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Assessing the Environmental, Economic and Social Impacts of a Greenhouse Gas Emission Tax in Swiss Agriculture

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ABSTRACT

Agriculture accounts for about one fifth of global greenhouse gas (GHG) emissions, making mitigation a key policy priority. Although policymakers are increasingly considering market-based approaches such as taxes, their broader impacts remain insufficiently assessed. This study examines the environmental, economic and social impacts of a GHG tax on Swiss agriculture. Using the agent-based sector model SWISSland, representing 3077 farms and capturing heterogeneous responses to taxation and structural change, we simulate tax levels of 100, 200 and 300 CHF/tCO_2eq for 2024–2030. We consider three mitigation pathways: technical measures, structural changes in land use and livestock numbers, and farm exits. We assess their impacts on GHG emissions, nitrogen surpluses, biodiversity, farm income, food production and food security. A GHG tax activates abatement mechanisms and induces dairy herd reductions, grassland extensification, shifts towards crop production for direct human consumption, and livestock farm exits. At 100 and 200 CHF/tCO_2eq, emission reductions are mainly driven by technical measures, whereas at 300 CHF/tCO_2eq they increasingly result from structural adjustment, including livestock farm exits and land reallocation to less emissions-intensive production. A tax of 100 CHF/tCO_2eq reduces emissions by 5%, while higher tax rates achieve greater reductions but increase sectoral income losses from 13% to 25%. Food self-sufficiency and calorie production remain stable. The model also shows environmental co-benefits, including lower nitrogen surpluses and increased biodiversity areas. These findings highlight synergies and trade-offs across sustainability dimensions and suggest that redistributing tax revenues could mitigate adverse effects and improve policy outcomes, while enhancing the policy's social acceptability.

JEL Classification: Q12, Q18, Q52, Q58

1 | Introduction

Agriculture accounts for approximately 18% of global greenhouse gas (GHG) emissions globally (FAO 2020), making the mitigation of GHG emissions in agriculture a global priority for policymakers, industries and researchers (IPCC 2019). Countries are implementing ambitious GHG reduction targets for the agricultural sector. For instance, the European Union aims to cut agricultural emissions by 50% by 2030 (Schebesta and Candel 2020). Switzerland, the focus of this study, is no exception: agriculture in the country accounted for nearly 15% of national emissions in 2023 (FOEN 2023), with enteric fermentation alone responsible for about 60% of the sector's emissions. In line with international efforts, Switzerland has set a target to reduce agricultural emissions by 20% relative to 1990 levels by 2030, all while ensuring more than 50% self-sufficiency to maintain stable domestic food production (BAFU 2022; BLW 2022c), with further reductions of 40% targeted by 2050. However, reducing GHG emissions in agriculture is challenging. Agriculture's multifunctional role in producing food, preserving ecosystem services, and supporting rural livelihoods comes along with various trade-offs and synergies. Market-based approaches, such as taxation or emission trading schemes, are increasingly being considered to reduce GHG emissions. For instance, New Zealand intends to integrate agriculture into its market-based climate policies by 2025 (He Waka Eke Noa, Ground Rules 2023),[1] while Denmark plans to introduce a livestock emission tax by 2030 (Blandford 2014; Niranjan 2024; Sørensen et al. 2025). Furthermore, the Netherlands has implemented a farm buy-out scheme since May 2023 (Boezeman et al. 2023). However, little is known about the holistic effects of such policies, which are crucial to accounting for agriculture's multifunctional role across environmental, economic and social dimensions (Boke Olén et al. 2021; Cairol et al. 2009; Mockshell and Kamanda 2018; Renting et al. 2009; Taoumi and Lahrech 2023). Assessing the direct and indirect impacts of a GHG emission tax within these dimensions can guide a more effective climate policy design, highlighting the need for ex-ante studies to evaluate policy effectiveness and potential impacts before implementation.

Here, we provide a holistic assessment of the environmental, economic and social impacts of a GHG emission tax on the Swiss agricultural sector. This study also analyses the synergies and trade-offs among the three sustainability dimensions. We use an agent-based modelling approach that represents 3077 Swiss representative farms based on Farm Accountancy Data Network (FADN) data. The model allows for reflecting the heterogeneity of farms as well as farm interactions, which are crucial to assessing sector-level effects of GHG emission taxes. We begin by assessing how a tax would enhance the adoption of technical GHG mitigation measures and affect shifts in land use, the number of livestock and the number of farms. We then analyse the impacts on the three sustainability dimensions (i.e., environmental, economic and social) of the Swiss agricultural sector. The effects of different tax rates are also examined, and the implications of our results for policymakers are discussed.

Previous ex-ante policy analyses—that is, analyses conducted prior to implementing a policy to provide evidence on the expected costs and benefits and inform policy decisions (El Benni et al. 2023)—have examined the design and implementation of market-based policies, such as taxation within the agricultural sector. For instance, Blandford (2014) and Dumortier and Elobeid (2021) analysed the impact of taxes on agricultural production, noting that increased production costs lead to a decrease in overall production. Other studies have quantified the environmental impacts of GHG taxes, assessing their cost-effectiveness and examining how production and emissions patterns shift in response to taxation (Bakam et al. 2012; Coderoni et al. 2024; Gren et al. 2021; Henderson et al. 2018; Key and Tallard 2012; Sørensen et al. 2025; Wirsenius et al. 2011), as well as how food security can be affected by such a policy (Frank et al. 2017). Furthermore, several studies have evaluated the effects of a GHG emission tax on various impact categories, including acidification potential (Mackenzie et al. 2017), reduction of wildfires and biodiversity conservation (Martins Pacheco 2022). Previous research has also shown that market-based instruments for carbon mitigation can support biodiversity goals (Gren et al. 2021; Ring et al. 2010). Recognising such synergies is important to ensure that climate policies contribute to broader environmental objectives (Essl et al. 2018). Despite this diverse body of literature, research explicitly linking emission outcomes to underlying structural adjustments within the agricultural sector remains limited. Previous studies have provided evidence of the effectiveness of GHG taxes in reducing emissions and the impacts on production (Bakam et al. 2012; Coderoni et al. 2024; Henderson et al. 2018; Key and Tallard 2012; Sørensen et al. 2025; Wirsenius et al. 2011). However, they often do not jointly assess and discuss the synergies and trade-offs across environmental, economic and social dimensions, nor do they explicitly capture how structural changes at the farm level contribute to these outcomes. This study aims to address these gaps by focusing on the structural transformations associated with emission reductions in Swiss agriculture, such as farm exits, reductions in livestock numbers and the extensification of land, thereby providing a more integrated basis for the design of coherent and effective climate policies.

We address these gaps by analysing the impact of a GHG emission tax on the Swiss agricultural sector. Using the SWISSland agent-based model, we simulate heterogeneous farm responses to a GHG emission tax and assess the resulting sectoral impacts. This model is essential to address our research question, which considers the heterogeneity of the sector and the interactions among farms through a land rental market (see Schmidt et al. 2021 for a comparison). Here, we consider three potential tax mitigation strategies of farms: (1) adoption of technical mitigation measures, (2) adjustment of production intensity (e.g., the number of livestock and land use) and (3) exit from farming. The SWISSland model offers a suitable modelling approach, as it captures individual farm-level adjustments (i.e., each farm is different and reacts differently to tax incentives) to the tax and quantifies the resulting structural changes that contribute to emission reductions. By representing land market dynamics, our model allows us to assess spillovers across farms; for example, if one farm exits in the sector due to GHG emission tax, other farms can take over their land. Our modelling approach analyses the impacts of three different GHG emission tax scenarios: 100 CHF/t CO_2eq, 200 CHF/t CO_2eq and 300 CHF/t CO_2eq.[2] First, we assess the impacts of the tax on its primary environmental goal, namely reducing GHG emissions. We further assess the indirect environmental effects on nitrogen surpluses and biodiversity, which are two other important environmental goals of agricultural policy. Second, we evaluate the economic impacts of these scenarios, focusing on the reduction in agricultural farm income. Finally, we examine and discuss the social implications of the tax, focusing on food security and farm abandonment. By integrating these aspects, our study provides a holistic perspective on the effects of GHG emission tax on agriculture. Moreover, a key contribution of our study is that we model the tax as being implemented alongside existing Swiss direct payments, allowing for a more realistic and policy-relevant analysis of its effects.

Our findings show that a GHG emission tax in Swiss agriculture can activate several interconnected abatement mechanisms. Key drivers include the reduction of ruminants, and the related exit of dairy and cattle farms, a shift in land use towards a lower intensity of grassland and more food production on arable land, and wider adoption of technical GHG mitigation measures. Collectively, these developments lead to reduced emissions. We find that a 100 CHF/tCO_2eq tax leads to a 5% reduction in GHG emissions compared to the reference scenario without a tax. Moreover, substantial environmental co-benefits, such as a

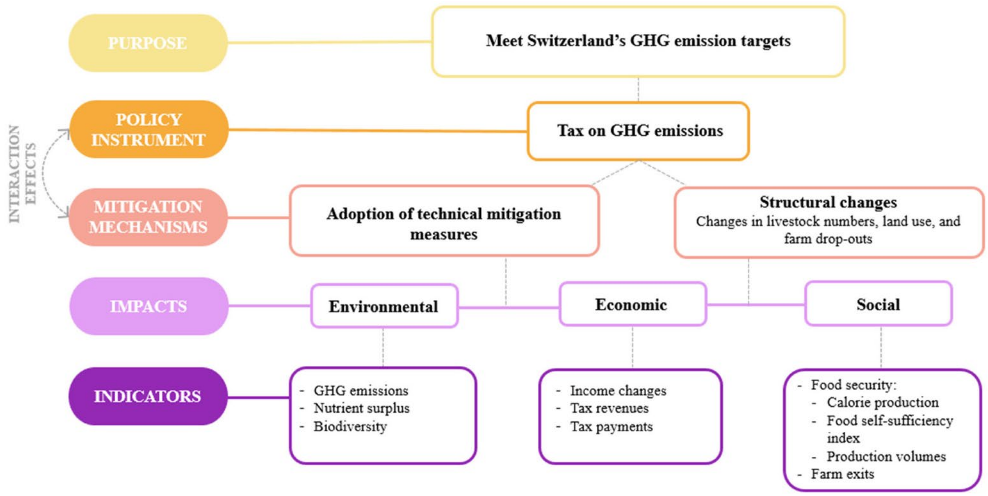

FIGURE 1 | Conceptual framework of our ex-ante analysis of taxing greenhouse gas (GHG) emission in Swiss agricultural sector. [Colour figure can be viewed at wileyonlinelibrary.com]

reduction in nitrogen surpluses, are observed only at a tax level of 300 CHF/t CO_2eq. These environmental gains come with trade-offs: Sectoral income declines by 13%–25% depending on the tax level, with dairy farms being the strongest affected. Food self-sufficiency and calorie production remain largely unaffected under taxes of 100 and 200 CHF/tCO_2eq. Higher tax rates lead to substantial structural changes and farm abandonment. Policymakers should therefore consider incorporating redistribution mechanisms to help mitigate the economic and social impacts of higher tax rates, especially farm exits, while supporting overall positive environmental outcomes as far as possible (Gren et al. 2021).

This paper is structured as follows. We provide a background section detailing the Swiss agricultural context and the conceptual modelling framework. We then describe our methodology, including an overview of the SWISSland model and the simulated scenarios. This is followed by a presentation of the results, which are analysed in Section 6. The conclusion section synthesises our findings and examines their broader implications.

2 | Swiss Agricultural Policy Goals and the Potential for a Tax on GHG Emissions

Switzerland's support for agriculture is one of the highest of all OECD countries, with direct payments being one of its most important components, alongside border protection mechanisms (Huber et al. 2024). This support is also connected to different economic, social and environmental goals. Apart from GHG emissions reduction goals, Switzerland also has targets to reduce nutrient surpluses in crop and livestock production by 20% by 2030 compared to the 2014–2016 period (BLW 2022a; Swiss Confederation 2022). Since 2023, stricter nutrient balance limits have been integrated into cross-compliance standards[3] to support this objective (Hanhart et al. 2024), contributing in particular to the mitigation of nitrous oxide (N_2O) emissions associated with excessive fertiliser use (Huber et al. 2024). In addition, 16% of agricultural land is targeted to be covered by ecological focus areas, with region-specific thresholds for mountain, hilly and lowland zones (Walter et al. 2013). This objective is supported by a well-established voluntary agri-environmental payment scheme for biodiversity that provides action-based, result-based and agglomeration payments (Mack et al. 2020).

However, currently, no market-based policies specifically target GHG emissions reductions in Switzerland (BLW 2022a, 2022b). Achieving GHG reduction targets requires policies that address emissions from all agricultural practices, including the most polluting ones. Thus, a tax on GHG emissions is a promising option for covering emissions across the sector, creating incentives for farmers to adopt low-emission practices. The success of a tax on GHG emissions depends on its level and the farmers' ability to adapt. When evaluating new policy instruments, such as a tax on GHG emissions, existing policy instruments must also be considered, as they influence farmers' decision-making. Thus, a market-based policy, such as a GHG emission tax, should complement existing direct payment schemes by offering stronger incentives to adopt sustainable practices, either by adopting technical mitigation measures or by changing land use or the number of livestock. Therefore, assessing the holistic impact of such a tax requires consideration of the broader agricultural policy context.

3 | Conceptual Framework

Figure 1 presents the framework and setup of our study, which is designed to assess the holistic impact of a tax. We assess three tax levels and consider key tax mitigation strategies that farms can employ: the adoption of technical GHG mitigation measures, land-use changes, and farm exits, in addition to paying the tax. We then evaluate how these strategies affect the three dimensions of sustainability by selecting indicators from the literature that are most relevant to the Swiss policy context, as recommended by Lichtfouse (2011).

To this end, for environmental impacts, we focus on GHG emission reductions as the primary indicator of interest in our study and evaluate changes in nitrogen surpluses and biodiversity indicators using changes in the area of EFAs in Switzerland as a measure. The three environmental indicators were chosen in line with the Swiss targets outlined above (Huber et al. 2024) and are supported and used by other studies (Boke Olén et al. 2021; Lichtfouse 2011; Mockshell and Kamanda 2018; Schmidt 2021). For economic impacts, we assess sector-level income changes, average income changes by farm type, potential tax revenues at the sector level, and the average tax burden by farm type. These indicators follow established approaches in previous research (Boke Olén et al. 2021; Lichtfouse 2011; Mockshell and Kamanda 2018), with the addition of tax-related indicators given their relevance for this study. For social impacts, we consider changes in production volumes, changes in calorie production and the food self-sufficiency index (FSI[4]) as indicators of food security. This framing is consistent with Article 104a of the Swiss Federal Constitution (Federal Constitution of the Swiss Confederation 1999), which explicitly links agricultural policy objectives to food security as well as the preservation of decentralised rural structures. Thus, in this context, we also consider farm exits, which have been identified as well in previous literature as a relevant social indicator (see, e.g., Nowack et al. 2023), reflecting farm viability and the social acceptability of the tax. These indicators have been used in earlier studies (Lichtfouse 2011; Mockshell and Kamanda 2018; Moz-Christofoletti and Pereda 2021; Piet and Desjeux 2021) and are selected here to reflect the specific context of our analysis.

Within this conceptual framework, technical mitigation measures play a central role in our analysis, as they provide farms with the possibility of lowering their tax burden without reducing production. Our study considers a variety of technical mitigation measures targeting both land-based and animal-based emissions (Table 1). The selection of mitigation measures is guided by different criteria: their (i) relevance within Swiss agriculture, (ii) effectiveness and efficiency without compromising production levels, and, in the context of our analysis, (iii) implementation at the individual farm level within the model framework and time horizon. To identify measures that are both relevant in Swiss agriculture and potentially effective and efficient, we follow Hao et al. (2026), which provides a Swiss-specific assessment of mitigation options, including consistent estimates of abatement potentials and associated costs. Hao et al. (2026), classify mitigation measures into six broad categories: carbon sequestration, soil-related GHG emissions, enteric fermentation, nitrogen use efficiency, manure management and herd management. The mitigation portfolio considered here directly represents the first four categories. Specifically, biochar and cover crops contribute to carbon sequestration, nitrification inhibitors and cover crops address soil-related GHG emissions, and the feed additive 3-nitrooxypropanol (3-NOP) inhibits enteric methane (CH_4). Nitrification inhibitors also improve nitrogen use efficiency by reducing nitrogen losses. The remaining categories are represented indirectly through mechanisms already embedded in SWISSland.[5] Manure management practices, such as slurry covers, are characterised by high baseline adoption rates and are reflected in the model structure. Herd management decisions, including lactation dynamics, are endogenously determined within the optimisation framework. Similarly, nitrogen use efficiency measures, including slurry application practices, are captured through existing production and nutrient management constraints.

Consistent with this representation of mitigation options, the selected measures reflect their suitability for the Swiss agricultural sector (Alig et al. 2015), their availability on the market and the availability of consistent cost and abatement data. The analysis focuses on measures that can be implemented at the individual farm level within the model framework and time horizon. Importantly, the adoption of these measures does not require substantial fixed investments beyond the acquisition of the respective inputs and allows production levels to be largely maintained. Several of the considered land-based mitigation measures can also generate additional improvements in crop productivity. Furthermore, according to semi-structured consultations with experts from research, industry and policy institutions (see Table S4A in Supporting Information A) and national inventory reports (e.g., FOEN 2023), these measures currently exhibit relatively low baseline adoption rates. Nevertheless, they are technically feasible, highlighting the relevance of evaluating mitigation options that offer both environmental and production-related benefits. Although farms may access a broader portfolio of mitigation strategies in practice, this analysis deliberately focuses on a model-consistent subset of technical measures compatible with SWISSland's structural framework.

Table 1 summarises the selected technical mitigation measures, including their average abatement potential and cost estimates, and the types of farms to which the measures can be applied. For the feed additive 3-NOP, we introduce further restrictions in our model based on the literature. Given that the effect of 3-NOP persists for only about 3 h after ingestion (Dijkstra et al. 2018; Kebreab et al. 2023), its mitigation potential cannot be maintained during long grazing periods. For this reason, we limit the use of 3-NOP during pasture periods by using region-specific grazing durations for plains, hills, and mountain areas (Islam et al. 2025). This implies that the abatement effectiveness of 3-NOP is reduced from a factor of 0.33 to a factor of 0.46, depending on the region (see the general abatement potential values in Table 1 and Supporting Information A, Table S1A for the exact values of 3-NOP abatement potential according to region). Organic farms are also excluded, as they are not permitted to use 3-NOP. For detailed information on the sources of abatement potentials, costs and additional benefits, please see Supporting Information A (both Word and Excel files), where each measure is further explained.

4 | Methodology

We used the agent-based agricultural sector model SWISSland to assess the effects of taxing farm GHG emissions. Agent-based models (ABMs) capture rich heterogeneity across agents by explicitly simulating interactions among individual farms, allowing insights to be generated at both the farm and regional levels using individual farm data. ABMs accommodate diverse decision-making and do not impose predefined system-wide rules (Groeneveld et al. 2017). As a result, ABMs can illustrate how large-scale outcomes, such as changes in land use or land cover, emerge from the aggregation of many individual decisions without requiring assumptions about aggregate system

TABLE 1 | Technical GHG mitigation measures included in the simulations.

Mitigation measure	Mechanisms of abatement	Mean abatement potential and types of emissions reduced	Yearly costs	Other effects	Type of eligible crops or livestock	References
1. Biochar	Biochar reduces GHG emissions by boosting soil carbon storage and improving soil health, using waste materials such as manure and crop residues	*Mean abatement potential*: 1080 $kgCO_2eq$/ha/year *Type of emissions*: N_2O soil emissions	*Amount*: 700 CHF/ha *Types of cost*: Purchasing costs of biochar	Yield increases by 15% Fertiliser use reduces by 11%	Bread grains, feed grains, grain maize, silage maize, sugar beets, fodder beets, potatoes, rapeseed, soybeans, sunflowers, pulses, vegetables	Agroscope (2021); Campion (2023); European Commission. Joint Research Centre (2024); Keel et al. (2023); Meulemans (2016); Wu et al. (2019); Zhang et al. (2020)
2. Nitrification inhibitors	Nitrification inhibitors (NIs) lower N_2O emissions by slowing ammonium conversion to nitrate, reducing both direct and indirect N_2O emissions. They also decrease nitrate leaching, boost crop yields, and reduce the need for synthetic fertilisers and field applications, thereby saving energy in the process	*Mean abatement potential*: 40% *Type of emissions*: Change in N_2O emissions per hectare per year when using a particular NI compared to conventional fertilisers	*Amount*: • Grain maize: 160 CHF/ha • Rapeseed: 218 CHF/ha • Feed crops (silage and fodder beets): 160 CHF/ha • Food cereals (wheat, rye, spelt): 171 CHF/ha • Feed cereals: 167 CHF/ha *Types of cost*: Purchase of nitrification inhibitors. The price for ENTENC 26 at the Swiss retailer Landor is 1.45 CHF/kg of NI	Yield increases by 7.5% Mineral fertiliser application is reduced by 30%	Bread grains, feed grains, grain maize, silage maize, rapeseed	European Commission. Joint Research Centre (2024); MacLeod et al. (2015); Sørensen et al. (2025)

(Continues)

TABLE 1 | (Continued)

Mitigation measure	Mechanisms of abatement	Mean abatement potential and types of emissions reduced	Yearly costs	Other effects	Type of eligible crops or livestock	References
3. Cover crops	Cover crops grow between main crops, reducing soil erosion, fixing nitrogen, and suppressing weeds. They also cut greenhouse gas emissions by boosting soil carbon, preventing nitrogen loss, and reducing fertiliser use	*Mean abatement potential*: 674.6 $kgCO_2e$/ha/year *Type of emissions*: Soil carbon sequestration	Amount[a]: 527 CHF/ha *Types of cost*: Seeds, cultivation, machinery and drilling, incorporating crop residue, savings in reduced fertiliser purchase	Yield increases by 12% and fertiliser use reduces by 30%	Bread grains, feed grains, grain maize, silage maize, sunflowers, pulses	Agridea (2024); Bergtold et al. (2019); Drakopoulos et al. (2021); European Commission. Joint Research Centre (2024); Kaye (2017); Keel et al. (2023); MacLeod et al. (2015); Schön et al. (2024); Tribouillois et al. (2018); Wittwer and van der Heijden (2020)
4. Feed additive 3-NOP	3-NOP (also known as Bovaer) cuts methane emissions in ruminants by inhibiting the enzyme MCR, shifting fermentation to produce less methane	*Mean abatement potential*: • Dairy: 22.5% • Suckler: 18.5% The abatement factors are adjusted to pasture times[b] *Type of emissions*: CH4 from enteric fermentation	*Amount*: 100 CHF/cow *Types of cost*: Purchase of the feed additive		Dairy and suckler cows (including heifers and calves) in non-organic farms; restrictions on average pasture times per region were considered	Doreau and Ferlay (2015); Hristov et al. (2022); Kebreab et al. (2023); Klimastar Milch (2023); Maigaard et al. (2024); Patra (2013); Vargas et al. (2020)

[a]Costs are based on Agridea (2024) reference values for Swiss feed cover crop systems (See Table S3A in Supporting Information A). While costs for cover crops differ across recent studies, our values reflecting Swiss conditions are within the range reported for comparable cover crop systems (e.g., Drakopoulos et al. 2021). The costs published by Agridea (2024) reflect the upper range due to differences in management intensity, system design, and accounting scope.
[b]We use the mean abatement potential for 3-NOP in the main analysis, while results for the upper and lower bounds reported in the literature are provided in Supporting Information A (Excel file). Moreover, the abatement potential is adjusted to account for pasture times, which reduces the overall effectiveness of 3-NOP. The exact values are provided in Supporting Information A (Excel file).

behaviour. In the following subsections, we describe the attributes and functionalities of the SWISSland model that are relevant to our analysis and the scenarios that we simulated in our study.

4.1 | The Agent-Based Model SWISSland

SWISSland was specifically developed to assess the ex-ante impacts of agricultural policies, making it a valuable tool for policy evaluation (Mack et al. 2023; Möhring et al. 2016; Schmidt 2021). It consists of two modules: (1) a single farm and structural change module and (2) a sectoral module (Dueri and Mack 2024). The single farm module consists of 3077 farm optimisation models, which were developed based on real farms that provided data to the Swiss FADN between 2016 and 2018. These farms represent the total number of farms (almost 50,000) in Switzerland (Renner et al. 2019). Thus, the model results at the farm scale reflect endogenous heterogeneous responses to policy changes in Switzerland. For ex-ante simulations, we incorporated exogenous price and direct payment projections until 2030 into the bio-economic farm optimisation models as defined by policymakers from the Federal Office for Agriculture.

We used recursive-dynamic, non-linear optimisation models to estimate land use and livestock decisions for each farm over a period of 10–15 years, including the option of investment decisions in stables (Mack and Kohler 2019). In particular, SWISSland follows a positive mathematical programming (PMP) approach. Unlike linear programming, PMP calibrates exactly to the base-year observed production and observed revenues, using bookkeeping data available for each represented farm, and thus prevents unrealistic concentration and overspecialisation in a few activities, without relying on arbitrary constraints (Mack et al. 2019). For further information, see Mack et al. (2019). The objective function of the farm models is shown in Equation (1):

$$\max(Z) = \sum_i p_i x_i + d_i x_i - L_{\text{costs}} - Q_{\text{costs}} \tag{1}$$

where the farm income (Z) consists of market revenues from agricultural activities i (with p_i denoting output prices and x_i the associated production quantities), direct payments d_i, and linear cost components L_{costs}, such as payments of the GHG emissions tax, as well as other costs including labour expenses. The quadratic costs term Q_{costs} represents private costs for crop and livestock activities. This quadratic term is calibrated so that each activity is just profitable at its observed production level, while any further expansion becomes less profitable at the margin. This approach relaxes the strict profit-maximisation assumptions typical of computable general equilibrium (CGE) and partial equilibrium (PE) linear programming models and leads to more realistic production responses.

A specific feature of ABMs is their representation of the interactions between individual agents. In SWISSland, this interaction is modelled using a land rental market, which allows the researcher to explicitly account for structural changes in the agricultural sector. Thus, SWISSland explicitly simulates farm succession, exit and land rental processes. Farm succession within the family and farm exits at retirement are modelled using heuristic rules, following Möhring et al. (2016). Farmers may also exit before retirement if they experience negative cash flows for more than three consecutive years. Land released by exiting farms is reallocated through a modelled rental market among neighbouring continuing farms, which can increase their income by leasing additional land. This reallocation is implemented via a plot-level bidding mechanism in which nearby farms compete for available plots, with each plot assigned to the farm achieving the highest expected income gain. If no lease occurs at the initial rental price, the pool of potential renters is gradually expanded, and the rent is reduced stepwise by 20% until the plot is leased (Mack et al. 2013; Zimmermann et al. 2015). In this process, only a limited set of geographically adjacent farms (typically the closest five neighbours) is considered in the initial allocation step, which ensures local competition. Land prices are assumed to be exogenous and are represented by the average prices for arable land and permanent grassland. Initial rental prices for arable land and grassland are derived from the FADN for each agent and remain constant over time. Moreover, the model does not account for changes in land ownership, as it focuses exclusively on land rental decisions.

We then used the sectoral upscaling module for projections at the national scale, through which the results of the single farms were upscaled to the Swiss agricultural sector, which consists of around 47,000 farms. Together, these modules enabled the modelling of heterogeneous farm responses to policy changes and the assessment of the sectoral impacts resulting from these responses. A detailed description of the model is available in Möhring et al. (2016).

To assess GHG emissions, emission factors from Swiss Ammonia and Greenhouse Gas Emission (SAGE) model (Gilgen et al. 2026; Winter et al. 2024) were incorporated into the farm optimisation models (see Supporting Information B for the values we used). The SAGE model considers three key emission pathways: (1) CH_4 from enteric fermentation, (2) CH4 and N_2O from manure management and (3) N_2O from agricultural soils, mineral fertiliser and manure application. In the first step, we used the SAGE model to calculate GHG emissions for the 3077 farms included in SWISSland in the base year. In the second step, we allocated the emissions (kg CO_2eq) from the different sources to the land use and livestock production activities of the farm optimisation models. For ex-ante simulations, total GHG emissions were calculated annually within the optimisation model and expressed in kg CO_2eq per farm. Finally, a tax on total farm GHG emissions was introduced in the objective functions of the farm optimisation models.

Nitrogen surpluses were calculated for each farm after the optimisation process using a farm gate N balance based on Oenema et al. (2003). This accounts for N input and output. N input comes from fertilisers, feed, animals, and N fixation and deposition, while N output comprises the amount of N leaving the farm through the agricultural products sold. Therefore, we estimated the N in the fertilisers used by each farm based on their fertiliser costs per hectare, which were available in the FADN database for most of their crops (Bystricky et al. 2023).

Based on the amount of concentrates fed to cattle in the base years, we calculated the N input from the concentrates. The N input from purchased animals was calculated by multiplying the simulated change in animal numbers in the scenarios by the average animal N content. In addition, the costs for purchased roughage available in the FADN database were used to estimate the amount of purchased roughage for each FADN farm (Bystricky et al. 2023).

For this study, we also incorporated the technical mitigation measures into the farm optimisation models by integrating mitigation costs and abatement potentials into the objective function, including the restrictions described in the conceptual framework section for the measure 3-NOP. Thus, through the optimisation process, farmers respond to the GHG emission tax by choosing the most cost-effective strategy. They adopt technical mitigation measures as long as the associated costs are lower than the tax they would otherwise pay for their emissions. If mitigation costs exceed the tax, they may opt to pay the tax instead. In cases where abatement or tax is too expensive, farmers may adjust their production patterns, such as reducing livestock numbers or shifting land use, to lower their emissions. Finally, if the tax burden becomes too great, some farms may exit from farming, particularly in the context of farm succession when a farmer reaches retirement age (i.e., successors are unwilling to take over due to low income potential of the farm) or when the farm has negative cash flows for three consecutive years. This leads to farm exits before the farmer reaches retirement age. The number of farms (i.e., structural change) is modelled endogenously within the SWISSland framework, allowing for these adaptive responses to emerge from the optimisation process. All exiting farms rent their land plots to neighbouring farms, allowing the remaining farms to increase their income by leasing additional land.

4.2 | Scenarios

We conducted simulations over a 10-year period (2020–2030) in which all current Swiss agricultural policies were implemented (i.e., a direct payment system). Four scenarios were considered: one reference scenario and three tax scenarios (see Table 2). In the reference scenario, farmers can adopt technical GHG mitigation measures. These measures are introduced as linear terms in the objective function rather than being embedded in the quadratic PMP calibration structure. No taxes are imposed in the reference scenario.[6] Therefore, it reflects the current situation of Switzerland's agricultural policy in which technical mitigation measures can be adopted. In our results, we compared the tax scenarios to the reference in the year 2030.

TABLE 2 | Scenario description.

Scenario name	Incentive tax on GHG emissions	Tax value
Reference	No	—
Tax 100	2024–2030	100 CHF/t CO_2eq
Tax 200	2024–2030	200 CHF/t CO_2eq
Tax 300	2024–2030	300 CHF/t CO_2eq

Note: The reference scenario is simulated without a tax; mitigation measure adoption emerges from income-maximising farm decisions.

The tax scenarios introduce a GHG emission tax from 2024 to 2030 and consider that all emissions included in the model can be taxed. The first scenario applies a tax of 100 CHF/t CO_2eq. This tax level was chosen for its empirical and policy relevance, as it aligns with the EU Emissions Trading System (EU-ETS) price range (European Commission 2019) and Switzerland's existing fossil fuel tax (FOEN, n.d.), providing a realistic policy benchmark. Its validity as a reference point is further supported by several studies that have examined its implications (Dumortier and Elobeid 2021; Henseler et al. 2020; Jansson et al. 2024; Lungarska and Chakir 2018; Sørensen et al. 2025). However, previous research has also shown that a tax below 200 EUR/t CO_2eq would be insufficient to drive substantial reductions in emissions from animal products (Bonnet et al. 2018; Henseler et al. 2020). Therefore, we designed two additional scenarios with tax levels of 200 CHF/t CO_2eq and 300 CHF/t CO_2eq to assess the impact of stronger economic incentives on emission reductions. We did not include transaction costs for monitoring, reporting and verification. As part of these transaction costs, the Swiss government could collect the necessary information to implement the tax, and the current adoption of mitigation measures, though not yet in the census, could be incorporated alongside existing data such as livestock units and farm hectares.

By comparing these tax scenarios against the reference scenario, we assessed the extent to which a higher carbon price could accelerate mitigation efforts. We evaluated the effects of these tax scenarios by comparing their outcomes to a reference scenario at the end of the simulation period in 2030. Price developments and direct payments were assumed to be the same across all scenarios, and they were exogenously included in the model based on the current policy and its projection until 2030 (see Supporting Information C). An overview of the scenarios is provided in Table 2. Furthermore, we conducted a sensitivity analysis for each scenario using the upper and lower bounds of the abatement potential of the considered technical mitigation measures (see Supporting Information D). This helps to better capture the range of possible outcomes from adopting mitigation measures and to provide estimates that more accurately reflect potential real-world results.

5 | Results

Table 3 summarises the main findings across the three sustainability impact indicators. The remainder of the results section is organised into four subsections. We begin by outlining the tax-driven mechanisms behind GHG emission reductions, focusing on the uptake of technical mitigation measures, farm abandonment, and the structural changes that emerge in response to the tax under the different scenarios. These mechanisms help explain the environmental, economic, and social impacts of a tax, which are presented in the second, third, and fourth subsections, respectively. The results across these three sustainability dimensions are reported using the indicators described in Section 4.3. We report all the results for the final simulation year 2030. Sensitivity analyses were conducted for each scenario, considering the upper and lower limits of the potential GHG reduction of the technical mitigation measures. In addition, for the highest tax scenario (300

TABLE 3 | Main results: Average key results on sustainability impacts. Values indicate changes relative to the reference scenario for each indicator in 2030. Colours are used to guide interpretation: Green reflects favourable outcomes, with darker shades indicating stronger improvements. Yellow texts indicate movement towards less desirable outcomes and red texts highlight negative impacts.

Main impact	Tax 100	Tax 200	Tax 300
Environmental: GHG emissions	−5%↓	−14%↓	−22%↓
Economic: Average farm income	−13%↓	−15%↓	−25%↓
Social: Reduction of farms	−2%↓	−5%↓	−10%↓

CHF/tCO_2eq), we performed a price sensitivity analysis in which the output prices for milk, beef, and pork are increased by 10%. We chose milk, beef, and pork because the production of these products decreases by 18%, 12% and 9%, respectively, in the Tax 300 scenario, and price responses due to this production decline might happen. This scenario was designed to assess the extent to which higher milk, beef, and pork prices could offset the impacts of a substantial emissions tax. The results of all the sensitivity analyses are presented in Supporting Information D, as well as the absolute values of all results.

Overall, the findings are robust across the sensitivity analyses, with relatively small changes observed for many indicators. For instance, under more optimistic assumptions (upper bounds of abatement potential), the 100 CHF/tCO_2eq tax leads to a 9% reduction in emissions compared to the reference scenario, whereas under more conservative assumptions (lower bounds), the reduction is only 3%. These patterns confirm that the general trends hold true across all scenarios, reinforcing the reliability of the main results regarding abatement potential.

The price sensitivity analysis for milk, beef, and pork yields similar conclusions. Higher milk, beef, and pork prices partially offset the impacts of the tax, resulting in higher livestock numbers, production levels, farm incomes, and farm survival rates compared with the main scenario. Moreover, GHG emissions increase moderately due to stronger production incentives. Overall, the results indicate that higher producer prices for milk, beef, and pork can mitigate some of the economic and structural impacts of the tax while leaving the main qualitative conclusions unchanged.

5.1 | Tax-Driven Mechanisms for Reducing GHG Emissions

5.1.1 | Adoption of Technical Mitigation Measures

Figure 2A shows the uptake rates of the technical mitigation measures among the SWISSland farms. In the reference scenario, land-based measures (i.e., nitrification inhibitors, biochar and cover crops) have already been adopted due to their yield-enhancing benefits, which make them profitable even without a tax. In particular, nitrification inhibitors are adopted by 59% of potential adopters, while biochar and cover crops have lower uptake rates, at 18.5% and 7%, respectively, in the reference scenario. The higher adoption rate of nitrification inhibitors primarily reflects their comparatively lower implementation costs within the income maximisation framework of SWISSland. The differences in adoption between the reference and Tax 100 scenarios remain modest for all technical mitigation measures, suggesting that this tax level only slightly boosts voluntary GHG mitigation compared to the reference scenario. For example, with a tax of 100 CHF/t CO_2eq, the feed additive 3-NOP is adopted by only 11% of all potential adopters. By contrast, under the Tax 200 and Tax 300 scenarios, the uptake of the feed additive 3-NOP rises considerably to 73% and 82% of the potential adopters, respectively. Furthermore, the adoption of biochar and cover crops shows a remarkable increase with rising tax levels, while higher taxes hardly contribute to the additional adoption of nitrification inhibitors.

5.1.2 | Farm Exits

Another relevant mechanism at the farm level that directly responds to the tax and affects all impact areas is the number of farm exits. Figure 2B shows the percentage change in the number of farms compared to the reference scenario, broken down by farm type. At a tax rate of 100 CHF/t CO_2eq, the number of farms remains similar to that in the reference scenario (below 5% differences). However, when the tax increases to 200 CHF/tCO_2eq, cattle, dairy and suckler cow farms are increasingly abandoned; that is, higher levels of tax accelerate structural change. At the highest tax level (3300 CHF/tCO_2eq), farm exits increase, particularly among dairy, cattle and suckler farms (and combinations of those). The number of suckler farms decreases by almost 14%. By contrast, the number of arable farms shows a minimal decline across the tax scenarios,[7] while the number of vegetable, fruit and winery farms increases slightly compared to the reference scenario.

5.1.3 | Structural Shifts in Livestock and Land Use at the Sectoral Level

Figure 2C shows the livestock numbers across the different scenarios, with the percentage of livestock types in each section of the bars. In the tax scenarios, changes in livestock numbers at the sectoral level result from two underlying mechanisms: (1) farms reducing their livestock numbers and (2) farm abandonment.

Table 4 provides a decomposition of livestock reductions, distinguishing between direct herd reductions and farm exits for the livestock categories most severely affected. Under the Tax 100 scenario, farms reduce their herds rather than exit. However, in the Tax 300 scenario, the reduction in livestock numbers, especially for dairy cows and heifers, is primarily due to farm exits (see Figure 2B). The shares of livestock remain mostly unchanged across scenarios (Figure 2C). However, livestock numbers decrease with increasing tax rates (Figure 2C). The number of dairy cows decreases by 5%, 9% and 18% under the Tax 100, Tax 200 and Tax 300 scenarios, respectively, compared to the reference scenario values, while the number of heifers declines by 4%, 10% and 20%, respectively, compared to the reference scenario values. The number of suckler cows, other cattle and pigs also exhibits sharp reductions under the highest tax rate,

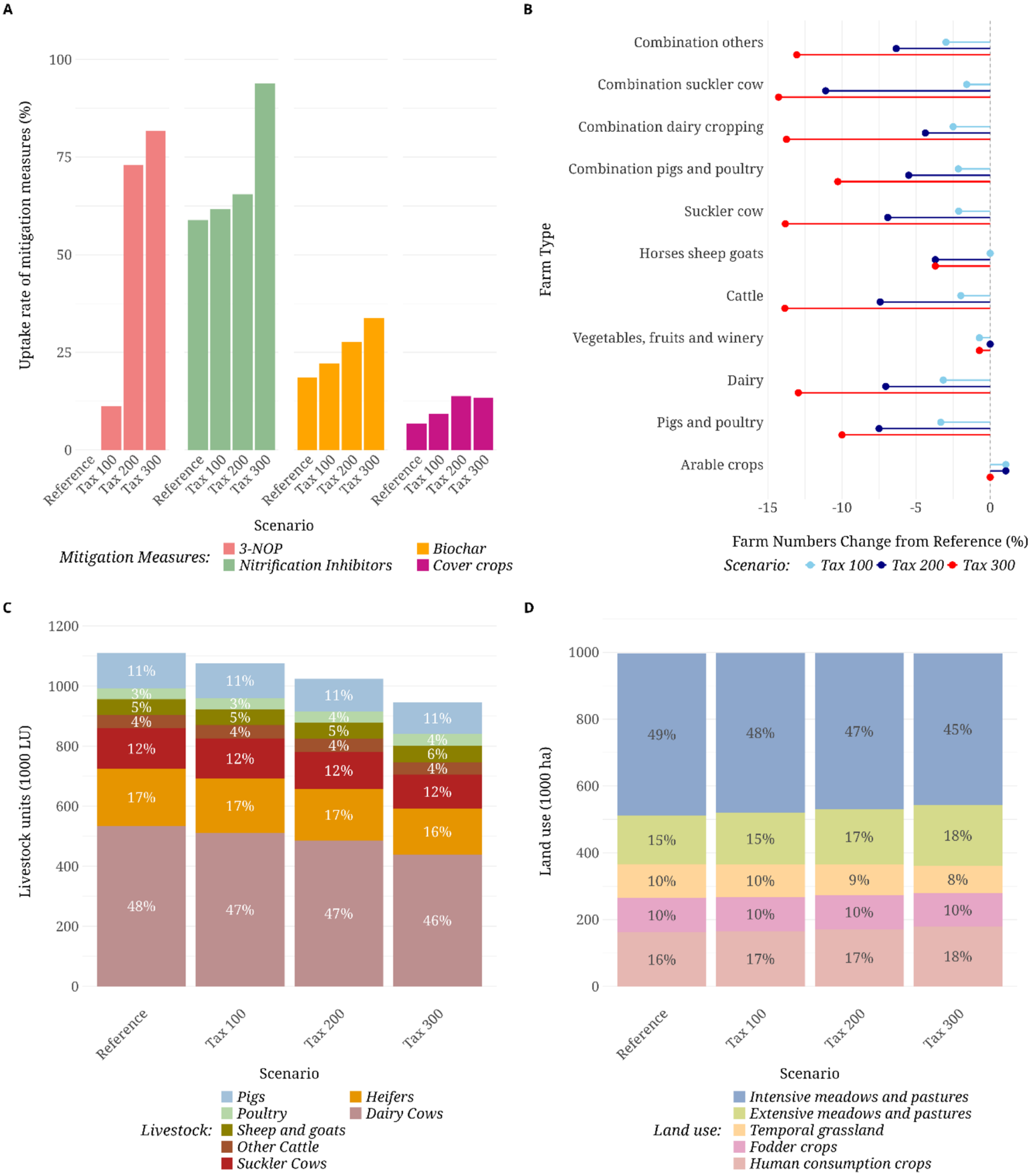

FIGURE 2 | The mechanisms activated by the tax to reduce GHG emissions in 2030. Panel A: Uptake rate of technical mitigation measures under each scenario (number of farms that adopt a measure in relation to the total number of farms that are able to implement the measure). Panel B: Changes in the number of farms compared to the reference scenario by farm type. Panel C: Total livestock units and the relative share of each livestock category by scenario. Panel D: Total land use and the relative share of each land use category by scenario. [Colour figure can be viewed at wileyonlinelibrary.com]

although their declines remain modest under the lowest tax scenario, Tax 100 (−1%, −2% and −1%, respectively, at 100 CHF/t CO_2eq) (Figure 2C). Dairy cows experience higher reductions, reflecting both their higher greenhouse gas emissions and a less favourable trade-off between economic returns and emissions compared to suckler cows. By contrast, the number of sheep and goats remains largely unaffected in absolute terms across all scenarios. This is consistent with their minimal contribution to total GHG emissions and their consequently low farm exit rates. However, the number of sheep and goats increases in relative terms under the tax, particularly in the Tax 300 scenario, as shown in Figure 2C and in the livestock emission shares reported in Supporting Information E. This increase in relative shares is due to the considerably stronger reduction in cattle production, which decreases the overall livestock population and increases the relative importance of sheep and goats within the remaining agricultural system.

Figure 2D illustrates land use at the sector level across the scenarios, showing that shares reshuffle slightly with increasing tax values. Due to the reductions in ruminants, the need for fodder from intensive meadows and pastures, temporary grasslands

TABLE 4 | Changes in the number of cows due to decreases in herd sizes and farm exits. The reference value for LU is 71,129, while the reference value for farm exits is 0.

Changes in the number of cows (LU)	Scenario		
	Tax 100	Tax 200	Tax 300
Decline in the total number of cows (LU compared to the reference scenario)	−4414	−9447	−16,708
Reduction in number of cows relative to the reference scenario (%)	−6%	−13%	−23%
Changes due to herd decrease (% of the total decline)	55%	45%	37%
Changes due to farm exits (% of the total decline)	45%	55%	63%

and fodder crops (i.e., maize silage) decreases. Consequently, the area of intensive meadows and pastures decreases under higher tax scenarios, with reductions of 2%, 4% and 7% under Tax 100, Tax 200 and Tax 300, respectively, compared to the reference scenario. Meanwhile, the area of extensively managed meadows and pastures (i.e., EFAs with grassland) increases by 6%, 14% and 26% for Tax 100, Tax 200 and Tax 300, respectively. Furthermore, reducing the area of temporary grassland and fodder crops on arable land increases the arable land available for growing crops for human consumption, including cereals (wheat, rye, spelt), oilseeds, potatoes, sugar beets and vegetables, with only their side streams utilised for feed, resulting in increases of 2%, 6% and 11% under Tax 100, Tax 200 and Tax 300, respectively, compared to the reference scenario. Although some of these crops may serve both food and feed purposes in practice, their representation here reflects production intended for human consumption, with only side streams utilised for feed. Thus, maintaining full cultivation of land with fewer animals implies a shift towards more extensive agricultural production, which refers to farming systems that rely more on grazing and pasture in grassland systems, use lower levels of external inputs such as fertilisers in arable systems, operate with lower stocking densities, and depend less on concentrate feed (Stoate et al. 2001). These systems typically achieve lower yields per hectare but require fewer inputs per unit of land. This finding highlights the fact that land-use changes tend to move towards more environmentally friendly farming practices. Finally, in the Tax 300 scenario, the high farm abandonment leads to a decrease in the total agricultural land of 8% in respect to the reference scenario.

5.2 | Environmental Impacts

Table 5 breaks down the total GHG emission reductions by source: livestock reduction, farm exits and adoption of mitigation measures. Technical mitigation measures constitute the largest source of emission reductions at the lower tax levels, accounting for around 50% and 49% of the total reductions in the Tax 100 and Tax 200 scenarios, respectively. However, their relative contribution declines as the tax increases, falling to 34% in the Tax 300 scenario. In the highest tax scenario, emission reductions associated with farm exits become the main driver of abatement, reflecting structural adjustment and land reallocation in the sector, followed by technical mitigation measures and livestock reductions in the remaining farms. This shift reflects the increasing tax burden, under which structural adjustment becomes more important relative to the adoption of mitigation technologies.

TABLE 5 | GHG emission reductions and their decomposition by source and scenario.

	Scenario		
	Tax 100	Tax 200	Tax 300
Total emissions reduced (kt of CO_2-eq compared to the reference scenario)	−271	−634	−997
Farm exits (% of the total emissions reduced)	41	43	58
Reduction of livestock from remaining farms (% of the total emissions reduced)	9	7	8
Adoption of technical mitigation measures (% of the total emissions reduced)	50	49	34
3-NOP (% of the total emissions reduced)	17	32	20
NI (% of the total emissions reduced)	8	3	2
Cover crops (% of the total emissions reduced)	2	1	1
Biochar (% of the total emissions reduced)	23	13	11

Note: Farm exits reduce emissions not only through associated declines in livestock production, but also by freeing land that is subsequently taken up by more profitable arable or vegetable production farms.

Small changes in livestock and land use (Figures 2C and 4D), together with a slightly higher uptake of mitigation measures (Figure 2A) and a low farm exit rate (Figure 2B), lead to a 5% reduction in emissions under a GHG tax of 100 CHF/tCO_2eq compared to the reference scenario (Figure 3). Increasing the tax to 200 CHF/tCO_2eq results in a 14% reduction, while in the highest tax scenario (Tax 300), the stronger decline in livestock number combined with a high adoption of technical mitigation measures and higher farm exits achieves a 22% reduction in GHG emissions.

Table 6 provides the emission reduction compared to the reference scenario as well as the progress towards 2030's goal to reduce emissions by 20% from the 1990s levels. We find that the reference scenario is close to but below the target, and a tax of 100 CHF/tCO_2eq slightly exceeds the goal.

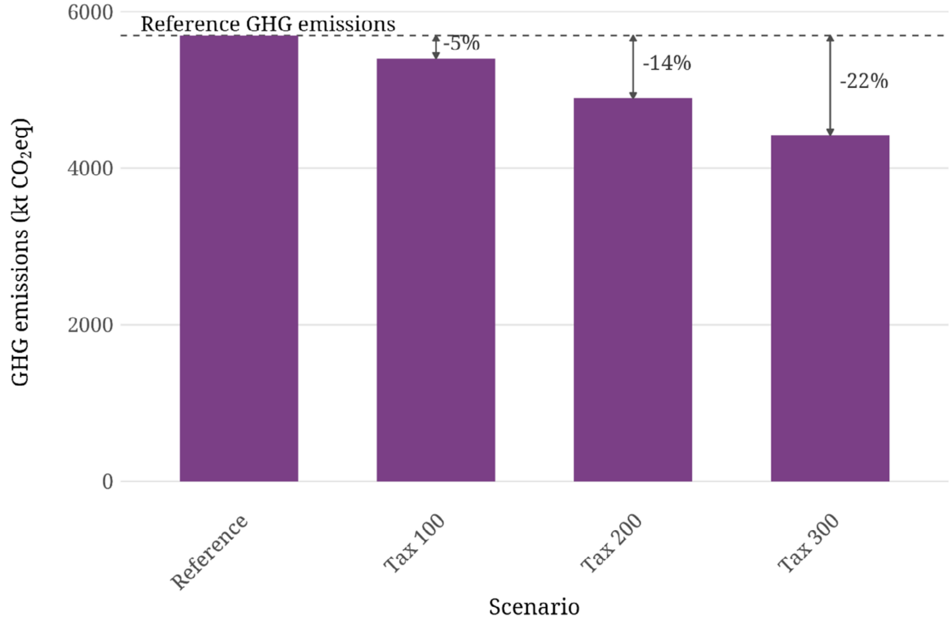

FIGURE 3 | GHG emissions by scenario in 2030 of the Swiss agricultural sector. The dashed line corresponds to the level of emissions in the reference scenario, while the arrows represent the percentage reduction in GHG emissions relative to the reference under each tax scenario. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 6 | GHG emissions under each scenario in 2030, the reduction relative to the reference scenario, and progress towards the 2030 target measured as the reduction relative to 1990 emissions (7042 kt CO_2-eq).

Scenarios (in 2030)	GHG emitted (kt CO_2-eq)	GHG reduction from Reference (%)	GHG reduction relative to 1990 (%)
Reference	5702	n/a	−18.5
Tax 100	5425	5	−21.6
Tax 200	4914	14	−28.6
Tax 300	4425	22	−35.4

Note: For contextual comparison, Switzerland's GHG emissions from agriculture amounted to 6000 kt CO_2-eq in 2023, the most recently reported inventory value (Greenhouse 2025), corresponding to a 14.8% reduction relative to 1990 levels. Both 1990 and 2023 emissions are observed inventory values, while scenario outcomes reflect model-simulated results within an income-maximising modelling framework.

Regarding co-benefits (Figure 4), the nitrogen surplus decreases as a result of the reduction in the number of livestock (Figure 4A). The surplus reduction remains modest at a tax level of 100 CHF/t CO_2eq (e.g., −0.5%), reflecting the relatively small decrease in livestock units (Figure 2C). However, larger surplus reductions could only be achieved at higher tax levels, at which more farms exit production and livestock densities further decline.

Furthermore, the reduction in intensive meadows and pastures, coupled with the expansion of extensive meadows and pastures, indicates a clear extensification process that supports greater biodiversity. This shift in land use is illustrated in Figure 2D, which shows a substantial increase in ecological focus areas (EFAs)[8] under all tax levels, with the simulated area changes reported at the sectoral level (Figure 4B). All four categories of EFAs show increases compared to the reference scenario. At a tax rate of 100 CHF/tCO_2eq, the action- and results-based EFAs and the agglomeration area on grasslands show gains of around 6%, while the EFAs on arable land exhibit smaller improvements, remaining below 5% across all tax scenarios.

5.3 | Economic Impacts

Figure 5A presents the average farm income of the farm sample across the scenarios. Under a tax of 100 CHF/t CO_2eq, the average farm income declines by 13%, followed by 15% and 25% declines for taxes of 200 and 300 CHF/t CO_2eq, respectively. Moreover, income changes relative to the reference scenario are computed using varying sample sizes to account for structural adjustments through farm exits. In the tax scenarios, farm exit is mainly experienced by farms with below-average incomes. Therefore, farm exits increase the average income of the remaining farm sample. We additionally calculated income changes using a balanced sample that includes only the farms that remain active until 2030 in all scenarios. Specifically, for each of these farms, we calculated the income change between each tax scenario and the reference scenario and then averaged these farm-level income changes across the balanced sample. If we calculate the average income of this balanced sample, the income reduction is substantially larger at 24%, 43% and 53% for the respective tax levels. Figure 5B shows the average changes in farm income by farm type and

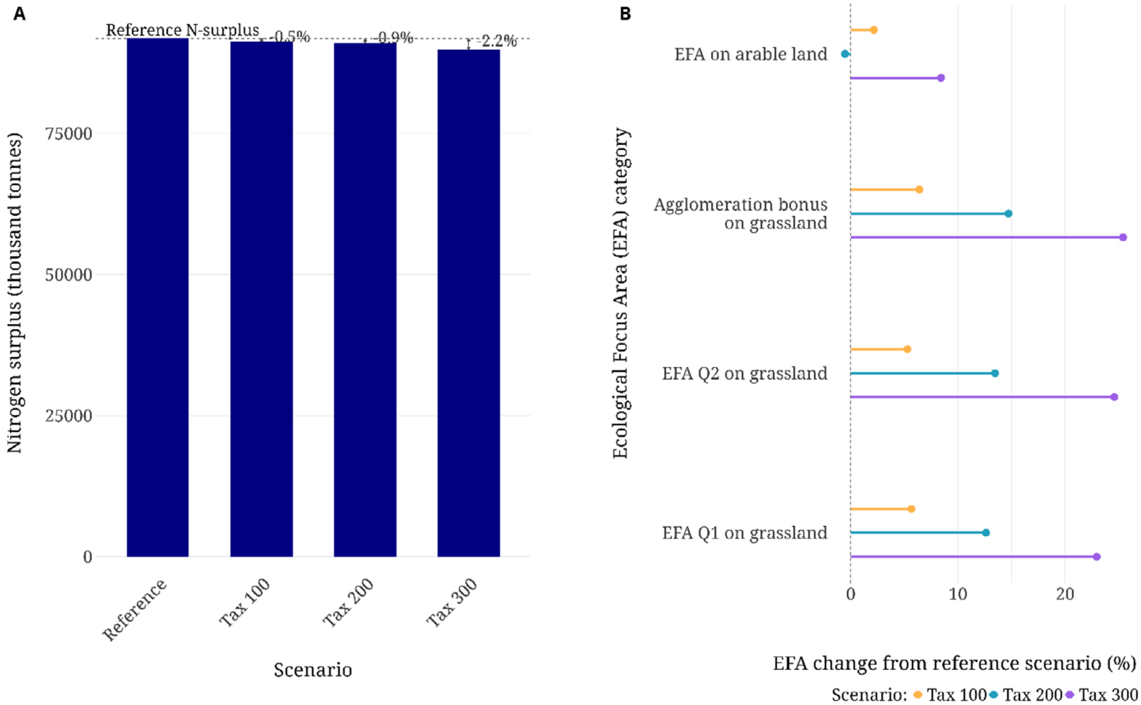

FIGURE 4 | Environmental co-benefits from a GHG emission tax in 2030 by scenario. Panel A: Nitrogen surplus (N surplus). The dashed line corresponds to the level of N-surplus in the reference scenario, while the arrows represent the percentage reduction in N surplus relative to the reference under each tax scenario. Panel B: Changes in the ecological focus areas (EFAs, in hectares) compared to the reference scenario in year 2030 under each tax scenario. Here, we present four types of EFAs. Q1 corresponds to action-based EFAs, and Q2 corresponds to result-based EFAs. [Colour figure can be viewed at wileyonlinelibrary.com]

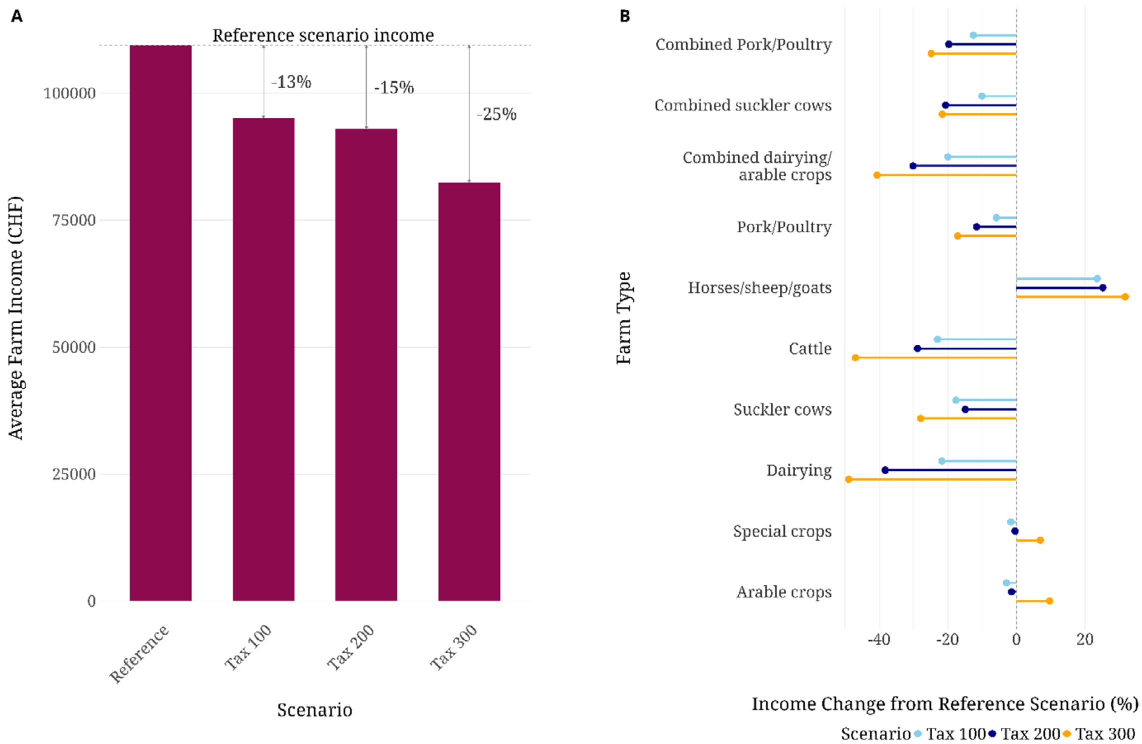

FIGURE 5 | Economic impacts of the GHG tax in 2030 across each tax scenario. Panel A: Average farm income. The dashed line indicates the income level in the reference scenario, while the arrows represent the percentage reduction in average farm income relative to the reference under each tax scenario. Panel B: Average income changes per farm type compared to the reference scenario. [Colour figure can be viewed at wileyonlinelibrary.com]

tax scenario compared to the reference scenario. These changes result from the additional costs of the technical mitigation measures, changes in revenues due to production changes and tax payments. For example, arable and special crop farms experience only minor income declines or even gains under the 300 CHF/t CO_2eq tax because these farms have a relatively low tax burden. The slight increase in income for vegetable farms is driven by land-use shifts (i.e., expansion of vegetable production through renting land from exiting farms) and by yield improvements from technical mitigation measures, such as nitrification inhibitors. Together, these factors reduce the impact of the tax on vegetable farms and enhance their profitability, ultimately contributing to higher incomes. By contrast, dairy farms, combined dairy farms, and other cattle-based farms experience substantial income losses, driven by livestock declines, higher tax payments, and the costs associated with technical mitigation measures such as 3-NOP. For example, the average income of dairy farms falls by nearly 22% under the 100 CHF/t CO_2eq tax and by almost 40% under the Tax 200 scenario and by almost 50% under the Tax 300 scenario.

Table 7 shows the median tax burden per farm type. Farms with the highest tax burden include dairy farms, combined dairy and arable cropping farms, pig and poultry farms, and combined pig and poultry farms, which are more heavily affected compared to other farm types. Combined farms show the highest values because they include more than one production system, which results in higher overall emissions on average and leads to higher tax expenditures (see Supporting Information E for the farm sizes). Although combined farms often face higher absolute tax payments, the relative burden is generally larger for specialised livestock farms, which exhibit the highest tax shares relative to pre-tax income. The table also shows the total sectoral tax revenues and how they increase with higher tax rates. These revenues could potentially be used to compensate farms that are most negatively affected by the tax.

5.4 | Social Impacts

Figure 6 presents the number of farms per region and the percentage reduction in the number of farms compared to the reference scenario across tax levels. Under a tax of 100 CHF/t CO_2eq, the farm exit rate is 2% higher than in the reference scenario. At a tax of 200 CHF/tCO_2eq, the exit rate is 5%, and at a tax of 300 CHF/tCO2eq, it is 10% higher than the reference scenario. The hill region is the most affected region, as it is characterised by limited cropland but highly productive grasslands, which results in comparatively high livestock densities on average (please refer to Supporting Information E for detailed numbers on the densities).

Figure 7A shows the changes in production volumes. Products primarily associated with high-emitting livestock, such as milk and beef, experience the largest decline in production, in line with the decrease in livestock numbers. Milk production decreases by 5%, 9% and 18% under the 100, 200 and 3300 CHF/tCO_2eq taxes, respectively. Beef and pork production are also affected but to a lesser extent, with reductions of around 1% under the 100 CHF/tCO2eq tax, 5% and 6% under the 200 CHF/tCO2eq tax, and 12% and 9% under the 300 CHF/tCO_2eq tax, respectively. By contrast, crop production increases across all scenarios. The observed shift in production reflects the increase in the area dedicated to crops for human consumption in the tax scenarios. Moreover, as shown in Figure 7A, feed cereal production also increases relative to the reference scenario; however, the corresponding absolute changes remain relatively moderate, rising from 285 thousand tonnes in the reference scenario to 297, 312 and 317 thousand tonnes under Tax 100, Tax 200 and Tax 300, respectively. This increase does not imply substantial oversupply, as domestic feed cereal production currently accounts for around 80% of the total gross Swiss feed requirements (Erdin 2023). In addition, a large share of feed demand originates from the poultry and pork sectors, which are comparatively less affected by the

TABLE 7 | Median tax expenditures per farm type under each tax scenario (in CHF) and sectoral tax revenues for each tax scenario (in millions of CHF). Values in parentheses indicate the share of tax payments relative to pre-tax income.

	Scenario		
Median tax payment per farm type (CHF)	**Tax 100 CHF/tCO_2eq**	**Tax 200 CHF/tCO_2eq**	**Tax 300 CHF/tCO_2eq**
Dairy	16,105 (17%)	30,855 (33%)	45,526 (48%)
Mother cow	10,856 (20%)	21,310 (39%)	30,895 (57%)
Cattle	13,607 (21%)	25,561 (39%)	35,436 (54%)
Horses sheep goats	585 (0.6%)	1405 (1%)	1635 (2%)
Pigs and poultry	16,852 (12%)	32,746 (24%)	50,965 (37%)
Cropping	6447 (6%)	14,486 (13%)	20,525 (19%)
Special cropping	517 (0.3%)	892 (0.4%)	1426 (0.7%)
Combination dairy cropping	19,439 (13%)	35,948 (24%)	54,114 (35%)
Combination mother cow	14,617 (18%)	27,927 (34%)	36,844 (45%)
Combination pigs and poultry	18,392 (11%)	35,037 (22%)	51,889 (32%)
Total sectoral tax revenues (Mio CHF)	542	982	1327

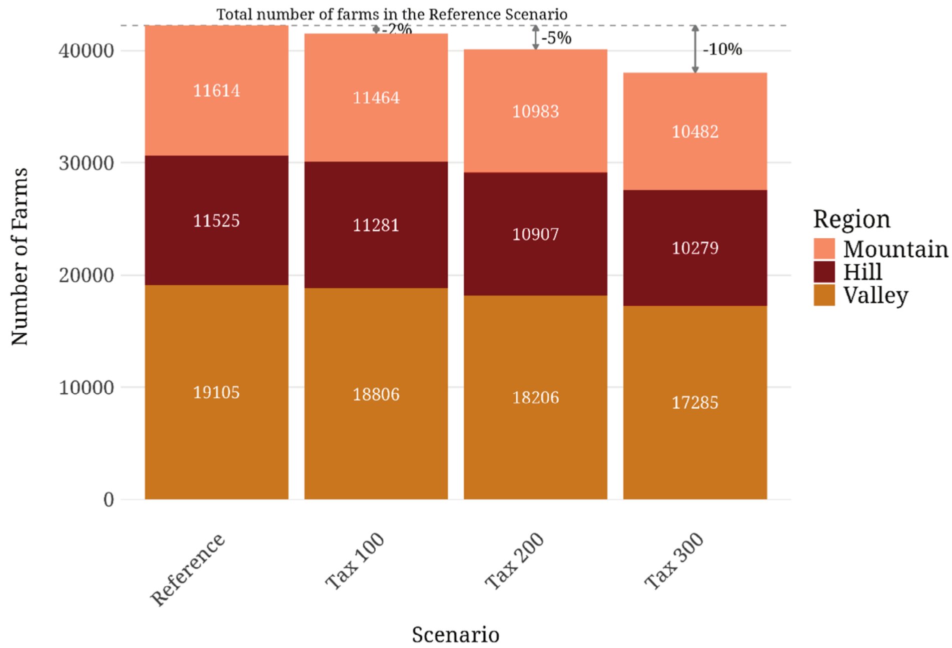

FIGURE 6 | Total number of farms per region and by scenario in 2030. The dashed line corresponds to the total number of farms in the reference scenario, while the arrows represent the percentage reduction of farms relative to the reference under each tax scenario. [Colour figure can be viewed at wileyonlinelibrary.com]

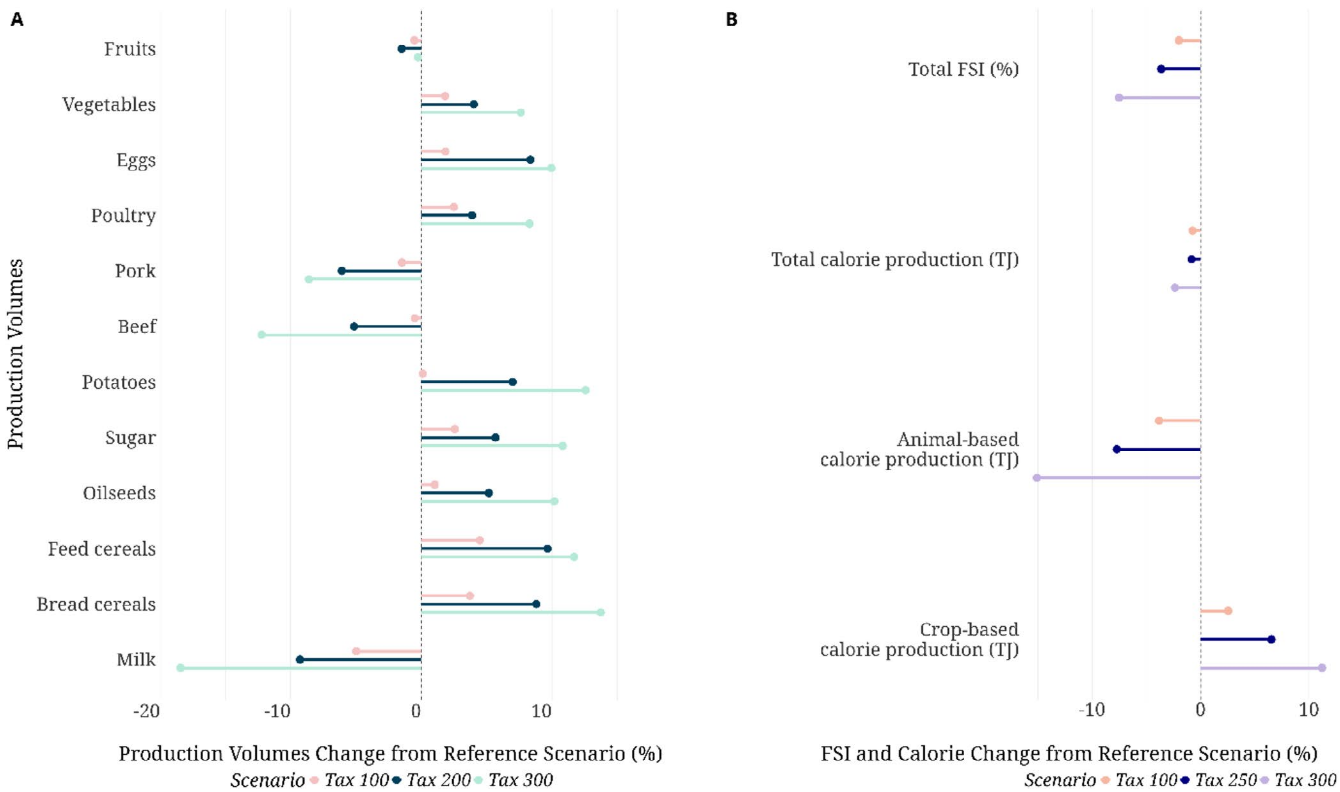

FIGURE 7 | Social effects due to the GHG tax in year 2030 under each tax scenario. Panel A: Changes in production volume (sector-level results) per product category compared to the reference scenario. Panel B: Changes in calorie production and the food self-sufficiency index (FSI) compared to the reference scenario. [Colour figure can be viewed at wileyonlinelibrary.com]

tax. Consequently, the additional domestic feed cereal production is likely to substitute for imports rather than generate excess supply.

Figure 7B presents the changes in calorie production and FSI relative to the reference scenario. Specifically, it shows the changes in animal-based and crop-based calorie production.

For the FSI, we report the gross total (i.e., the aggregate FSI for all food products combined). Our results show that crop-based calorie production increases across all tax scenarios, rising by 3% under the 100 CHF/tCO_2eq tax, 7% under the 200 CHF/tCO_2eq tax, and reaching an 11% increase under the highest tax level. By contrast, animal-based calories drop by approximately 4% under the 100 CHF/tCO_2eq tax, by around 8% under the 200 CHF/tCO_2eq tax, and by 15% under the 300 CHF/tCO_2eq tax. Despite these sharp reductions in animal-based calories, total calorie production decreases more moderately—by just 0.7% under the 100 CHF/tCO_2eq tax, 1% under the 200 CHF/tCO_2eq tax, and slightly over 2% under the 300 CHF/tCO_2eq tax. We also observe that the gross total FSI mirrors the sector's total calorie production, as both exhibit percentage decreases of similar magnitude compared to the reference scenario.

6 | Discussion

The findings of this study show how reducing GHG emissions in agriculture through a carbon tax can trigger shifts across environmental, economic and social dimensions in Switzerland. The analysis shows that agricultural emissions are fundamentally linked to production practices. Lowering them requires changes in key production practices, such as land use, livestock numbers and farm exits. Thus, by identifying these mechanisms, we can better understand the impacts of the tax across the three sustainability domains, offering valuable evidence to support policymakers in reaching climate targets. Specifically, a tax of 100 CHF/tCO_2eq reduces GHG emissions by 5% compared to the reference scenario with no tax. At a tax level of 200 CHF/tCO_2eq, the GHG emission reduction reaches 14%, and at 300 CHF/tCO_2eq, it reaches 22%.

To contextualise the magnitude of emissions reductions, Table 6 relates the results to Switzerland's agricultural climate policy targets. The benchmark is the 1990 emissions level of 7042 kt CO_2-eq, consistent with national policy objectives to reduce agricultural GHG emissions by 20% by 2030 and 40% by 2050 relative to 1990 levels. Against this benchmark, all scenarios in our model achieve substantial reductions. The reference scenario yields an 18.5% reduction, remaining slightly below the 2030 target, while a tax of 100 CHF/tCO2-eq results in an approximate 21.6% reduction, thereby meeting the policy objective. These findings indicate that structural adjustments and the adoption of technical mitigation measures can contribute significantly to emissions reductions, even in the absence of a tax. However, these outcomes reflect the model's income-maximising framework and may therefore overestimate real-world adoption levels, particularly in the reference scenario, where mitigation uptake occurs without an explicit tax price signal. Although the results appear optimistic, additional reductions will be required by 2050. However, given that the considered mitigation measures are still rarely adopted in practice (Hao et al. 2026), the analysis provides insight into their potential role and highlights the relevance of a GHG emissions tax as a mechanism to support their uptake.

Overall, the results illustrate how the different abatement mechanisms work hand in hand, highlighting the strong interconnectedness of the agricultural sector. The tax not only incentivises the adoption of technical mitigation measures but also leads to farm exits, which in turn drive down livestock numbers, as vegetable farming becomes more profitable and takes over the exited farms. This leads to increasing emission reductions as tax rates increase, because higher tax rates induce more farm exits and therefore result in greater reductions in total emissions. At lower tax levels (Tax 100 and Tax 200), emission reductions are primarily driven by the adoption of technical measures, whereas at higher tax levels (Tax 300), livestock reductions due to farm exits become the dominant source of abatement, reflecting a reallocation of agricultural land towards less emissions-intensive uses within the sector. As in the model, land from exiting farms is leased to neighbouring farms, facilitating structural adjustment by allowing the remaining farms to expand their operated land areas. These farm exits and the accelerated structural changes resulting from the tax have important social implications. At the farm level, they provide a crucial indicator to assess the tax's impact, highlighting regional disparities, potential acceptance of the tax, and the farm types most affected.

This farm-level perspective is also essential for understanding broader social and economic dynamics, as the reduction in the number of active farms partly explains the concurrent shifts in income, emissions and production. Moreover, the decline in livestock production triggers substantial shifts in land use and production patterns. As pasture and fodder areas decline, land becomes available for crop production and is taken up by vegetable producers, who expand the area devoted to crops such as vegetables and bread cereals by renting new available land. Because vegetable production becomes relatively more profitable under the tax, this expansion occurs across all tax scenarios (Figure 4D), which in turn drives an increase in average incomes in crop farming (Figure 7B). Consequently, plant-based food production remains relatively stable, which helps maintain food self-sufficiency and domestic calorie production, despite the decline in animal-based production. These changes are also reflected in farm incomes, with dairy, mixed dairy, and other livestock-focused farms experiencing the most significant losses under higher tax scenarios.

Moreover, these changes generate moderate environmental co-benefits. For example, land-use shifts not only contribute to maintaining food self-sufficiency and domestic energy output by increasing crops for human consumption, but the extensification of land also contributes to biodiversity gains across all tax levels. At the same time, reductions in livestock numbers lead to lower nitrogen surpluses. Thus, although the tax is primarily aimed at reducing GHG emissions, it also has a positive impact on other environmental indicators. As discussed by Ring et al. (2010), market-based instruments for carbon mitigation can create synergies with biodiversity conservation. One way to realise these synergies is through the redistribution of resources towards biodiversity goals. Therefore, it is essential to consider such synergies when designing market instruments to ensure the protection of other environmental values, such as biodiversity (Essl et al. 2018).

Our findings confirm prior results and extend them by evaluating all three sustainability areas together and linking the changes to the structural adjustments that occur at the farm level in response to a GHG emission tax. For instance, Blandford (2014), who examined the trade-offs between food production and a GHG emission tax in Norwegian agriculture, found that such a tax would particularly reduce beef and sheep production, while encouraging extensification, leading to lower emissions per hectare. Similarly, Coderoni et al. (2024) emphasised the importance of incorporating technical mitigation measures, noting that taxation can incentivise their uptake and reduce emissions beyond what can be achieved through livestock reduction alone—a pattern also evident in our results. Sørensen et al. (2025) observed a shift from livestock to crop production under a GHG tax but argued that most emissions reductions stem from output declines, as mitigation options in agriculture are often costly. Henderson et al. (2018) found that a uniform global GHG tax on ruminant livestock can be efficient but may harm producers and consumers in low-income countries, highlighting the need for subsidies to protect food production. Although our results show small reductions in food self-sufficiency and gross energy output under a tax of 100 CHF/tCO_2eq, and even an increase for crop-based calorie production, some production systems are disproportionately affected, pointing to the importance of tax redistribution to ensure policy acceptability, particularly for higher tax rates. However, the outcomes would depend on the chosen redistribution mechanism. A per-hectare lump-sum payment could help offset losses for combined farms due to their larger land areas, although it remains uncertain whether this approach would effectively address income inequality.

Moreover, when interpreting our results within the context of Swiss agricultural policy, it is important to recognise that responsiveness to the tax may be lower than in other national settings. This is due to the substantial financial support Swiss agriculture receives through direct payments. For example, besides direct payments provided to all farm types, animal welfare-related direct payment programmes such as BTS (animal-friendly housing), RAUS (outdoor access for livestock), GMF (grassland-based milk and meat production), and payments for extending the longevity of cows are directly linked to ruminants. All these payments are incorporated into the SWISSland model and are therefore part of the reference scenario. Thus, the tax is introduced alongside existing direct payments, indicating that their effects are inevitably intertwined. In this context, the tax may also change the adoption of certain direct payment schemes. As shown in Figure 4B, areas under different biodiversity conservation schemes expand under each increasing tax scenario. To further promote such practices, a support of biodiversity conservation and other environmentally friendly measures measure consistent with suggestions from previous literature (Ring et al. 2010) would be to redistribute tax revenues in and, in the case of Switzerland, adjust direct payments accordingly.

Overall, our findings align well with the broader literature. However, differences in modelling frameworks make direct comparisons challenging. Our study adds to this literature by linking environmental, economic, and social outcomes to the structural adjustments that occur at the farm level in response to a GHG emission tax. While other studies have examined the environmental and economic effects of such taxes, our approach highlights how these outcomes emerge through farm-level changes, providing insights into the mechanisms behind emission reductions in Swiss agriculture. In contrast to computable general equilibrium and partial equilibrium models, which typically represent sectors through aggregate structures and equilibrium conditions, our positive mathematical programming and agent-based model approach with SWISSland captures heterogeneous farm-level decision-making without imposing predefined aggregate behaviour. Policy outcomes therefore emerge from the aggregation of individual responses rather than from assumed system-wide rules. Moreover, prices are not endogenously determined through market clearing, so the analysis focuses on within-farm adjustment mechanisms and abstracts from feedback operating through price changes. This comprehensive approach provides insight into not only how much emissions can be reduced but also potential pathways for realising the reduction, offering valuable input for policymakers designing GHG taxation schemes.

Despite the relevance of our results, several limitations must be acknowledged. First, our analysis is specific to Switzerland, meaning that the quantitative results cannot be directly generalised to other countries. Still, the mechanisms and drivers we present are relevant beyond the Swiss context and can help illustrate how a GHG tax might function elsewhere. Second, the model includes a limited number of technical mitigation measures that do not apply uniformly across all farm types or production systems. For example, no measure directly targets emissions from pig farming. In practice, farmers would likely have access to a wider range of technical mitigation options than those included in our model, potentially leading to greater overall abatement. Moreover, mitigation measure adoption is determined by the income-maximising framework of SWISSland, which may overestimate real-world uptake and favour lower-cost options, such as nitrification inhibitors, relative to other land-based measures.[9] This implies that mitigation responses in the model may be stronger than those observed in reality. However, because this potential overestimation affects both the reference and tax scenarios, the estimated differences between them are likely to remain representative of the effect of the tax.

Moreover, our simulations assume that the implementation year for the measures is 2024, but the adoption of mitigation measures and the tax's effects are likely to evolve over time, possibly following different trajectories in real-world conditions. Increased demand for mitigation options could lower their costs and foster the development of new technologies, as Sørensen et al. (2025) suggested. Moreover, monitoring, reporting, and verification costs associated with the tax are not explicitly modelled as transaction costs. However, their potential impact can be indirectly explored by considering higher tax rates that implicitly capture additional cost burdens. Our model does not account for behavioural factors, such as social norms or reluctance to change, as other agent-based model studies (see Tarruella et al. 2025) that may influence the choice between adapting production and paying the tax, nor does it consider the demand side, which leaves carbon leakage a potential concern. In the model, input and output prices are treated as exogenous price trajectories. To that end, we used price and cost estimates from market experts of the Federal Office of Agriculture over the forecasting period. These estimates are included in Supporting Information C. This means that prices and costs evolve over time rather than being determined endogenously within the model. Furthermore, price trends are assumed to be the same in all scenarios. This further implies that the model cannot account for potential market responses, such as milk price increases when milk production declines. This might overestimate the decline in milk production and income. To assess the potential effects of higher producer prices, we conducted a sensitivity analysis in which milk, beef, and pork prices were increased by 10% under the 300 CHF/tCO_2eq tax scenario (Supporting Information D). These products were selected because their production declines the most in the Tax 300 scenario (18%, 12% and 9%, respectively), making price adjustments plausible. The results show that higher output prices partially offset the impacts of the tax. Livestock numbers, farm incomes and farm numbers remain higher than in the main Tax 300 scenario (i.e., no price sensitivity applied), while GHG emissions increase by 6%. Average farm income rises by 7.5%, with income losses reduced across all farm types (e.g., dairy farm income declines are 19% smaller). Milk and beef production also increase relative to the main Tax 300 scenario, although they remain below reference levels. Overall, higher producer prices mitigate, but do not eliminate, the economic and production impacts of the tax.

Finally, our results do not account for any redistribution of tax revenues. As Coderoni et al. (2024), Henderson et al. (2018), Schaper et al. (2025) and Himics et al. (2020) argued, redistributing these revenues could help address issues of competitiveness and support the adoption of mitigation technologies, factors crucial to the long-term success of such a policy.

7 | Conclusion

This study evaluates the environmental, economic and social impacts of a GHG emission tax on Swiss agriculture, showing that emission reductions stem from both technical measures and broader sectoral changes, including livestock reductions, land-use shifts and farm exits. These dynamics generate co-benefits, such as increased biodiversity, lower nitrogen surpluses and minimal effects on food self-sufficiency, highlighting the need to consider trade-offs and incentives across all sustainability dimensions. From a policy perspective, a moderate tax of 100 CHF/tCO_2eq can help Switzerland approach its 2030 targets, while higher rates may achieve or exceed them but risk reducing farm viability, especially in livestock-intensive regions. Complementary measures, such as redistributing tax revenues to support affected farms and investing in mitigation technologies, can enhance equity, acceptance and overall policy effectiveness (Finger and Pedersen 2025; Gren et al. 2021; Schaper et al. 2025).

Future research could expand the modelling approach by including additional mitigation measures (e.g., carbon sequestration and agroforestry) and by collecting and integrating observational data on mitigation adoption to enable empirical validation of simulated uptake patterns. Further extensions could incorporate interactions with other modelling frameworks to account for consumer demand, international trade and endogenous price formation. Integrating market feedback mechanisms would enable a more comprehensive assessment of production adjustments, carbon leakage risks and food system resilience. Finally, evaluating how different tax revenue recycling schemes influence these outcomes, as well as accounting for the net social implications of the tax scenarios by considering both farm income losses and generated tax revenues, could further inform the design of efficient, effective and socially acceptable climate policies in agriculture.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Endnotes

[1] Although New Zealand has started implementing its Emissions Trading Scheme in 2025, the agricultural sector is required to report but not yet pay for its emissions (About the New Zealand Emissions Trading Scheme 2023).

[2] As of January 2026, these values are estimated at 108, 217, and 325 €/tCO_2eq, as well as 161, 258, and 388 \$/tCO_2eq.

[3] Cross-compliance is the practice of providing public payments to farmers only if they adhere to certain environmental standards (Mann 2005; Schmidt et al. 2019).

[4] The food self-sufficiency index (FSI) is defined as follows: $\text{FSI}\,(\%) = \frac{\text{Domestic food production}}{\text{Domestic food consumption}} \times 100.$

FSI = 100% indicates that the country produces exactly the amount it consumes. Values above 100% means that the country produces more than it consumes. Values below 100% indicates that domestic production is insufficient to meet consumption and that the country depends on imports. Both food production and consumption are measured in calories.

[5] A few mitigation measures discussed in the literature are not explicitly represented for structural modelling reasons. First, measures requiring fundamental production system transitions or long-term land-use changes (e.g., agroforestry) are beyond the model horizon. Second, measures requiring spatially explicit targeting (e.g., rewetting organic soils) cannot be represented due to SWISSland's non-spatial structure. Third, measures involving high fixed investments or cross-farm coordination (e.g., biogas plants or energy infrastructure measures) are outside the farm-level adoption framework. Finally, certain practices are already endogenously captured or widely adopted in the Swiss baseline, including slurry spreading, grassland management intensity, and feeding optimization decisions. SWISSland further represents policy instruments that indirectly affect emissions, including direct payments for grassland-based production, lactation dynamics, and SuisseBilanz constraints.

[6] Consistent farm-level observational data on the uptake of the mitigation measures considered here are currently not available in Switzerland, which prevents direct empirical validation of simulated adoption levels. Evidence suggests that the adoption of several emerging mitigation measures remains negligible or close to zero (Hao et al. 2026). The reference scenario is therefore hypothetical and represents a simulation without a tax price signal, in which adoption decisions emerge from the model's income maximisation framework, assuming full knowledge of costs and effects.

[7] Grain crops account for the majority of arable land in Switzerland (40.4%), with winter wheat as the most common crop (Rees et al. 2025). Other common crops include oilseeds (i.e., rapeseeds, sunflower seeds), potatoes, maize, and sugar beets.

[8] Ecological focus areas (EFAs) are biodiversity-promoting elements on agricultural land, such as extensively managed grasslands, hedges, or buffer strips, supported through agri-environmental schemes that compensate farmers for income foregone via action-oriented (Q1), result-oriented (Q2), or collective payment schemes (Mack et al. 2020).

[9] While the model does not aim to reproduce observed adoption rates, our results have been compared to observed patterns and are economically consistent with the currently low uptake of such measures in Swiss agriculture, despite their technical feasibility (Büchi et al. 2020; Hao et al. 2026; Oberholzer et al. 2024).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Supporting Information A:** Additional Information on the technical mitigation measures. **Table S1A.** Pasture reduction factors and the corresponding corrected 3-NOP abatement potential by region. **Table S2A.** Detailed information on the mitigation measures values and the corresponding sources. **Table S3A.** Agridea (2024) economic reference values for cover crop feed systems in Switzerland. Source material obtained from the paid Agridea database available at the Agridea online shop. **Table S4A.** Overview of expert consultations used for parameterization and validation. **Supporting Information B: Supporting Information C: Supporting Information D: Supporting Information E:**