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A food tax only minimally reduces the N surplus of Swiss agriculture

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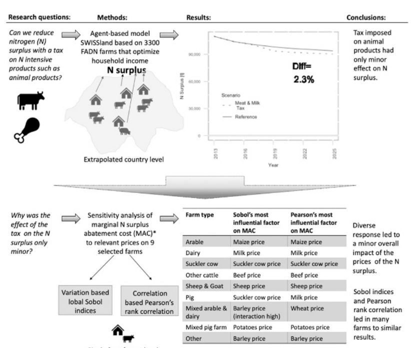
HIGHLIGHTS

- Nitrogen surpluses of Swiss agriculture remain on a high level since the 90's.
- We assessed the effects of a food tax on nitrogen surplus in the agent-based model SWISSland.
- Food taxes on milk and meat products reduced nitrogen surpluses by 2.1% to 2.3%, respectively.
- A robust sensitivity analysis on different model agents revealed that distinct agents react differently to varying prices.
- Food taxes are not effective to reduce nitrogen surpluses as distinct farms react non-uniform to changing prices.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Most Western-European countries exceed the critical loads for nitrogen (N) losses. High nitrogen (N) inputs make agriculture one of the largest contributors to N pollution. There might be a potential to reduce this losses with an output tax on animal products, as they have low N use efficiency and a tax has the potential to reduce the consumption of this products.
OBJECTIVE: We want to assess the potential of a food tax on animal products to reduce the N surplus of Swiss agriculture.
METHODS: We implemented a tax on meat and a tax on milk and meat in the agent-based model SWISSland. The model combines an agent-based model with a microeconomic model at the farm scale. To better understand the low response of the food tax, we applied in a second step a robust two-step global sensitivity analysis of abatement costs of individual model agents.
RESULTS AND CONCLUSIONS: Imposing a tax led to an N surplus reduction of 2.1% where only meat was taxed and 2.3% where both milk and meat were taxed. The sensitivity analysis showed that distinct agents reacted non-uniformly to changing prices, so that the effect of the tax was sometimes even cancelled out. This calls for more differentiated policies to reduce the negative impact of N losses.
SIGNIFICANCE: The overall impact of the food tax was minor as the distinct agents react not uniformly to lower producer prices.

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1. Introduction

Nitrogen (N) is a key limiting nutrient in agricultural production. However, due to excessive inputs of reactive N and low N use efficiency in agricultural production, N surpluses are above the critical loads in most Western European countries, including Switzerland (Sutton et al., 2011). N surpluses represent unutilised N and thus indicate a risk of environmentally harmful N losses, such as through ammonia (NH_3) volatilisation, nitrate (NO_3^-) leaching and nitrous oxide (N_2O) emissions. Reactive N released into the environment has adverse effects on ecosystem services and functions, such as the provision of drinking water and clean air, biodiversity conservation and climate regulation (Galloway et al., 2003). Agriculture is one of the largest contributors to N pollution, responsible for 90% of NH_3, 70% of N_2O and 60% of NO_3^- losses worldwide, and thus offers a substantial potential for N loss mitigation through improved N management on farms (Sutton et al., 2011; de Vries, 2021).

The Swiss Federal Offices for the Environment and for Agriculture defined agri-environmental goals for NO_3^- concentrations in water bodies and agricultural NH_3 and greenhouse gas emissions in 2008 and 2016 (BAFU (Bundesamt für Umwelt) and BLW (Bundesamt für Landwirtschaft), 2008; BAFU (Bundesamt für Umwelt) and BLW (Bundesamt für Landwirtschaft), 2016). Despite these goals, recent water quality measurements have indicated NO_3^- concentrations above the stipulated 25 mgl^{-1} (BAFU (Bundesamt für Umwelt) and BLW (Bundesamt für Landwirtschaft), 2016). To comply with the critical N loads, a 40% reduction in NH_3 emissions is required in comparison with 2005 levels. This is in addition to the reduction in N_2O emissions, which have so far seen only a minor reduction (BAFU (Bundesamt für Umwelt) and BLW (Bundesamt für Landwirtschaft), 2016). The level of N surpluses in Switzerland has been stagnant since the 1990s, at about 110 kg N ha^{-1} yr^{-1} (Spiess, 2011). Their reduction at national level was initiated in the early 1990s by introducing a cross-compliance scheme that limited mineral fertiliser inputs on farms and included farmyard manure in the fertilisation regime (Spiess, 2011; Jan et al., 2017).

Agricultural N pollution is diffuse, so it is difficult to determine where, when and in which chemical form N enters the N cycle (Galloway et al., 2003). The mitigation of N pollution cannot be measured directly because accurate monitoring would be extremely costly (Wirsenius et al., 2011). Technical mitigation measures may cause pollution swapping, e.g. riparian buffer zones aim to reduce NO_3^- in water bodies but might increase N_2O emissions (Stevens and Quinton, 2009). Most of the policies already implemented in different countries, such as limits on mineral fertiliser applications (e.g. Jan et al., 2017 or Galloway et al., 2014), aim to reduce environmental impacts by considering only the production side (Abadie et al., 2016). Furthermore, it has previously been established that, due to low price elasticities of demand for N inputs, input taxes are not sufficiently effective in reducing N pollution (Schmidt et al., 2017; Finger, 2012; Jayet and Petsakos, 2013; Mérel et al., 2013). Alternative approaches to reduce the environmental impact of agricultural products and their consumption should therefore be considered, e.g. increasing food prices in the form of a tax aiming to reduce demand for products causing high environmental impact, such as meat, and internalizing external costs.

Considering the demand side of food is especially recommended where it is difficult to monitor the pollution originating from production, where there is little opportunity for a technical solution and where substitution of the output is possible (Schmutzler and Goulder, 1997). Changes in producer prices induced by a tax would inevitably change N surplus abatement costs. Marginal abatement costs (MAC) represent the costs or lost income associated with reducing pollution by a single unit. Westhoek et al. (2014) estimated that halving the global consumption of animal products would raise N use efficiency by 100% and reduce NH_3 emissions by 40%. Output taxes on animal products could benefit not only the environment but also human health, as the consumption of saturated fat would decrease (Edjabou and Smed, 2013). Moreover, global greenhouse gas emissions would decrease by 40–55% with a diet regarded as healthy in terms of saturated fat intake (Abadie et al., 2016). In addition, an output tax does not favour imports, in contrast to measures implemented on the production side (Abadie et al., 2016). Lengers et al. (2014) showed that product prices have a significant impact on abatement costs for carbon dioxide (CO_2) emissions from agricultural production in Germany. Furthermore, the farmer's decision on production activities is influenced not only by the income from product sales, but also by direct payments.

This study aimed to evaluate the effectiveness of a food tax on meat and milk products in reducing N surpluses in Swiss agriculture. Animal products have a higher N footprint than arable crops (Leach et al., 2012). Two different scenarios of a food tax on a) only meat products and b) meat and milk products were simulated using the agent-based agricultural sector model SWISSland. The effects of the scenarios were so minor that we decided to further investigate the effects of product prices (e.g. milk price) and subsidies on MAC by a robust sensitivity analysis of farmer behaviour on individual agents representing individual farms.

Sensitivity analysis is a fundamental approach used to identify the most influential factors affecting model output (Saltelli et al., 1999). Furthermore, it improves the model understanding, transparency and reliability and helps to verify and simplify the model (Zadeh et al., 2017; Lacirignola et al., 2017; Schmidt et al., 2019; Locatelli et al., 2017; Sarrazin et al., 2016). Sensitivity analysis can be conducted locally by analyzing only one-factor-at-time or globally by assessing their whole uncertainty ranges (Saltelli and Annoni, 2010). Different approaches in quantifying sensitivities suggest that the results are non-identical and in some cases quite different, but at the same time they are complementary as they disclose various aspects of the sensitivity to the variation in factors. Sobol's decomposition of variance allows the influence of numerous factors to be studied while they vary simultaneously within their uncertainty intervals, and thus explores the full factor space (Sobol, 1990). The Sobol method has been widely used to evaluate key input variables determining the model output. On the other hand, the Spearman's correlation coefficient, as a sensitivity measure, describes a global degree of a linear association between the model output and a selected factor, which varies over its whole uncertainty range. Correlation-based sensitivity measures are directional, and thus provide a direction of the relationship. The disadvantage is that they evaluate a single factor at a time and thus do not allow interactive effects to be taken into account (Wallach et al., 2014; Botshekan et al., 2019). These methods have been used to study the influence of e.g. surface roughness on dissipated energy (Botshekan et al., 2019), different feed strategies on cost in cattle rearing (Abdullah et al., 2016) and vulnerability of wells on nitrate concentrations (da Silva et al., 2020).

By studying the responses of single different agents representing distinct farm types, we aimed to understand why the product tax led to an insignificant reduction in N surplus at national level. We believe that the two different approaches provided complementary sensitivity estimates for a robust evaluation of the relationships between product prices, direct payments and MAC on all selected farms.

2. Methods

2.1. Agent-based model SWISSland

The agent-based agricultural sector model SWISSland provides trends in agricultural production and income at farm and sectoral level as well as the associated structural change, change in land use, livestock population and product prices It is developed to support policy decisions by assessing the impact of new agricultural policies (See Fig. 1). It was used to assess the impact of different policies that aim to reduce N surpluses in Swiss agriculture (Schmidt et al., 2017, 2021). It combines the agent-based approach with a microeconomic model at the farm scale (Möhring et al., 2016). Agents in SWISSland are represented by 3100 Swiss farms, based on average values of the Farm Accountancy Data

Network (FADN) data in the years 2011–2013 (hereafter referred to as base years). The farm-specific FADN dataset provides data on production resources (land area, labour resources, stable capacity), production costs, revenues, product prices and direct payments for each production activity. Production activities of the model agents were calibrated on the base years using a positive mathematical programming (PMP) approach (Mack et al., 2020; Buysse et al., 2007). A detailed description of the model is provided in the ODD (Overview, Design and Details) Protocol in Zimmermann et al. (2015).

2.1.1. Model agent

The individual agents representing various farm types were assumed to maximise the farm income in the forecast year considering the following constraints (Eq. 1 and 2):

$$max(Z) = \sum p_i x_i + d_i x_i - 1\Big/2\, x_i Q_{ii} x_i \quad (1)$$

$$subject\ to: A_{w,i} x_i \leq B_w \text{ and } x_i \geq 0 \quad (2)$$

The farm income (Z) was a result of direct payments (d_i), market revenues from farm activities i (p_i: price, x_i production quantity associated with the activity i) and the quadratic cost term considering private costs (Q_{ii}). Q_{ii} was a symmetric and positive (semi-) definite matrix defined as follows (Eq. 3):

$$Q_{i,i} = 1\Big/\rho_{i,i} {}^*\pi^+ \Big/ x_i^+ \quad (3)$$

where ρ represents the supply elasticity (considered as one due to a lack of specific data) and x_i^+ considers the observed production levels in the base years. The optimisation of income was limited by the demand A of the resource w for the production quantities x_i to not exceed the total resource endowment B of the resource w. The model considered the following limiting resources: animal housing capacities, family labour resources and land endowment. Following optimisation of the model, a farm gate N balance was estimated for each agent independently (Schmidt et al., 2017).

Because the structural change is modelled as an endogenous process in the SWISSland model, the model agents can give up production for two reasons: retirement and unsatisfactory low income. When agents reach the age of 65 or have had a negative farm income over more than three years, they decide to hand over their farm to the next generation or give up their production activities. When an agent exits from farming, the land is leased to other agents clustered in the same spatial community structure (Möhring et al., 2016).

2.1.2. Farm gate N balance

N balances calculate the N surplus that represent the potential N losses to the environment (Oenema et al., 2003. A farm gate N balance was estimated by considering all N inputs from feeds, fertilizers, bought animals, N fixation, atmospheric N deposition, and N outputs from plant and animal production. In contrast to a soil surface balance, the system boundaries of the farm gate balance apply at farm scale and thus this balance considers bought feed as an input and animal production as an output, but not the inputs via farmyard manure and the output of own consumed feed (Oenema et al., 2003). The fertiliser N inputs were estimated from fertiliser costs for each crop in the accountancy data by considering the price per mass unit of fertiliser and recommended application rates (Agridea, 2013a). N inputs via concentrates in animal production activities were estimated from concentrate costs, data on feed mixtures typically used by individual agents and their N contents (Agridea, 2013b). For N outputs, the product quantities were multiplied by their standard N content (Flisch et al., 2009). Inputs through N dry and wet atmospheric deposition and N fixation were considered based on measurements by Boller et al. (2003) and Jan et al. (2013). A detailed description of the farm gate N balance calculation is provided in Schmidt et al. (2021), and the responses of N surplus to the variation in N input prices, direct payments, product prices and model specifications such as PMP are given in Schmidt et al. (2017).

2.1.3. Extrapolation

Model results for each agent were extrapolated to sectoral level depending on the farm type as the FADN dataset was not fully representative of Swiss agriculture regarding different farm types. Some dairy farms were therefore disregarded, whereas some sheep, goat and horse farms were duplicated in the dataset to increase the representativeness of the agent population (Zimmermann et al., 2015).

2.1.4. Market module

The market module of SWISSland was used to determine the product prices based on sectoral agricultural production in the supply module. The market module represented an applied recursive, partial-equilibrium, multiple-commodity model of the Swiss agricultural market.

The reduced-form model captured the economic behaviour of the Swiss market framework and its consumers. This submodule considered parameters related to consumption, imports, exports, world prices of stocks, and domestic consumer and producer prices. Agricultural products that were freely traded were modelled to reach the market equilibrium (Hamilton, 1994). Twenty-four commodities were considered (Table 1) and all were treated as tradeable with the exception of liquid milk and raw milk. Uniform prices were applied for each product category. In the core set of policies, we included specific export and import taxes or subsidies, consumer and producer subsidies and tariff rate quotas (Möhring et al., 2016). Data for the model parameters stemmed from various sources, including the Swiss Meat Market (Schluep Campo and Jörin, 2004), the Food and Agricultural Policy Simulator (FAPSIM; Koch and Rieder, 2002), the CAPRI (Common Agricultural Policy Regionalised Impact) model (Britz and Witzke, 2014) and the OECD (Organisation for Economic Co-operation and Development) Aglink model (Conforti and Londero, 2001).

2.1.4.1. Demand side.

A food demand equation was created for all products except raw milk and meals of soy bean, rape seed and sunflower seed, because these were already considered in the markets for feeds or milk products. The demand was specified per capita and then extrapolated to the sectoral level based on forecasts of population size in Switzerland (Federal Statistical Office (FSO/BFS) (2015):. The food demand per capita for each commodity i in year t was represented by a function of an income per capita ($FOOD_{pcr}$) in real terms (RGD_{pct}) and consumer price (PC_{rj}) as follows (Eq. 4):

$$Food(pc)_{m} = Consfo_{i,t} \prod_{i \in food} PC_{i,t}^{\sigma_{i,j}} RGD\,(pc)_t^{\varepsilon_i} \text{ for i} \in \text{food} \quad (4)$$

where $Consfo_{i,t}$ represented a measure for the interaction between per capita demand and consumer price and per capita income; $\sigma_{i,j}$ denoted the own- and cross-price elasticity of demand; and ε was the income elasticity of demand for commodity i in year t.

The applied systems of demand elasticities were synthetic because they were not estimated as systems. Individual elasticities stemmed from various sources (details in Möhring et al., 2016).

2.1.4.2. Prices.

Domestic prices for all traded commodities $DOMP_{i,t}$ were determined endogenously and depended on world prices, transportation costs $Transc_{i,t}$, import prices $PIM_{i,t}$, exchange rates ER_t and country-specific policies (see Eq. 5).

$$\mathrm{PIM_{i,t}}{}^*\mathrm{ER_t}{}^*\left(1 + \mathrm{TM_{it,in}} + z_{it}{}^*\mathrm{TMi_{t,out}}\right) + \mathrm{Transc_{i,t}} \quad (5)$$

The import price $PIM_{i,t}$ of commodity i at time t depended on the exchange rate ER_t, which was defined exogenously. The market module explicitly treated over-quota $Tm_{i,t}$, out and in-quota tariffs $Tm_{i,t}$, in for tariff rate quota (z_{it}) commodities with a discontinuity in the tariff rate as soon as the threshold for the quota amount had been reached. The

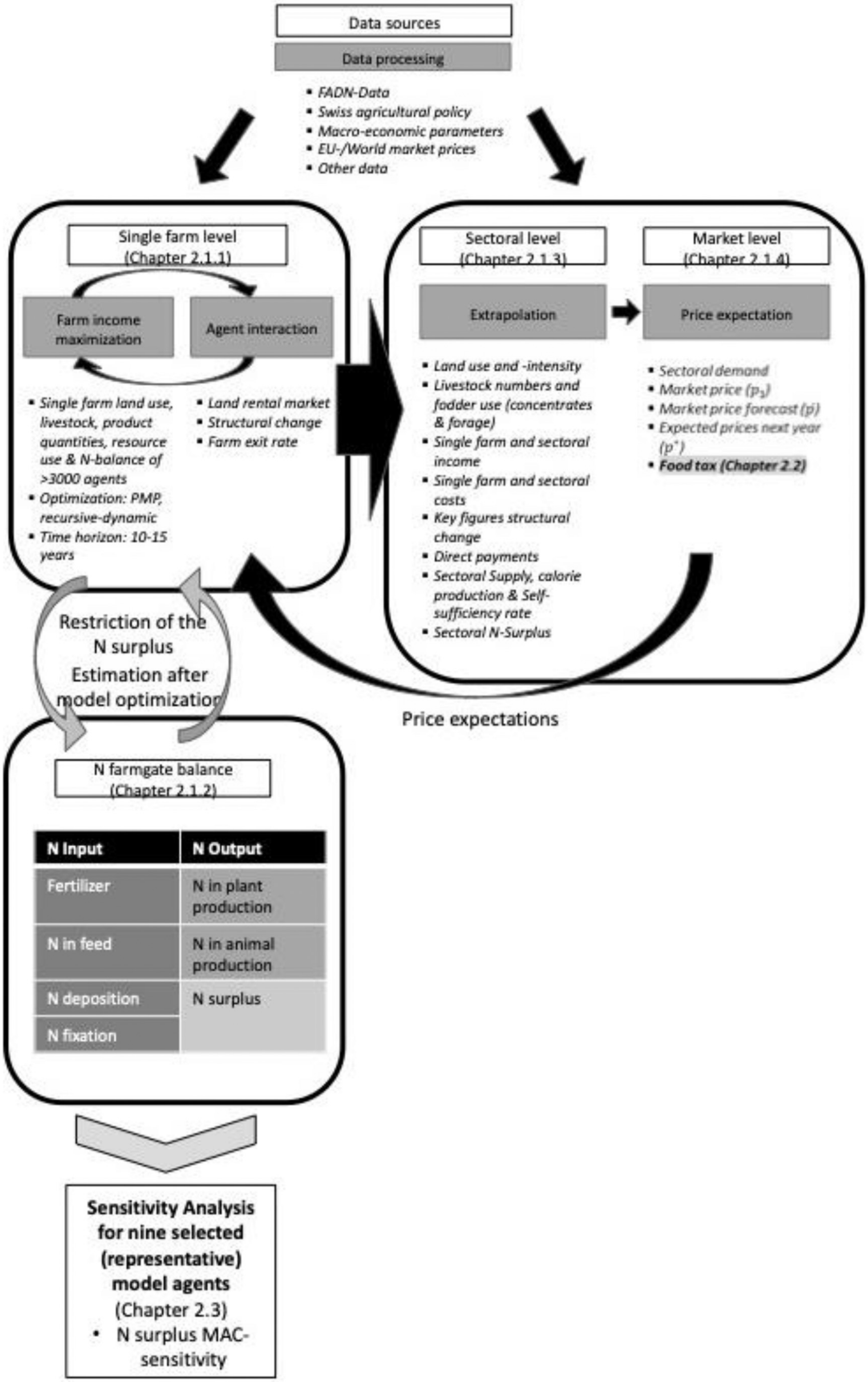

Fig. 1. Overview of the model components of SWISSland.

Table 1
Agricultural commodities considered in the market module of the SWISSland model categorised by production group.

Meat	Milk products	Crops
Beef	Milk	Wheat
Veal	Whole milk powder	Other coarse grain
Pork	Fresh cheese	Grain maize
Poultry	Soft cheese	Potatoes
	Semi-hard cheese	Rape seeds
	Hard cheese	Sugar
	Extra-hard cheese	Soy beans
	Cream	Sunflower seeds
	Butter	Soybean oil and meal
	Other dairy product	Rape seed oil and meal

relationship between world and domestic prices was held when imports were larger or smaller than the quota with the additional tariff. In cases where the imports were equal to the quota, the relationship between world price and domestic price could not be determined directly.

The domestic prices for non-tradeable commodities (raw milk, fluid milk) were determined by domestic supply-demand equilibria. The producer and consumer prices depended on the domestic prices. The producer prices were specified by an exogenous marketing margin that was determined by the ratio between observed domestic prices and producer prices. The consumer prices were adjusted by a factor considering the costs for marketing, processing and transport.

2.1.4.3. Trade. The model balanced demand and supply for each tradeable commodity i at time t as follows (Eq. 6):

$$\mathrm{NET_{it}} = \mathrm{PRD_{it}} - \mathrm{CON_{it}} + \Delta\mathrm{EST_{it}} \tag{6}$$

where $NET_{i,t}$ represented the quanity, $PRD_{i,t}$ production, $CON_{i,t}$total consumption of food and feed and $\Delta EST_{i,t}$considered stocks variation. The markets for each tradeable commodity were cleared, by specifying one of the variables import or export as relatively free to allow the market to clear. Cross price elasticities were considered. Two model iteration A detailed description of the market module can be found in Möhring et al., 2016.

2.2. Food tax scenarios for milk and meat

Two different food tax scenarios implemented in the market module for this study were simulated during the period 2013–2025. In the Meat scenario, we applied the tax only to meat products (Table 2). In the Meat & Milk scenario, the tax was applied to both meat and milk products. The tax level for meat products was defined by their N content multiplied by CHF 100 per kg of N and applied to the domestic prices. For milk, the tax was set at CHF 0.20 per kilogram, which is around half of the original tax rate because the levy could not be executed at a level close to 100%. The two scenarios were compared with a reference scenario without the food tax, which was based on the agricultural policy that was introduced in 2014 (AP 2014–17; described in Mann and Lanz, 2013).

Table 2
Tax levels imposed on meat and milk products and proportion of tax in the product price.

Agriculture product	Tax level [CHF/kg]	Proportion of the product price in 2011–2013 [%]
Beef	2.80	33
Pork	2.20	54
Poultry	2.60	65
Veal	2.40	17
Milk	0.20	31

2.3. Sensitivity analysis of marginal N surplus abatement costs

2.3.1. Calculation of the marginal abatement cost (MAC)

For calculation of the MAC we considered the year 2015 because the direct payment scheme changed completely in 2014 and this would affect the magnitude of MAC as this change influenced the prices and farm income (Mann and Lanz, 2013). Details on the calculation of the MAC can be found in Schmidt et al. (2021). The calculation involved two model runs. In the first model run, we simulated N surplus (S_i) and farm income ($FI(1)_i$) without a restriction. In the second model run, the restriction for the N surplus was set at 80% and the corresponding farm income ($FI(0.8)_i$) was estimated to calculate N surplus MAC. The MAC_i of each agent *i* was calculated by dividing the difference in farm income without ($FI(1)_i$) and with the restriction ($FI(0.8)_i$) by the 20% reduction in the initial N surplus (ΔS_i) (Eq. 7).

$$\mathrm{MAC_i} = \left(\mathrm{FI}(1)_\mathrm{i} - \mathrm{FI}(0.8)_\mathrm{i}\right)/\Delta\mathrm{S_i} \tag{7}$$

The agents were able to reduce their N surplus by reducing N fertilisation intensity by 10% or 20% in field crop activities, by reducing the use of concentrates in milk production, or by changing animal stocking or land use. The reduction in fertiliser and concentrate use was rewarded by additional direct payments. A switch to organic farming (growth in organic farms is small), application of farmyard manure (use of farm manure is already encouraged by the current policies) and use of different feeding strategies (the potential is rather small (Schmidt et al., 2017)), except those in dairy production, were not considered in this study due to the modelling restrictions, even though these strategies would affect N surpluses. Because there was no feedback from the individual agent model to the market module, the product prices stayed constant between the two model runs.

2.3.2. Sensitivity analysis approach

The aim of the sensitivity analysis was to examine how variation in agricultural product prices influences the N surplus MAC on individual farms to better understand the low response of the food tax. A previous sensitivity analysis revealed that direct payments have more influence on farm gate N surplus than the prices of N inputs (Schmidt et al., 2017). Our sensitivity analysis therefore considered direct payments along with the prices of agricultural products.

A global sensitivity analysis generally requires an intensive sampling method to draw a representative sample of values from their probability distributions (Locatelli et al., 2017). To ensure the convergence of the analysis, the size of a representative sample of values per factors (n) will depend on the number of studied factors (M) determining the number of model runs, i.e. scenarios (N) (Sarrazin et al., 2016). Based on preliminary model runs, a sample size $n = 500$ was chosen as sufficient to approximate the normal probability distribution of N surplus output. This sample size resulted in the following number of model runs: $N = M^2/2*n$ for the estimation of Sobol indices and $N = 2*M*n$ for the Spearman's rank correlation. The probability distributions of selected factors were assumed to be normal, i.e. the middle values were assumed to have the highest probability. This approach was chosen due to limited availability of data on the probability distributions. The values randomly sampled with the Monte Carlo algorithm from each probability distribution were stored in a matrix generated with the *rnorm* function in R (R Core Team, 2016). This matrix was permuted by the *soboljansen* function embedded in the sensitivity R package (Iooss et al., 2018). The model runs were processed in GAMS (General Algebraic Modelling System) (GAMS Development Corporation, 2013) and model output was computed for each scenario. With the R function *tell*, we imported the model output for the sensitivity analysis conducted with the *sensitivity* package (Iooss et al., 2018). The Sobol's sensitivity indices were computed using the *soboljansen* function.

We selected the microeconomic model of nine representative agents in terms of farm size, animal numbers and N surplus that belong to nine distinct farm type categories (see Table 3). The agents did not had any feedback with the sector model. For the selected farms, we assessed the influence of all relevant direct payments and agricultural product prices concerning the agent MAC for N surplus. As each agent has a different portfolio, the number of varying sensitivity factors differs between agents. Both the agricultural product prices and direct payments were set to vary with a coefficient of variation of ±5% of the prices and direct payments in 2015 (see Tables A1 and A2).

First order Sobol sensitivity index (i.e. main effect) describes the average influence of a factor on the model output, but does not take into account the interaction effects involving this factor. The total sensitivity index equals the sum of all factorial indices involving this particular factor (Wallach et al., 2014). These indices allowed us to estimate an interaction index for each studied factor as a difference between the total and first order indices. Due to residual errors in the calculations, the first order indices may reach a value slightly larger than 1.

The Spearman's rank correlation coefficient describing strength and direction of monotonic relationship between N surplus MAC on one side and direct payments and product prices on the other side was computed independently for each representative agent, also in R software (R Core Team, 2016).

While Spearman's rank correlation describes the strength and direction of a monotonic relationship between the response variable and a selected factor individually, the Sobol's first order index and interaction index are computed from the variance decomposition of the response variable related to the selected factor, while considering the influence of the other factors.

3. Results

3.1. Food tax scenarios

The effect of the tax on the N surplus was not detectable until three years after its introduction because the tax mainly affected farm exits (Fig. 2). After three years, agents with negative income could stop their production activity and lease their land to other agents.

Average farm income decreased by 5.6% in the 'Meat' scenario and increased by 4.2% in the 'Milk & Meat' scenario compared to the reference scenario (Table 4). The higher average income in the 'Milk & Meat' scenario relates to larger farm size as a consequence of farm exits. The decrease in fertilizers is probably related to an increase in unfertilized ecological compensatory area to compensate for the income loss.

In the reference scenario, the N surpluses were reduced by 15% during the study period in response to the agricultural policy that was introduced in 2014 (Fig. 2). This reduction was driven by a decline in animal numbers due to the abolition of direct payments linked to ruminants, and by a switch from open arable land to grassland.

In the 'Meat' scenario, the number of animals decreased by 6.8% and meat imports increased (with increases ranging from 4.7% for beef to 229% for pork) due to lower meat production (Table 5). In the 'Meat & Milk' scenario, the number of animals decreased by 7.1% whereas meat imports increased, with increases ranging from 6% for beef to 232% for pork. The additional N surplus reduction compared to the reference scenario was 2.1% in the 'Meat' scenario and 2.3% in the 'Milk & Meat' scenario (Table 4).

Both tax scenarios had the same effect on the price of meat. For beef and poultry meat, the price induced by the tax on the producer price remained constant over time (Fig. 3a & c). Both tax scenarios reduced the producer price of beef by 1.10 CHF per kg and the price of poultry meat by 1.69 CHF per kg. For pork, the price decreased drastically by 1.80 CHF per kg initially (Fig. 3b) and then almost recovered by 2024, although it was still substantially lower than in the reference scenario.

The difference in prices between the reference scenario and the tax scenarios appeared to become smaller over time in the case of raw milk and pork. The price of milk was slightly higher in the 'Meat' scenario than in the reference scenario, although only for a short period, because milk production is linked to beef production and a reduction in beef quantities will inevitably decrease milk production. As raw milk is considered only indirectly in the market module, the model cannot estimate the net imports, production and consumption for milk and milk products. In the scenario with the tax on meat and milk products, the price of milk developed in parallel with the 'Meat' scenario from 2015 to 2018 and remained at some points at the same level as for the reference scenario (Fig. 3d). Because wheat was not taxed, the price remained at the same level in all scenarios (Fig. 3e).

3.2. Sensitivity analysis of marginal N surplus abatement costs of individual agents

In this section, we present the sensitivity of selected individual model agents. The MAC were negative for some agents (Fig. 4) due to the negative PMP cost function term (Eq. 1) that corrects for non-optimal behaviour in the base year. For farms with sub-optimal production, a decrease in N inputs often led to an increase in income because cost savings were higher than the revenue loss. The difference between the first and third quantiles of the MAC signifying the interquartile range

Table 3
Characterisation of average farm types represented in the sensitivity analysis. Note that, due to the confidentiality of the data, we cannot provide the data of selected agents (LU = livestock unit; N = nitrogen).

Farm type	Agricultural Area [ha] (Hoop and Schmid, 2013)	Average annual animal stocking from the base year [LU](Hoop and Schmid, 2013)	Estimated N surplus [kg ha^{-1} yr^{-1}] (own calculations)
Arable	20.4	0.7	81.5
Dairy	14.4	18.8	157.6
Suckler cow	14.6	12.3	43.7
With other cattle	16.9	15.6	76.6
Sheep and goat	11.9	10.6	34.8
Pig	12.9	36.7	136.3
Mixed dairy and arable	26.7	34.9	37.5
Mixed suckler	35.0	30.7	41.9
Mixed pig	18.4	39.6	147.2
Other	20.5	28.4	62.7

Table 4
Estimated changes in various indicators of Swiss agriculture modelled by the SWISSland model for two output tax scenarios at sectoral level in comparison with the reference scenario in the year 2024. The 'Meat' scenario refers to the food tax applied to meat, whereas the 'Milk & Meat' scenario refers to the food tax applied to both meat and milk products. (LU = Livestock unit; CHF: Swiss Franc (1CHF ~1.1$)).

Indicator	Unit	Reference	Meat [%]	Milk & Meat [%]
N surplus	kg N ha^{-1}	91.0	−2.1	−2.3
Average farm income	CHF	72,081	−5.6	4.2
Number of farms		43,021	−6.6	−7.7
Fertiliser use	t	43,306	−3.6	−3.5
Concentrate use	t	829,083	−1.9	−2.8
Open arable land	1000 ha	233	−4.8	−4.8
Permanent grassland area	1000 ha	677	2.3	2.8
Ecological compensatory area	1000 ha	154	5.0	7.5
Numbers of animals	1000 LU	1256	−6.8	−7.1

Table 5
Estimated changes in prices, consumption, production and net import of meat and the price and processed amount of milk modelled by the SWISSland model for two output tax scenarios in comparison with the reference scenario in the year 2024. The 'Meat' scenario refers to a food tax applied to meat, whereas the 'Meat & Milk' scenario refers to the food tax applied to both meat and milk products.

		Reference	Meat	Milk & Meat
Milk	Producer price of milk [CHF l^{-1}]	0.66	3.5%	2.3%
	Processed milk [1000 t]	3598	−1.9%	−3.2%
Beef	Production [1000 t]	107	−1.9%	−2.1%
	Consumption [1000 t]	140	−0.4%	−0.2%
	Net import [1000 t]	55	4.7%	6.0%
	Price [CHF kg^{-1}]	8.2	−14.3%	−14.3%
Pork	Production [1000 t]	235	−36.7%	−35.7%
	Consumption [1000 t]	253	−18.6%	−17.5%
	Net import [1000 t]	17	229.9%	232.5%
	Price [CHF/kg]	5	−17%	−17.0%
Poultry	Production [1000 t]	87	−32.9%	−35.0%
	Consumption [1000 t]	144	−1.5%	−0.5%
	Net import [1000 t]	55	50.7%	54.4%
	Price [CHF kg^{-1}]	3.7	−28.7%	−28.7%

ranged from 0.3 CHF for the mixed pig farm to 3.0 CHF for the sheep and goat farm (Fig. 4e and h).

For most agents, except for the mixed arable farm (Fig. 4g), the results of Spearman's correlation and Sobol's decomposition point towards similar patterns of MAC sensitivity with respect to the studied factors. In the case of mixed arable farming, the Sobol's interaction indices are larger, indicating more complex relationships. In addition, Spearman's rank correlation showed high positive and negative Spearman's ranks for the mixed arable farm. The sensitivity analysis for the other agents revealed only minor interaction effects between the factors, and the Spearman ranks are mostly one-directional.

For the arable farm, both sensitivity analyses consider the price of maize as the most influential factor defining the N surplus MAC (Fig. 4a). Additionally, the Sobol indices detect a higher level of MAC sensitivity to rape seed, while the correlation-based rank associated a higher level of MAC sensitivity with the price of sunflower, sugar beets, payments for grassland and payment for cultivation. There are no significant interactive effects on MAC. Furthermore, all the evaluated factors correlate negatively with the response variable, except for the price of rape seed, wheat and sheep meat. This suggests that lower producer prices would lead to higher abatement costs on N surplus.

For the dairy farm (Fig. 4b), the Sobol main index and the correlation rank show the highest MAC sensitivity to the price of milk. The MAC sensitivities are almost identical between the two sensitivity approaches. Interactive effects between the considered factors are almost negligible. Remarkably, food security payments correlate positively with the abatement cost, indicating that for this agent the new payment for food security makes it more difficult to meet the goals for N surplus reduction.

Both the Sobol's main index and the Spearman's rank correlation reveal that the price of sucker cows is the most influential for N surplus MAC on the suckler cow farm (Fig. 4c). In addition, the payments for food security and for organic farming correlate positively with the abatement costs, suggesting synergies in their effects. Interactive effects between the factors on N surplus MAC are negligible for this agent.

MAC sensitivity to selected factors estimated by rank correlations and by Sobol's main indices shows a very similar pattern for the beef farm other than dairy or suckler cows (Fig. 4d), with the price of beef having the highest impact on N surplus MAC, followed by prices of horses, dairy cows and milk. However, the order of MAC sensitivity to the most influential factors differs between the two sensitivity indicators. The Sobol main index indicates that MAC has higher sensitivity to horse prices and lower sensitivity to milk prices than the rank correlation. The Sobol's interaction index is almost zero for all factors considered in the analysis for this agent.

For sheep and goat farm, the price of sheep consistently shows the highest influence on MAC of all factors according to the rank correlation

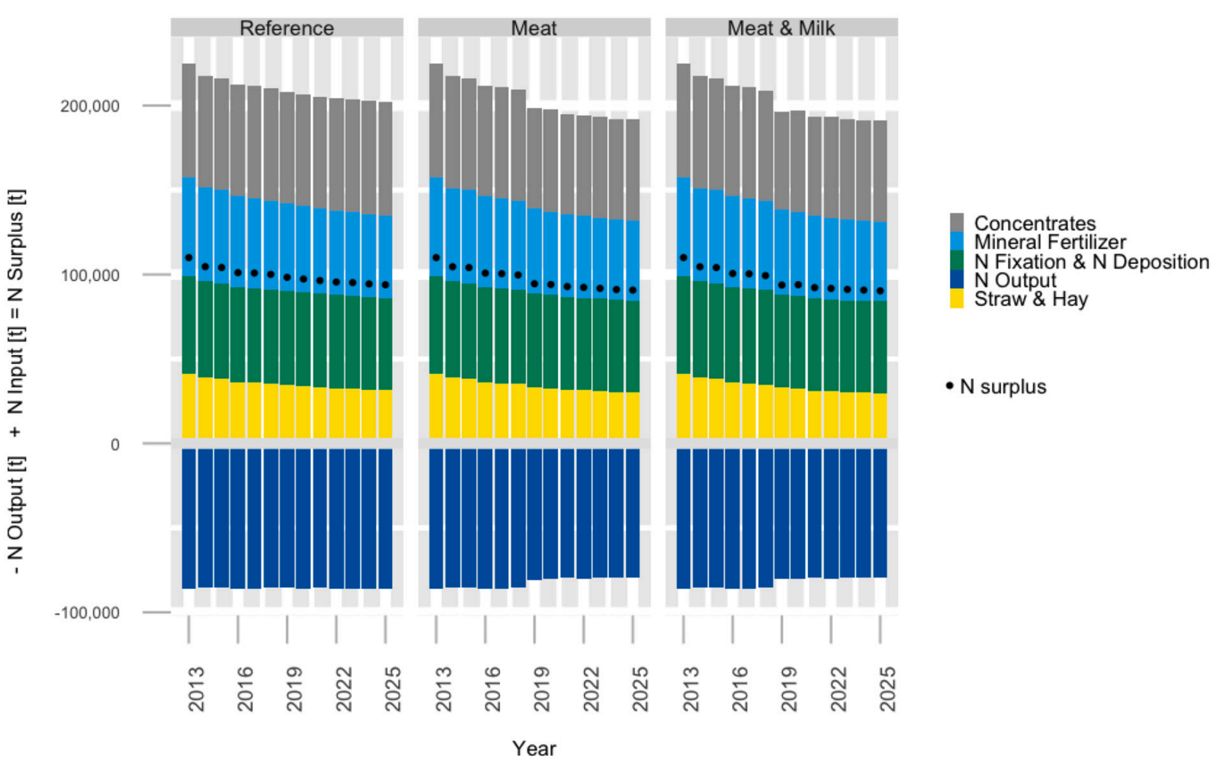

Fig. 2. N SURPLUSES and associated nitrogen (N) inputs and outputs (kg N ha^{-1} yr^{-1}) of SWISS AGRICULTURE estimated with the SWISSland model for 2013–2025 at sectoral level for a) the reference scenario, which considers the agricultural policy introduced in 2014 (AP 14–17), b) the meat scenario where meat is taxed, and c) the milk and meat scenario where both milk and meat are taxed.

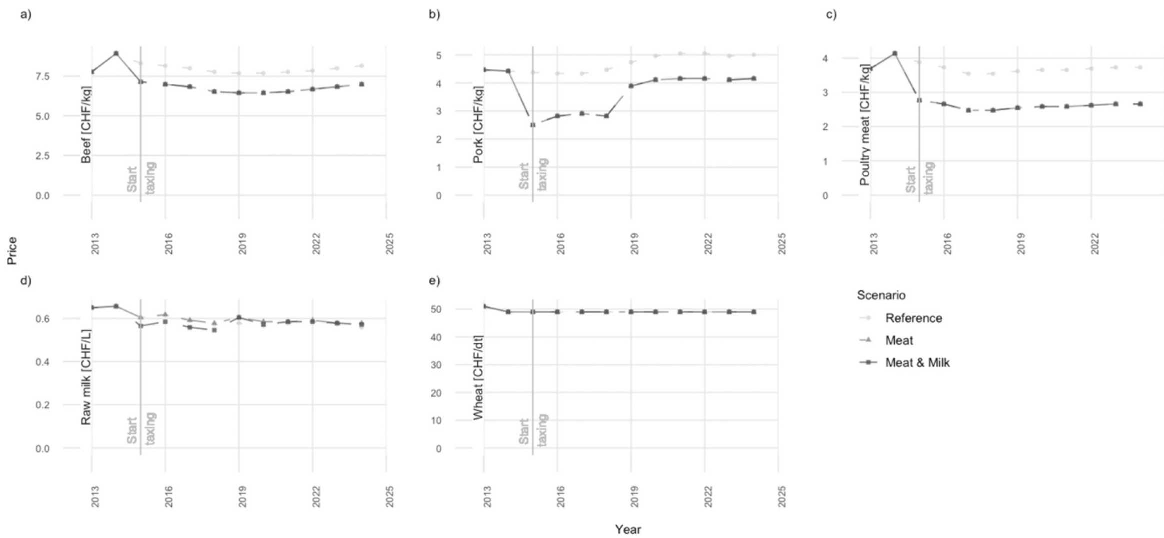

Fig. 3. Projected agricultural product prices during the study period for a) beef, b) pork, c) poultry meat, d) raw milk and e) wheat in the reference scenario, the meat output tax scenario and the meat and milk products output tax scenario. Prices are presented as three-year rolling averages.

and Sobol's main index (Fig. 4e). The payment for food security increases N surplus abatement costs. The payment for animal welfare shows no influence in the Sobol analysis, while the rank correlation reveals a correlation between this factor and the MAC. The interaction effects between the factors are negligible for this agent.

The correlation rank shows the price of milk to be the most influential factor, while the Sobol's main index reveals the price of suckler cows to have the highest effect on MAC on the pig farm (Fig. 4f). Again, no interactions are revealed that would explain the difference in the most influential factors. However, the model considers a direct relationship between price of beef and price of suckler cow.

In the mixed arable and dairy farm, a high level of interaction is observed between the factors in their influence on N surplus MAC (Fig. 4g). The Sobol's main indices show a different pattern of MAC sensitivity than the correlation rank. While the Spearman's rank correlation indicates that the highest MAC sensitivity is associated with the prices of wheat, beef, milk and barley, the Sobol main indices indicate that the MAC is mainly influenced by the price of barley, sugar, milk and payments for cultivation. Almost all considered factors influence the N surplus MAC to some extent according to the Sobol main indices, apart from the price of beef, while the price of suckler cow is negligible in Spearman's rank correlation. This seems to be the same as in Fig. 4f. For the prices of wheat, beef and barley, no interactions were identified; despite this, the Spearman's rank correlation shows some levels of sensitivity of MAC to them. Conversely, interaction effects of prices of sugar, rapeseed, milk and payment for cultivation with other factors are highly influential on the variation of the MAC. The price of potatoes correlates negatively with the MAC.

The MAC of N surplus on the mixed pig farm is consistently most sensitive to the price of potatoes, as indicated by both Sobol's main index and Spearman's rank correlation (Fig. 4h). The interaction effects between the factors are more noticeable than in other examples, e.g. in the case of the potato price, where the Spearman's rank correlation shows a negative relationship. The Spearman's rank relationship shows a negative correlation between MAC and the price of potatoes and a positive correlation with the price of rapeseed, horses and barley, which do not appear as influential in the Sobol sensitivity analysis.

For the remaining type of farm, the price of barley is the most influential factor as indicated by both the Sobol's main index and the Spearman's rank correlation (Fig. 4i). The price of wheat also has some influence on MAC according to both sensitivity methods. The interaction effects between the factors considered for this agent are only minor. The rank correlation indicates a degree of MAC sensitivity to the payments for food security, which is not confirmed by the Sobol sensitivity analysis.

Overall, the results of both Sobol indices and rank correlations are very similar for specialized farms, while more interaction effects as well as differences between the rank correlation and Sobol indices are observed for mixed farms. The effects of the factors considered in the analysis have very distinct influences on N surplus MAC of individual agents; most of them have a positive influence, thus increasing the N surplus MAC on the farms where they are increasing. The price of milk is an influential factor for N surplus MAC on all farms focusing on milk and it increases the MAC, but on farms where milk production has a minor role, MAC are not sensitive to milk price and correlate negatively with it (e.g. Fig. 4i). Prices of suckler cows and beef are confounded in the model (demand for beef influences the demand for suckler cows), so one method associates all the influence on MAC with beef while the other associates it with suckler cows. The prices of fattening pigs and dairy cows and the payments for animal welfare and for the ecological compensatory area have negligible effects on the N surplus MAC among the agents. Overall, the influence of direct payments on MAC is smaller than the influence of product prices for all farms.

4. Discussion

Our results show that the tax applied to meat only reduced the sectoral N surplus by 2.1% and in the 'Milk & Meat' scenario by 2.3% over the simulation period 2015 to 2025 compared to the reference scenario. Meat prices were increased by 17 to 65% compared with those in the base years due to the introduction of the tax.

These low responses can be explained by three factors:

1) Prices did not seem to affect the demand for products to the extent that would be necessary to meet the agri-environmental goals, as the demand for food in Switzerland is rather inelastic due to the low proportion of income spent on food. Higher food prices will also encourage cross-border shopping where food prices are lower.

2) Price feedback led to a higher milk price than in the reference scenario. Agents with a high proportion of milk production might increase their milk production as the marginal abatement costs increase and thus the opportunity costs to move to other farm activities increase. In some agents, higher prices for specific products lead to a lower MAC

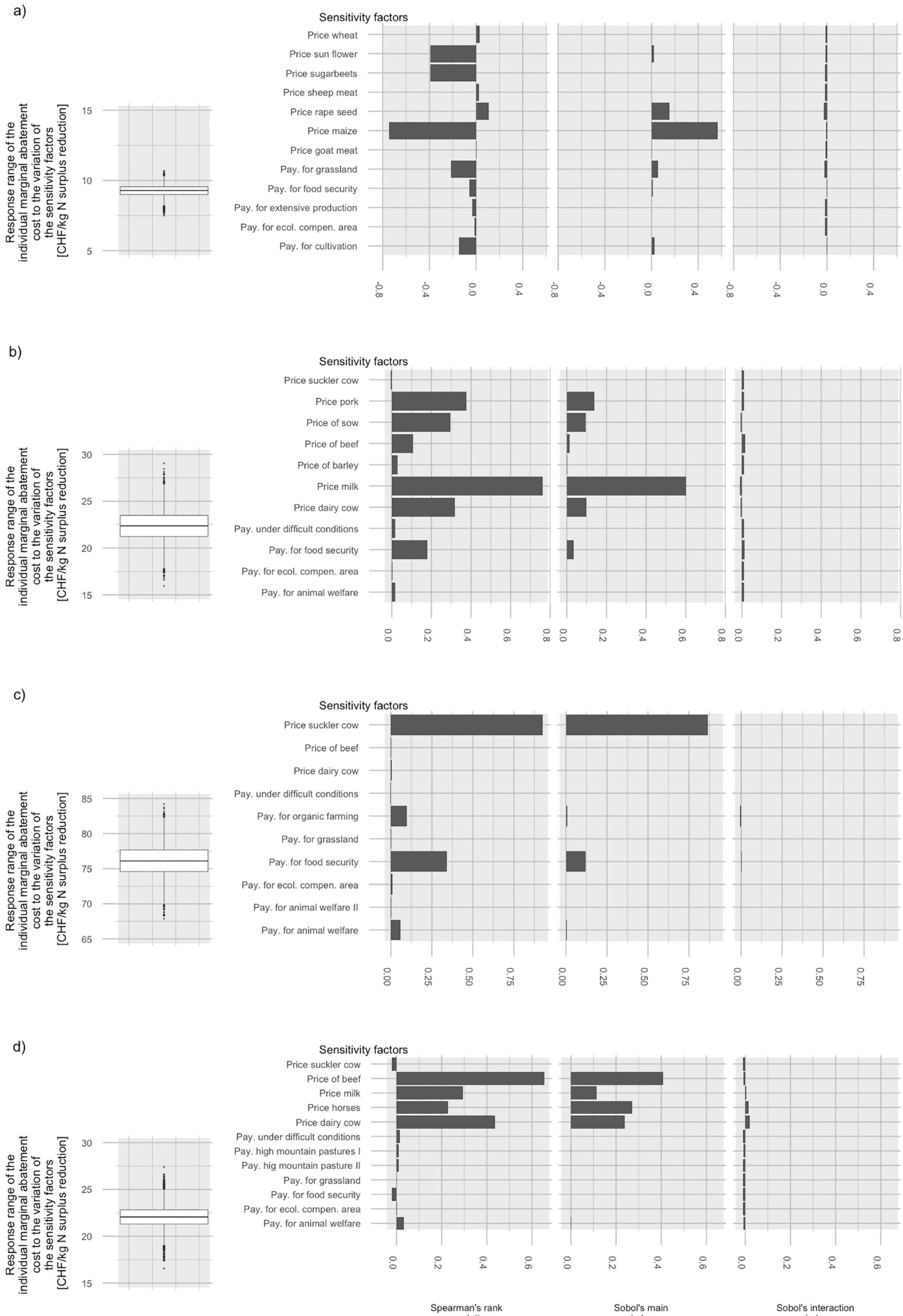
a)
Sensitivity factors
Price wheat
Price sun flower
Price sugarbeets
Price sheep meat
Price rape seed
Price maize
Price goat meat
Pay. for grassland
Pay. for food security
Pay. for extensive production
Pay. for ecol. compen. area
Pay. for cultivation
b)
Sensitivity factors
Price suckler cow
Price pork
Price of sow
Price of beef
Price of barley
Price milk
Price dairy cow
Pay. under difficult conditions
Pay. for food security
Pay. for ecol. compen. area
Pay. for animal welfare
c)
Sensitivity factors
Price suckler cow
Price of beef
Price dairy cow
Pay. under difficult conditions
Pay. for organic farming
Pay. for grassland
Pay. for food security
Pay. for ecol. compen. area
Pay. for animal welfare II
Pay. for animal welfare
d)
Sensitivity factors
Price suckler cow
Price of beef
Price milk
Price horses
Price dairy cow
Pay. under difficult conditions
Pay. high mountain pastures I
Pay. hig mountain pasture II
Pay. for grassland
Pay. for food security
Pay. for ecol. compen. area
Pay. for animal welfare
Response range of the individual marginal abatement cost to the variation of the sensitivity factors [CHF/kg N surplus reduction]
Spearman's rank correlation
Sobol's main index
Sobol's interaction index

Fig. 4. Global sensitivity analysis and uncertainty range of the marginal abatement costs for a 20% reduction of N surpluses on individual a) arable farm, b) dairy farm, c) suckler cow farm, d) other cow farm, e) sheep, goat or horse farm, f) pig farm, g) mixed dairy and arable farm, h) mixed pig farm, i) other farm for the year 2015: Spearman rank correlation coefficients refer to a correlation-based sensitivity measure associated with individual sensitivity factors (range from −1 to 1), while the Sobol main index is a variance-based measure of sensitivity considering all sensitivity factors (range 0 to 1) as well as the interaction indices (range slightly negative due to residual errors to 0).

because the farmer invests more in this activity to have higher returns with lower N surplus. An example is the price of potatoes in the mixed pig farm (Fig. 4h).

3) Divergent reactions of agents to price changes buffered the effect of a food tax on the N surpluses at sectoral level. Our sensitivity analysis of nine selected model agents showed that the MAC of representative agents of distinct farm types responded non-uniformly to varying prices (see Fig. 4a to i). The most influential product price differed among the selected agents, so that the tax did not affect all agents evenly. This reduced the overall effectiveness of the tax.

The strongest effect on the N surplus was observed for the model agents that stopped farm activities in response to the imposed tax. This response might be due to the limited possibilities to counterbalance the tax expense with a lower input of fertilizers or feed to reduce costs. Direct payments are mostly moderately positively correlated with the MAC of the examined agents. The payment for food security had an effect in the sheep, goat and horse farm.

Previous studies have suggested that food taxes do not lead to better environmental performance in production. Food taxes offers no incentive for more environmentally friendly production and thus its effect on environmental impact is rather small (Edjabou and Smed, 2013). Particularly in terms of N pollution, a differentiated policy is needed because uniform policies do not consider local critical loads that should not be exceeded. An effective policy needs to integrate a global approach to prevent spatial pollution swapping, a specific approach that addresses local problems such as soil conditions or sensitive ecosystems (Jayet and Petsakos, 2013) and an approach considering consumer patterns to reduce the total N footprint of consumption (Galloway et al., 2014). However, many countries only apply uniform instruments, as it is difficult to determine the individual's contribution to N pollution (Hasler et al., 2019).

Säll and Gren (2015) also showed that consumers appeared to be more sensitive to changes in meat prices than to milk prices. They explained the lower response to the milk prices by the relatively inelastic demand for milk. Abadie et al. (2016) found that an output tax had the potential to reduce environmental emissions by 10% with a 40% beef price increase in Norway. Similarly, Edjabou and Smed (2013) reported that an output tax of 0.15–1.73 Danish krone per kg of greenhouse gas emissions could reduce such emissions by 10–20% in Denmark. The study by (Gren et al. (2019)) estimated that, in a perfect market, Sweden could reduce greenhouse warming potential by 16% to 25% by applying a tax level of between 30% and 45% on beef. These studies show higher responses to a tax than our study does, due to different indicators. Jansson and Säll (2018) found low demand and supply elasticities when they simulated a greenhouse gas tax of up to 290 Euro per t using the CAPRI model for the European Union.

The uncertainty of the abatement costs with varying prices and direct payments was low and was caused mostly by changes in prices. Direct payments are decoupled from production and should therefore have only a minor effect on production and thus the associated N losses. However, our analyses indicate that prices and direct payments tended to have contrasting effects on N surplus MAC for different agents of distinct farm types and for most agents one single key factor was associated with the variation in N surplus MAC. This was one reason why the total effect of price changes on MAC tended to be small. Lengers et al. (2014) reported that greenhouse gas abatement costs were influenced by the type of indicator chosen: simpler indicators that considered only animal numbers or crop type showed higher abatement costs than specific indicators that also considered management options such as feeding strategies. This suggests that the MAC might be overestimated as the farm gate balance is less differentiated.

We were not able to include potential adaptations of consumer behaviour (e.g. changing consumer patterns due to more environmental awareness caused by information-based instruments that would accompany such a policy intervention) or producers behaviorus (e.g. introduction of N use efficient measures) in the model. This could lead to an underestimation of the effectiveness of the tax. The described scenarios are very rough instruments without a possible redistribution of tax benefits to lower the social impacts of such a tax, which would affect the demand elasticities or more differentiated tax levels depending on the products. Also, vegetable, which have also a high N foot print, were neglected as they are not represented in the market module due to their high variety of products. Instead of using more sophisticated indicators for levying the tax, we decided to have a more differentiated look at the effects of prices on the agent's level. In addition, due to a high computational cost, we only were able to analyse a subset of nine individual agents representative of the various farm types in the SWISSland model. We are therefore unable to make any statements regarding the total uncertainty of up-scaled results or the most influential factors at sectoral scale.

Comparing the two methods used to calculate the sensitivity of MAC to the prices of agricultural products and direct payments showed that Sobol's indices and Spearman's rank correlation led to very similar results for farms specialising in livestock, despite considering different criteria to calculate the sensitivity of the response variable. The Sobol's method considers the associated variance, while the Spearman's rank correlation considers the strength of a relationship between the response variable and the evaluated factor. Our results are consistent with other studies comparing Sobol indices and Spearman rank correlations (e.g. Botshekan et al., 2019). However, mixed farms showed that a less robust Spearman rank correlation is not an adequate measure of MAC sensitivity on more complex farms, specifically because it considers one factor at a time and does not take account of interaction effects.

5. Conclusions

Output taxes such as taxes on products with a high environmental impact have advantages over emission or input measures in cases where monitoring costs are high, technical solutions are restricted and output substitution is possible. These conditions are mostly satisfied in the case of diffuse N pollution. However, our agent-based SWISSland model showed that an output tax on meat and on meat and milk products has a limited effect on N surplus in Swiss agriculture. The reasons behind the low effectiveness are that not all agents' MACs are affected by the same products. Therefore, the differing effects of prices between various agents representing distinct farm types need to be considered when developing effective output tax instruments. It is most likely that increased product prices alone will not change demand to the extent that would be necessary to reach Swiss agri-environmental goals. Other approaches are needed, involving changes in both producer and consumer behaviour. On the producer side, spatial pollution swapping should be prevented by a global instrument and specific instruments are needed to address local conditions. However, the N footprint of consumption should be reduced either by means of better informing the consumer or by more targeted approaches that consider the actual environmental impact of each product differentiated for the production conditions.

The global sensitivity analysis showed that the prices of agricultural products had different effects on the N surplus MAC of the various

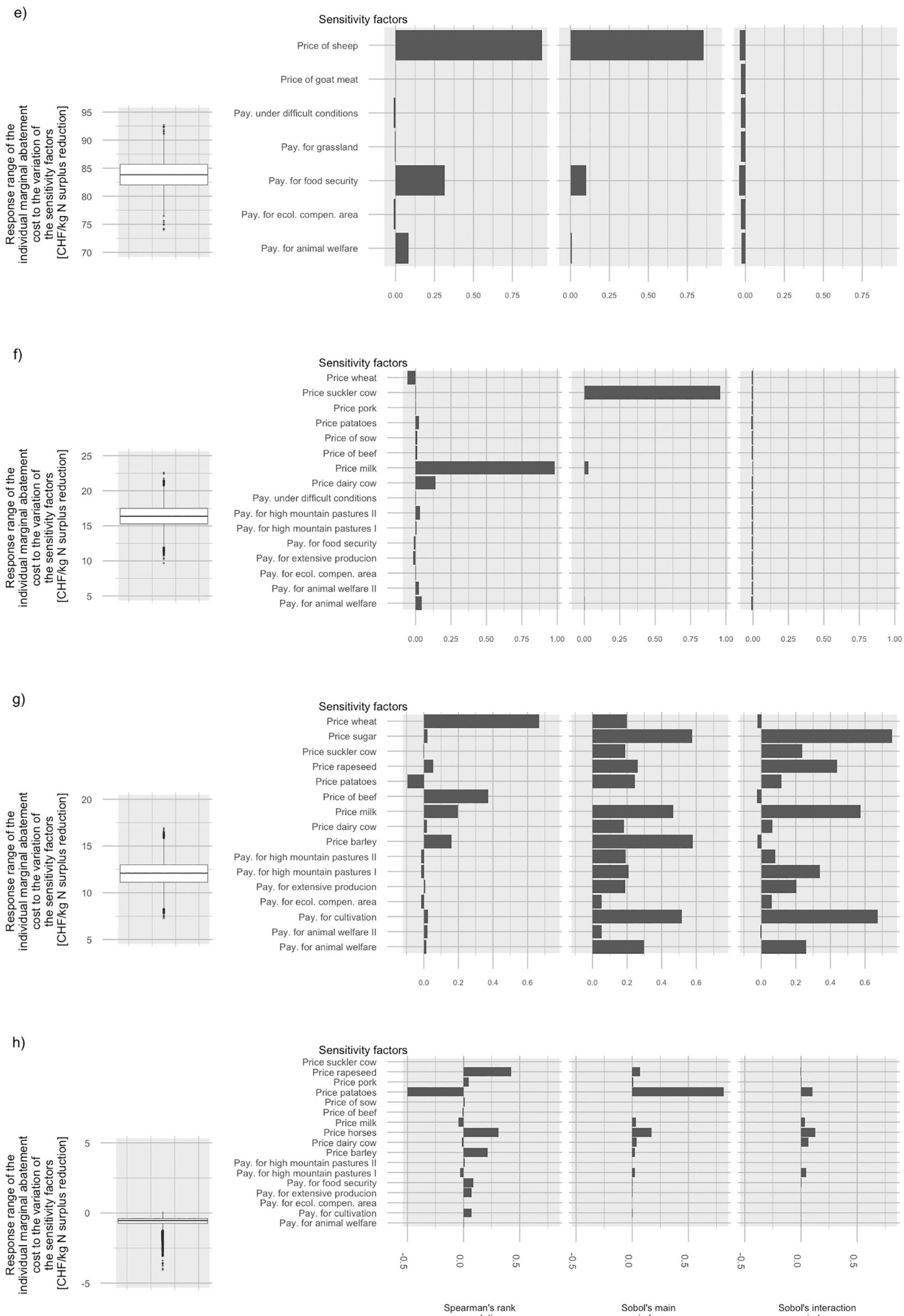

Fig. 4. (*continued*).

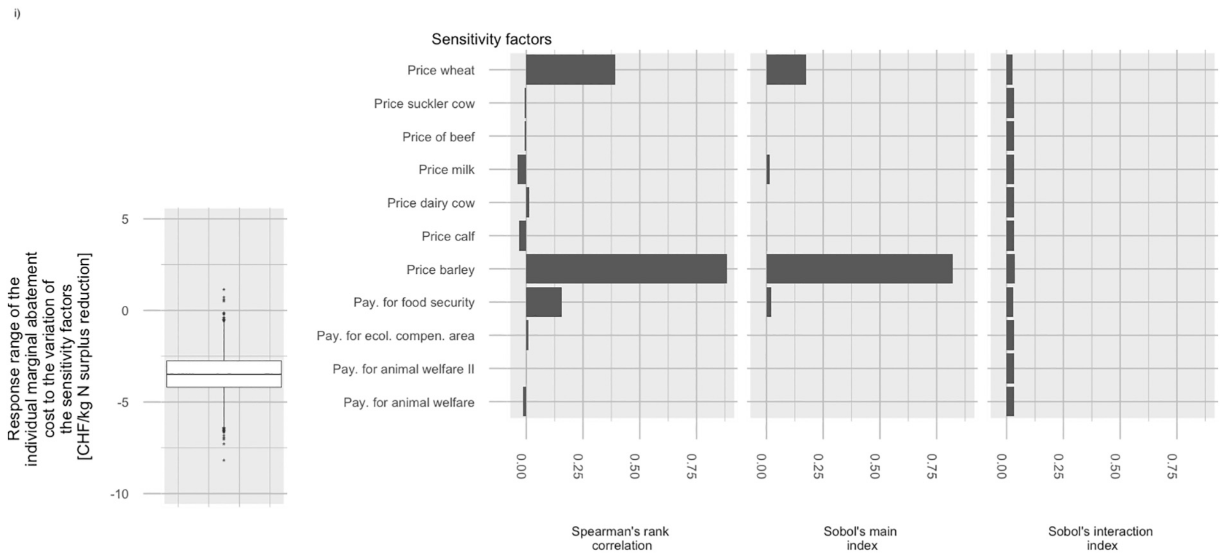

Fig. 4. (*continued*).

modelled farm types. Comparison of the Sobol indices and Spearman rank correlations revealed that both methodologies produced similar MAC sensitivities for farms specialising in animal production. However, where higher complexities had to be considered, as in the case of mixed farms, the results of these two methods differed and Spearman ranks were considered insufficient to address the MAC sensitivities.

Declaration of Competing Interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2021.103271.

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