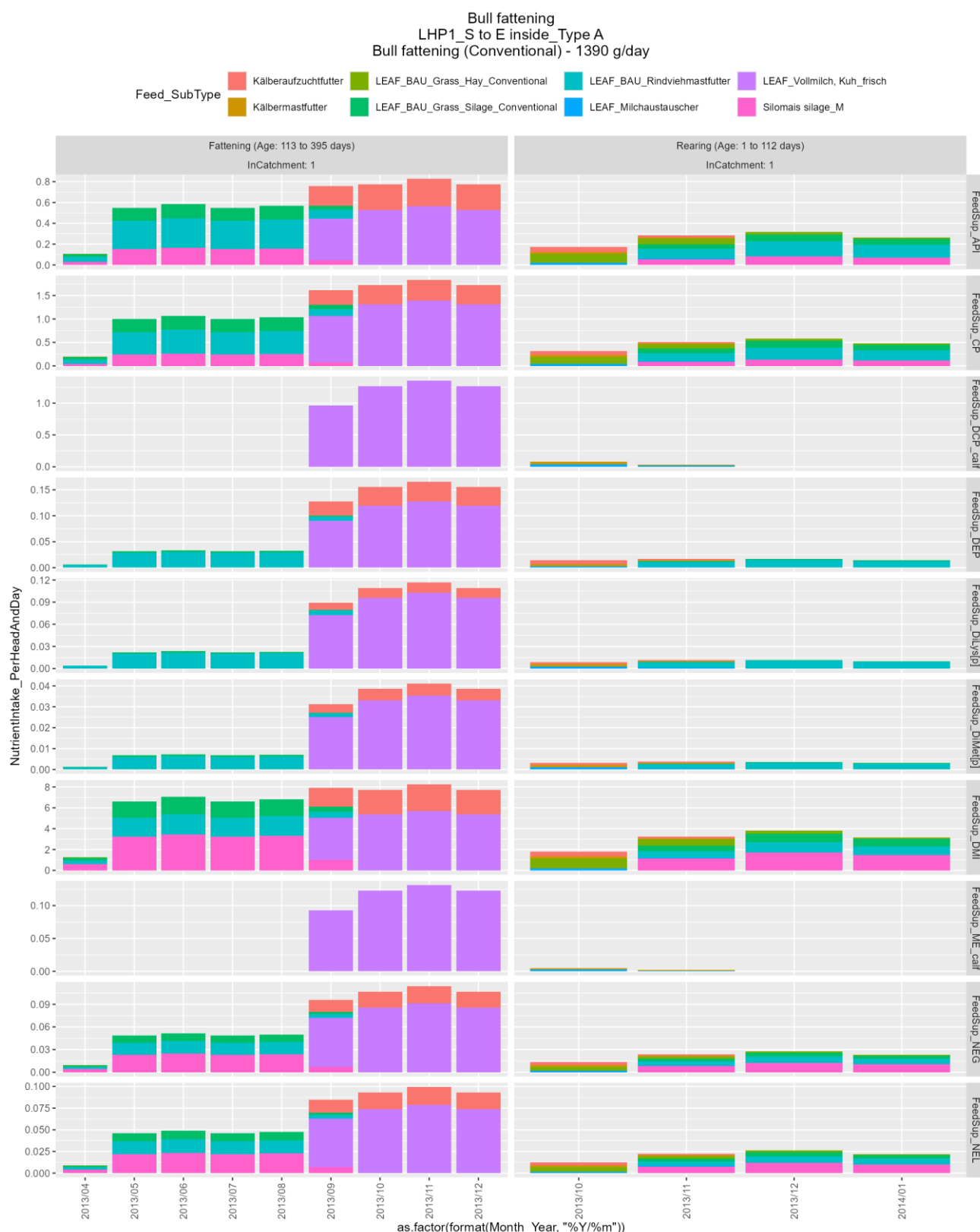


Figure SM3/37: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan BI.



Figure SM3/38: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B1.

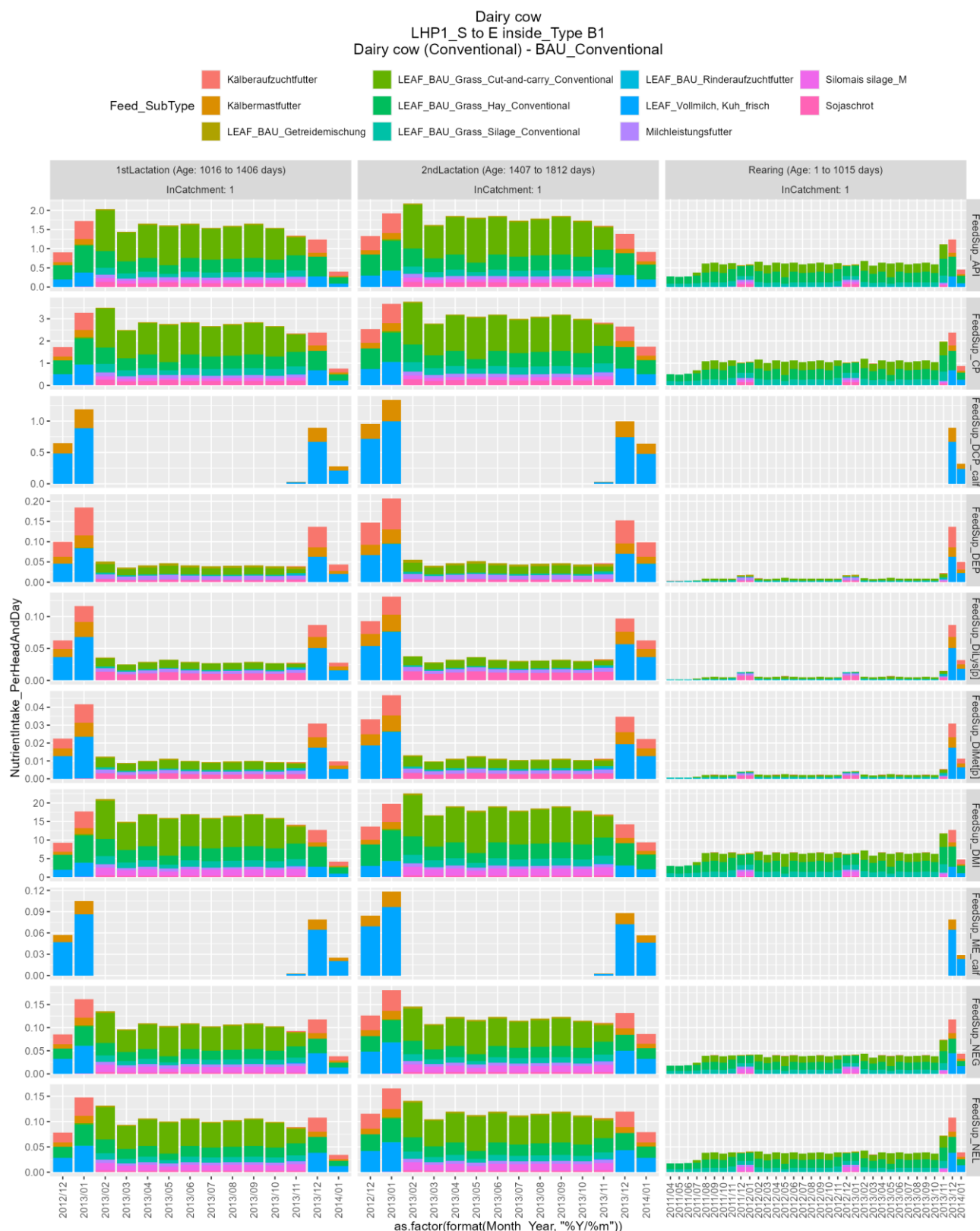


Figure SM3/39: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B1.

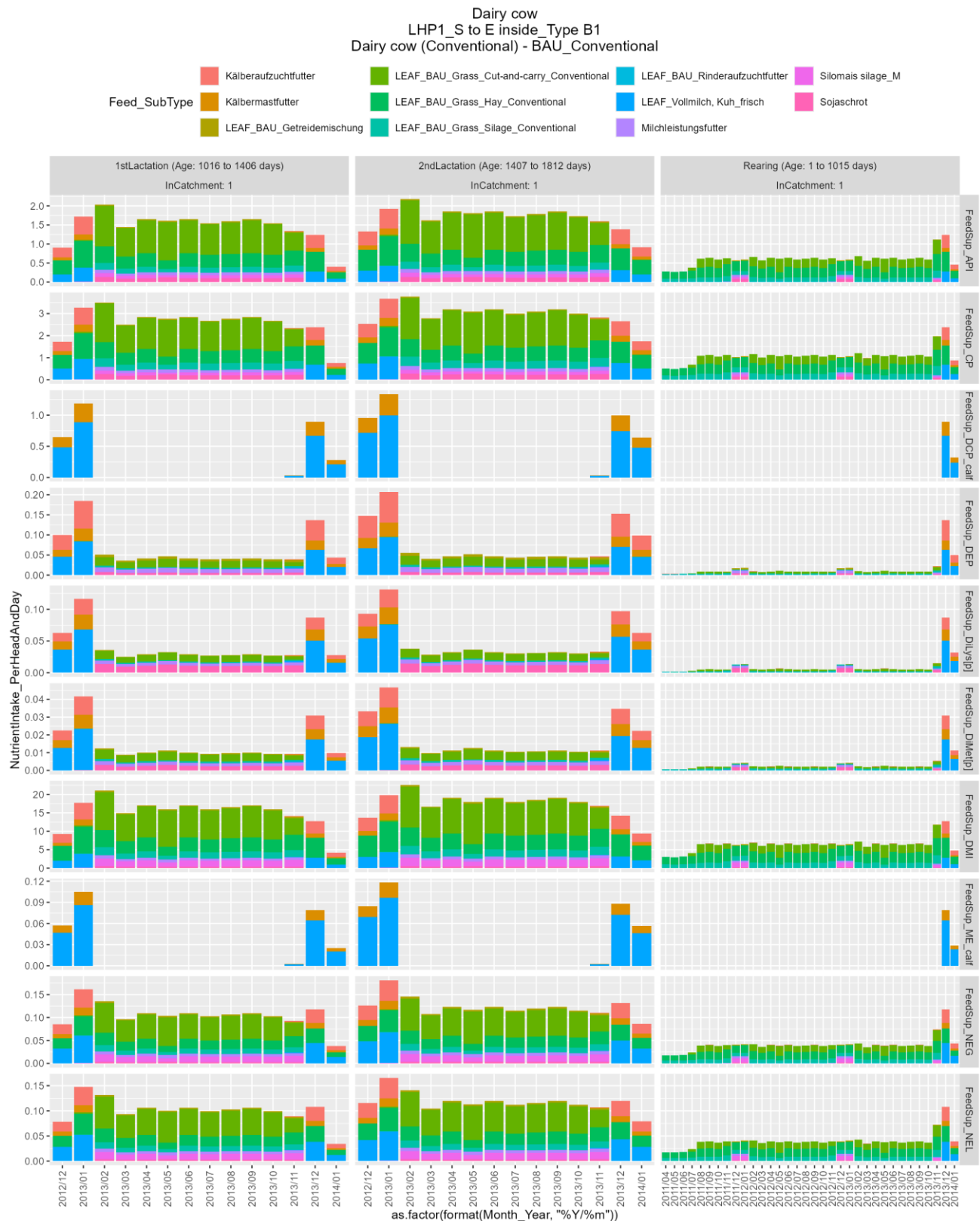


Figure SM3/40: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B1.

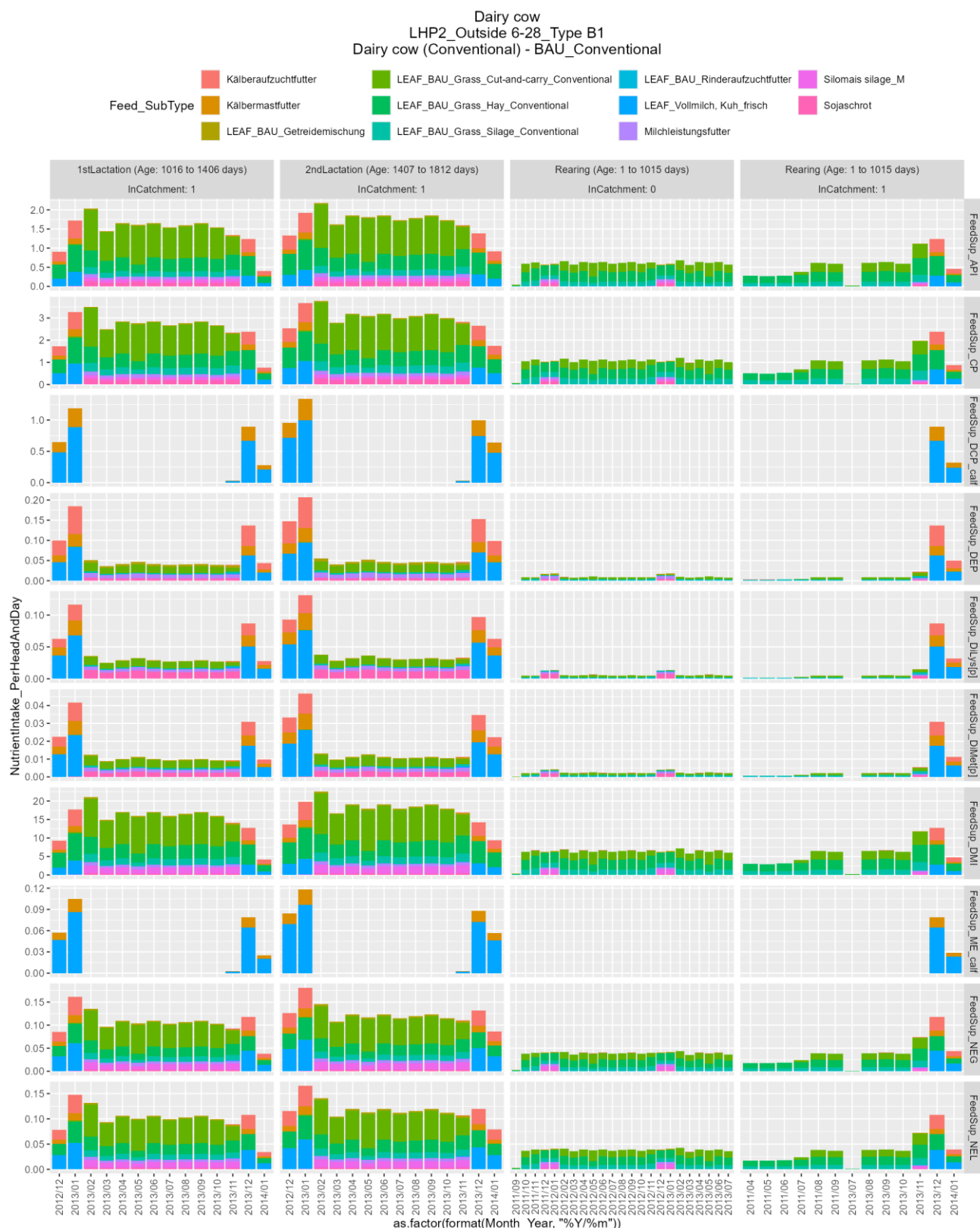


Figure SM3/41: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B1.

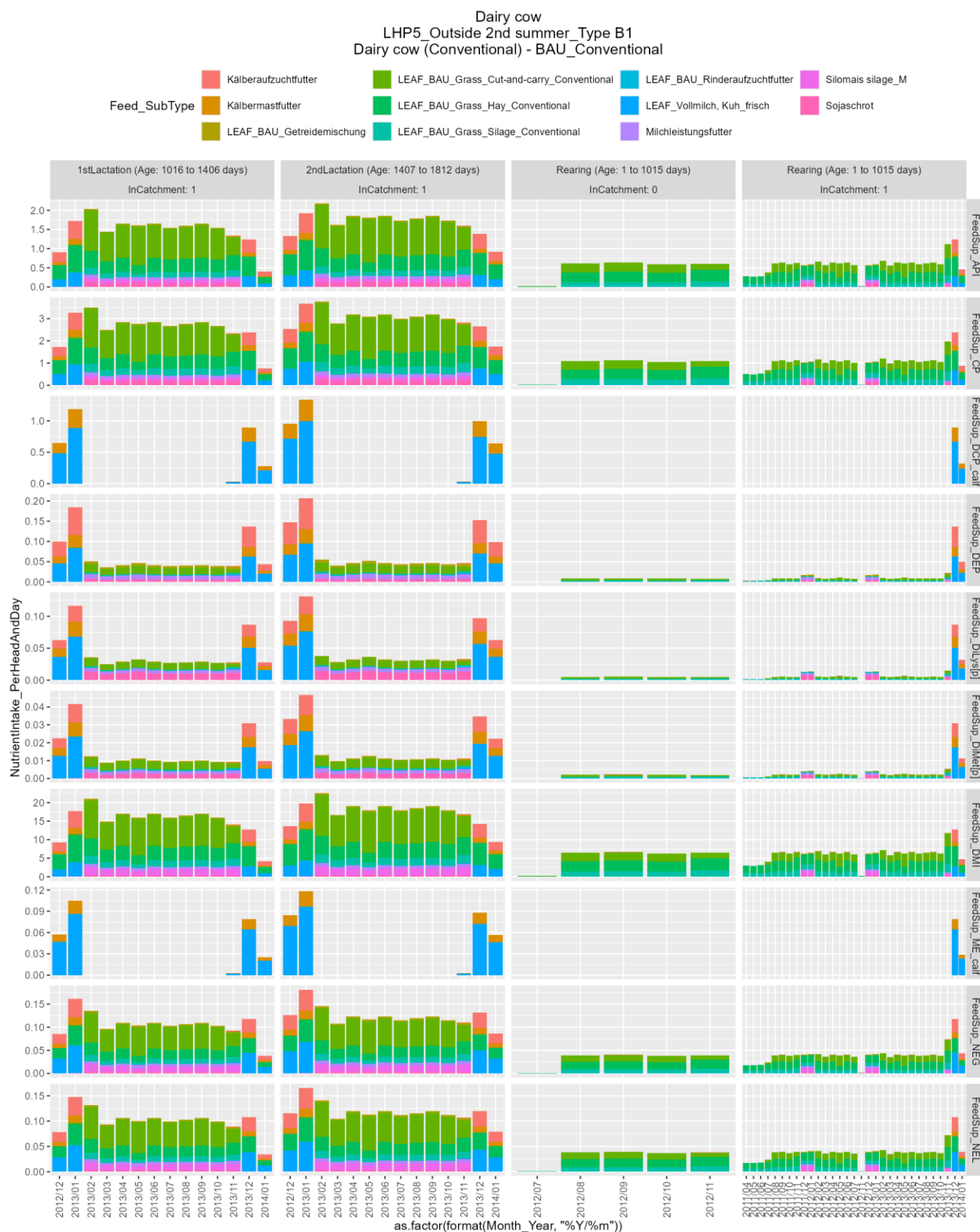


Figure SM3/42: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B1.

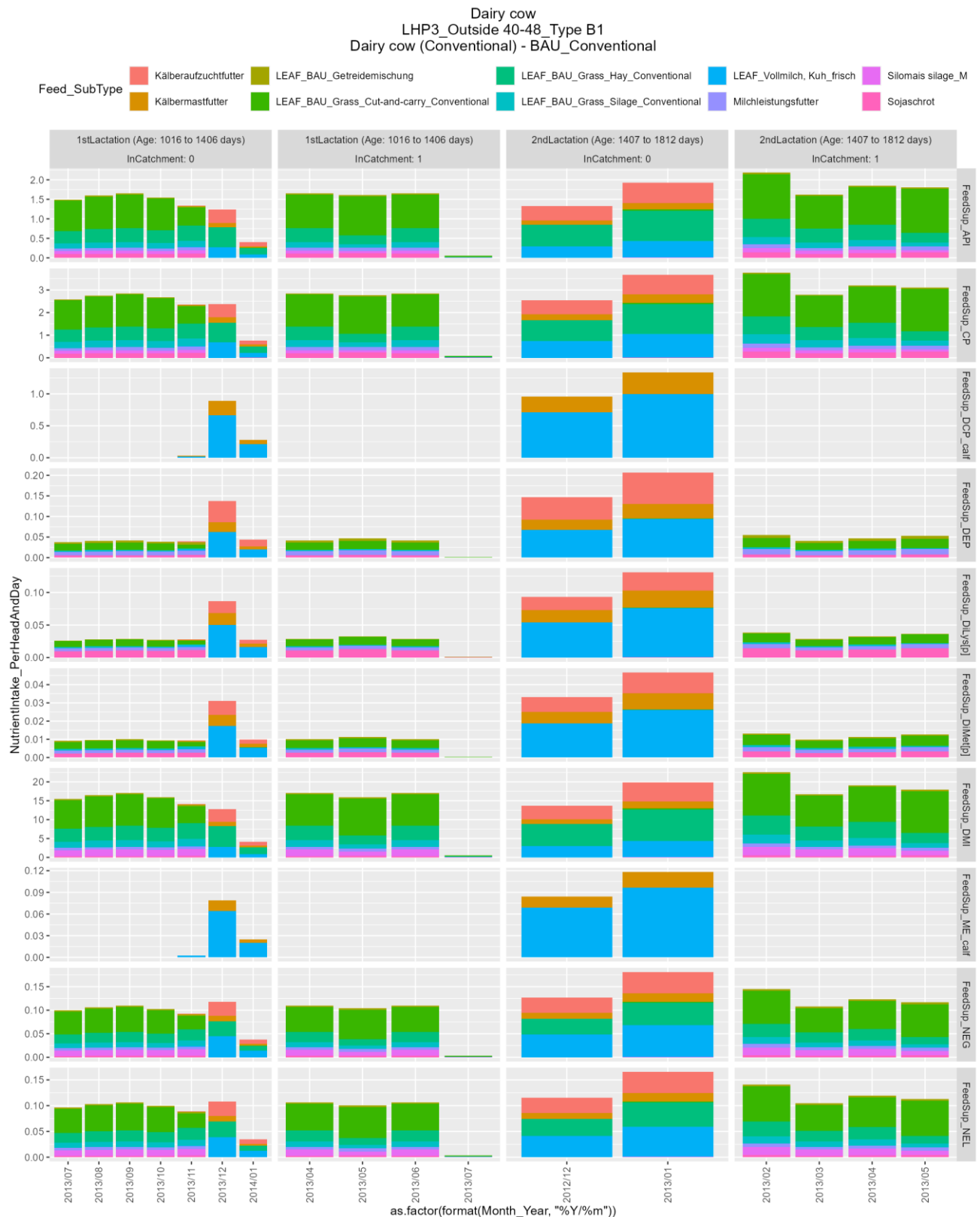


Figure SM3/43: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B1.



Figure SM3/44: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan BI.

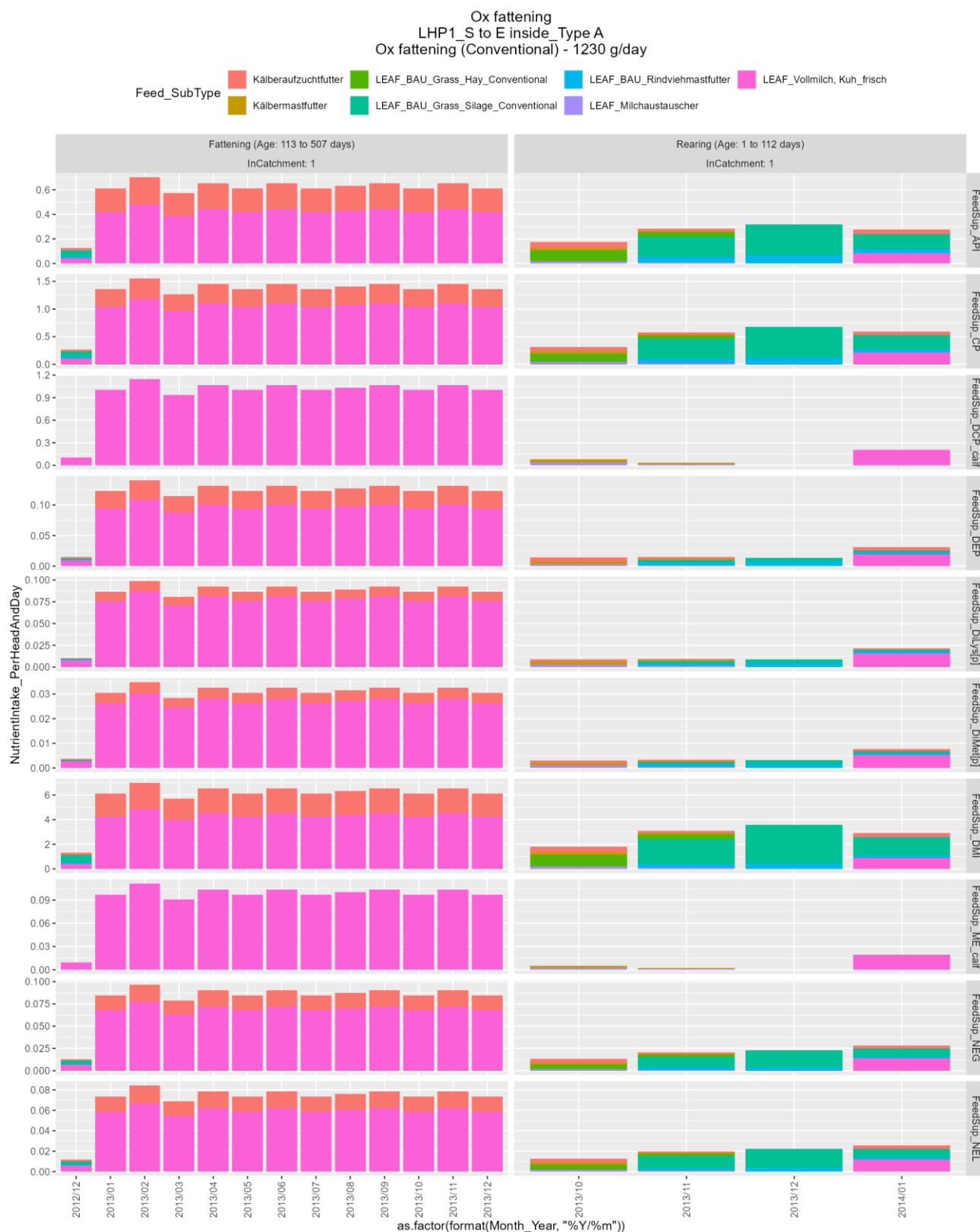


Figure SM3/45: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan BI.



Figure SM3/46: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B1.

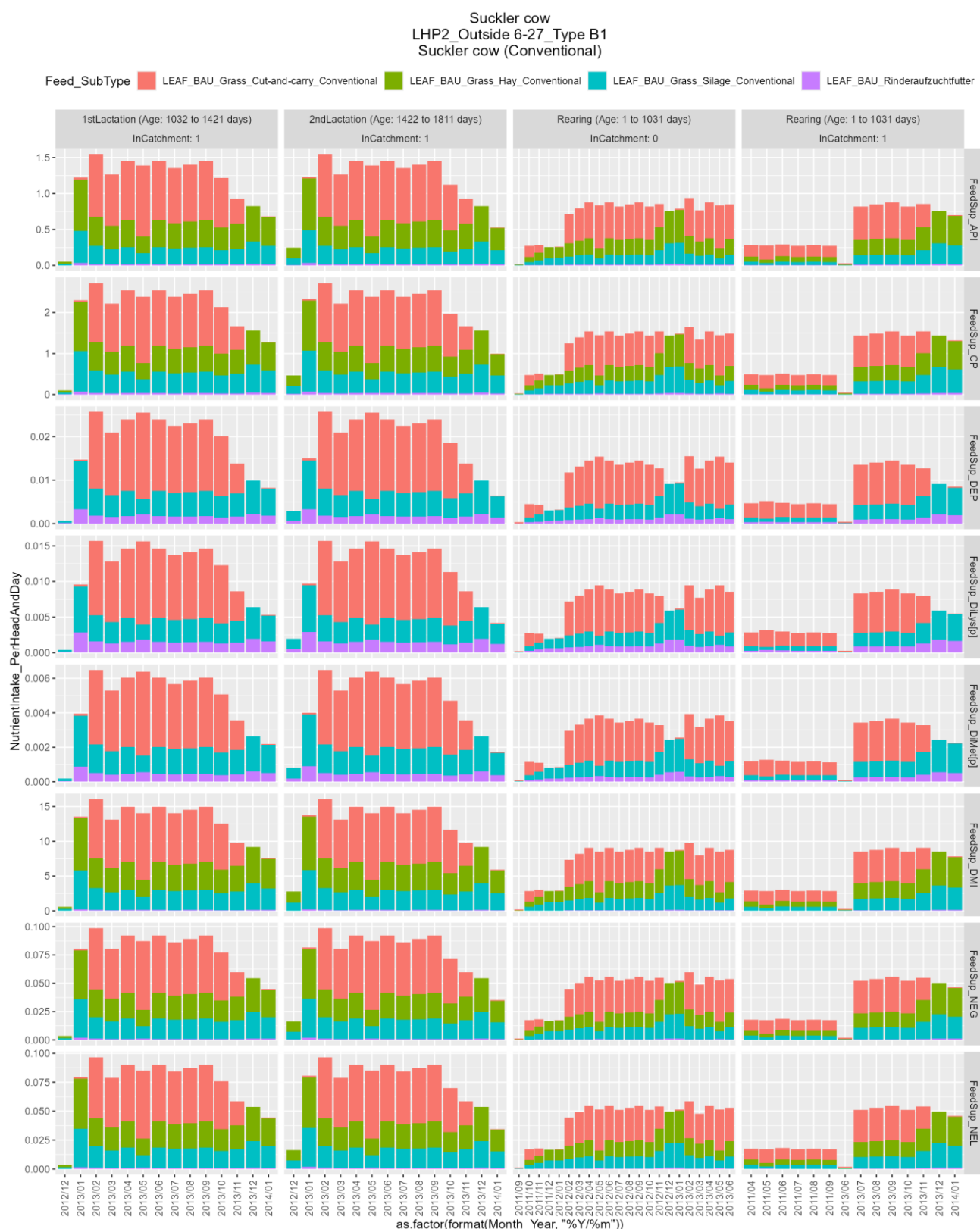


Figure SM3/47: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B1.

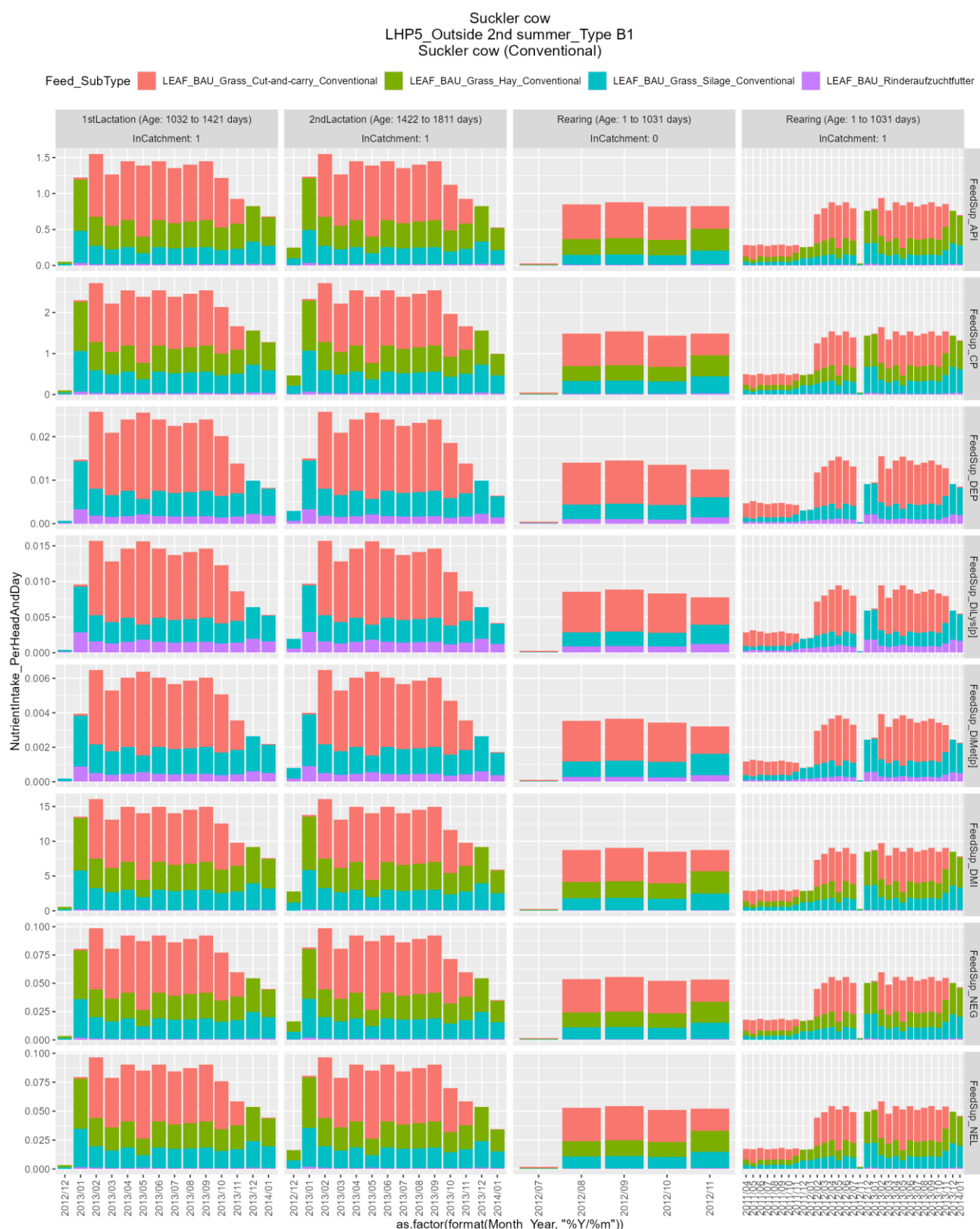


Figure SM3/48: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B1.

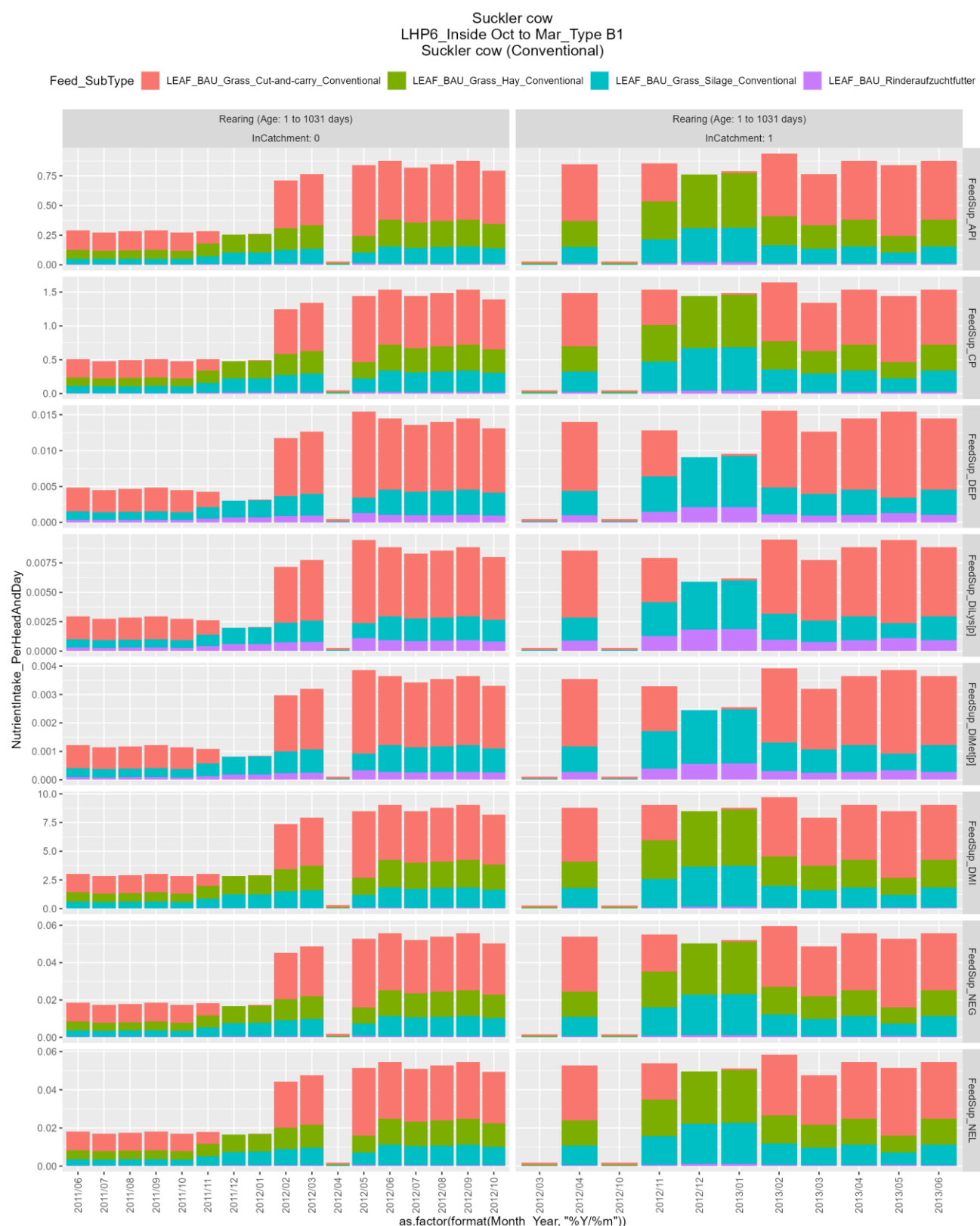


Figure SM3/49: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B1.



Figure SM3/50: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B1.



Figure SM3/51: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B1.

SM3 / 5.3.2. Feeding plan B2



Figure SM3/52: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/53: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.

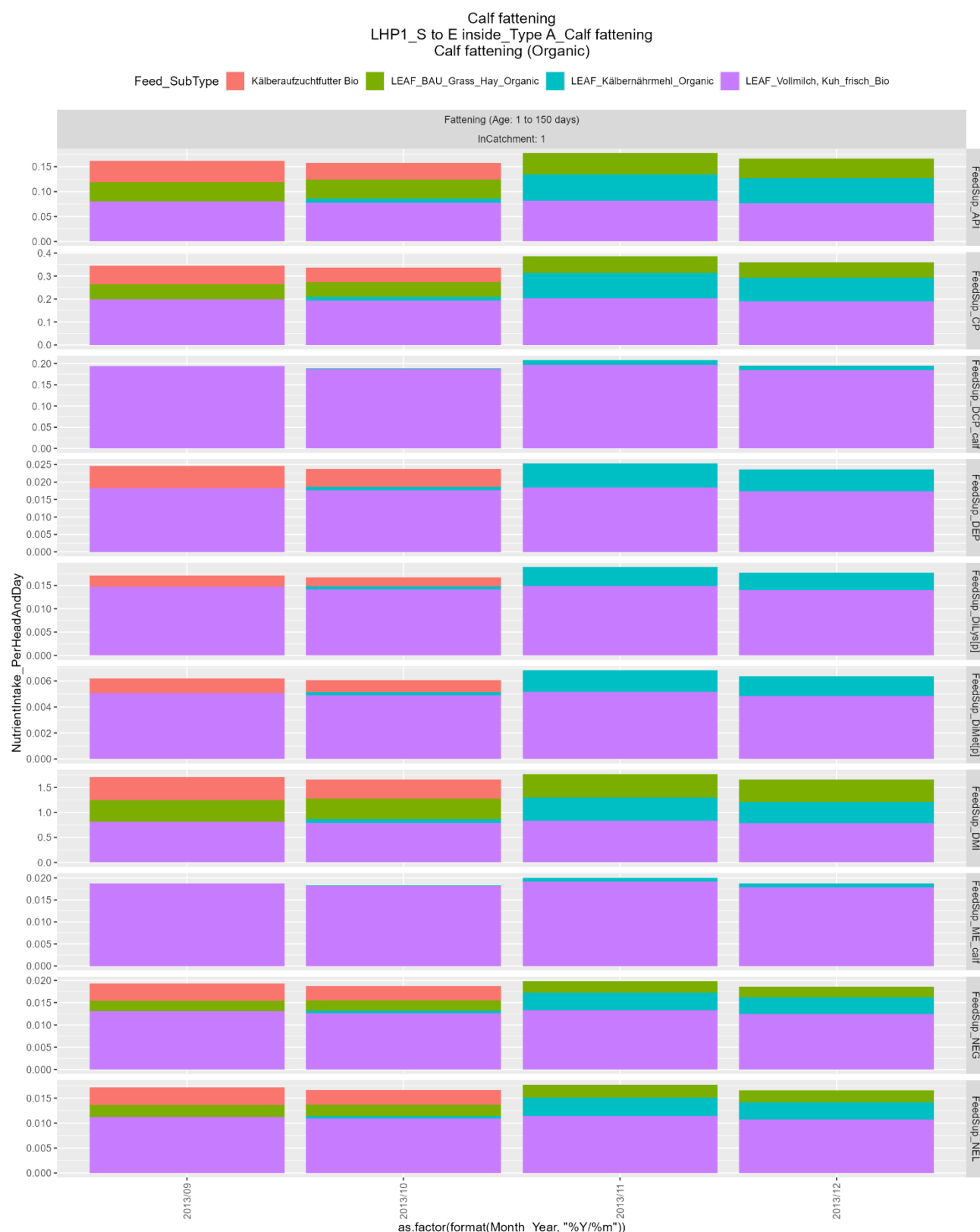


Figure SM3/54: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (1 = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/55: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/56: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/57: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/58: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/59: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/60: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/61: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.

SM3 / 5.3.3. Feeding plan B3

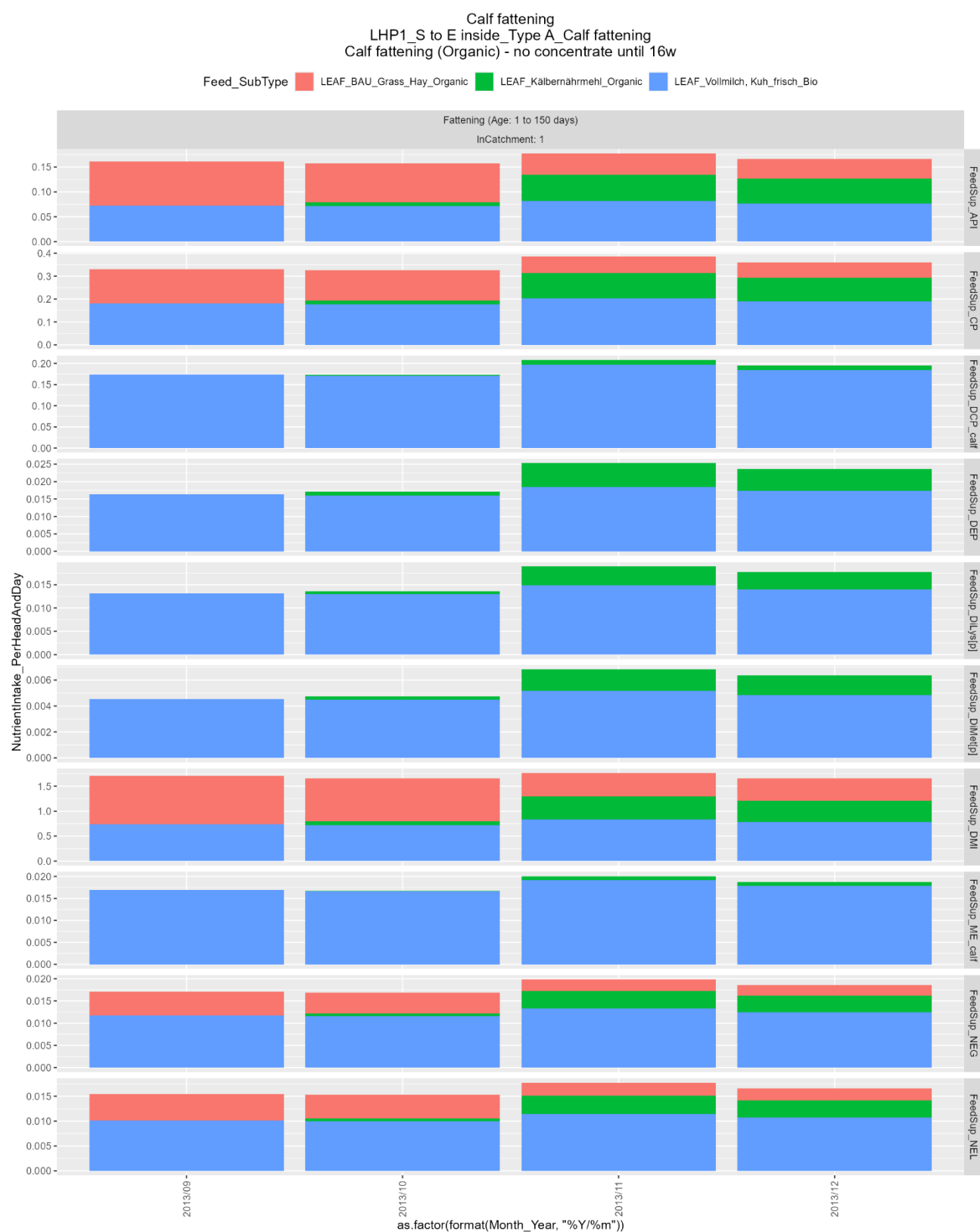


Figure SM3/62: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (1 = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/63: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/64: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (1 = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/65: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/66: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.

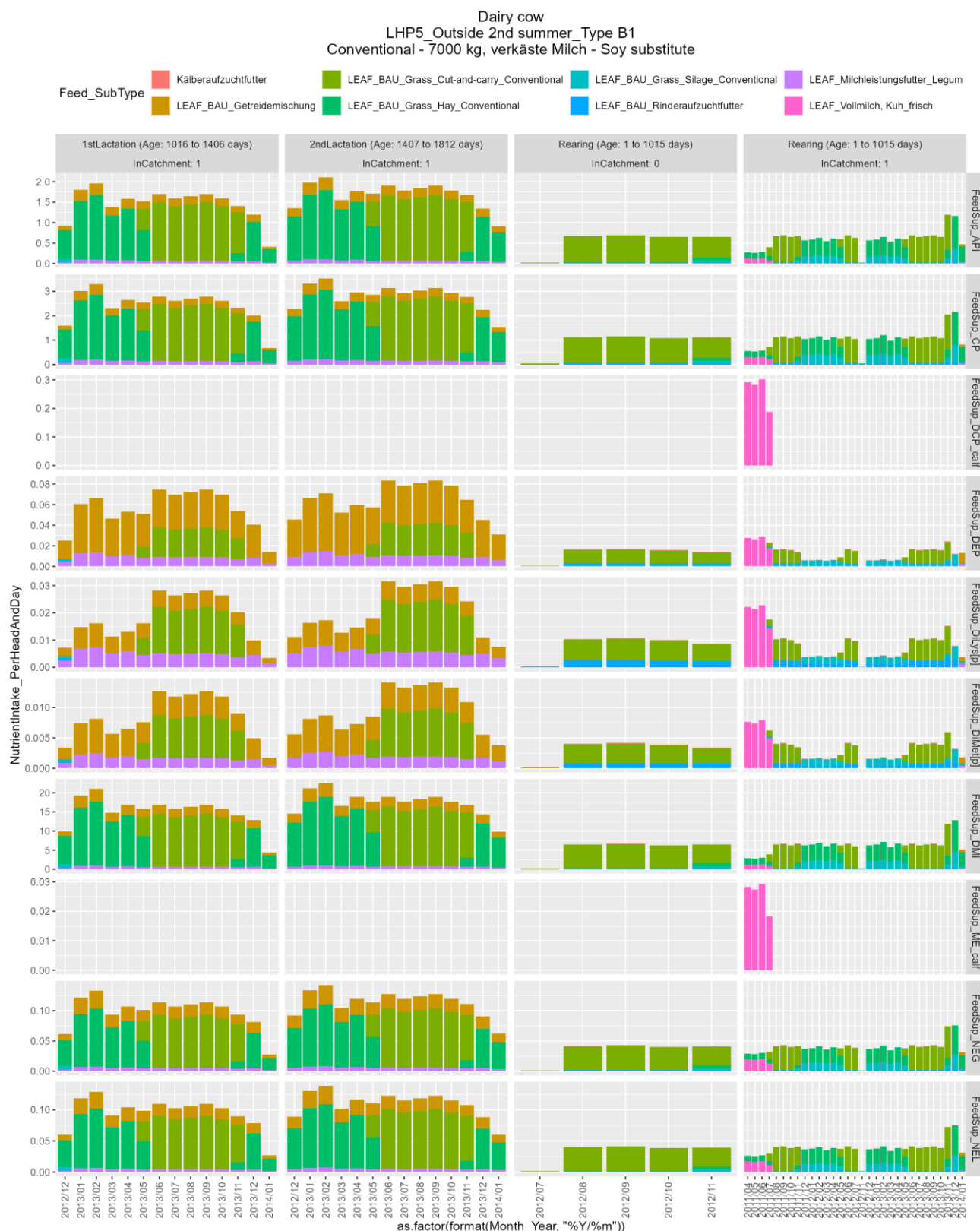


Figure SM3/67: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.



Figure SM3/68: Daily nutrient supply per animal head, differentiated by feed source (colors). The livestock type, movement type, and feeding plan are indicated in the title. Horizontal facets show different nutrient parameters; vertical facets show life stages, including their duration (in days) and the origin of feed demand (I = inside the catchment, 0 = outside the catchment). Data correspond to feeding plan B2.

SM3 / 6. Results

SM3 / 6.1. General overview

Table SM3/I5: Summary statistics of indicators for assessing P reduction strategies across all scenarios as well as across the livestock composition groups.

	Total			Pig-dominated Scenarios			Dairy-dominated Scenarios			Suckler-dominated Scenarios			Mixed Scenarios		
Number of observations	4'924'812			1'969'932 (40%)			748'440 (15.2%)			736'776 (14.96%)			1'469'664 (29.84%)		
	Mean (SD)	Min	Max	Mean (SD)	Min	Max	Mean (SD)	Min	Max	Mean (SD)	Min	Max	Mean (SD)	Min	Max
LSU (per year)	5951.2 (±1416.8)	3693.9	8208.6	5951.2 (±1416.8)	3693.9	8208.6	5951.2 (±1416.8)	3693.9	8208.6	5951.2 (±1416.8)	3693.9	8208.6	5951.2 (±1416.8)	3693.9	8208.6
In catchment remaining P excretion (tons P per year)	63.2 (±20.4)	27.1	119.3	59.7 (±19.1)	27.1	98.8	71.3 (±21.9)	32.7	119.3	62.9 (±19.9)	27.4	101.4	63.9 (±20.2)	28.5	102.9
Animal-source protein (tons ASP per year)	975.4 (±378.3)	75.3	2084.2	1243.3 (±317.8)	592.9	2084.2	881.2 (±256.9)	329.9	1876.5	476.2 (±156.7)	75.3	979.9	914.7 (±262.7)	383.6	1697.2
Land use for feed production: arable land (ha per year)	2606.2 (±1494.7)	0	7406.6	3988 (±1066.9)	1999.8	7406.6	1376.5 (±633.2)	347	4784.4	776.9 (±482.8)	0	3087.4	2297.3 (±733)	851.7	4445
Land use for feed production: grassland (ha per year)	1873.1 (±1011.8)	0	4604.5	936.6 (±391.1)	0	1841.8	2915.9 (±763.1)	1112.6	4604.5	2903 (±756.3)	1129.5	4479.6	2081.2 (±581.4)	1116	3617
Plant-source protein competition (score)	1.8 (±0.2)	1.1	3.4	1.9 (±0.1)	1.5	2.2	1.6 (±0.2)	1.1	2.4	1.8 (±0.4)	1.1	3.4	1.8 (±0.2)	1.3	2.5
N _{available} :P ratio of FYM	3.3 (±0.3)	2.7	3.8	3 (±0.1)	2.7	3.1	3.6 (±0.1)	3.2	3.7	3.6 (±0.1)	3.2	3.8	3.4 (±0.1)	3.2	3.5

Table SM3/I6: Comparison of viable and non-viable scenarios across indicators for assessing P reduction strategies.

	Not viable scenarios			Viable scenarios		
Number of observations	4'410'732			514'080 (10.4%)		
	<i>Mean (SD)</i>	<i>Min</i>	<i>Max</i>	<i>Mean (SD)</i>	<i>Min</i>	<i>Max</i>
LSU (<i>per year</i>)	5876.4 (±1468.7)	3693.9	8208.6	6593.2 (±513.5)	5335.6	7387.7
In catchment remaining P excretion (<i>tons P per year</i>)	62.6 (±21.4)	27.1	119.3	68.2 (±7)	48.2	78
Animal-source protein (<i>tons ASP per year</i>)	922.9 (±362.9)	75.3	2084.2	1426.5 (±117.1)	1256.1	1875.8
Land use for feed production: arable land (<i>ha per year</i>)	2371.8 (±1390.5)	0	7406.6	4616.6 (±547.4)	2124.6	6665.9
Land use for feed production: grassland (<i>ha per year</i>)	1984.4 (±1004)	0	4604.5	918.7 (±377.8)	0	2725.3
Plant-source protein competition (<i>score</i>)	1.8 (±0.3)	1.1	3.4	1.9 (±0.1)	1.5	2.1
N_{available}:P ratio of FYM	3.3 (±0.3)	2.7	3.8	3 (±0.1)	2.7	3.4

Table SM3/17: Comparison of Pareto and non-Pareto scenarios across indicators for assessing P reduction strategies.

Number of observations	Non-Pareto scenarios			Rank I Pareto scenarios		
	506'906			7'174		
	<i>Mean (SD)</i>	<i>Min</i>	<i>Max</i>	<i>Mean (SD)</i>	<i>Min</i>	<i>Max</i>
LSU (<i>per year</i>)	6595 (±513)	5335.6	7387.7	6464.2 (±528.8)	5335.6	7387.7
In catchment remaining P excretion (<i>tons P per year</i>)	68.2 (±7)	51.4	78	66.7 (±7.1)	48.2	78
Animal-source protein (<i>tons ASP per year</i>)	1426.3 (±117.1)	1256.1	1709.7	1443.2 (±119.2)	1256.1	1875.8
Land use for feed production: arable land (<i>ha per year</i>)	4616.7 (±546.7)	2171.4	5661.1	4611.8 (±596.1)	2124.6	6665.9
Land use for feed production: grassland (<i>ha per year</i>)	919.5 (±377.8)	535.7	2646.5	856.2 (±366.8)	0	2725.3
Plant-source protein competition (<i>score</i>)	1.9 (±0.1)	1.5	2.1	1.9 (±0.1)	1.5	2.1
N_{available}:P ratio of FYM	3 (±0.1)	2.9	3.4	3 (±0.1)	2.7	3.4

SM3 / 6.2. Defining the viable option space

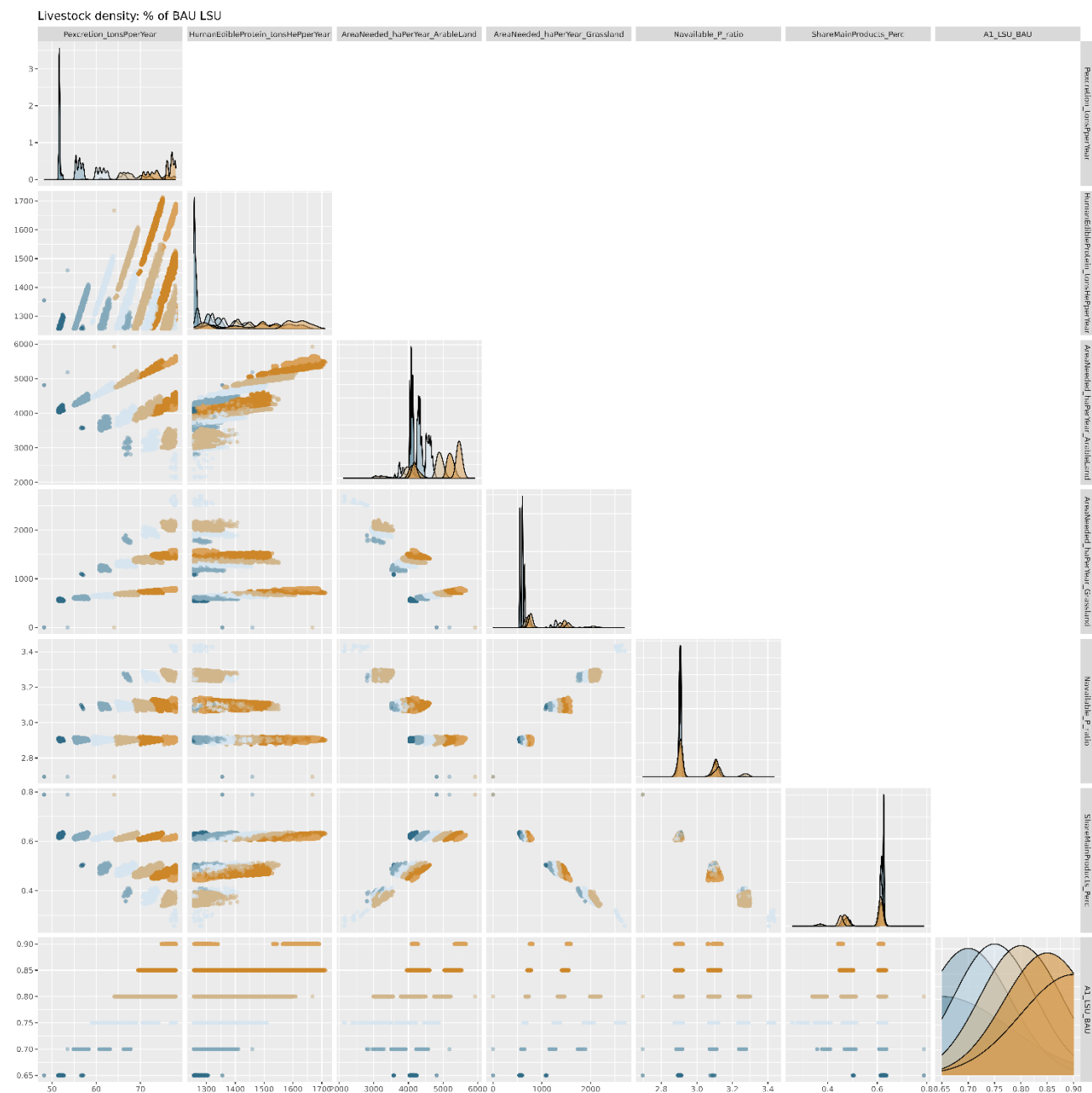


Figure SM3/69: Performance of viable scenarios across indicators. Colors indicate livestock density relative to BAU (% of LSU).

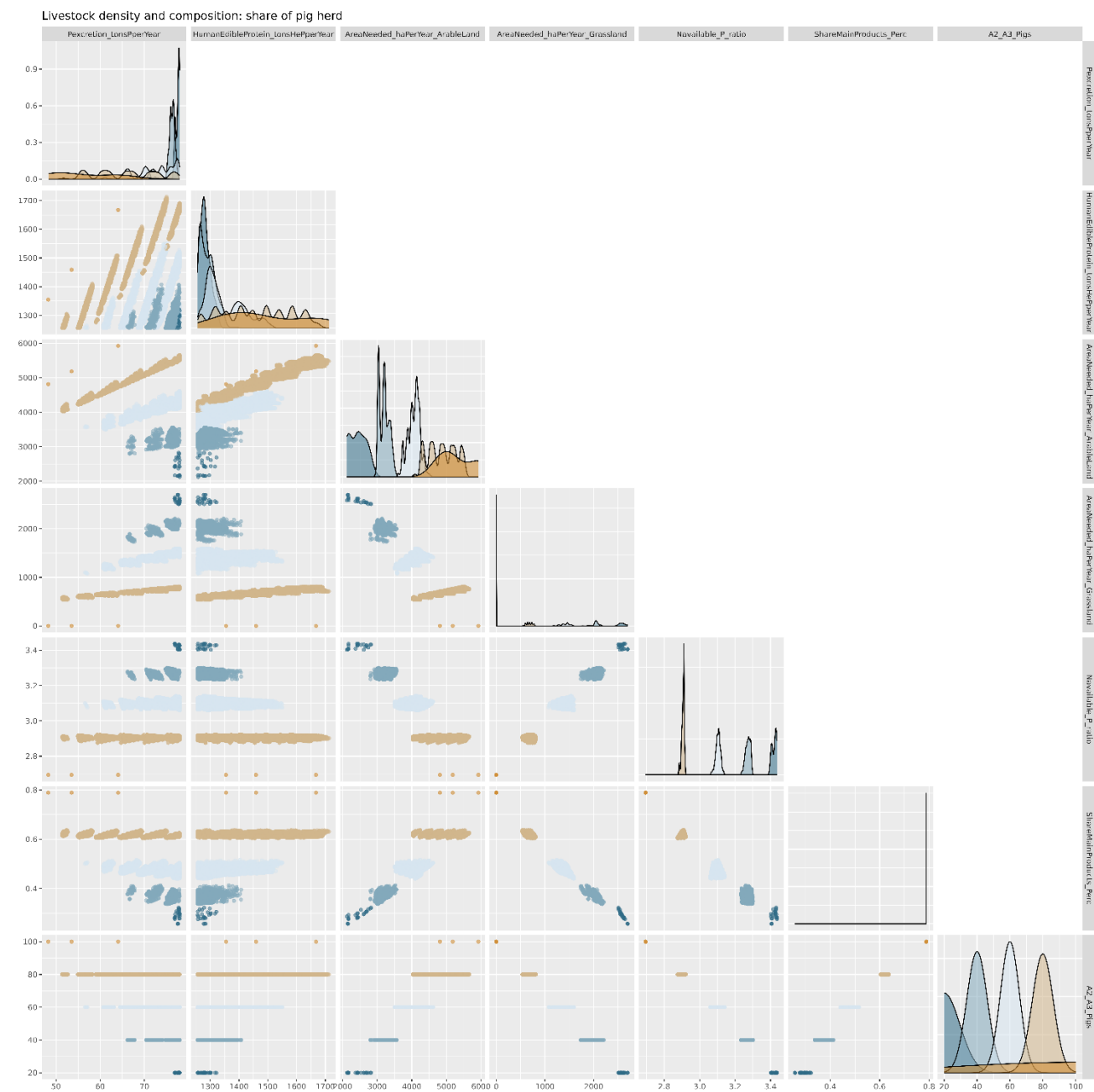


Figure SM3/70: Performance of viable scenarios across indicators. Colors indicate the share of pig herd (0–100% of total LSU/ha, 20% steps).

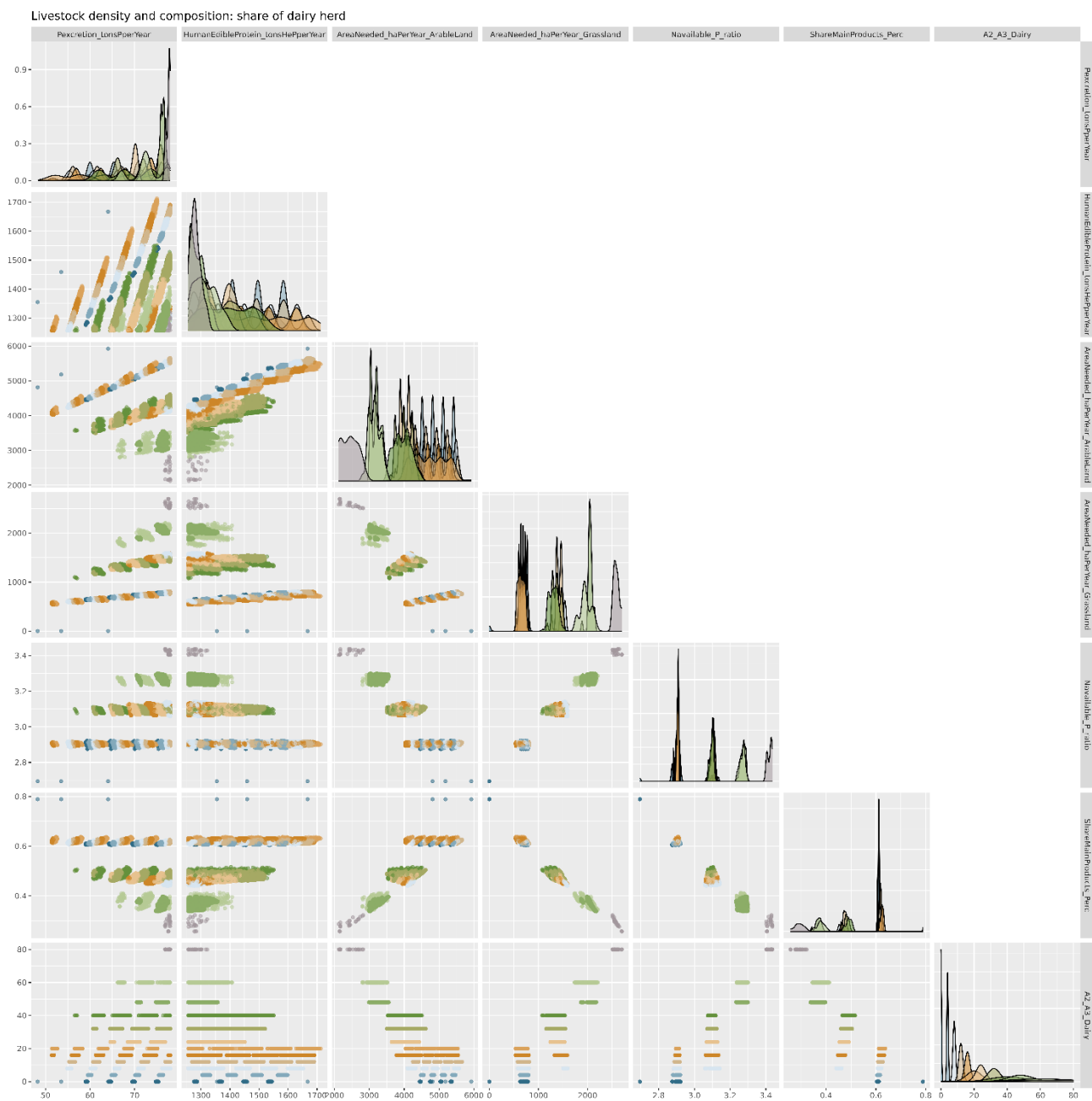


Figure SM3/71: Performance of viable scenarios across indicators. Colors indicate the share of dairy herd (0–100% of total LSU/ha, 20% steps).

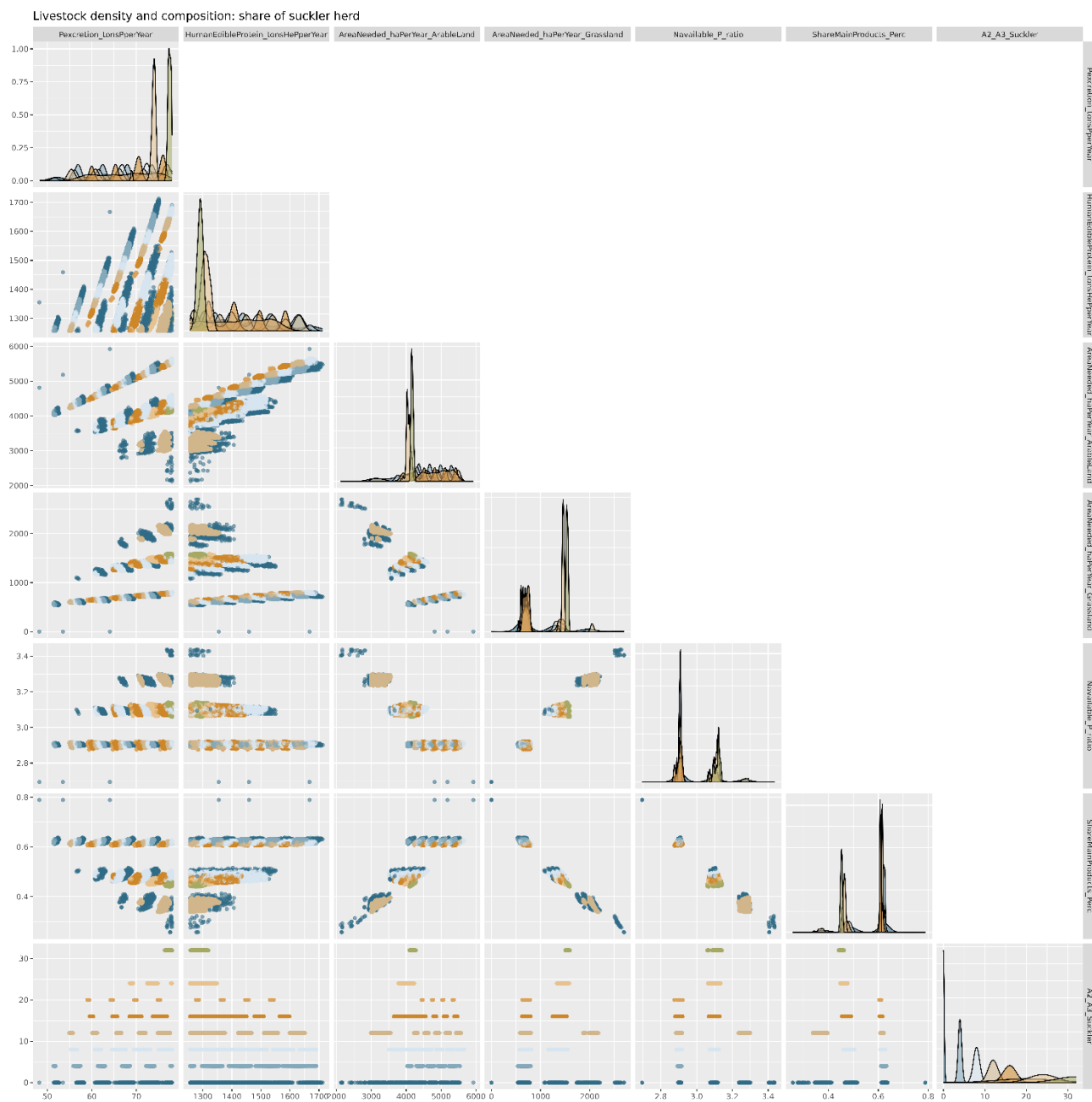


Figure SM3/72: Performance of viable scenarios across indicators. Colors indicate the share of suckler herd (0–100% of total LSU/ha, 20% steps).

SM3 / 6.3. Key features of viable and Pareto scenarios

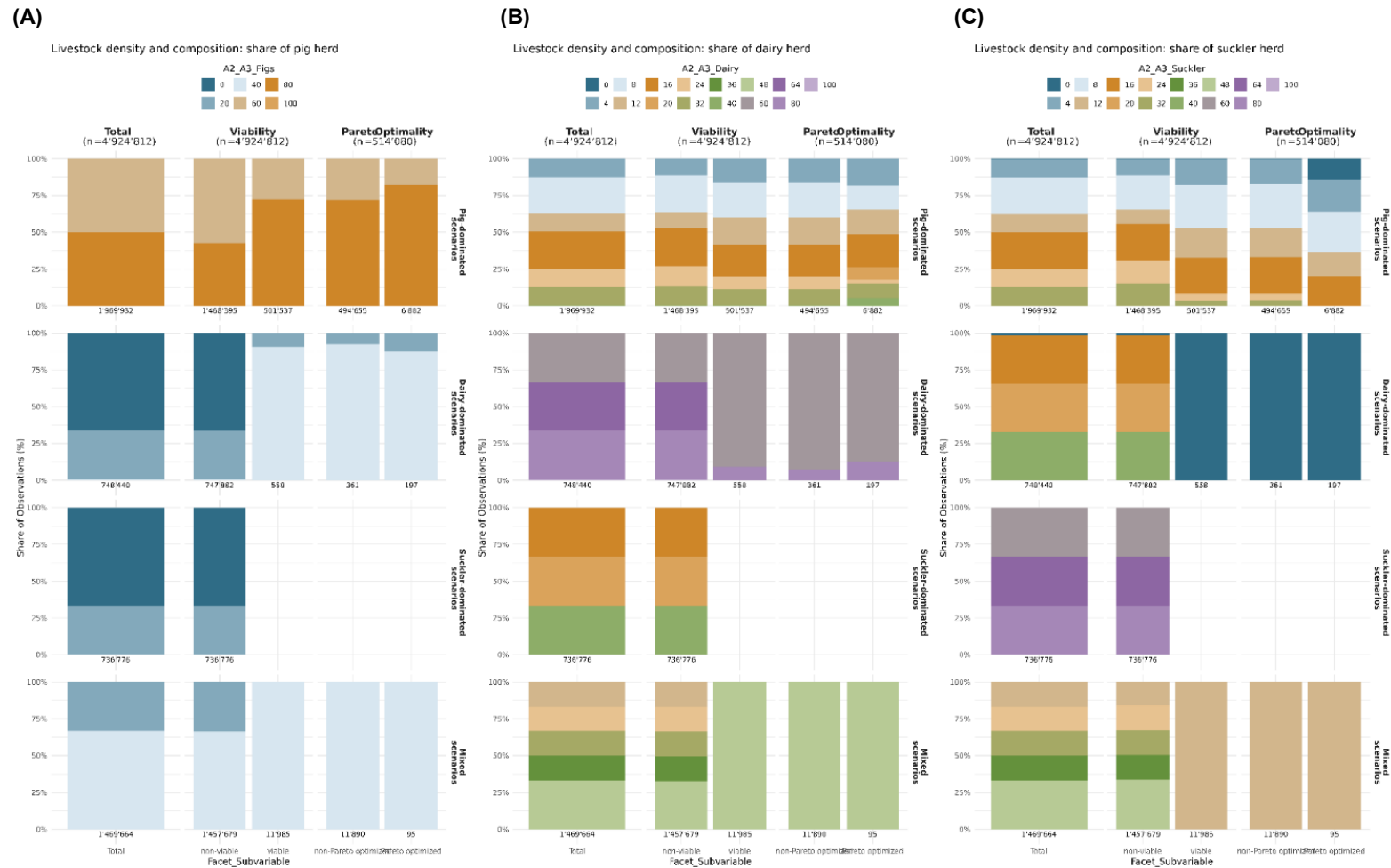


Figure SM3/73: Proportional contribution of the pig (A), dairy (B), and suckler (C) herds to total livestock units (LSU) across all scenarios (P reduction strategy A2 and A3). The vertical facets distinguish between the full scenario set (left), viable vs. non-viable scenarios (middle), and Pareto-optimal vs. non-Pareto scenarios (right). Horizontal facets indicate different livestock composition groups.

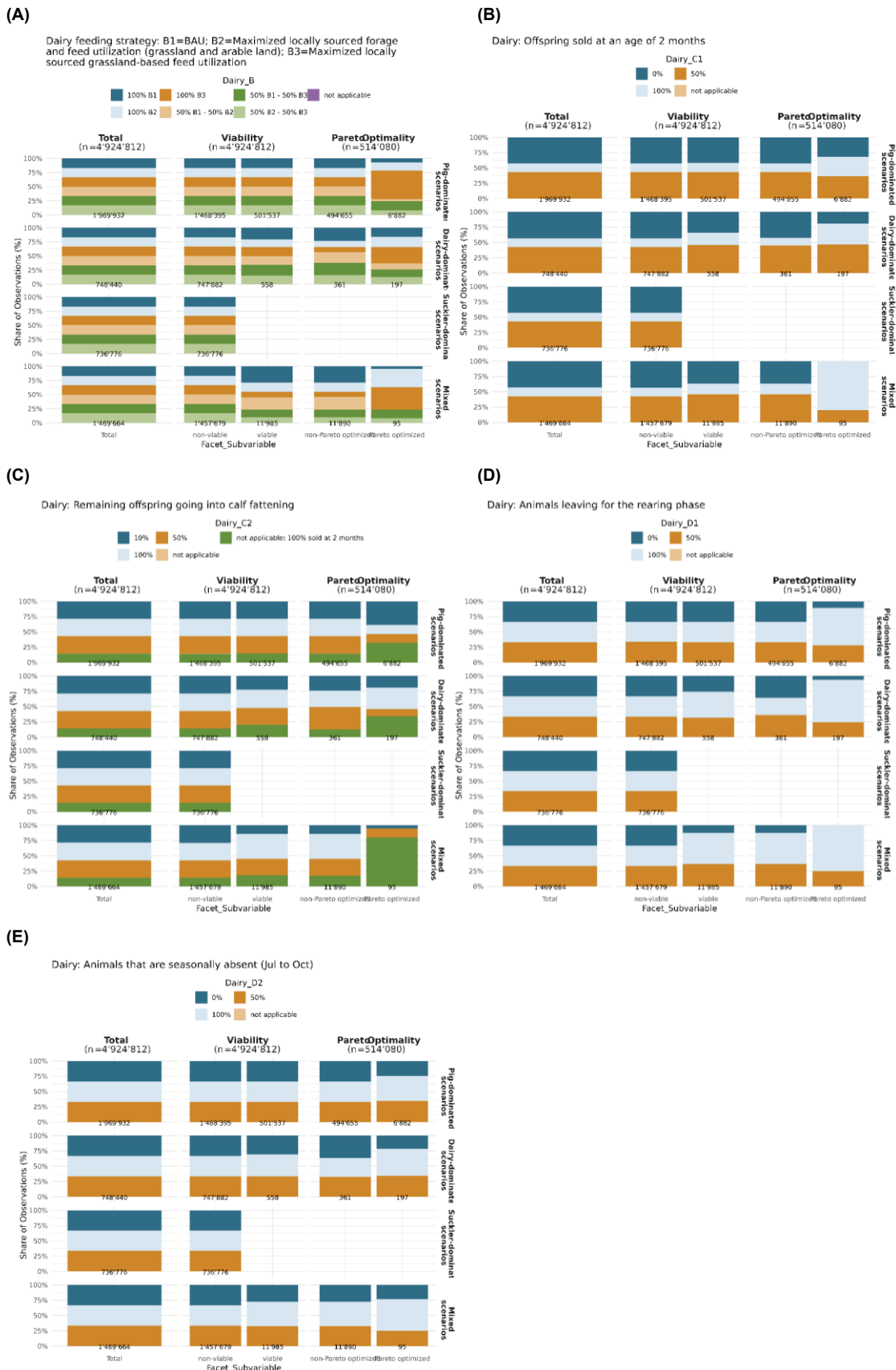


Figure SM3/74: Shares of (A) dairy feeding plans (P reduction strategy B), (B) dairy offspring sold at an age of two months (strategy C1), (C) remaining offspring going into calf fattening (strategy C2), (D) replacement heifers for dairy cows leaving the catchment for the rearing phase (strategy D1), and (E) dairy animals seasonally absent from the herd (strategy D2). Vertical facets compare the full set of scenarios (left), viable vs. non-viable scenarios (middle), and Pareto-optimal vs. non-Pareto scenarios (right). Horizontal facets represent different livestock composition groups.

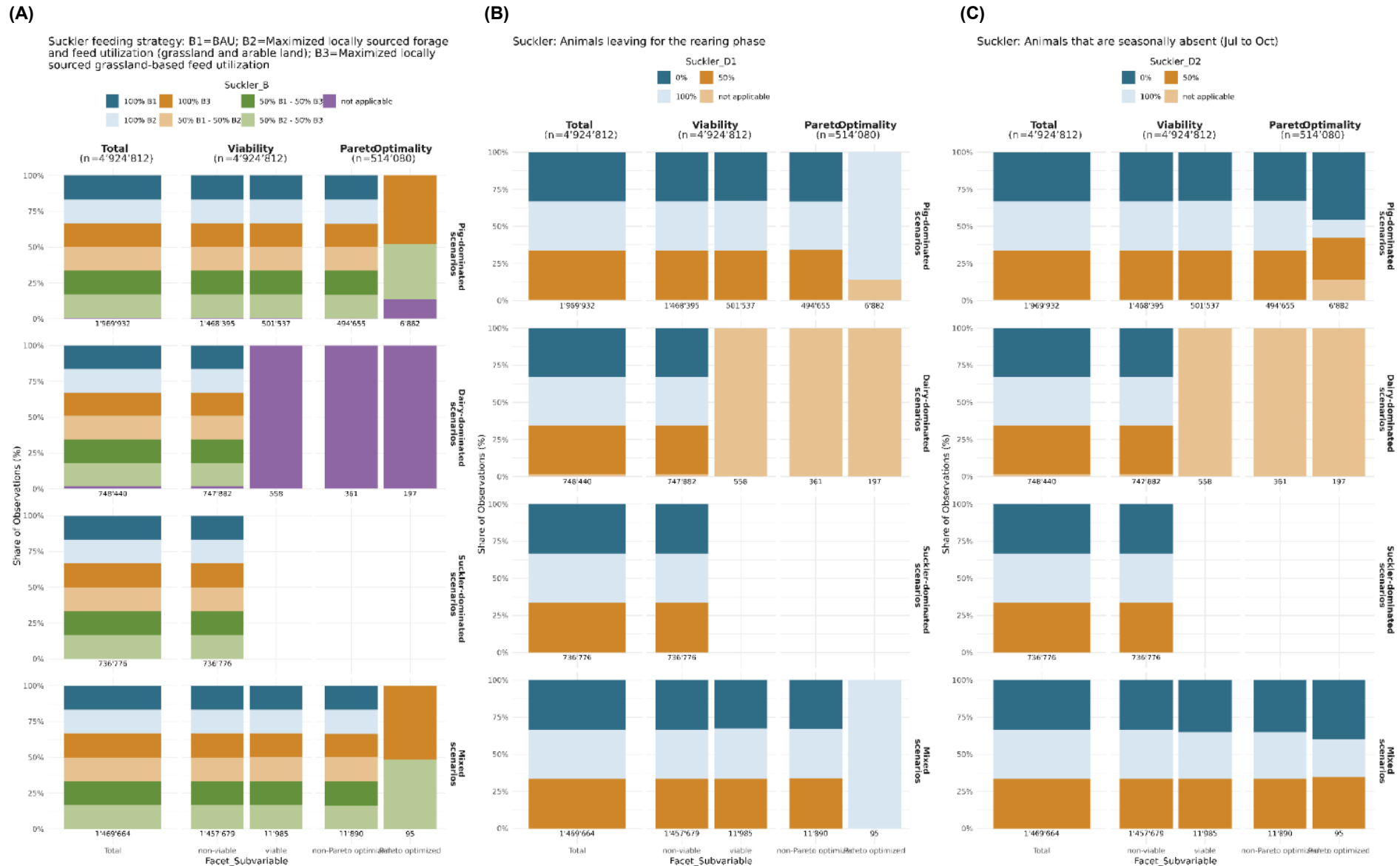


Figure SM3/75: Shares of (A) suckler feeding plans (P reduction strategy B), (B) replacement heifers for suckler cows leaving the catchment for the rearing phase (strategy D1), and (C) suckler animals seasonally absent from the herd (strategy D2). Vertical facets compare the full set of scenarios (left), viable vs. non-viable scenarios (middle), and Pareto-optimal vs. non-Pareto scenarios (right). Horizontal facets represent different livestock composition groups

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Supplementary material of chapter 4

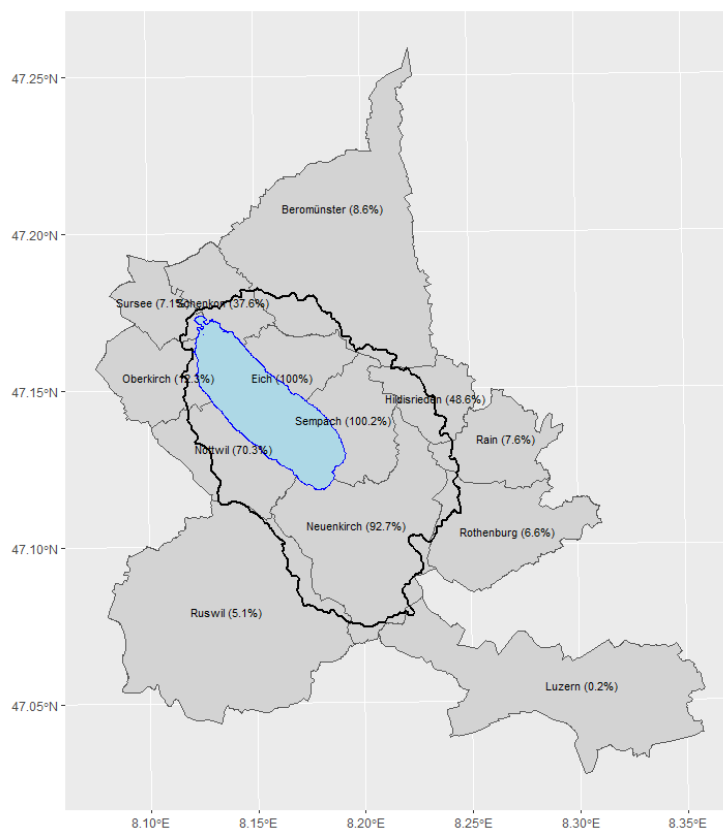


Figure SM4/1: Municipalities intersecting with the Sempachersee catchment. The thick black outline marks the full catchment boundary, the lake is shown in blue, and labels report municipality names with the corresponding percentage of their land area falling inside the catchment.

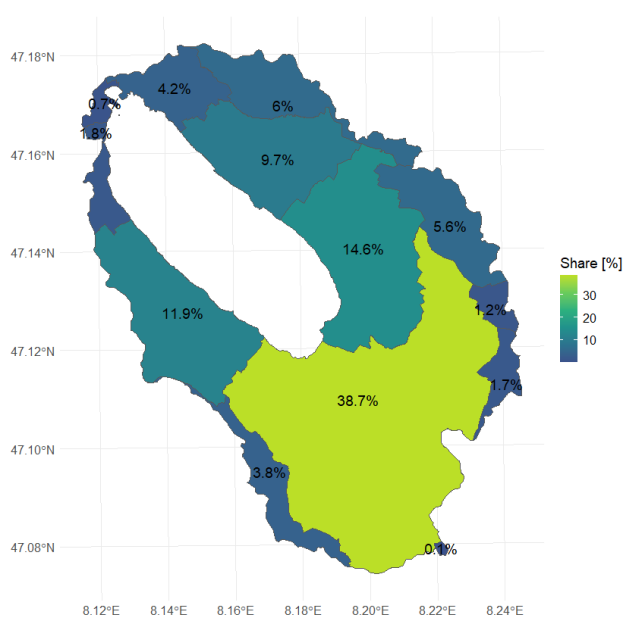


Figure SM4/2: Share of the total catchment area accounted for by each municipality (excluding the lake). Colors and labels indicate the proportion of the catchment contributed by each municipality.

Table SM4/I: Municipalities within the catchment area. The table shows the total land area of each municipality (excluding lakes and other water bodies), the portion of this land area located within the catchment, and the corresponding share of the municipality within the catchment.

ID	Municipality	Land area of municipality (excluding lakes, etc.)	Land area of municipality located within the catchment	Share of municipality located within the catchment
1102	Sempach	891	892.4	100%
1084	Eich	594	593.7	100%
1093	Neuenkirch	2548	2'363.2	93%
1094	Nottwil	1033	726.5	70%
1088	Hildisrieden	704	342.3	49%
1099	Schenkon	674	253.7	38%
1095	Oberkirch	910	111.9	12%
1081	Beromünster	4213	363.6	9%
1037	Rain	942	71.5	8%
1103	Sursee	583	41.2	7%
1040	Rothenburg	1549	102.5	7%
1098	Ruswil	4525	231.4	5%
1061	Luzern	2910	6.4	0%

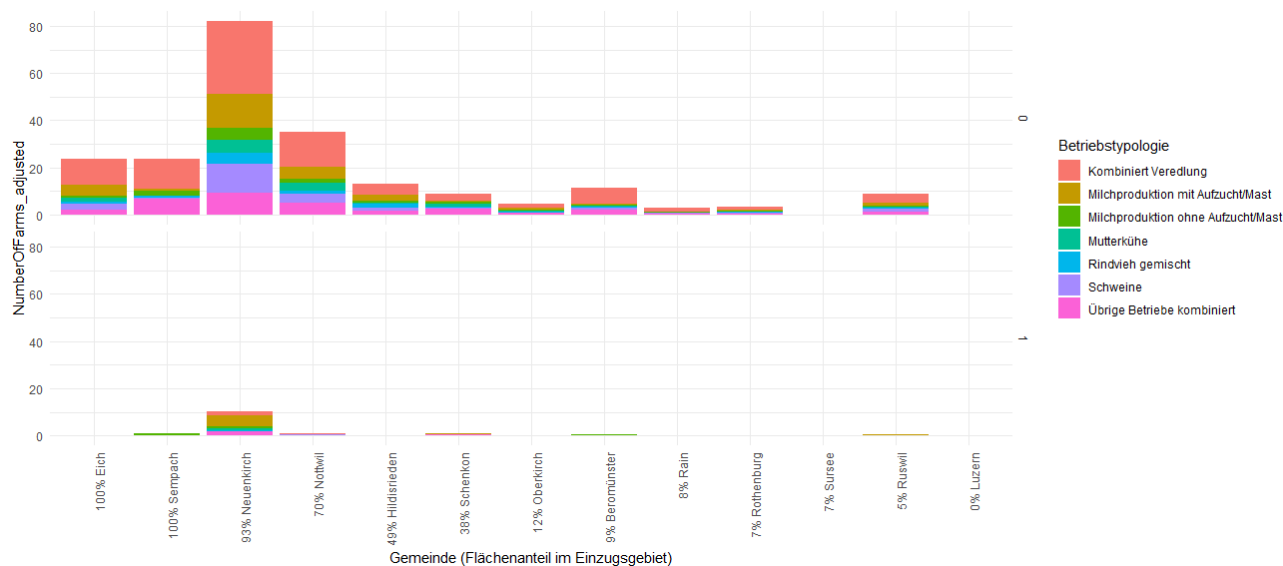


Figure SM4/3: Number of farms per farm type and municipality. The upper panel shows conventional farms, the lower panel organic farms. The percentage preceding each municipality name indicates the share of its total area located within the catchment. Farm numbers were adjusted accordingly (e.g., since 70% of Nottwil lies within the catchment, 70% of its farms are included).

Farm type	Number of farms	Number of animals per farm								
		Dairy herd					Suckler herd		Pig herd	
		Dairy cow	Calf fattening	Bull fattening	Ox fattening	Cattle fattening	Suckler cow	Suckler cow husbandry	Finishing pig	Breeding sow
Dairy production with rearing/fattening	33	39.1	1.9	0.7	0.2	1.0	-	-	-	-
Dairy production without rearing/fattening	11	27.5	1.2	0.5	0.1	0.6	-	-	-	-
Mixed cattle - rearing	8	30.1	-	-	-	-	-	-	-	-
Mixed cattle fattening - beef	2	-	-	132.5	92.0	110.0	-	-	-	-
Mixed cattle fattening - veal	2	1.6	87.8	-	-	-	-	-	-	-
Suckler cows (average-scale)	19	-	-	-	-	-	21.5	14.7	-	-
Suckler cows (large-scale)	6	-	-	-	-	-	89.8	52.0	-	-
Pig finishing	44	26.8	2.4	1.8	0.8	3.7	-	-	153.6	-
Pig finishing (without cattle)	5	-	-	-	-	-	-	-	331.7	-
Pig breeding	36	24.9	1.6	0.5	0.1	1.0	-	-	219.8	47.7
Pig breeding (without cattle)	13	-	-	-	-	-	-	-	401.7	97.7
Combined pig breeding and finishing	24	32.7	2.3	1.0	0.3	1.2	-	-	192.0	10.3
Combined pig breeding and finishing (without cattle)	3	-	-	-	-	-	-	-	801.1	121.9
Remaining farms combined	36	20.8	1.5	1.1	0.6	1.8	1.2	1.5	2.2	0.5

Comparison to AMD (2023)

105%	99%	95%	99%	69%	87%	124%	153%	130%
95%	101%	105%	101%	145%	116%	81%	65%	77%

Correction factor

	Number of farms	Number of animals per farm								
		Dairy herd					Suckler herd		Pig herd	
Farm type		Dairy cow	Calf fattening	Bull fattening	Ox fattening	Cattle fattening	Suckler cow	Suckler cow husbandry	Finishing pig	Breeding sow
Dairy production with rearing/fattening	33	37.3	1.9	0.8	0.2	1.5	-	-	-	-
Dairy production without rearing/fattening	11	26.2	1.2	0.5	0.1	0.9	-	-	-	-
Mixed cattle - rearing	8	28.7	-	-	-	-	-	-	-	-
Mixed cattle fattening - beef	2	-	-	139.4	92.5	159.4	-	-	-	-
Mixed cattle fattening - veal	2	1.5	88.4	-	-	-	-	-	-	-
Suckler cows (average-scale)	19	-	-	-	-	-	24.8	11.9	-	-
Suckler cows (large-scale)	6	-	-	-	-	-	103.7	42.0	-	-
Pig finishing	44	25.6	2.4	1.9	0.8	5.4	-	-	100.2	-
Pig finishing (without cattle)	5	-	-	-	-	-	-	-	216.4	-
Pig breeding	36	23.8	1.6	0.5	0.1	1.4	-	-	143.4	36.7
Pig breeding (without cattle)	13	-	-	-	-	-	-	-	262.1	75.1
Combined pig breeding and finishing	24	31.2	2.3	1.0	0.3	1.7	-	-	125.3	7.9
Combined pig breeding and finishing (without cattle)	3	-	-	-	-	-	-	-	522.7	93.8
Remaining farms combined	36	19.9	1.5	1.2	0.6	2.6	1.4	1.2	1.4	0.3

Comparison to AMD (2023)

[illegible]

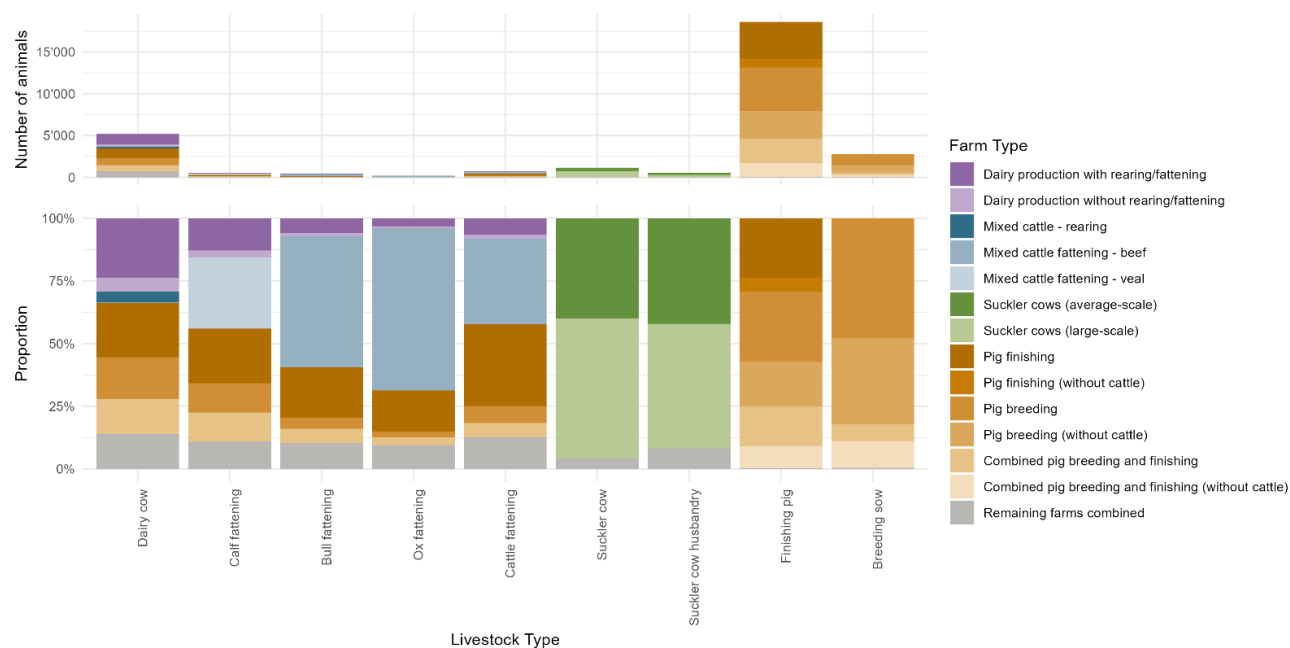


Figure SM4/4: Number of animals in the catchment by livestock type and farm type in 2020 (status quo).

Table SM4/3: Resistance matrix, indicating resistance against shifts between farm types (rows: current farm type; columns: target farm type). Resistance is rated on a scale from 0 to 3, where 0 = No resistance, 1 = Low resistance, 2 = Medium resistance, and 3 = High resistance. The matrix reflects resistance against (a) switches to another farm type, (b) switches to another farm type including a transition to the B3 feeding plan, (c) extensification through full-farm conversion to organic production, and (d) complete exits from livestock production.

	(a) Switches to another farm type														(b) Switches to another farm type including a transition to the B3 feeding plan										(c) Extensification through full-farm conversion to organic production										(d) Exit			
From farm type ↓ to farm type →	Dairy production with rearing/fattening	Dairy production without rearing/fattening	Mixed cattle - rearing	Mixed cattle fattening - beef	Mixed cattle fattening - veal	Suckler cows (average-scale)	Suckler cows (large-scale)	Pig finishing	Pig finishing (without cattle)	Pig breeding	Pig breeding (without cattle)	Combined pig breeding and finishing	Combined pig breeding and finishing (without cattle)	Remaining farms combined	Dairy production with rearing/fattening [B3]	Dairy production without rearing/fattening [B3]	Mixed cattle fattening - beef [B3]	Pig finishing [B3]	Pig breeding [B3]	Combined pig breeding and finishing [B3]	Remaining farms combined [B3]	Dairy production with rearing/fattening [B3] [Extensification through full-farm conversion to organic production]	Dairy production without rearing/fattening [B3] [Extensification through full-farm conversion to organic production]	Mixed cattle - rearing [Extensification through full-farm conversion to organic production]	Mixed cattle fattening - beef [B3] [Extensification through full-farm conversion to organic production]	Mixed cattle fattening - veal [Extensification through full-farm conversion to organic production]	Suckler cows (average-scale) [Extensification through full-farm conversion to organic production]	Suckler cows (large-scale) [Extensification through full-farm conversion to organic production]	Pig finishing [B3] [Extensification through full-farm conversion to organic production]	Pig finishing (without cattle) [Extensification through full-farm conversion to organic production]	Pig breeding [B3] [Extensification through full-farm conversion to organic production]	Pig breeding (without cattle) [Extensification through full-farm conversion to organic production]	Combined pig breeding and finishing [B3] [Extensification through full-farm conversion to organic production]	Combined pig breeding and finishing (without cattle) [Extensification through full-farm conversion to organic production]	Remaining farms combined [B3] [Extensification through full-farm conversion to organic production]	Exit of livestock production		
Dairy production with rearing/fattening	0	0	1	1	1	2	3	3	3	3	3	3	3	0	0	0	1	3	3	3	0	1	1	3	3	3	2	3	3	3	3	3	3	3	3	3	1	2
Dairy production without rearing/fattening	0	0	1	2	2	2	3	3	3	3	3	3	3	0	0	0	2	3	3	3	0	1	1	3	3	3	2	3	3	3	3	3	3	3	3	3	1	2
Mixed cattle - rearing	2	2	0	2	2	2	3	2	3	3	3	3	3	2	2	2	2	2	3	3	2	2	2	2	3	3	2	3	3	3	3	3	3	3	3	3	2	1
Mixed cattle fattening - beef	3	3	2	0	2	2	3	2	3	3	3	3	3	3	3	3	0	2	3	3	3	3	3	3	3	3	2	3	3	3	3	3	3	3	3	3	3	1
Mixed cattle fattening - veal	2	2	2	2	0	2	3	2	3	3	3	3	3	2	2	2	2	2	3	3	2	2	2	2	3	3	2	3	3	3	3	3	3	3	3	3	2	1
Suckler cows (average-scale)	3	3	1	2	3	0	1	3	3	3	3	3	3	3	3	3	2	3	3	3	3	3	3	3	3	3	1	1	3	3	3	3	3	3	3	3	1	
Suckler cows (large-scale)	3	3	1	2	3	0	0	3	3	3	3	3	3	3	3	3	2	3	3	3	3	3	3	3	3	3	1	1	3	3	3	3	3	3	3	3	1	
Pig finishing	2	1	2	2	3	3	3	0	1	2	3	2	3	2	2	1	2	0	2	2	2	2	1	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2
Pig finishing (without cattle)	3	3	3	3	3	3	3	0	3	3	3	3	3	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	
Pig breeding	2	1	3	3	3	3	3	2	2	0	1	1	2	2	2	1	3	2	0	1	2	2	1	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2
Pig breeding (without cattle)	3	3	3	3	3	3	3	3	2	3	0	3	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	
Combined pig breeding and finishing	2	1	3	3	3	3	3	1	1	2	2	0	1	2	2	1	3	1	2	0	2	2	1	3	3	3	3	3	3	3	3	3	3	3	3	3	2	2
Combined pig breeding and finishing (without cattle)	3	3	3	3	3	3	3	3	1	3	2	3	0	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	
Remaining farms combined	0	0	1	1	1	2	3	3	3	3	3	3	3	0	0	0	1	3	3	3	0	1	1	3	3	3	2	3	3	3	3	3	3	3	3	3	1	2

Step-by-step procedure for identifying the lowest feasible global tolerance level

We identified a set of farm-type changes using a mixed-integer linear programming (MILP) model that reallocates farms between farm types to achieve the predefined livestock targets. Input data included the number of farms per farm type, the number of animals per farm and livestock type, and resistance scores for all transitions. For each livestock type, target changes were defined based on the scenario specifications (i.e. pig-dominated or dairy-dominated target scenario) and relaxed by a tolerance interval. The optimization model assigns an integer number of farms to each transition, minimizing the weighted use of high-resistance transitions while ensuring that aggregate changes of animal numbers fall within the tolerance-adjusted target bounds per livestock type and that changes do not exceed the number of available farms per origin type. The

model was solved using the GLPK solver. The resulting solution yields a set of farm type changes and the implied final farm and livestock structure at the catchment scale. Below, you can find a step-by-step description of the process to identify the lowest global tolerance level:

1. Definition of scenario, targets, and tolerances

- Selection of target scenario to be matched (i.e. pig-dominated or dairy-dominated target scenario).
- Define a global tolerance around each livestock target (tested iteratively at different levels).
- Set a random seed for reproducibility.
- Define a consistent ordering of livestock categories for later aggregation and output.
- Define a helper function to:
 - Check whether target livestock changes are theoretically achievable given: Available farms, per-transition livestock deltas, the chosen tolerance
 - Report feasible vs. infeasible targets before optimization.

2. Import and prepare input data

- Load all required input tables:
 - Target livestock changes (current vs. target situation).
 - Number of farms per farm type.
 - Resistance scores for farm-type transitions.
 - Additional constraint table (D1 constraint).
 - Livestock numbers per farm type.
- Overwrite resistance scores with D1-constraint values where available (prioritising stricter constraints).
- Load livestock delta tables. For each livestock type, read the corresponding delta table illustrating the differences in animal numbers per livestock type.

3. Construct the transition dataset

- Convert resistance matrix to long format (from-type → to-type).
- Join number of farms per origin type and livestock delta tables for all livestock types.
- Replace missing values with zeros.
- Remove transitions with zero feasibility (i.e. highest resistance).
- Result: a transition table, where each row represents one feasible transition option with resistance score, available farms, livestock deltas for all animals

4. Extract target livestock changes

- Extract numeric target changes for each livestock type.
- Store targets in a named vector.

- Run the resistance check:
 - Compare tolerance-adjusted targets with the maximum/minimum achievable change.
 - Report resistance before solving the optimization problem.
- 5. Build the mixed-integer optimization model
 - Define one integer decision variable per transition: x_i = number of farms assigned to transition i
 - Define the objective function: Minimize the total “transition cost”. Each transition is weighted by the resistance score. Low-resistance transitions are preferred.
 - Add livestock target constraints: For each livestock type, the sum of animal number changes across all selected transitions must lie within target $\pm$ tolerance and within the technically achievable range.
 - Add farm availability constraints: For each origin farm type, the number of farms transitioning out cannot exceed the available farms.
- 6. Solve the optimization problem
 - Solve the MILP using the GLPK solver via ompr and ROI.
 - Impose a time limit to ensure tractability.
 - Extract the optimal solution:
 - Keep only transitions where $x_i > 0$
 - Attach the selected number of farms back to the transition table
- 7. Format transition-level results
 - Compute total livestock changes per transition: Per-farm delta $\times$ number of farms transitioned
 - Produce a clean table of origin type, destination type, resistance, number of farms transitioned, resulting animal changes
- 8. Compute final farm and livestock structure
 - Aggregate farm inflows and outflows by farm type. Compute initial number of farms, arms transitioning *from*, farms transitioning *to*, final number of farms per type
 - Multiply final farm counts by livestock numbers per farm type.
 - Compute final livestock totals by farm type and overall totals across all farm types
 - Export results

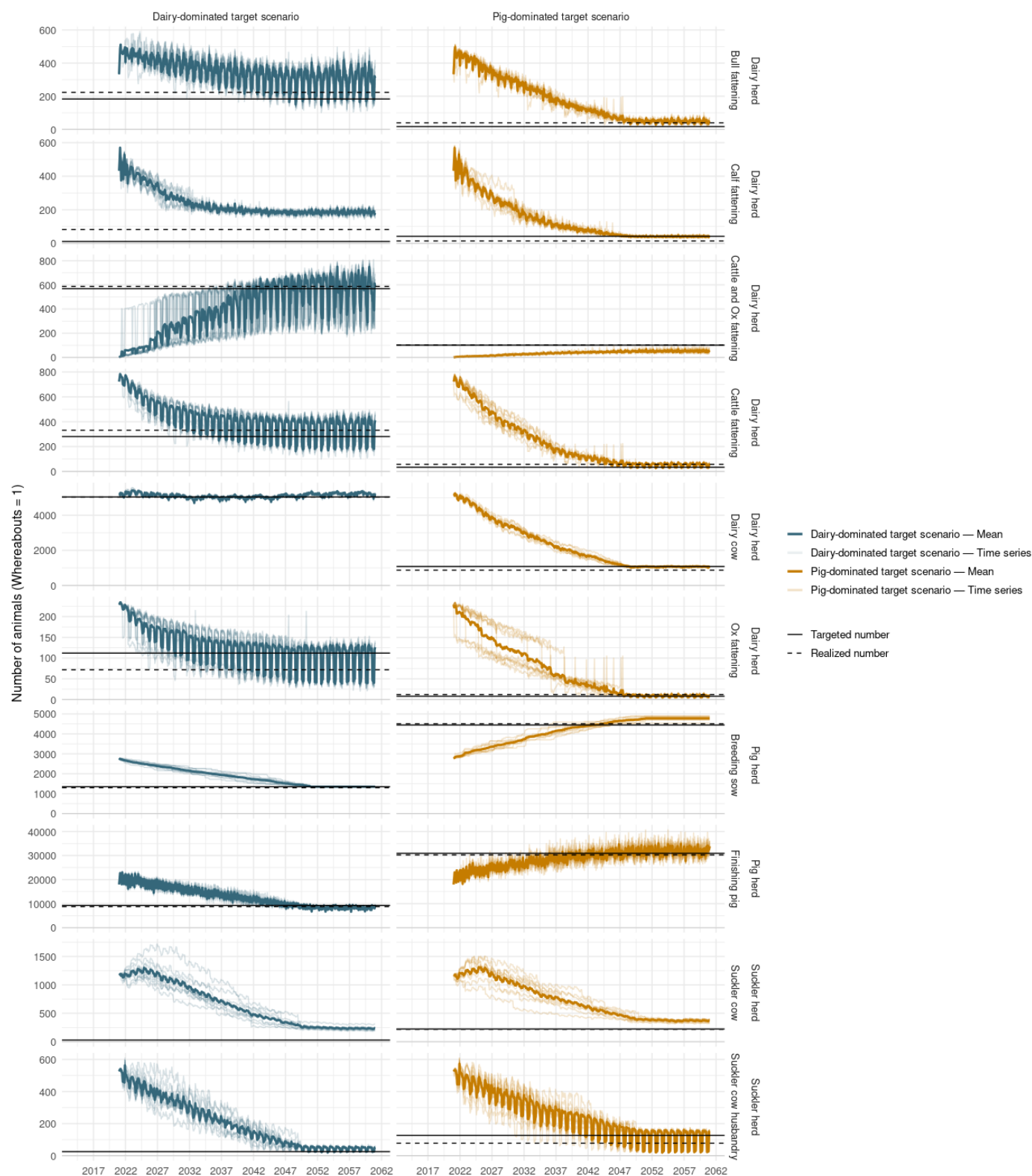


Figure SM4/5: Development of animal numbers per livestock herd and livestock type (rows) towards the two target scenarios (columns). Lighter orange lines show individual transition pathways (time series 1 to 10) toward the pig-dominated target scenario, with the thicker orange lines indicating the respective mean. Lighter blue lines show individual transition pathways toward the dairy-dominated target scenario, with the thicker blue lines indicating the respective mean. Horizontal lines indicate the target animal numbers for 2025 and the realized numbers obtained through the optimization process. Y-axes are scaled independently for each facet.

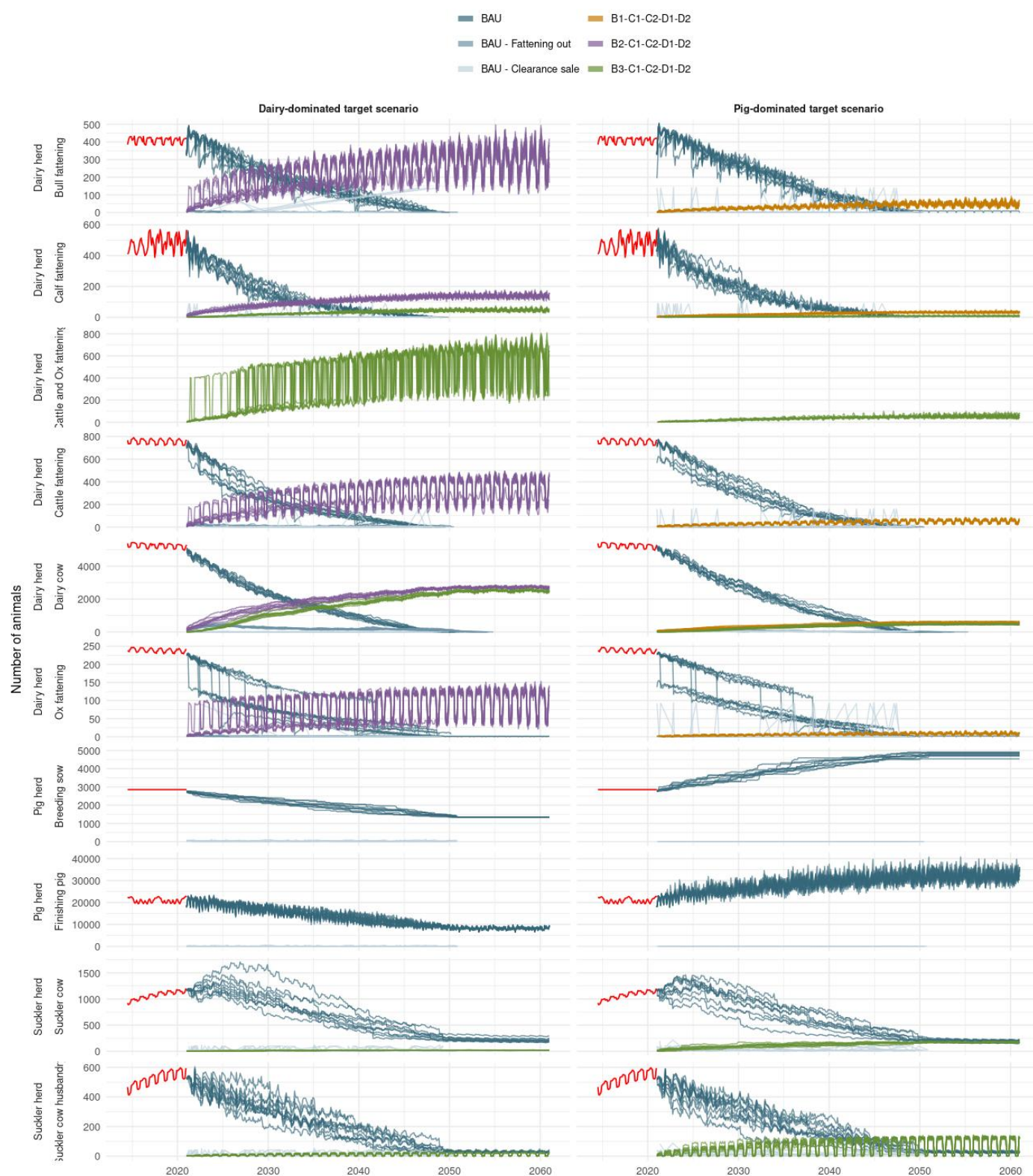


Figure SM4/6: Development of animal numbers per livestock herd and livestock type (rows) towards the two target scenarios (columns). The red line shows the baseline until 12/2020. Colored lines indicate alternative livestock management strategies: dark blue represents animals under BAU management; light blue shows animals under BAU management but only for fattening out with offspring entering the target strategy B3-C2-D1-D2; green depicts animals under B3-C2-D1-D2; orange and violet show animals under the same configuration as green but with feeding plans B1 and B2, respectively. Y-axes are scaled independently for each facet.

References

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).