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Exploring the strategic potential for Switzerland to reduce nitrogen and phosphorus surplus in agriculture

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ABSTRACT

Switzerland aims to further reduce nitrogen and phosphorus emissions from agriculture. We explore the potential of three types of food system interventions. National farm gate budget calculations are complemented with additional indicators for efficiency, sufficiency, and circularity in nutrient management. Calculations also include the part of the global food system that produces agricultural products imported to Switzerland. Our results suggest that the potential to reduce nitrogen and phosphorus surplus through a combination of strategies exceeds the anticipated effect of currently prioritized measures. Our work also highlights how the additional indicators and extended system boundaries broaden the assessment and reveal aspects that would be concealed if relying solely on national farm gate budget calculations within Switzerland. Based on a refinement of our preliminary assumptions and estimations, future work could identify the crop and animal production systems that offer most leverage, as well as help define priority strategies and measures.

1. Introduction

Nitrogen (N) and phosphorus (P) are important plant nutrients. The discovery of technical processes to produce P fertilizers in the early 19th century (Boulaine 2006) and to fix N from the atmosphere in the early 20th century (Ertl 2012) laid the foundation for a marked increase in world food production and human population (Erisman et al., 2008). Since the 1960s, global N fertilizer use has increased more than tenfold while global P fertilizer use has increased more than threefold (Dawson and Hilton 2011; Heffer and Prud'homme 2013; Lu and Tian 2017). The multiplication of N and P inputs to agricultural land also meant increased N and P emissions from agriculture, not least from livestock (Leip et al., 2015), and especially so in areas with high livestock densities (Wang et al., 2018; Svanbäck et al., 2019). In addition, N and P emissions from urban wastes have increased nearly twofold throughout the twentieth century (Morée et al., 2013) and are expected to further increase over the coming decades (Van Puijenbroek et al., 2019). N emissions to the atmosphere in the form of nitrous oxide contribute to climate change (Gong et al., 2024) while emissions of reactive nitrogen affect terrestrial biodiversity (Dise et al., 2011; Clark et al., 2013). N and P emissions to water bodies fuel algal blooms in lakes and oceans (Lougheed 2011; Glibert et al., 2014) and impact drinking water quality in surface and groundwater (Ward et al., 2018). Nutrient accumulation in water bodies is further aggravated as the role of wild animals transporting nutrients from the deep sea back to the continental interiors (upward movement in the ocean by marine mammals followed by transfer from the sea to land by seabirds and anadromous fish) has been much diminished as a result of massive population declines, especially of larger animals (Doughty et al., 2016). According to the Planetary Boundaries Framework (Rockström et al., 2009), the global boundaries for N (in terms of N fixation from the atmosphere) and P (in terms of P flowing into the oceans) are currently both transgressed (Richardson et al., 2023).

From the 1970s onwards, more stringent environmental legislation was put in place to mitigate nutrient pollution (Wuepper et al., 2024). Despite continued efforts to curb N and P emissions from agriculture and urban water management, nutrient pollution remains a threat to terrestrial and aquatic ecosystems (e.g., the Midland Lakes in Central Switzerland, the Baltic Sea in Northern Europe and the Lake Erie Basin in North America). Moreover, the progressive depletion of high-grade phosphate rock reserves has implications for food security (Cordell et al., 2009). In light of geopolitical dynamics, this seems particularly important, as three quarters of the known high-grade phosphate rock reserves are located in Morocco and Western Sahara (Elser and Bennett

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2011; Cordell and White 2013). Regarding N, there is no shortage in supply in principle, as N is abundant in the atmosphere (Dawson and Hilton 2011). But the energy-intensive Haber-Bosch process applied for its transformation to reactive N still largely depends on natural gas (Manning 2018) and thus contributes to climate change (Smart 2022). While greener alternatives for ammonia synthesis are receiving considerable attention, they are not yet operational at industrial scale (Razon 2018; Smart 2022).

The need to further curb the release of N and P to the environment, together with the need for alternative supplies, has emphasized the necessity of recovering both N (Smart 2022) and P (Van Dijk et al., 2016; Wang et al., 2024) from agricultural and urban wastes for reuse in agriculture. At the same time, the relocation of significant quantities of both N (Lassaletta et al., 2014) and P (Lun et al., 2018) through global trade across different countries and regions means that N and P tend to accumulate where more feed and food are consumed and deplete where more feed and food are produced (Harder et al., 2021b; Chen et al., 2023). When forging new policies to curb nutrient emissions and tap into alternative nutrient supplies, it thus appears sensible to analyze how nutrient flows are connected across different locations (Harder et al., 2021b) and multiple spatial scales (Koppelmäki et al., 2021).

Switzerland, like many other European countries, is currently in the process of amending legislation with the aim to further reduce N and P emissions from agriculture. Hereby, a farm gate nutrient budget at the national scale (as formulated by OSPAR (1995)) is used as indicator to evaluate the effectiveness of measures (Spiess and Liebisch 2020). In Switzerland, N surplus in agriculture has decreased from over 120 kg N ha^{-1} in 1980 to about 90 kg N ha^{-1} in 1995 and has since then remained fairly stable (Fig. 1**a**). Switzerland still falls short of the reduction target for N flows to the North Sea as agreed in the OSPAR contract in 1992 – while the target was a 50 % reduction from 1985 to 2020, the actual reduction amounted to less than 30 % (BAFU 2022). Nitrate concentrations in groundwater aquifers still exceed regulatory thresholds at about 15 % of all monitoring locations and at about 50 % of monitoring locations in areas with intensive agriculture (BAFU 2022). P surplus has seen a stronger relative decrease than N surplus, from over 26 kg P ha^{-1} in 1980 to around 13 kg P ha^{-1} in 1995 and further to around 5 kg P ha^{-1} in 2005, having remained fairly stable since then (Fig. 1**b**). Even though OSPAR reduction targets for P were already met in 1995, given the legacy effects of excessive P inputs in the past, current P inputs are still problematic. Over 60 % of the larger Swiss lakes do not meet regulatory thresholds for oxygen content or require artificial aeration (BAFU 2022). The current consensus reduction targets that have emerged from the political process are 15 % for N and 20 % for P until 2030 (relative to the reference period 2014–2016) (BLW 2023) (Fig. 1).

During the political process, various actors with a stake in nutrient management expressed the need to complement the national farm gate budget with a suite of agro-environmental indicators and to also consider imports and domestic consumption (BLW 2022). In that light, the current focus on improvements in technology and nutrient management in the agricultural sector could be complemented by two additional levers for reducing the environmental effects of food systems, namely dietary change towards more plant-based diets and reductions in food loss and waste (Springmann et al., 2018).

The primary aim of the present study is to assess how three food systems interventions can help Switzerland reduce N and P surplus in agriculture, relative to one another and in contrast to business as usual and current measures anticipated by federal authorities. To this end, we explore an extended set of indicators (in addition to the national scale farm gate nutrient budget) along with the consideration of feed and food imports and consumption (thus feed and food produced outside Switzerland). In doing so, we seek to showcase if and how this could broaden the assessment and allow for a more nuanced discussion and decision making on national scales towards implementation of measures for better nutrient management and reduced nutrient losses to the environment.

2. Methods

2.1. The Swiss agrifood system

Switzerland is a landlocked alpine country located in Europe with a total area of 41 285 km^2. In 2020, 15 095 km^2 (37 %) were used for agriculture and 12 683 km^2 (30 %) for forestry. Population was 8.7 million in 2020 and is expected to increase to 9.4 million in 2030 and 10.4 million in 2050 (BFS 2022). At the same time, large areas of the Swiss Plateau and Alpine valley bottoms face strong urbanisation pressure, while much of the alpine pastures face risk of abandonment (Price et al., 2015). For most feed and food commodities, imports to Switzerland by far exceed exports. An overview of the Swiss agrifood system in terms of agricultural land use, animal units, feed and food trade, and food self-sufficiency is provided in Section 1 of the Supporting Information (SI).

2.2. Scenarios

There are at least three leverage points for reducing nutrient losses from agriculture to the environment. First, reducing the supply of fertilizers and feedstuffs while aiming to maintain agricultural productivity – this leverage point corresponds to the concept of nutrient use efficiency (e.g. Gerber et al., 2014; Johnston and Bruulsema 2014; Nakachew et al., 2024; Maurya et al., 2024). Second, scaling down feed and food production while still aiming to meet dietary requirements of the world population – this leverage point corresponds to the concept of sufficiency (e.g. Jaisli and Brunori 2024; Spiller et al., 2024). Third, recovering nutrients that would otherwise be lost and reusing them in agricultural production – this leverage point corresponds to the concept of nutrient circularity (Senthilkumar et al., 2014; Van Der Wiel et al.,

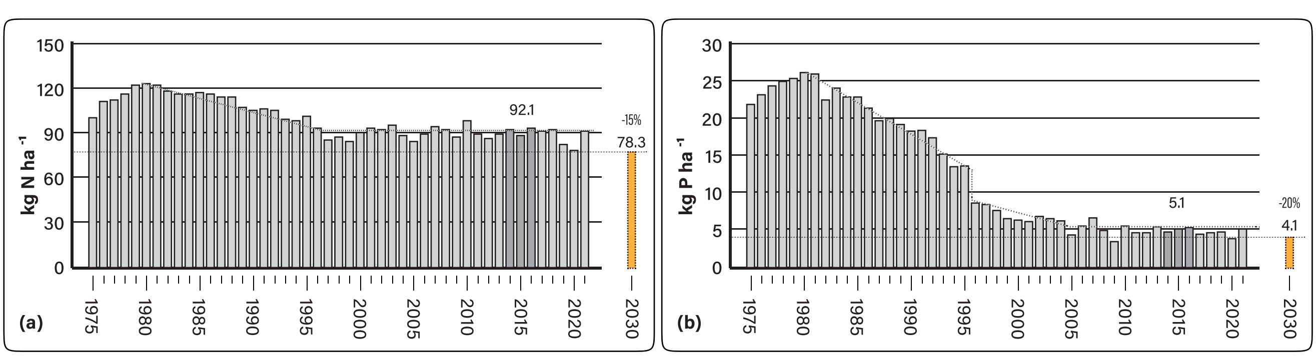

Fig. 1. Nutrient surplus in Swiss agriculture from 1975 to 2021 for (a) nitrogen and (b) phosphorus (data from Spiess and Liebisch 2023), along with current consensus reduction targets for 2030, shown per hectare of agricultural land use. Bars in dark grey indicate the reference period for the reduction target (i.e., 2014–2016).

2019; Davis et al., 2024).

The present study focuses on efficiency and sufficiency as leverage points. Rather than evaluating the potential of individual measures to reduce N and P surplus, we forged a number of scenarios that reflect distinct strategies combining measures towards a more sustainable food system. Our intention was to assess the potential of these strategies to reduce N and P surplus, relative to one another and in comparison with the current situation and current political ambition level. **BU:** The *business as usual* scenario takes into account projected population growth, and thus an increase in food demand, while food production remains unchanged. **TM:** The *technology and management* scenario assumes that best available agricultural practice in nutrient management (notably crop fertilization, animal feeding, and manure management) is implemented in Switzerland. **FW:** The *less food loss and waste* scenario assumes that measures to reduce food loss and waste are taken along the food chain in Switzerland, which in turn means a decrease in food demand. **CA:** The *circular agriculture* scenario encompasses changes in food consumption and consumption patterns. On the one side, it assumes the implementation of circular agriculture principles in Switzerland: plant biomass production for human consumption is prioritized over feed production, agricultural by-products are increasingly utilized as fertilizer or animal feed, and farm animals are kept mainly to convert human inedible by-products and grass resources. On the other side, it implies a reduced consumption of animal products in Switzerland (see also Von Ow et al., 2020). **SC:** The *strategies in combination* scenario combines food loss and waste reduction and the implementation of circular agriculture principles with best available nutrient management practices. The scenario specifications are summarized in Section 2.1 in the SI. All scenarios account for projected population growth until the year 2030. Note that we consider all scenarios implementable in principle but did not assess their feasibility in detail.

2.3. Analytical framework

Switzerland is embedded in a global food system. Thus, nutrient surplus associated with the production of food imported into Switzerland arises outside of Switzerland, while a part of the nutrient surplus that arises in Swiss agriculture is associated with food consumption outside of Switzerland. The analytical framework of our study thus distinguishes between an *internal* and an *external* system (see also Harder et al., 2021b). The internal system encompasses the production and consumption of agricultural products within Switzerland: agricultural production is further divided into production for domestic consumption and for export, which allows to estimate the part of domestic nutrient surplus that does not contribute to domestic feed and food supply. The external system encompasses the production of agricultural products outside Switzerland for consumption in Switzerland, as well as the consumption outside of Switzerland of agricultural products produced in Switzerland. In other words, the external system is that part of the global food system that supplies the imports of agricultural products to Switzerland, or that receives the exports of agricultural products from Switzerland. For a first gross assessment, no distinction is being made regarding the origin of imports or the destination of exports. The types of nodes and nutrient flows distinguished by the analytical framework are shown in Fig. 2. Additional details are provided in Section 2.2 of the SI.

2.4. Nutrient management indicators

Nutrient budgets are an established method to calculate N and P surplus or deficit. In Switzerland, the so-called OSPAR and OECD budgets are typically applied. The OSPAR budget is a national farm gate budget, where agriculture is seen as a single business (Fig. 3a). The OECD budget is a national soil surface budget, where the gross amounts of animal manure excreted by livestock are taken into account, without deducting losses during manure management (Fig. 3b). The final balance (i.e. surplus or deficit) reflects the magnitude of changes in soil reserves as well as losses via various pathways. For N, changes in the soil reserve due to build-up or loss of humus are usually small, so that total losses are almost as high as the surplus. For P, enrichment in the soil pool can be much greater than losses to the environment; vice versa, mobilization from the soil pool can even mask losses (Spiess and Liebisch 2020). However, the final balance alone is not sufficient to understand which factors contribute how much to changes in nutrient surplus or deficit over time.

Assessing food system performance in terms of nutrient management benefits from the concurrent estimation of multiple indicators related to among others nutrient inputs, emissions, use efficiency, circularity, recovery efficiency, and reuse efficiency (Vingerhoets et al., 2023). Moreover, it is also of interest to assess the extent to which a country or region can provide its own nutrient inputs from local nutrient sources – an indicator referred to as nutrient self-sufficiency (Van Der Wiel et al., 2021) or nutrient self-reliance (Harder et al., 2021a,c) and related to import dependency (Zoboli et al., 2016). In the present paper, in addition to calculating nutrient budgets at the national scale, indicators for nutrient efficiency, circularity, and self-sufficiency were explored

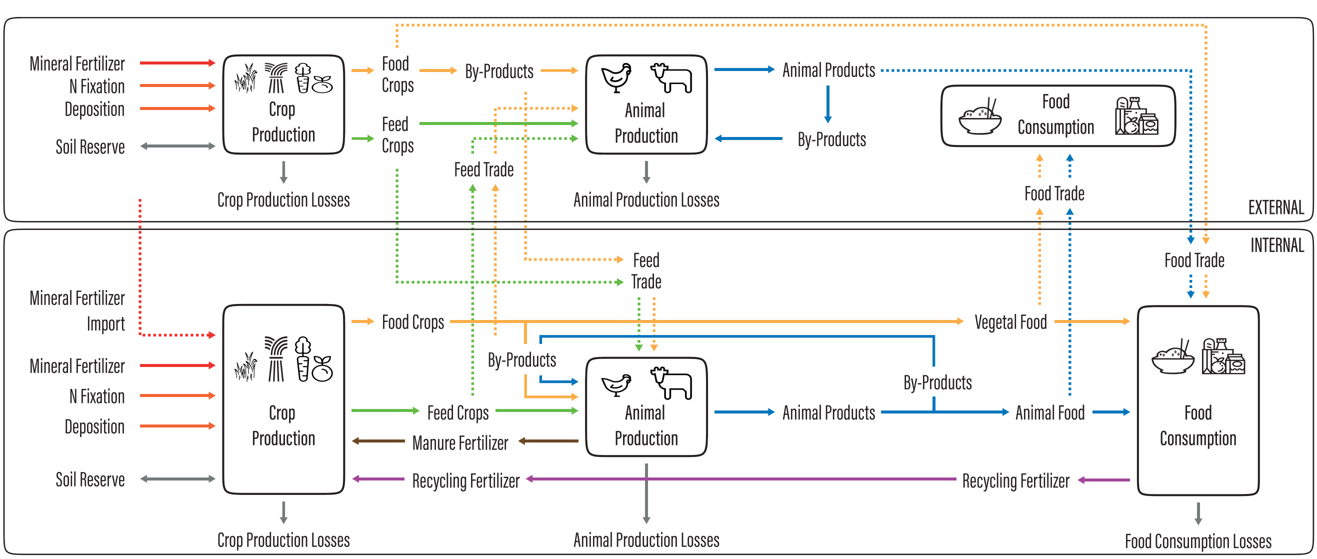

Fig. 2. Overview of the types of nodes and flows distinguished by the analytical framework.

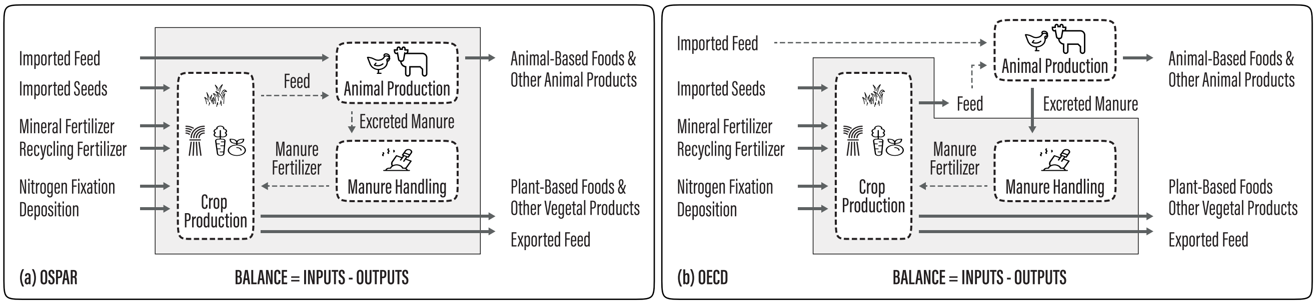

Fig. 3. Calculation of nutrient budgets according to (a) OSPAR and (b) OECD methods.

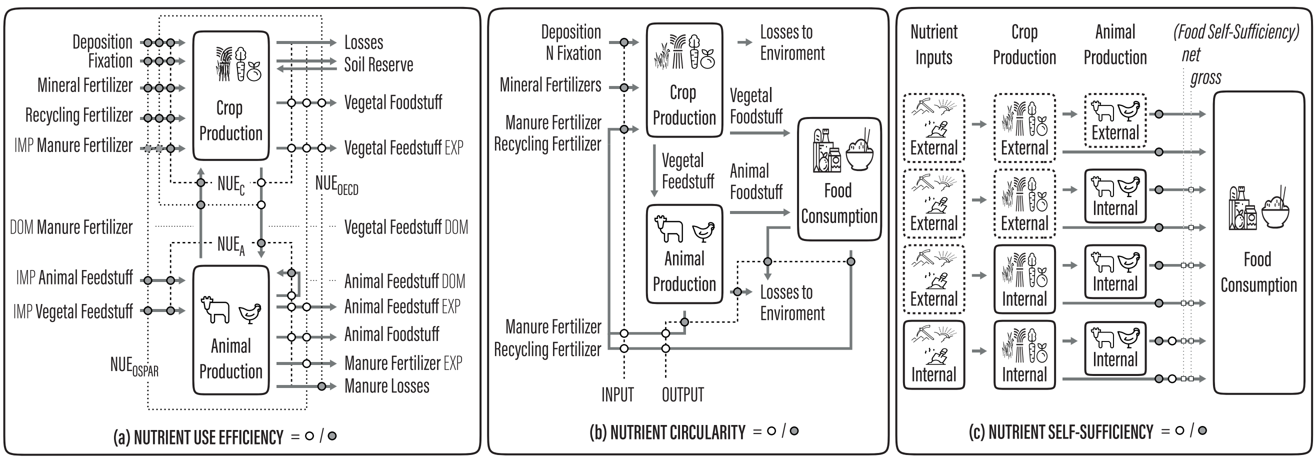

Fig. 4. Indicators of nutrient use efficiency (a), circularity (b), and self-sufficiency (c). White circles represent the numerator and gray circles the denominator in the calculation of the respective indicators. IMP = Import. DOM = Domestic. EXP = Export.

(Fig. 4). While there are more indicators that could be considered depending on the type of study (see e.g. Vingerhoets et al., 2023), the selected suite of indicators ought to be sufficient to capture relevant effects of the investigated food system interventions on nutrient management in the present study.

Nutrient use efficiency refers to the ratio of nutrient outputs through primary products and co-products over the total amount of nutrient inputs (Fig. 4**a**); it can be estimated separately for crop and animal production, or for agricultural production as a whole.

Nutrient reuse efficiency refers to the share of N and P recirculated from or with organic residues in relation to total nutrient inputs; it is intended as an indicator of input circularity (Fig. 4**b**). *Nutrient recovery efficiency* refers to the fraction of N and P found in organic residues that is recirculated to agricultural production (i.e., not lost to the environment); it is intended as an indicator of output circularity (Fig. 4**b**) and can be estimated separately for individual organic residues or for organic residue management as a whole.

In case of net import of N and P to the internal system through feed and food trade, a considerable proportion of the N and P found in organic residues produced domestically may originate from nutrient inputs in the external system. Consequently, in the internal system, nutrient reuse efficiency (input circularity) may exceed nutrient recovery efficiency (output circularity). This is because the accumulation in organic residues of N and P imported through feed and food trade increase the availability of N and P in organic residues domestically in relation to the N and P required for domestic crop production. *Nutrient accumulation* refers to the ratio of total N and P in organic residues over the amount that originates from domestic crop production; like nutrient recovery efficiency, it can be estimated separately for individual organic residues or for organic residue management as a whole.

Nutrient self-sufficiency refers to the fraction of N and P in food consumed domestically that originate from the input into domestic crop production of domestically sourced nutrients (i.e., domestic atmospheric deposition and nitrogen fixation, as well as domestically sourced mineral fertilizer and that part of manure and recycled fertilizers that originate from domestic nutrient inputs) (Fig. 4**c**). Note that nutrient self-sufficiency is different from food self-sufficiency in that domestic food production that relies on imported fertilizer or feed does contribute to food self-sufficiency but not necessarily to nutrient self-sufficiency.

2.5. Model implementation and parameterization

The calculation model was implemented as a spreadsheet in Microsoft® Excel for Mac Version 16 based on the overall model structure outlined in Section 2.3 of the SI. One of the key challenges was to ensure that modelling results are robust (in terms of the magnitude of considered flows) while keeping data collection feasible. Baseline data are described in detail in Section 2.4 of the SI. This section focuses on describing key assumptions and data processing steps that underpin scenario calculations. Note that all scenarios account for a projected population increase of about 10 % from 2015 to 2030, which was assumed to translate into a 10 % increase in food demand, thus requiring baseline availability of each food commodity to increase by 10 %.

2.5.1. Improved nutrient management (TM and SC)

This scenario was justified by best management practices (BMPs) and best available technologies (BATs) recommendations (Sutton et al., 2022). In particular we used Swiss guidelines on fertilization, feeding optimization and manure management (Agroscope 2017; Agroscope 2021) in conjunction with available studies on improving current N and P use efficiency (Kupper et al., 2020) combined with farm consensus data (Kupper et al., 2022; Gilgen et al., 2023) and technology adoption (Groher et al., 2020). The derived potential was conservative as to give a truly realistic value being achievable in the near future. For crop production, a reduction of inputs by 10 % for N and 5 % for P was considered achievable while maintaining average crop offtake. For animal production, a reduction in feed nutrient content by 5 % for both N and P was deemed feasible while maintaining the production of animal products (more conveniently modeled such that 5 % more of the N and P in feed ends up in animal products). For manure management, we assumed N losses can be reduced by 20 % whereas P losses are not reduced any further.

2.5.2. Reduced food loss and waste (FW and SC)

Regarding food loss and waste, we deemed a reduction by 30 % feasible, which is in line with the target set for EU member states for 2030 (EC 2023). Given that, from farm to fork, about a third of the edible parts of the food produced for consumption in Switzerland ends up in waste streams (BAFU 2019), a 30 % reduction of food loss and waste roughly translates into a 10 % reduction in food demand. As this 10 % reduction in food demand roughly compensates for the 10 % increase due to projected population growth , required food availability under reduced food loss and waste is at baseline level.

2.5.3. Reduced consumption and production of animal products (CA and SC)

To approximate feed and food production and demand under circular agriculture, we made a few crude expert assumptions. (1) There is no net import or export of feed to or from Switzerland. Only domestic roughage and by-products from food processing are available as feed for animal production. There is also no net import or export of animal food commodities to or from Switzerland. In other words, demand for animal food commodities in Switzerland is determined by production capacity in Switzerland with domestic roughage and by-products from domestic food production. (2) The reduced consumption of animal food commodities is compensated by an increased consumption of pulses. (3) Cropping areas no longer required for feed production are instead allocated to the production of crops for human consumption. This assumption meant that the feed ration had to be adjusted. This was done as follows. (i) Ruminants (i.e., cattle, sheep, and goats) are fed only roughage (i.e., grass, hay, and grass silage). For swine, the share of roughage is increased to 50 % of feed protein supply (demonstrated in at least one farm in Germany), the rest consisting of by-products from food processing. For poultry, the entire feed ration consists of by-products from food processing. (ii) Overall feed demand is increased by 10 % for roughage (to compensate for a lower feed conversion efficiency) and 50 % for by-products from food processing (to compensate for their relatively lower energy-to-protein ratio as compared to feed concentrates). (iii) Based on this adjusted feed ration, animal production in Switzerland is scaled down such that it matches the production of roughage and by-products from food production in Switzerland. Detailed calculations for the feed ration and scaled-down production are provided in OSM 5 while detailed calculations for feed and food production and demand are provided in OSM 6 (see data availability statement).

3. Results

3.1. Nutrient flows

Nutrient flows reflect changes in agricultural production and consumption patterns. Nutrient flows are visually summarized in Fig. 5.

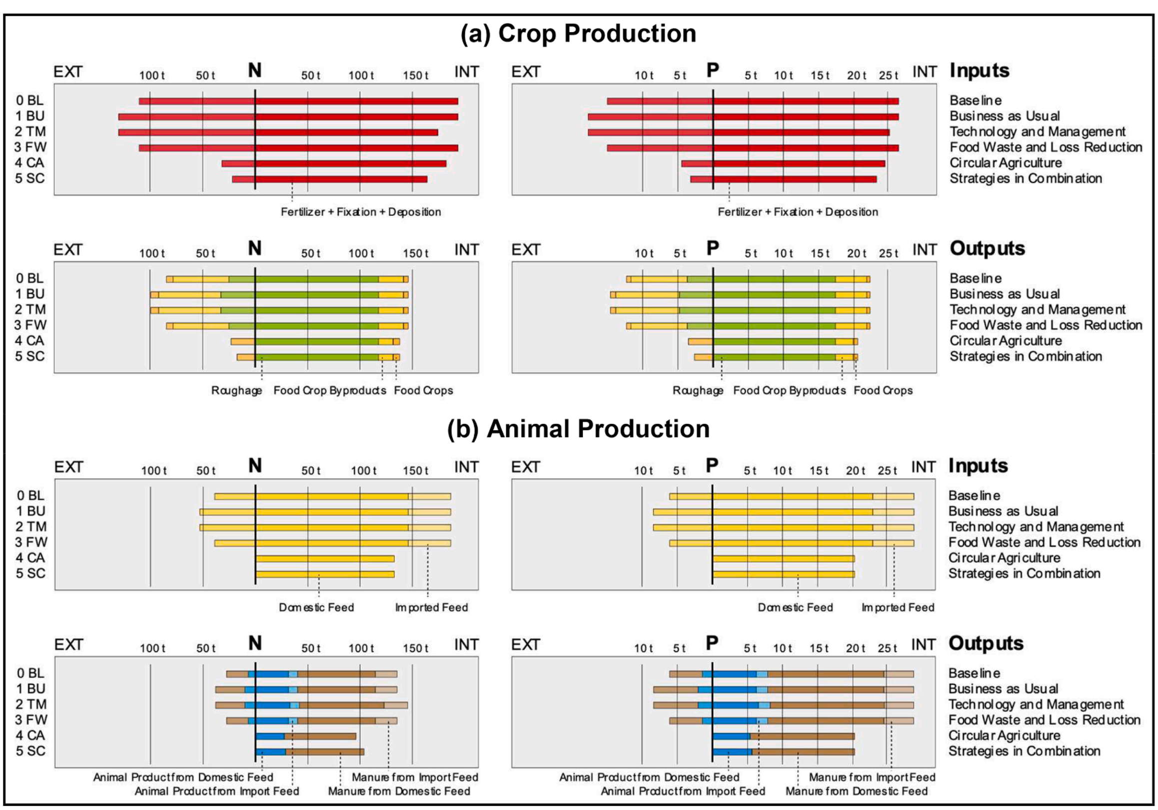

Fig. 5. Nutrient flows in crop production (a) and animal production (b) across all scenarios. Flows and associated colors as in Fig. 2. INT = Internal system (Swizerland). EXT = External system.

More detailed visual representations of nutrient flows are provided in Section 3.1 in the SI while Section 3.2 in the SI provides an overview of agricultural land use and animal units for the baseline and all scenarios.

BU: Projected population growth means an increase in land use and animal units in the external system compared to BL while production in Switzerland remains constant. This translates into increased nutrient flows through crop and animal production in the external system. **TM**: Land use and animal numbers are like in BU but improved nutrient management practices in Switzerland translate into lower nutrient inputs to crop production and a larger share of nutrients excreted ending up in manure fertilizer. **FW**: The 30 % reduction in food loss and waste compensates for projected population growth, thus land use and animal units are at baseline level both in Switzerland and the external system. Thus nutrient flows are like in BL. **CA**: There is no more animal production in the external system while animal numbers in Switzerland are reduced. With feed rations shifting to roughage and by-products only, areas used for feed crop production in Switzerland are entirely converted to food crop production while grassland areas remain the same. Nutrient flows through animal production in Switzerland are thus reduced while nutrient flows through crop production remain largely unaffected. In the external system, the area used for food crop production is reduced. This means that nutrient flows through crop production is much reduced. **SC**: The effects of TM, FW and CA apply in combination.

3.2. Nutrient surplus

Nutrient surplus in the internal and external system across scenarios is shown in Fig. 6 and Table S5 in Section 3.3 in the SI. In short, for both N and P, the potential of different strategies to reduce nutrient surplus in agriculture in Switzerland ranks: SC > TM > CA > FW. In the external system, the potential ranks: SC > CA > TM > FW. Overall potential for reducing nutrient surplus associated with Swiss food production and consumption (thus in the internal and external system together) ranks: SC > CA > TM > FW.

In Fig. 7, nutrient surplus is compared to the reference period 2014–2016 and to current targets in Switzerland (CH) and the European Union (EU). If only Switzerland is considered, improvements in technology and management (TM) have a much greater potential to reduce nutrient surplus than a shift to circular agriculture principles (CA). This is because the reduction in nutrient surplus that is achieved with CA is mainly due to the reduction in animal numbers and hence lower amounts of animal manure, whereas TM achieves reductions in both crop and animal production including manure management by means of more efficient N and P use. The reduction of food loss and waste (FW) does not affect nutrient surplus in Switzerland as the production level in Switzerland remains the same as with business as usual (BU). In the external system, however, the effect of CA is more pronounced than in the internal system. The reason is that most of the reduction in land use and animal numbers that results from a reduced demand for animal products in Switzerland in the CA scenario is in the external system (in fact there is no more feed and animal production for Switzerland in the external system). Thus, the full potential of circular agriculture to reduce nutrient surplus associated with Swiss feed and food consumption becomes evident only once the external system is taken into account in addition to food production in Switzerland. For overall nutrient surplus (in both the internal and external system), CA shows a slightly higher potential than TM (in this scenario only implemented in Switzerland). A much higher potential reduction of overall nutrient surplus can be achieved if all strategies are combined and improvements in technology and management are also implemented in the external system (SC).

3.3. Complementary indicators

The additional indicators of nutrient use efficiency, circularity, accumulation, and self-sufficiency can in principle be calculated for the internal and external system individually or in combination. However, they are more meaningful when the calculation encompasses all production and consumption in a geographical area. This applies only to the internal system where the full extent of feed and food production and consumption is considered. Fig. 8 thus presents the additional indicators for Switzerland (the internal system) only. Associated data tables are provided in Section 3.4 in the SI.

Nutrient use efficiency expressed as nutrient outputs divided by inputs in the OSPAR or OECD budget is improved by both TM and CA. The effect is more pronounced for TM than for CA because TM also encompasses reduced losses in crop production while CA only encompasses reduced losses in manure management due to lesser animal numbers.

Nutrient recovery efficiency decreases slightly for BU compared to BL as an increasing population means there is more food waste and human excreta, from which currently a lower fraction of nutrients is recovered than from animal manure (the amount of which remains constant). For CA, recovery efficiency decreases even more as the share of animal manure in total organic residues further diminishes in relation to food waste and human excreta. For TM, recovery efficiency for N increases as less N is lost from manure given improved manure management (for P no such improvement can be expected because losses are already minimal). *Nutrient reuse efficiency* increases for TM as less nutrient inputs are required and more nutrients are recovered from manure, which means that a larger share of nutrient outputs are again available as inputs. For CA, input circularity decreases as there is less animal manure while nutrient inputs to crop production remain roughly the same.

Nutrient accumulation increases for BU compared to BL as more food is imported to Switzerland while agricultural production remains the same. For FW, this effect is cancelled out as less food demand means less food is imported. For TM, nutrient accumulation (for N but not P) decreases slightly as compared to BU as more of the excreted N makes its way into manure fertilizer, thus increasing the availability of N in domestic organic residuals. For CA, there is an even sharper decrease as less feed and food are imported. *Nutrient self-sufficiency* decreases for BU as a larger demand for food means that more food and thus more nutrients are imported from the external system. TM increases nutrient self-sufficiency as less nutrients are lost and thus less inputs required.

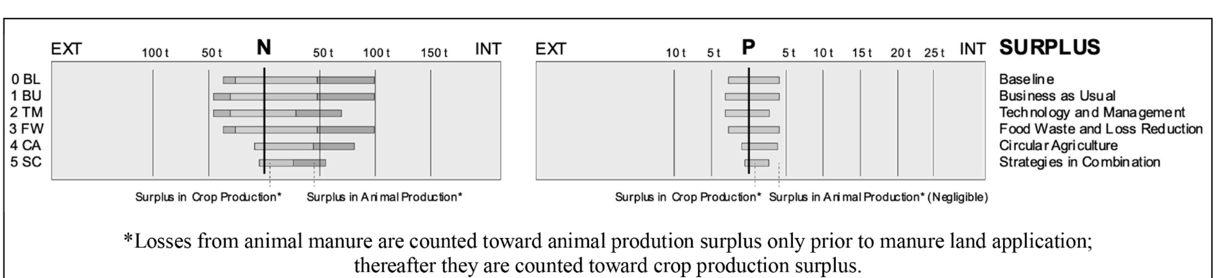

Fig. 6. Nutrient surplus in the internal and external system across scenarios.

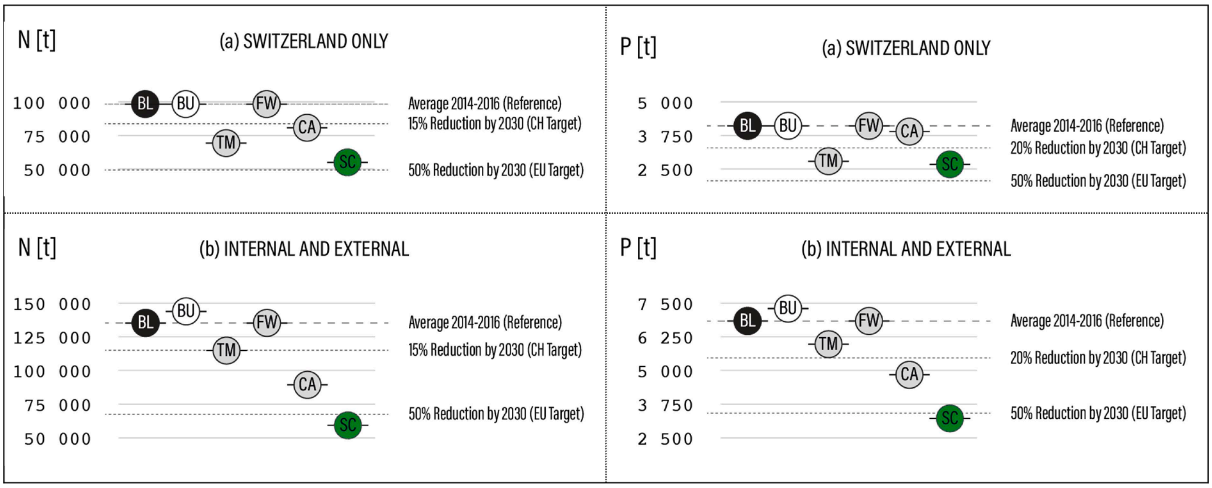

Fig. 7. N and P surplus in Switzerland only (a) compared to total surplus in both the internal and external system (b). BL referes to the baseline situation (reference year 2014–2016). For scenario abbreviations see Section 2.2.

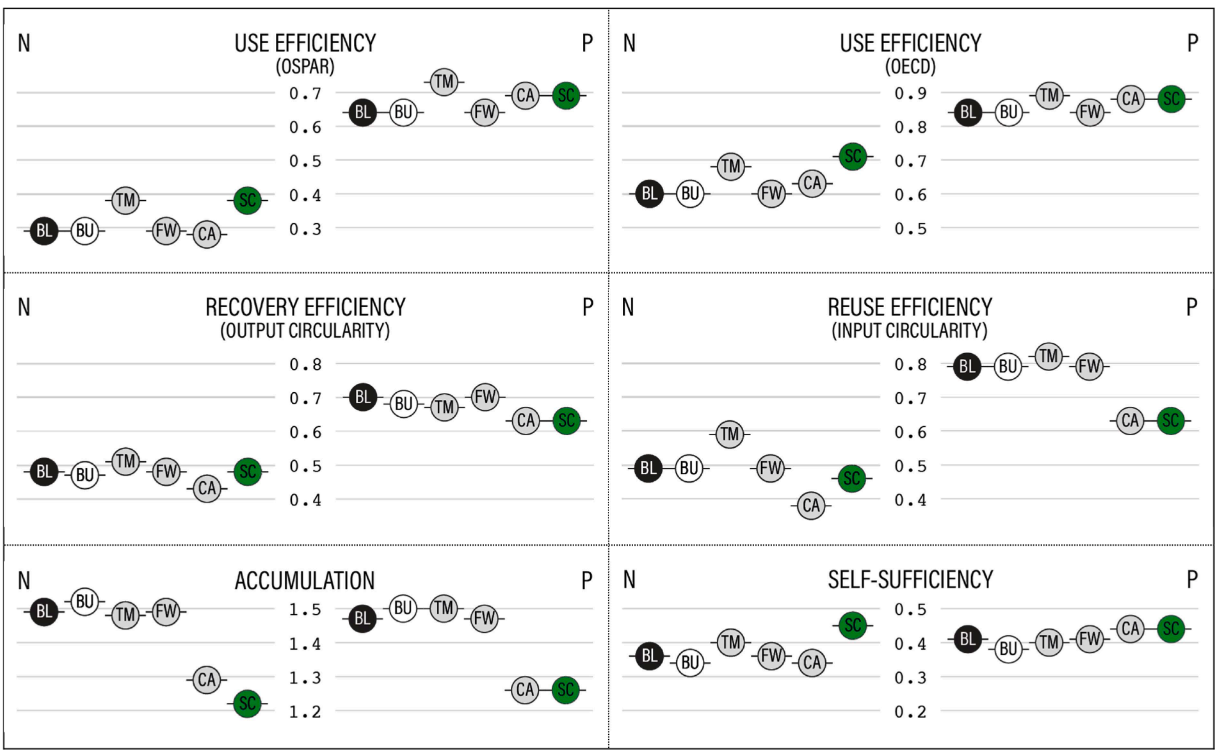

Fig. 8. Nutrient use efficiency, circularity, accumulation, and self-sufficiency in the internal system across scenarios. Nutrient use efficiency is shown for both the OSPAR and OECE budget. BL referes to the baseline situation (reference year 2014–2016). For scenario abbreviations see Section 2.2.

Somewhat counterintuitively, nutrient self-sufficiency for N is not improved in CA as the reduced amount of animal manure needs to be substituted by imported mineral fertilizers that are sourced externally. A high nutrient accumulation can thus partially mask shortcomings in both nutrient self-sufficiency and recovery efficiency.

4. Discussion

The aim of our study was to support the ongoing discussion and decision making process regarding the identification and implementation of measures to reduce nutrient surplus and consequently nutrient losses in agriculture. More specifically, we built our analysis around three food system interventions that are generally considered as effective in contributing to food system sustainability: improvements in technology and management, reductions in food loss and waste, and dietary change towards more plant-based diets (Springmann et al., 2018). To evaluate these food systems interventions regarding their strategic potential to reduce N and P surplus in agriculture, we went beyond a farm gate budget calculation for Switzerland in two ways. On the one hand, by extending the system boundaries and including external production required to fully meet Swiss food demand. On the other hand, by complementing budget calculations with a suite of additional indicators related to nutrient use efficiency, circularity, and self-sufficiency. These extensions cater to current requests from stakeholders regarding the assessment of better nutrient management in the Swiss food system (BLW 2022).

The novelty of our study is that the effect of food system interventions on nutrient surplus is quantified not only within the territorial boundaries of a given country, but also for nutrient surplus 'externalized' to other countries as a result of feed and food trade – while at the same time complementing the traditional national nutrient budget approach typically used by national authorities to track nutrient surplus with a suite of additional indicators that can facilitate a more nuanced discussion and quantification of important levers toward sustainable nutrient management. Such an approach could be implemented not only at the level of an individual country but also at the level of individual regions and sectors – also beyond Switzerland.

4.1. Reliability and plausibility of results

Our modelling approach sought to keep data collection efficient while keeping results meaningful. For instance, baseline nutrient use and recovery efficiencies relied on values averaged across crop and animal production systems rather than on values representing individual production systems (that are currently not readily available). Scenario parameterization relied on educated broad assumptions of what appears feasible but did not specify in detail the measures that would be needed for the assumptions to hold true. With this in mind, our results are to be seen as rough indications of orders of magnitude. As long as their interpretation is limited to broadly contrasting the potential of different strategies to reduce N and P surplus, we believe that our approach is sufficiently robust and reliable.

To check the plausibility of the baseline, nutrient surplus in our baseline model for the reference period 2014–2016 was compared with the Swiss national N and P budget that is calculated on an annual basis by Spiess and Liebisch (2023). Even though the national N and P budget calculations have a different scope and partly rely on differing statistics, we found that N and P surplus as well as key individual N and P flows in our baseline were generally well aligned with none of the flows deviating more than 20 % from those in Spiess and Liebisch (2023). Moreover, modeled N and P surplus for the baseline is roughly similar to the OECD soil surface budget for Switzerland in the same period of time (Section 4.1 in the SI). Given the uncertainties generally inherent to nutrient budgeting, this suggests our baseline model and parameterization is plausible.

To check the plausibility of scenario outcomes, modeled N and P surplus was compared with N and P soil surface budgets (as formulated by OECD) for Switzerland and selected other countries (Section 4.1 in the SI). The lowest modeled N and P surplus for the scenarios are higher than what is already achieved in some neighboring countries, suggesting that our scenario assumptions do not produce unrealistic model estimates. Modeled reduction potential for N and P surplus was also interpreted in the context of the targets set in Switzerland and in the EU Farm to Fork (F2F) strategy (EC 2020). For some scenarios, the modeled reduction potential exceeds current targets for Switzerland, which are much less ambitious than those in the F2F strategy. Yet, across all scenarios, the modeled reduction potential remains below the EU targets, which in the long term seem achievable albeit challenging. Our findings also align well with previous studies showing that diet change appears to be an essential condition to achieve deep nitrogen reduction targets on the order of 50 % (Leip et al., 2022). This reinforces our confidence that our modeled reduction potential for N and P surplus is plausible.

4.2. Relevance of approach

The presented budgeting approach proved meaningful to broaden the assessment of strategies for Switzerland to reduce N and P surplus in agriculture. Relying solely on farm gate budget calculations within the geographical boundaries of Switzerland conceals to what extent Swiss food consumption causes nutrient surplus elsewhere, as a result of feed and food imports that by far exceed exports. Similarly, it conceals a potential shift of nutrient surplus from the internal to the external system that may arise as a result of changing production and consumption patterns. The explicit consideration of the external system revealed that for the baseline, external nutrient surplus is around half of the internal nutrient surplus and thus significant. In fact, it is only through the consideration of the external system that the full potential of for instance the CA strategy to reduce nutrient surplus (in Switzerland and the places from where feed and food is imported) becomes evident. Additionally, the indicators for nutrient use efficiency, circularity, and self-sufficiency are complementary to the farm gate budget and help distinguish effects of different drivers behind changes in the overall N and P surplus: notably efficiency gains in nutrient management and effects of structural changes in the food system.

4.3. Promising measures to reduce nutrient surplus

The assessment of individual strategies and measures in terms of their potential contribution to reduce nutrient surplus was beyond the scope of the present study. Assessing the potential contributions to reducing N and P surplus of individual measures, packages of measures, or individual production systems, would necessitate a more detailed approach requiring more input data. Nevertheless, for the technology and management strategy, we would like to briefly outline the kind of measures that could potentially add up to what was deemed feasible improved nutrient management in crop and animal production. Improved nutrient management and associated technologies ideally integrate crop and animal production systems at the landscape and agroecological level. Such integration benefits from a better understanding of nutrient flows along crop production from field to food, as well as along the nutrient cascade in animal production from feed to excreted manure, including manure storage and application. Often best management practices (BMPs) and best available technologies (BATs) help to implement N and P loss mitigation and abatement measures. Such exist for instance for feeding strategies (Angelidis et al., 2021) and animal housing systems (Bjerg et al., 2023), the use and storage of organic fertilizers (Bittman et al., 2014), fertilizer application and crop nutrition (notably 4R and 4R Plus) (Johnston and Bruulsema 2014; Snyder 2017), but also for the optimization of cropping systems (e.g., agroforestry, improved crop rotations) (Cherry et al., 2008; Hanrahan et al., 2021) and landscape features (Schoumans et al., 2014). As for the two other strategies, inspiration can be found elsewhere in the literature regarding a shift towards circular food system approaches and more plant-based diets (Von Ow et al., 2020; Kopainsky et al., 2020; Frehner et al., 2022a, Frehner et al., 2022b; Simon et al., 2024) as well as reducing food waste and loss (Beretta et al., 2013; Betz et al., 2015; Von Ow et al., 2020; Salvatore et al., 2024) in Switzerland.

4.4. Implications for implementation of measures

The potential for Switzerland to reduce nutrient surplus through a combination of strategies exceeds both the current ambition level and the currently anticipated reduction of nutrient surplus through regulation PaIv 19.475, see Section 4.2 in the SI. This indicates the possibility to reach current reduction targets for Switzerland without disruptive measures. However, in comparison to other sectors such as energy and industry, agriculture is a relatively heterogenous sector (due to differences in farm type and size, as well as geographical, environmental and cultural context). Implementing changes may thus be complex and take time, while it also depends on external factors such as fertilizer prices (Schaub and El Benni 2024).

Either way, we believe it is important for Switzerland, but also for other countries, to broaden the perspective and look beyond nutrient surplus within national borders. More specifically, it may be responsible to extend incentives to reduce nutrient surplus beyond national borders to the entire food supply chain and food consumption. It is in this context where a shift towards a more plant-based diet along with a reduction of food waste and loss reveal their full potential as strategies that complement technology and management to improve nutrient management. In fact, in Switzerland there are endeavours to develop agricultural policy more towards a food system policy (BR 2022).

In light of fast changes in global nutrient supplies (e.g., access and price), it appears sensible for Switzerland to not only focus on agricultural nutrient management policies reducing nutrient input and surplus, but also on fostering the reuse of nutrients recovered from organic and inorganic waste streams. Hereby, not only animal manure but also food waste and human excreta, among others, are of interest. As none of the strategies discussed in this work are particularly effective to this end, we believe it would be expedient to combine agricultural with waste management policies in order to significantly improve nutrient recovery and reuse through better alignment and integration across sectors. In fact, the EU F2F strategy is a central pillar of the EU Green Deal that focuses on climate and sustainability needs for the whole economy and society rather than solely on agriculture. In contrast, PaIv 19.475 (BLW 2024) has a focus on agriculture only. We hypothesize that lower nutrient surplus targets in Switzerland compared to EU targets result in part from the focus on the agricultural sector and in part from not considering that reducing nutrient losses needs a holistic approach. While water protection aspects are likely considered for setting reduction targets, it can be assumed that indirect effects of N and P surplus, such as on climate and biodiversity convervation targets, may not yet have been fully factored in.

4.5. Opportunities to refine our approach

4.5.1. Harmonization with national nutrient surplus calculations

The calculation principles that underpin our approach are similar to the national nutrient budget as outlined in Spiess and Liebisch (2020). Yet there remain differences regarding data sources and how commodities were grouped and aggregated. In principle, it is possible and sensible to harmonize both approaches, but we do not expect this to significantly change the results or conclusions of our study.

4.5.2. Integration with other models

Our modelling approach could benefit from integration with existing nutrient flow models such as those used by Kros et al. (2024). Moreover, rather than making a set of crude assumptions to model structural change in agriculture and food consumption (scenario CA), it would be possible to rely on the results of food system models such as *Swiss-FoodSys* that should soon become available – similar to the joint use of the Swiss food system model *SWISSland* (Möhring et al., 2016) with the nutrient flow model *MODIFFUS* to estimate nutrient emissions to surface water bodies for a suite of scenarios (Prasuhn et al., 2017). The integration of more specific models could enable the coupling of the nutrient budgeting approach with scenario development and forecast studies for the Swiss food system based on more detailed quantitative information and selection of measures for implementation.

4.5.3. Use of life cycle inventory data

The Swiss Agricultural Life Cycle Assessment (SALCA) method features life cycle inventory (LCI) models for nitrogen and phosphorus emissions (Nemecek et al., 2024), thereby distinguishing a more disaggregated set of emission pathways than what is modeled by our approach (and nutrient budgets in general). It might be worthwile investigating whether LCI data available for Swiss agricultural production can be used to distinguish different emissions pathways. This would allow to better evaluate which emission pathways provide most leverage for reduction by specific potential measures and thus improve the basis for developing scenarios as used in this study.

4.5.4. Use of farm monitoring data

The Swiss farm monitoring program (MAUS) among others features data on nutrient inputs and outputs per crop (e.g., wheat, rye, potato), cropping sytem, farm and region (Gilgen et al., 2023). Such data can potentially be used to derive nutrient use efficiencies per crop, cropping system, farm or region rather than relying on average numbers for crop production as a whole (as we did in the present study). While this might not change relative differences between the three strategies investigated in the present study, using specific data and parameters would allow to identify specific measures giving most leverage on emission reduction. In this regard, digitalization and integrated data managment across levels (from farm to regional and national to international) can further enhance useability and robustness of nutrient budgets among others. The potential of combining farm-level data with modeling at larger spatial scales has been explored for instance for the impact on dairy cow longevity on reducing greenhouse gas emissions (Winter et al., 2024).

4.5.5. Sensitivity and uncertainty analysis

Performing a detailed uncertainty and sensitivity analysis would improve the robustness of the approach and would be desirable when further refining our approach. At the same time, in light of the plausibility checks and good agreement with other studies, we do not expect that a detailed uncertainty and sensitivity analysis would have changed our findings in terms of overall patterns and conclusions.

4.6. Comparison with findings from other studies

Our finding that gains in nutrient use efficiency are a potent lever to reduce nutrient losses – especially if the focus is on the internal system – align well with other studies at the national (Zoboli et al., 2016; Kirk et al., 2024; Kros et al., 2024) and catchment (Svanbäck et al., 2019) scales. In this regard, the importance of spatial prioritization (Kirk et al., 2024; Hietala et al., 2024) and regional approaches (Kros et al., 2024), along with a distinction of different farm types (Vonk et al., 2025), have also been highlighted – which are relevant considerations also for Switzerland. The need for dietary change and associated reduced livestock numbers in addition to efficiency improvements – especially so when considering 'externalized' nutrient losses was also highlighted in other studies, in particular the importance of reducing feed imports and consequently livestock numbers and consumption (Zoboli et al., 2016; Svanbäck et al., 2019; Van Der Wiel et al., 2021; Vingerhoets et al., 2023; Billen et al., 2024; Vonk et al., 2025). Last but not least, several studies point at the importance of recycling of nutrients found in organic residuals (from agriculture and society alike) (Zoboli et al., 2016; Hietala et al., 2024) – as a multi-target measure that helps not only reduce nutrient emissions to the environment, but also increase self-reliance and decrease import depencency. This last point is in line with the call to better integrate circularity with efficiency and sufficiency strategies in agri-food systems (Spiller et al., 2024) and are also reflected in our recommendations to foster the reuse of nutrients recovered from organic and inorganic waste streams in Switzerland along with a reduction of nutrient inputs.

5. Conclusions and outlook

We are confident that our budget approach contributes new dimensions to ongoing discussions about reducing nutrient surplus associated with food production and consumption in Switzerland. This proof of concept suggest that it is feasible for Switzerland to reach the national reduction targets for N and P surplus in agriculture by 2030 through a set of technical and structural measures. Future work should address some of the simplifications inherent to our budget approach in order to arrive at a more refined and robust assessment. This may allow for the identification of hot spots, both in terms of crop and animal production systems to target, as well as measures to prioritize in order to get most effect with least intervention. In this regard, our approach may be relevant not only at the national scale but could be also used on local and regional scales or with a focus on specific agricultural sectors – not only in Switzerland but also in other countries.

CRediT authorship contribution statement

Robin Harder: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Frank Liebisch:** Writing – original draft, Validation, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108239.

Data availability

The following data and calculation sheets are available as online supporting material at doi: 10.17632/j3m2ycjrw2.3.

OSM 1 XLS Food Production and Demand (Baseline)

OSM 2 XLS Baseline Feed Production and Demand (Baseline)

OSM 3 XLS Nutrient Contents of Feed and Food Commodities (Baseline)

OSM 4 XLS Nutrient Use Efficiencies in Crop and Animal Production (Baseline)

OSM 5 XLS Parameters for Animal Production and Product Systems (Baseline and Scenarios)

OSM 6 XLS Parameters for Feed and Food Production and Demand (Scenarios)

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