

## Strategies to mitigate greenhouse gas and nitrogen emissions in Swiss agriculture: the application of an integrated sector model

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# Strategies to mitigate greenhouse gas and nitrogen emissions in Swiss agriculture: the application of an integrated sector model

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## Abstract

Environmental impacts of agricultural production, such as greenhouse gas (GHG) and nitrogen emissions, are of major concern for scientists and policy makers throughout the world. Global agricultural activities account for about 60% of nitrous oxide and about 50% of methane emissions. From a global perspective, methane and nitrous oxide constitute crucial GHGs. They contribute substantially to climate change due to their high potential for effecting global warming compared to carbon dioxide. Emissions of these gases depend on the extent of agricultural production and applied technologies. Therefore, analysis of potential mitigation opportunities is challenging and requires an integrated approach in order to link agricultural economic perspectives to environmental aspects. In view of this, a mathematical programming model has been developed which enables assessment of cost-effective strategies for mitigating GHG and nitrogen emissions in the agricultural sector in Switzerland. This model is applied to improve understanding of the agricultural sector and its behavior with changing conditions in technology and policy. The presented recursive-dynamic model mimics the structure and interdependencies of Swiss agriculture and links that framework to core sources of GHG and nitrogen emissions. Calculated results for evaluation and application indicate that employed flexibility constraints provide a feasible approach to sufficiently validate the described model. Recursive-dynamic elements additionally enable adequate modeling of both an endogenous development of livestock dynamics and investments in buildings and machinery, also taking sunk costs into account. The presented findings reveal that the specified model approach is suitable to accurately estimate agricultural structure, GHG and nitrogen emissions within a tolerable range. The model performance can therefore be described as sufficiently robust and satisfactory. Thus, the model described here appropriately models strategies for GHG and nitrogen abatement in Swiss agriculture. The results indicate that there are limits to the ability of Swiss agriculture to contribute substantially to the mitigation of GHG and nitrogen emissions. There is only a limited level of mitigation available through technical approaches, and these approaches have high cost.

**Keywords:** resource use, environmental economics, greenhouse gas emission, nitrogen emission, integrated modeling

# 1 Introduction

Over the last decades, the contribution of agricultural production to climate-relevant emissions has emerged as a major concern for scientists and policy makers. From a global point of view, carbon dioxide (CO<sub>2</sub>) from fossil fuel use and deforestation is the most important anthropogenic greenhouse gas (GHG), representing 77% of total anthropogenic GHG emissions in 2004 (IPCC, 2007a). Methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) constitute crucial non-CO<sub>2</sub>-GHGs, accounting for 14% and 8%, respectively, of total anthropogenic GHG emissions in 2004. About 60% of nitrous oxide and about 50% of methane are associated with agricultural activities such as keeping livestock and soil cultivation (IPCC, 2007a). Methane and nitrous oxide substantially contribute to global warming because their potentials for effecting global warming are 21 (methane) and 310 (nitrous oxide) times higher, respectively, than that for carbon dioxide (CO<sub>2</sub>) (IPCC, 2007b). Therefore, emissions of methane and nitrous oxide are of special relevance. The potential of agriculture to contribute to GHG mitigation at a relatively low cost is the subject of recent studies (cf. EPA, 2006a; Beach et al., 2008; UNFCCC, 2008).

Diffuse nitrogen emissions through agriculture act as another main source for harming the climate. General nitrogen emissions can result in further GHG production: Mineralization of nitrogen in soils results in the release of ammonium (NH<sub>4</sub><sup>+</sup>) or ammonia (NH<sub>3</sub>). In the process of nitrification, ammonium is oxidized via nitrite (NO<sub>2</sub><sup>-</sup>) to nitrate (NO<sub>3</sub><sup>-</sup>). Ammonium and nitrate that are not taken up by the plant can get lost to the atmosphere or hydrosphere. Nitrate can easily be leached down into the ground water and both nitrite and nitrate can be denitrified to nitrous oxide (McNeill and Unkovich, 2007). Therefore, ammonium can act as an indirect GHG as well. As a result, nitrogen losses, such as ammonia and nitrate, are subject to several international agreements (e.g., OSPAR, 2003). Emissions of GHG and nitrogen are related to the extent of production, applied technologies and existing structures in

agriculture. Both the high degree of heterogeneity in farming practices and the transboundary character of GHG and nitrogen emissions make an assessment of additional mitigation potential challenging.

Therefore, assessment of mitigation strategies necessitates analysis at a more disaggregated level (e.g., national levels). In addition, the relationship with agricultural production implies links between GHG, the nitrogen cycle and other environmental factors. Thus, a holistic view of the agricultural production process is required in order to evaluate different mitigation strategies. However, Povelato et al. (2007) stated that an analysis comparing the cost-effectiveness of different mitigation measures, such as political and technical ones, is still an open issue.

This paper aims to describe and evaluate a normative mathematical programming model that enables assessment of strategies to mitigate GHG and nitrogen emissions in Swiss agriculture. The developed integrated modeling approach links the agricultural production process to environmental aspects. The model is applied at the national level and mimics agricultural production and its structural development in Switzerland.

The paper is organized as follows: Section 2 provides an overview of major caveats in mathematical programming models analyzing environmental aspects and deduces the requirements for an adequate modeling approach to our research question. Section 3 focuses on the methodological framework. The model setting and its specifications are presented in Section 4. Model evaluation and selected results from its application are given in Section 5. In Section 6, we discuss the methodological approach and the results obtained for evaluation and application. Conclusions are drawn in Section 7.

## 2 Problem statement

Agricultural production is a complex process, not only combining different marketable products but also affecting different environmental goods and services that are linked to each other and are not separable (Heal and Small, 2002). Therefore, improvements in the agricultural system have to be sought for the system as a whole and cannot be achieved by changes in one component without regard to the rest of the system (Spedding, 1987). Additionally, agriculture's effect on the environment varies substantially due to heterogeneity of the natural environment. An adequate approach is required both to understand and to manage agricultural resource use from an economic point of view.

Mathematical programming models are widely used in agricultural economics, primarily to analyze impacts on the agricultural sector due to changing conditions, such as policies or technologies. A wide range of different mathematical programming models exists, from disaggregated single farm optimization models to highly aggregated sectoral models (Heckelei et al., 2001). These models feature specific characteristics that fit their various purposes. However, the motivation behind these models is straightforward: mathematical programming models are based on a sound theory (neoclassical economics). In this theory, economic agents are profit optimizers. Combined with limited resources, represented by model restrictions, these normative model approaches incorporate the fundamental economic problem: making the best out of limited resources (Buysse et al., 2007). Applying such normative approaches focuses either on seeking an optimal solution for this economic problem or on gaining an improved understanding of such a problem. In the latter case, one might not be interested in an optimal solution itself, but rather in discovering decisive variables of the economic problem (Buysse et al., 2007).

In order to combine these economic aspects with biophysical/environmental aspects of farming activities, an integrated modeling approach is required (Payraudeau and van der Werf, 2005; Parker et al., 2002; van Ittersum et al., 2008). Applying integrated model approaches is especially meaningful in analysis of the environmental impacts of agriculture through a centralized pool of data and a common set of functions and assumptions. Thus, integrated model approaches enable consistent calculation of emission parameters, taking into account the physical linkages between agricultural activities (Pérez Domínguez, 2005). They permit a precise description and easy modeling of production sets through constraints and technical parameters (De Cara and Jayet, 2000). The easy modeling of production sets is important in modeling animal feeding-driven methane emissions, for instance, which are not only determined by prices but also by the minimal levels of nutrition requirements for each animal type.

When mathematical programming models are used to predict farmer's reactions to changing conditions, calibration to real world data is challenging. Assumptions and results of such model types can deviate from real world data for several reasons (Wiborg et al., 2005): (1) aggregation of individual farms, (2) absence of detailed data (production functions, transaction costs and prices), (3) lack of market information, (4) differences in the objective function (e.g., risk behavior) and (5) the issue of overspecialization. The methods are miscellaneous to overcome these drawbacks. Positive Mathematical Programming (PMP) is a common approach to improve the validity of sector models by using non-linear cost terms in the objective function. The non-linear cost terms are specified by opportunity costs of each activity (Howitt, 1995). Thus, PMP allows a subtle convergence of model results to real world data. However, applying PMP might lead to discretionary modeled behavior, usually due to the use of single observations to specify PMP terms (Heckelei and Wolff, 2003). Therefore, the PMP approach has been further developed

in different ways (de Frahan et al., 2007; Heckelei and Britz, 2005). Estimation of elasticities can help the model cope with the lack of data (Howitt, 2005). Other solutions to deal with overspecialization and calibration problems are the introduction of flexibility constraints (e.g., through recursive modeling), incorporating risk adverse behavior and demand-based approaches.

Implementation of dynamics constitutes another challenge in applying mathematical programming models to analyze several options for mitigating GHG and nitrogen emissions. Environmental impacts strongly depend on both agricultural production structure and employed technologies. However, short- and medium-term developments in agricultural production depend on existing agricultural endowment (Johnson and Quance, 1972) and are often path dependent (Balmann et al., 1996). In this context, sunk costs and investments play an important role in predicting future developments of agricultural structures and their corresponding effects on environmental assets.

Given the strengths and the challenges of applying mathematical programming models, construction of an analytical tool to assess mitigation strategies in GHG and nitrogen emissions for Swiss agriculture over the medium term must focus on three factors:

- combining environmental and economic parameters in an integrative approach,
- considering dynamics and interlinkages in agriculture to mitigate GHG and nitrogen emissions,
- validating the model with observable real world data.

The purpose of the following model is to economically evaluate political and technological mitigation opportunities for agriculture in Switzerland. This model (1) provides guidance for monitoring and decision-making and (2) facilitates gaining a better understanding of the Swiss agricultural system and its behavior.

### 3 Methodological framework

Concerning GHG and nitrogen emissions, agricultural-sector models are suitable to assess impacts of changing conditions (Britz and Witzke, 2008; Pérez Domínguez, 2005). These types of models often include bio-physical/environmental parameters as well. They have been applied to assess impacts on both GHG emissions (Schneider et al., 2007) and nitrogen and GHG emissions together (Baranger et al., 2008).

In order to address the issues and purposes mentioned above, we developed a recursive, linear, sectoral, supply model of Swiss agriculture named S\_INTAGRAL (Swiss integrated agricultural allocation model). This model is based on a regional farm approach and covers the Swiss agricultural sector (national level). The methodological framework of our model is presented in Figure 1.

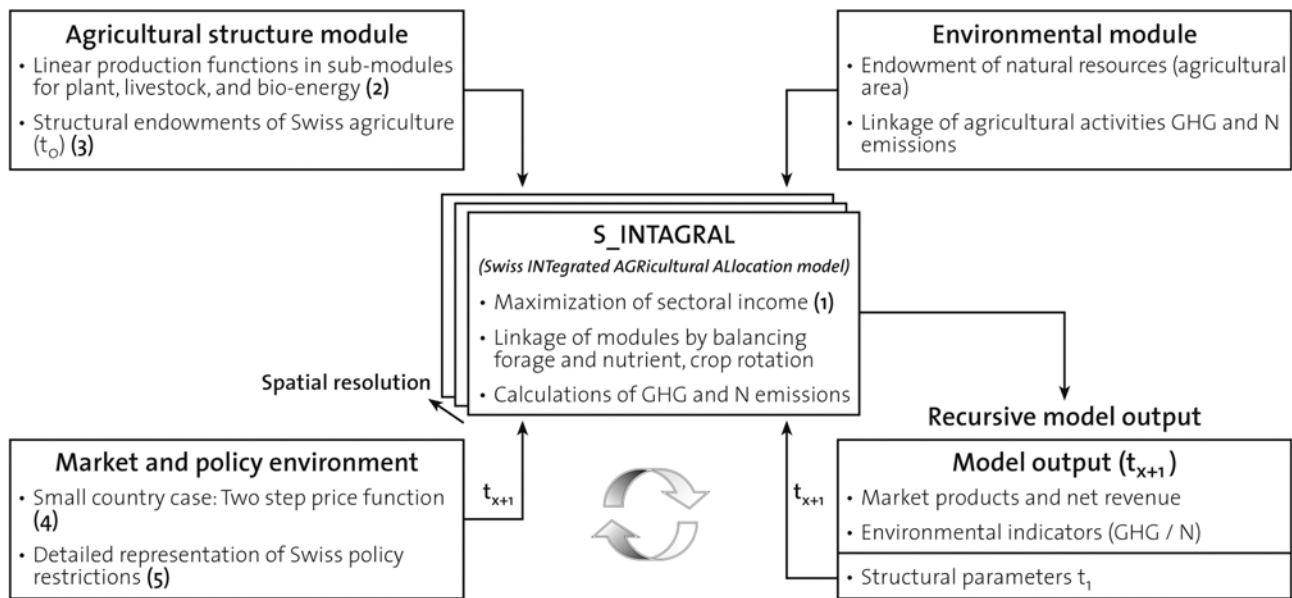


Figure 1: Methodological framework of S\_INTAGRAL



According to Hazell and Norton (1986), sector models contain five elements: (1) a description of producers' economic behavior and their decision rules (objective function), (2) a description of production functions and available technologies to relate yields to input, (3) a definition of the resource endowments (e.g., land, labor, initial stocks), (4) specification of the market environment and (5) specification of the policy environment of the sector.

In our framework, the sectoral income over all regions (or land units) is maximized assuming complete rational economic behavior (1). Production functions and available technologies are defined in the agricultural structure module, which includes relevant specifications of livestock and plant production and their interactions as forage or nutrient balances (2). Relationships between in- and outputs are linear. However, the model differentiates between several production technologies when representing a step like supply function. In order to minimize jumpy behavior of linear models and to address dynamics as well, a recursive modeling approach is applied (cf. Janssen and van Ittersum, 2007; Wallace and Moss, 2002; Day, 1978; Day and Cigno, 1978). In addition, the structure module accounts for the agricultural endowment (stables, agricultural area, labor supply, etc.) at a certain point in time (3). The market environment is modeled with a two-step price function. Thus, producer prices are assumed exogenous but differentiated between a higher and a lower price level. The latter is applied for surplus production that is not marketable on Swiss markets (4). This rather rough approach is sufficient because Switzerland is a small, open economy with no influence on world market prices and a well-equipped system of tariffs in the agricultural sector (however, these tariffs are in transition from border protection to market liberalization). The specification of the policy

environment in S\_INTAGRAL depicts in detail Swiss agricultural policies (5). It includes relevant forms of both general direct payments as well as ecological and ethological direct payments.

In addition to this standard implementation of an agricultural sector model, we added an environmental module. This covers indicators for carbon sequestration as well as emissions of GHG (methane, nitrous oxide, carbon dioxide) and nitrogen (ammonia, nitrate, nitrous and nitrogen oxides). Calculation of these indicators is based on recommended international and national methodologies. Thereby, we explicitly assess each kind of GHG and nitrogen emission according to agricultural structures and associated technologies. Furthermore, land-use intensities, pesticide application and participation in agri-environmental programs are assessed.

S\_INTAGRAL maximizes the output of a base year, taking into account empirical agricultural structure data. Optimal model output generates new structural parameters, which provide a basis for optimization in the next year. This iterative approach allows (a) continuous adaptation to changing output prices, (b) implementation of sunk costs by considering existing agricultural buildings and (c) adequate modeling of livestock population dynamics. Moreover, implementing population dynamics allows smooth flexibility constraints from an agricultural point of view to be introduced. Enlarging the population of livestock, for instance, is bounded by the extent of last year's breeding animals. Combining a recursive modeling approach with a step-like supply function, as well as legal constraints like crop rotation and milk quotas, effectively attenuated the tendency toward overspecialization, as shown in the results.

## 4 Model setting

The model setting will here be described in more detail, including the objective function, policy and market factors, agricultural structure, environmental factors and the data used both to parameterize and to validate the model.

### 4.1 Objective function

S\_INTAGRAL maximizes the agricultural sector income by subtracting aggregated costs from aggregated revenues of crop, livestock and biogas production (cf. eq. 1). This net profit compensates for area and labor beyond their opportunity costs.

The first term of eq. (1) describes sales of agricultural products derived from modeled activities. Revenues from direct payments are represented by the second term, taking into account direct payments for area as well as ecologically and animal-friendly farming activities. The third and fourth terms of eq. (1) summarize production costs, including both variable and fixed costs. Fixed costs are made up of depreciation and the interest rates for houses and machinery. Opportunity costs, in the sense of the minimal requirements for factor compensation for land use, are equivalent to the fifth term of eq. (1), while the last term takes into account opportunity costs for family labor and salaries for employees.

$$\text{Max } Z = \sum_y Y_y p_y + \sum_x X_x d_x - \sum_x X_x c_x^{\text{var}} - \sum_x X_x c_x^{\text{fix}} - \sum_x X_x l_x - \sum_x AK_x la_x \quad (1)$$

with:

*variables*

$Z$  = agricultural income [CHF]

$Y$  = quantity for market sale [t]

$X$  = livestock or area activities [ha or livestock unit]

$AK$  = labor [hours]

*indices*

$y$  = output products

$x$  = production activity

*parameters*

$p_y$  = price agricultural products [CHF/unit]

$d_x$  = direct payment specific to activity [CHF/unit]

$c_x^{\text{var}}$  = variable costs specific to activity [CHF/unit]

$c_x^{\text{fix}}$  = fixed costs specific to activity [CHF/unit]

$l_x$  = area lease costs [CHF/ha]

$la_x$  = labor costs [CHF/hour]

## 4.2 Policy

Our assessment also indicates the need to cover relevant policy instruments, which are therefore implemented adequately into the model. Environmental regulations for agricultural production were strengthened in 1992, bringing a major change to the Swiss agricultural sector. Stepwise decoupled farm payments have been introduced to link them to environmental objectives (e.g., water protection or reducing fertilizer input) and rural development objectives (e.g., contribution to hillsides or ensuring utilization of farmland). Since 1999, farmers have received general direct payments only if they meet the legal requirements of the so-called “proof of ecological performance” (PEP), which represents cross compliance (Herzog et al., 2008). For example, PEP prescribes a restricted use of fertilizer, crop rotation and an appropriate proportion of ecological compensation area to be set aside. General direct payments include those for total farmland, for sloping terrain in mountain areas, for grazing animals and for animals kept under difficult production conditions. More than 90% of Swiss farms are qualified to get these general direct payments. In addition to general direct payments, farmers can get ecological direct payments, e.g., for organic farming, extensive production and for particularly animal-friendly conditions.

## 4.3 Market

Since Switzerland is a small, open economy with no influence on world market prices and with a well-equipped system of tariffs, an incremental price function with two steps represents the demand in the S\_INTAGRAL framework (cf. Figure 2).

This means that a decreasing supply (equivalent to moving to the left along the supply curve in Figure 2) does not lead to increasing producer prices, but rather leads to increasing imports. In contrast, an increasing supply (equivalent to moving to the right along the supply curve in Figure 2) leads to increasing exports. Equation (2) denotes this relevant and adequate model feature.

Agricultural supply (denoted by  $Y$ ) is restricted to Swiss demand. The latter is represented by consumption per capita at the farmgate, the population and observed imports (cf. eq. 2). If agricultural supply exceeds Swiss demand, the surplus is marketable only by exports at a lower price level, which cannot be influenced by Swiss producers.

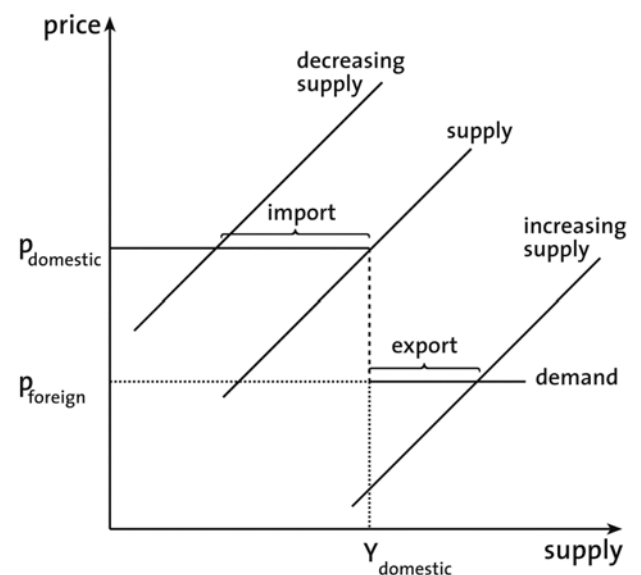


Figure 2: Incremental price function with two steps

$$p_{domestic} \text{ if } Y \leq Y_{domestic}, p_{foreign} \text{ if } Y > Y_{domestic} \text{ with: } Y_{domestic} = (K_{domestic} * P_{domestic}) - IMP \quad (2)$$

with:

variables

$P$  = producer price [CHF]

$Y$  = supply of livestock and plant products [t]

$K$  = consumption per capita at farmgate [kg/capita]

$P$  = population [population]

$IMP$  = imports [t]

indices

$domestic$  = Switzerland

$foreign$  = abroad

## 4.4 Agricultural structure module

Relevant activities of the Swiss agricultural sector and their interrelations are modeled, spatially split up into areas that are plains, hills and mountains.

### Plant production

Table 1 summarizes the underlying model specifications for plant production, including significant crops for market, forage and energy use at three intensity levels.

**Table 1:** Specifications for plant production

index	description	details
<b>z</b>	zone	n = 3 plain, hill, mountain
<b>b</b>	soil type	n = 2 mineral, organic
<b>bb</b>	soil cultivation	n = 2 plough, no-till
<b>k</b>	crops (market, forage, energy use)	n = 13 winter wheat, winter colza, potatoes, sugar beets, winter barley, triticale, protein peas, silage maize, grain corn, rotational fallow land, natural grassland, temporary ley, catch forage
<b>l</b>	intensity	n = 3 intensive, intermediate-intensive, extensive

$$\sum_k X^{area} * FF_k \geq 0; FF_k = \begin{cases} (1 - FF_{ff}^{max}) * -1, & k \in ff \\ FF_{ff}^{max}, & k \notin ff \end{cases} \quad (3)$$

with:

*variables*

$X^{area}$  = land use decision [ha]

$FF_k$  = coefficient for crop rotation [%]

$FF_{ff}^{max}$  = maximum share of acreage of (grouped) crops ff [%]

*indices*

$k$  = crop

$ff$  = (grouped) crops (e.g., cereals)

The core of modeling plant production is the distinction between crop acreage and the area of permanent grassland. Crop rotation on crop acreage is legally required to obtain direct payments. Therefore, a maximum share of each crop or grouped crops is defined as a legal limit, including also an ecological compensation area, as depicted in eq. (3).

Land use allocation (denoted by  $X^{area}$ ) depends on region, crop, production system and intensity (cf. Table 1), and it is restricted by a legal maximum share of (grouped) crops (denoted by  $FF_{ff}^{max}$ ). For example, the share of wheat on crop acreage is restricted to a maximum of 66%. Thus, the first part in eq. (3) would become negative if a solution results in the share of wheat exceeding 66%.

### Livestock production

Model specification for livestock production is shown in Table 2. Livestock production includes four animal species (cattle, swine, sheep and poultry) that are sub-classified into 13 animal types. Moreover, the system and the size of livestock houses, the livestock efficiency and management style are specified.

S\_INTAGRAL is driven with recursive dynamic development of the livestock population, which is parameterized in eq. (4) for dairy and suckler cattle.

**Table 2:** Specifications for livestock production

index	description	details
<b>z</b>	zone	n = 3 plain, hill, mountain
<b>ti</b>	animal type	n = 13 dairy cattle, suckler cattle, fattening calf, fattening bullock, rearing cattle, fattening swine, breeding swine, piglet, sheep, lamb, pullet, laying hen, broiler
<b>s</b>	house system	n = 13 cubicle house, deep litter house, tie stall barn (conventional), tie stall barn (liquid manure), swine fattening house (dual area box), swine fattening house (multi area box), swine breeding facility, piglet box, sheep house, baby cattle house, fattening cattle house, poultry house (dung channel), poultry house (manure)
<b>g</b>	house size	n = 7 15 places, 25 places, 40 places, 100 places, 200 places, 500 places, 4000 places
<b>l</b>	livestock efficiency	n = 8 5000_kg, 7000_kg, 9000_kg, Natura_Beef, low, high, standard, profi
<b>kf</b>	concentrate	n = 3 0%, 20%, 40% (of dry matter-ratio)
<b>a</b>	management style	n = 5 no pasture, part-time pasture, full pasture, run, no run

$$(1 - \eta) \cdot X_{(t-1)}^{cattle} \leq X_t^{cattle} \leq (1 - \eta) \cdot X_{(t-1)}^{cattle} + \alpha \cdot R_{(t-1)} \quad (4)$$

with:

*variables*

$X^{cattle}$  = dairy and suckler cattle activity [livestock unit]  
 $\eta$  = culling rate of cattle [1/life expectation]

$\alpha$  = survival rate of cattle [%]

$R$  = rearing cattle > 2 years [livestock unit]

*indices*

$t$  = time

The total number of dams (denoted by  $X_t^{cattle}$ ) must be equal to or greater than the number of existing dams from the previous year, which constitutes a lower bound. Moreover, this number must be equal to or less than the population that could be achieved by the existing population of 2-year-old rearing cattle (denoted by  $R_{(t-1)}$ ) of the previous year, which creates an upper bound.

The share of this population cannot exceed the capacity  $B$  of this holding system at time  $t$ , which depreciates at the rate  $\delta$  and can be increased with adequate investments  $I$  at time  $t$ , as shown in eq. (5):

$$X_t^{cattle} \leq B_t \text{ with } B_t \leq (1 - \delta) * B_{(t-1)} + I_t \quad (5)$$

with:

*variables*

$X^{cattle}$  = dairy and suckler cattle activity [livestock unit]  
 $\delta$  = constant depreciation [%]

$B$  = existing house systems

$I$  = investment [CHF]

*indices*

$t$  = time

From an economic point of view, eq. (5) denotes sunk costs. These costs arise if existing but not depreciated house system capacities are not used to capacity (denoted by  $X_t^{cattle} < B_t$ ). Sunk costs are considered by the objective function as undepreciated house system capacities induce fixed costs. Thus, considering sunk costs as a decisive feature of the model allows taking into account slow structural adjustments in the agricultural sector. Equation

$$X^{youngstock} = X^{dam} * \mu * (1 - \sigma) \quad (6)$$

with:

*variables*

$X^{youngstock}$  = number of young stock [livestock unit]

$X^{dam}$  = number of dam [livestock unit]

$\mu$  = birth rate [per livestock]

$\sigma$  = still birth rate [%]

The population of dams in one period determines the maximum number of young animals that can either go into meat production or be raised for maintaining or increasing the livestock population. Equations (4) to (6) ensure that livestock dynamics vary in a realistic range and take relevant agricultural determinants into account.

### **Linking plant and livestock production**

Balancing the supply and demand of roughage, feed concentrates and nutrients links the livestock with plant production in S\_INTAGRAL. The formal procedure of balancing

(5) therefore also represents dynamic development of structure capacities.

Another framework property is the accumulated annual number of young stock as shown in eq. (6), which is determined by the birth rate of the dams (denoted by  $\mu$ ) and the still birth rate (denoted by  $\sigma$ ).

is shown in eq. (7), which demonstrates the procedure for nutrients. The nutrient balance additionally forms a legal requirement for receiving direct payments.

The nutrient balance relates nutrients' supply and demand. Applied manure and fertilizer have to meet a minimum need for crop acreage and permanent grassland, which is denoted by the left term in eq. (7). The right term in eq. (7) denotes a maximum standard allowance, according to PEP, including an admissible surplus.

$$\sum_k X^{area} * Nb \leq NS + \sum_{kd} KD * g \leq (1 + To) \sum_k X^{area} * Nb \quad (7)$$

with:

*variables*

$X^{area}$  = land use [ha]

$Nb$  = crop specific nutrient demand [kg/ha]

$NS$  = nutrient supply from manure [kg]

$KD$  = fertilizer input [kg]

$g$  = fertilizer specific nutrient content

$To$  = tolerated surplus [%]

*indices*

$kd$  = type of fertilizer

$k$  = crop

## 4.5 Environmental module

In order to assess GHG and nitrogen emissions with S\_INTAGRAL, the environmental module is linked to the variables described above for plant and livestock production. Adjusted methodologies recommended by the IPCC are used to model agricultural GHG emissions of methane and nitrous oxide. Modeled emission parameters rely on Swiss-specific data, so IPCC's Tier 2 and Tier 1b approach are used (NIR, 2008). Table 3 summarizes the drivers for GHG emissions in S\_INTAGRAL. In addition, carbon dioxide emissions from machinery are assessed, although they are not counted by the IPCC as agricultural GHG emissions, but rather as energy GHG emissions.

Nitrogen emissions are calculated by balancing inputs and outputs of nitrogen, based on a Swiss-specific method for calculating the nitrogen cycle (cf. Spiess, 1999). The inputs

include imported feedstuff and nutrients (mineral fertilizer, nitrogen deposition), while the outputs consist of plant and animal food products. These numbers enable the model to estimate the nitrogen loss potential (NLP) and the efficiency of nitrogen use in agriculture. The latter refers to the proportion of nitrogen derived from outside the system and the amount of output for human food. The NLP comprises both environmentally relevant and harmless nitrogen emissions, as shown in eq. (8).

The explicit assessment of each environmentally-relevant nitrogen emission (cf. eq. 8) composes a further decisive element of S\_INTAGRAL. Table 4 summarizes the underlying specific methods of calculation for Switzerland.

Dinitrogen emissions act as a residual figure as they do not contribute to environmental pollution. Thus, they are not taken into account.

**Table 3:** Modeled indicators for GHG emissions

Indicator	source in S_INTAGRAL	depending on/affected by in S_INTAGRAL:	based on
<i>CH<sub>4</sub> methane</i> • implemented as: emission factor	<ul style="list-style-type: none"> <li>enteric fermentation</li> <li>manure management</li> </ul>	feed absorption, digestibility, animal specific methane rate  animal specific amount of digestible excrements, methane formation capacity, a housing specific amount of manure	IPCC (1997); UNFCCC (2000, 2003); NIR (2008); Minonzio et al. (1998)
<i>N<sub>2</sub>O nitrous oxide</i> • implemented as: emission factor	<ul style="list-style-type: none"> <li>manure management (direct)</li> <li>agricultural soils (direct)</li> <li>indirectly</li> </ul>	livestock population, house system, management style, storage and deploy of slurry and manure, storage time  N-leaching crops, N-loss grassland, fertilizer, N-fixation, crop residues, organic soils  from emissions of ammonia, nitrate and nitrogen oxide	IPCC (1997); NIR (2008); Schmid et al. (2000); Schmid et al. (2001)
<i>CO<sub>2</sub> carbon dioxide</i> • implemented as: emission factor	<ul style="list-style-type: none"> <li>machinery fuel consumption</li> </ul>	fuel consumption for plant activities depending on zones and performance	IPCC (1997); Ammann (2007)
<i>potential for C-sequestration in agricultural soils</i> <sup>a)</sup> • coefficients		no-till farming, conversion arable to permanent pasture	Leifeld et al. (2003)

Note:

<sup>a)</sup> Other carbon sinks such as extensification of grasslands or renaturation of agriculturally-used organic soils are not considered due to a lack of adequate data.

$$NLP = \sum_{env\_relevant} \text{nitrogen emission} + \sum_{env\_harmless} \text{nitrogen emission} \tag{8}$$

with:

$$\text{nitrogen emission}_{env\_relevant} = NH_3 + NO_3^- + N_2O + NO_x$$

$$\text{nitrogen emission}_{env\_harmless} = N_2$$

with:

*variables*

*NLP* = nitrogen loss potential

$NH_3$  = ammonia

$NO_3^-$  = nitrate

$N_2O$  = nitrous oxide

$NO_x$  = nitrogen oxide

$N_2$  = dinitrogen

*indices*

*env\_relevant* = environmentally relevant nitrogen emission

*env\_harmless* = environmentally harmless nitrogen emission

**Table 4:** Modeled indicators for nitrogen emissions

Indicator	source in S_INTAGRAL	depending on/affected by in S_INTAGRAL:	based on
<i>NH<sub>3</sub> ammonia</i> • implemented as: emission factor	<ul style="list-style-type: none"> <li>• livestock</li> <li>• deploy fertilizer</li> <li>• agricultural soils</li> </ul>	animal type, house system, manure storage and deploy, livestock efficiency, management style fertilizer specific nutrient content share on crop acreage and crop specific factors	Reidy and Menzi (2005); Reidy et al. (2008)
<i>NO<sub>3</sub> nitrate</i> • implemented as: emission factor	<ul style="list-style-type: none"> <li>• agricultural soils</li> </ul>	share on crop acreage and crop specific factors	Braun et al. (1994)
<i>N<sub>2</sub>O nitrous oxide</i> • implemented as: emission factor	<ul style="list-style-type: none"> <li>• manure management (direct)</li> <li>• agricultural soils (direct)</li> </ul>	livestock population, house system, management style, storage and deploy of slurry and manure, storage time N-leaching crops, N-loss grassland, fertilizer, N-fixation, crop residues, organic soils	Schmid et al. (2000); Schmid et al. (2001)
<i>NO<sub>x</sub> nitrogen oxides</i> • implemented as: emission factor	<ul style="list-style-type: none"> <li>• manure and fertilizer</li> </ul>	livestock population, amount of manure and fertilizer	Schmid et al. (2000)



## 4.6 Mitigation options

Optimal strategies to mitigate GHG and nitrogen emissions in S\_INTAGRAL can occur through (1) changes in plant and livestock production, (2) changes in the intensity of production activities and (3) applied technological opportunities (cf. Peter et al., 2009). The third group comprises opportunities for lipid supplementation of diets for cattle, anaerobic digestion of slurry and manure, slurry additives, manure coverage and manure spreading by trailed hoses.

## 4.7 Data

Official and published price statistics and calculations provide the basis for price and cost information, i.e., the model framework is in line with official and standardized data and statistics. This information is drawn from data provided by AGRIDEA (2008a+b) for Switzerland and by ZMP (2008a-e) abroad. To attain likely developments of price

and cost estimates, recent outlooks from OECD-FAO (2008) are used. Data for the agrarian structure and agricultural endowment were obtained from the Swiss Federal Statistical Office, while legal policy data were extracted from the Swiss Federal Office for Agriculture.

## 4.8 Technical aspects of modeling

S\_INTAGRAL has been generated using the mathematical language LPL (cf. Virtual-Optima, 2008; Hürlimann, 1999 and 1993) and solved with CPLEX 8.1 (ILOG, 2002). A major advantage of using LPL is the possibility of implementing compound sets. These sets allow irrational combinations of agricultural production technologies to be defined, reducing computing time considerably. However, by integrating economic and environmental data, our model approach requires time-consuming maintenance.

## 5 Results

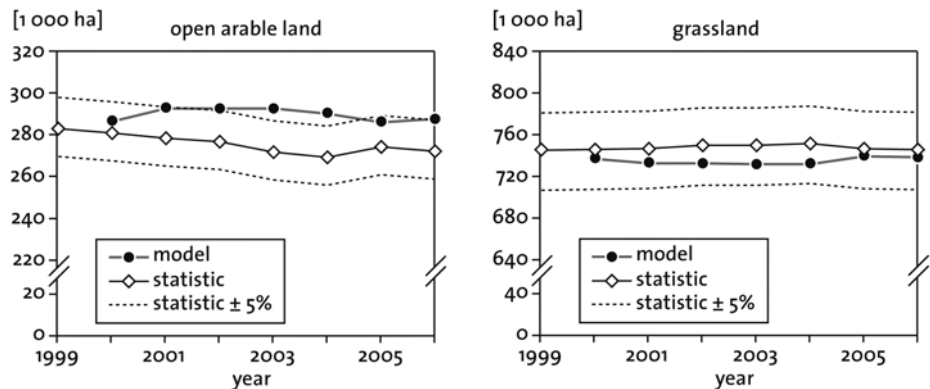
This section presents results from both evaluation and application of the S\_INTAGRAL model.

### 5.1 Evaluation

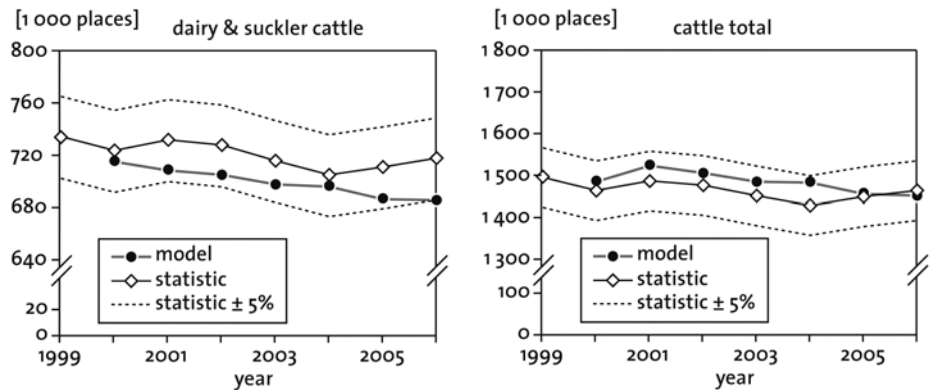
Conditions and statistical data in the year 1999 compose the baseline for calibration of S\_INTAGRAL. In the next step, modeled results have been validated against observed data for the period 2000 to 2006 to evaluate the quality and suitability of S\_INTAGRAL to project the future. It is important to note in this context that complete correlation might not be expected for the following reasons:

(1) Exogenous shocks and their impacts, such as the BSE-crisis in the beginning of this century, cannot be considered properly. (2) Inventory data are subject to a certain systematic error as emissions are mostly driven by underlying agricultural policy and economic conditions and their change over time. (3) Differences in observed and modeled data arise from applied methodology and its underlying assumptions. Given the neoclassical economic theory which mathematical programming models are based on, our model approach assumes perfect information, no time lags and rational behavior. These aspects, however, can hardly be assumed for real-world decisions.

plant production

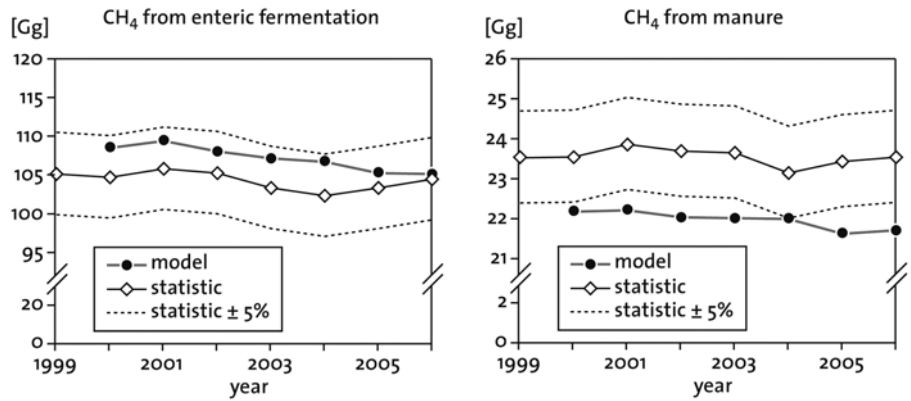


livestock

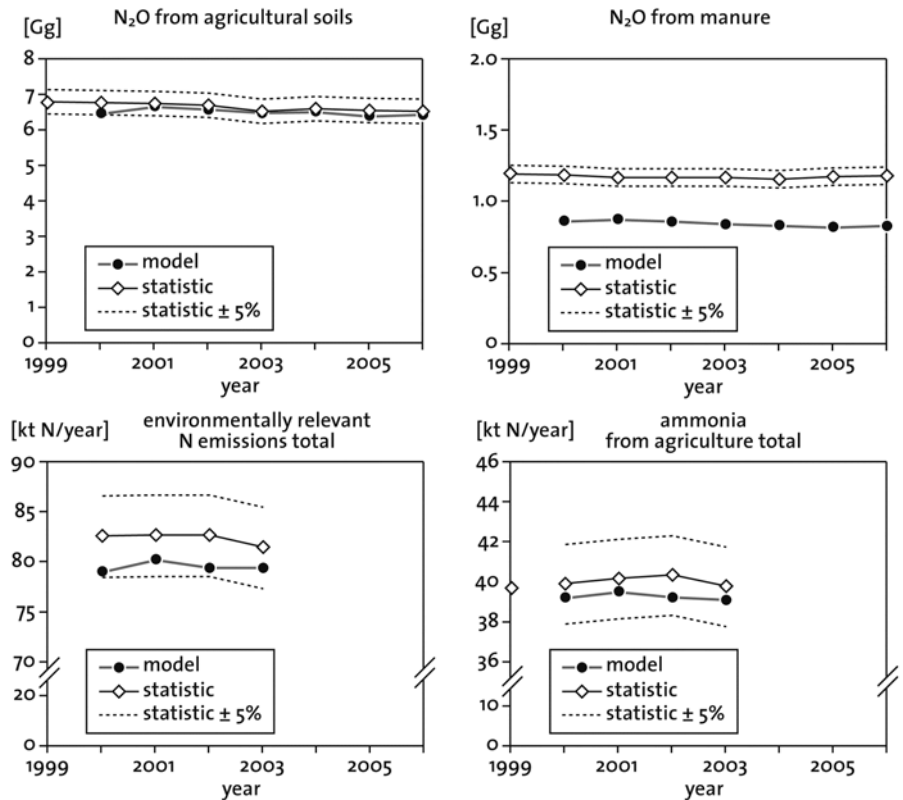


**Figure 3:** Modeled (solid-circled line) and observed (solid-squared line) data for selected structure variables. Depicted is +/- 5% range of observed data (dashed line)

GHG emissions



nitrogen emissions



**Figure 4:** Modeled (solid-circled line) and observed (solid-squared line) data for selected environmental variables. Depicted is +/- 5% range of observed data (dashed line)

Thus, results for validation are presented with a goodness of fit ranging between -5 to +5% of observed data. Figure 3 presents decisive computed results for plant and livestock production, while Figure 4 displays results for GHG and nitrogen emissions.

Given our static parameters, results for grasslands are underestimated, although with a fit within the -5% range

(cf. Figure 3). Results for open arable land are overestimated, more than +5% from 2002 to 2004 and in 2006. This divergence between observed and modeled data can be explained by the methodological reasons mentioned above. Observed data may indicate already to the adjustment of production structures by Swiss farmers as a reaction to pending Free Trade negotiations with the European Union and thus a lower level of domestic crop prices. In

contrast, modeled results pose an optimal solution given underlying theory and assumed price and cost conditions for the specific year. Due to underestimated grassland production in S\_INTAGRAL, the corresponding modeled number of dairy and suckler cattle is underestimated as well. This difference, however, ranges within -5% (cf. Figure 3). The underestimated number of suckler cattle is compensated for by a modeled number of rearing cattle, which is calculated to be above the observed data (not shown). Therefore, the modeled number of total cattle is overestimated, ranging within +5%.

In consequence, the computed amount of methane from enteric fermentation exceeds the observed data within +5% (cf. Figure 4). Modeled results in methane from manure fall below observed data, even -5%. This occurs because the calculated amount of methane from manure is derived from the number of animals for each cattle type multiplied by their corresponding emission factor. The IPCC emission factor applied to Swiss suckler cattle was four times as large (8 kg CH<sub>4</sub>/head/year) as the factor for rearing cattle (2 kg CH<sub>4</sub>/head/year) in the year 2000. Given the underestimated number of suckler cattle and the overestimated number of rearing cattle, as a result the total amount of methane from manure is relatively lower than observed data.

Nitrous oxide emissions from agricultural soils fit the observed data within -5%. However, emissions from manure rank lower than -5%. This can be explained by differences in the ratios of housing systems. The modeled ratio between liquid and solid manure is assumed (based on

Schmid et al., 2000) to be above the ratio taken in the Swiss GHG inventory. However, the implied emission factor in the GHG inventory for solid manure (0.02 kg N<sub>2</sub>O-N/kg N) is nearly twenty times that factor for liquid manure (0.001 kg N<sub>2</sub>O-N/kg N). Thus, the higher modeled share of house systems based on liquid manure contributes relatively less to nitrous oxides from manure.

Results for both environmentally-relevant nitrogen and ammonia (cf. Figure 4) are slightly underestimated by the model, however, within the range of -5%.

## 5.2 Application

Results presented in this section refer to the three options mentioned to mitigate GHG and nitrogen emissions (cf. chapter 4) within S\_INTAGRAL.

In the first step, the parameterization has been modified. For this purpose, two scenarios have been applied to analyze the period 2007 to 2020. The milk quotas are abolished in both scenarios from the year 2007 forward. The scenarios are distinct in their producer price and cost levels. Continuation of current agricultural policy with border protection refers to *scenario status quo*. The transition to market liberalization and thus a lower level of domestic producer prices corresponds to *scenario liberalization*.

Results for plant and livestock production are compared in Figure 5, and results for GHG and nitrogen emissions are shown in Figure 6.

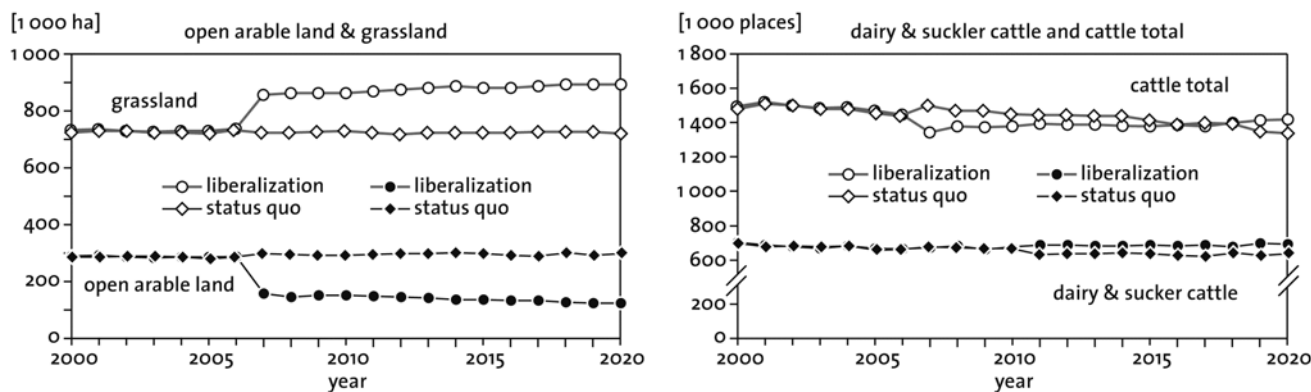


Figure 5: Projected model results for plant and livestock production

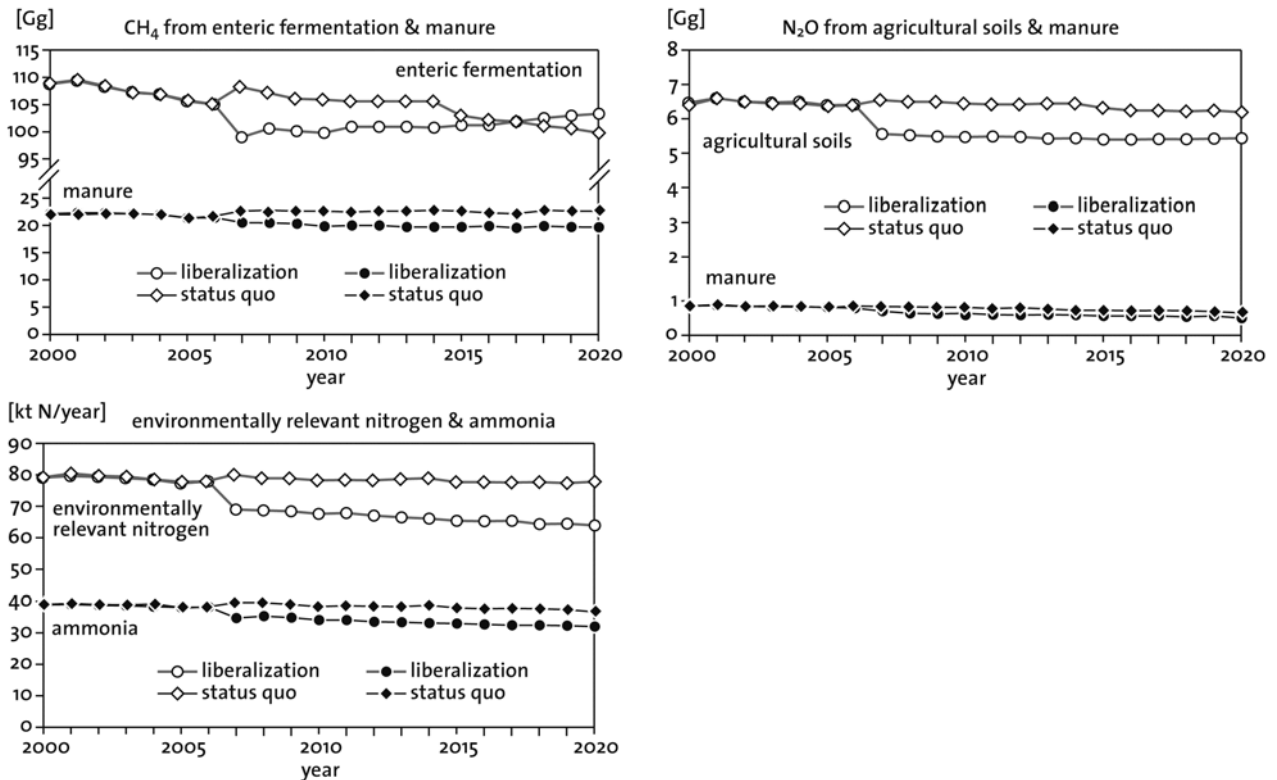


Figure 6: Projected model results for GHG and nitrogen emissions

Referring to *scenario status quo*, results for land use development show only a slight increase in open arable land (1%) between 2007 and 2020, while the area of grasslands slightly decreases by 1%. These changes follow from the quantitative decrease by 9% of both dairy and suckler cattle and the cattle total between 2007 and 2020 (cf. Figure 5). In consequence, the amount of methane from enteric fermentation and from manure in *scenario status quo* decreases by 8% and 2%, respectively (cf. Figure 6). Nitrous oxide from agricultural soils and from manure decreases by 5% and 18%, respectively, between 2007 and 2020. Environmentally relevant nitrogen emissions are estimated to decline by 2% between 2007 and 2020 (cf. Figure 6). These results indicate the strong linkages within livestock and plant production in Swiss agriculture given our applied methodological approach. No large structural alterations are expected, due to minimal changes in relative prices.

Two effects are distinct in the results of *scenario liberalization*. First, *scenario liberalization* refers to changes in relative prices that lead to structural alterations as one major effect. This transition is represented by a sharp bend in Figures 5 and 6 from 2006 to 2007. Modified imports and animals' feeding, for instance, affect the total number of cattle, which decreases by 7% from 2006 to 2007 (cf. Figure 5). This leads also to a decline in open arable land by 45% while grassland area increases by 17% from 2006 to 2007 (cf. Figure 5). As a consequence, methane from enteric fermentation (-5%), nitrous oxide from agricultural soils (-13%) and environmentally relevant nitrogen (-11%) decline as well from 2006 to 2007 (cf. Figure 6).

The second major effect of interpreting the results of *scenario liberalization* is the subsequent adjustment by S\_INTAGRAL, seeking annual optimal solutions for the period 2007 to 2020. Thus, the number of dairy and suckler cattle, and the total number of cattle, increases by 4% in *scenario liberalization* between 2007 and 2020 (cf. Figure 5). Consequently, land use development results show a decrease by 20% in open arable land, while grasslands increase by 4% between 2007 and 2020. These alterations in *scenario liberalization* affect development of methane from enteric fermentation as well. The increase in the number of cattle leads to an increase in methane from enteric fermentation by 4% between 2007 and 2020 (cf. Figure 6). The decline in open arable land in *scenario liberalization* also affects emissions of nitrous oxide. Declining open arable land leads to consequences such as reduced application of mineral fertilizer and reduced losses by leaching. Thus, nitrous oxide from agricultural soils and environmentally relevant nitrogen emissions drops by 2% and 7%, respectively, between 2007 and 2020 (cf. Figure 6).

To sum up the results so far, mitigation in GHG and nitrogen emissions is achieved by (1) changes in plant and livestock production and (2) changes in the intensity of production activities. However, no technological opportunity enters the solution. In an additional step, an amount of money per metric ton CO<sub>2</sub>eq mitigated by technology is

introduced. This incentive for using mitigation technologies successively rises from 0 to 5000 CHF/t CO<sub>2</sub>eq. Thus, a supply curve for technological opportunities is estimated. Figure 7 displays the results of this estimate in the year 2020, distinguishing scenario status quo and scenario liberalization.

Only three of the technical opportunities (cf. chapter 4) enter the solution and exhibit small differences between the scenarios. Supply curves of these three technical opportunities show a non-linear increase, meaning higher reduction levels are linked to high monetary incentives. Lipid supplements to diets might contribute between 220 to 240 kt CO<sub>2</sub>eq to GHG mitigation, which is equivalent to 5% of total GHG emissions modeled in 2020. However, this effort requires an incentive of at least 2000 CHF/t CO<sub>2</sub>eq. At costs less than 100 CHF/t CO<sub>2</sub>eq, manure coverage might contribute between 80 to 100 kt CO<sub>2</sub>eq to GHG mitigation. This amount is equal to 2% of total GHG emissions modeled in 2020. Applying trail hoses to deploy manure contributes 45 kt CO<sub>2</sub>eq at maximum, but only if the incentive exceeds 1000 CHF/t CO<sub>2</sub>eq. This contribution corresponds to 1% of total GHG emissions modeled in 2020. The summed contribution of these three technological opportunities to mitigate modeled GHG emissions in 2020 corresponds to 8% of total GHG emissions modeled in 2020.

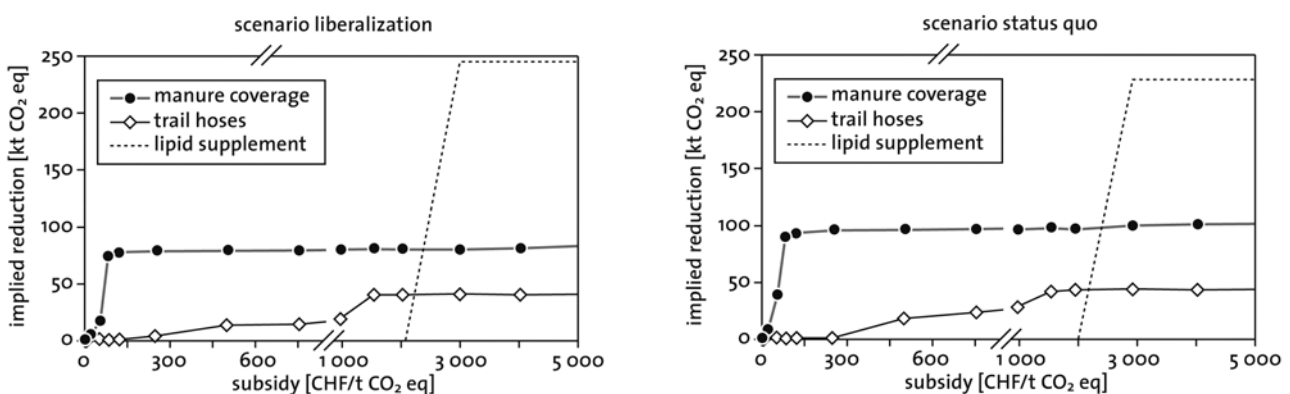


Figure 7: Supply curves for technical mitigation

## 6 Discussion

Using Swiss agriculture, we analyzed from an economic point of view mitigation strategies for GHG and nitrogen emissions. For this purpose, the recursive, linear, sectoral, supply model S\_INTAGRAL has been developed. Cost-effective strategies are therefore solutions of this integrated model.

### 6.1 Discussing the methodological approach

Applying mathematical programming models provides advantages but also faces challenging issues, such as overspecialization and dynamics. To overcome the problem of overspecialization, S\_INTAGRAL is driven by recursive elements, resulting in smooth flexibility constraints. These constraints are justifiable from an agricultural point of view. This approach decisively helps to limit the typically jumpy behavior of linear programming models. Additionally, applying recursive elements enable us to adequately model the development of livestock dynamics and investments in buildings and machinery, the latter of which takes into account sunk costs. This application indicates that flexibility constraints provide a feasible approach to sufficiently validate S\_INTAGRAL with regard to the ratio of results:time. This “fitness for purpose” is also pointed out by Jakeman et al. (2006).

Results of this evaluation indicate that S\_INTAGRAL is suitable for estimating agricultural structure variables, GHG emissions and nitrogen emissions correctly within a certain range of tolerance. Our evaluation results for plant and livestock production range within a similar magnitude as those calculated with the model CH-FARMIS (Sanders, 2006; Schader et al., 2008a+b). CH-FARMIS originates from FARMIS (Osterburg et al., 2001) and is adapted to the Swiss context. Validation results of CH-FARMIS estimate grasslands to be 6-8% lower than observed data. Arable land is calculated to be 4% higher and 6% lower than observed for organic and non-organic farms, respectively. Aggregated livestock units are overestimated by 2-4% for

both organic and non-organic farms (Sanders, 2007). PMP has been applied to calibrate CH-FARMIS. However, PMP calibration by implementation of elasticities is difficult for sector modeling in Swiss agriculture. Either elasticities rely just on assumptions (Schader et al., 2008a) or they are set to unity due to a lack of empirical data (Mack et al., 2007; Mack and Mann, 2008).

Using sector models often requires aggregation of data from individual farms. Handling highly aggregated data limits the ability to obtain farm-specific information yet. We are aware that S\_INTAGRAL is limited in obtaining such information as well. However, this limitation seems acceptable due to the intended purpose of assessing cost-effective strategies for the Swiss agriculture system as a whole.

### 6.2 Discussing the data and assumptions

Our assumptions might constitute another limitation of S\_INTAGRAL. Even though we strongly referred to recommended methodologies to model GHG and nitrogen emissions, uncertainty in the effective magnitude of emissions and in activity data remains. Leifeld and Fuhrer (2005) report an uncertainty for methane emissions from enteric fermentation under Swiss conditions in the range of +/- 20%. For nitrous oxide emissions, they indicate an uncertainty varying by +/- 15%, which does not include the large uncertainty in nitrous oxide emissions of 80% from the IPCC (1997). Soussana et al. (2007) found that methane emissions from free-range management systems seem to be higher than those estimated by the IPCC (2000). Schmid et al. (2001) concluded that the IPCC emission factors, which are based on short-term measurement data, probably underestimate the long-term effects of fertilizer applications. Flechard et al. (2007) argue for climate-sensitive emission factors for nitrous oxide, instead of the current IPCC default value, as progress has been made in measuring nitrous oxide fluxes. Menzi et al.

(2006) refer to a “Swiss  $\text{NH}_3$  gap”, as an increase in measurement of nitrogen emissions does not confirm the decline of inventory calculations.

### 6.3 Discussing the application of S\_INTAGRAL

Referring to plant and livestock production, our results of *scenario liberalization* show an increase in the number of both dairy cattle and total cattle compared to numbers under *scenario status quo*. As grasslands provide the main source for milk production in Switzerland, over time grasslands substitute for arable land. Economically spoken, grassland-based milk and meat production hold a comparative advantage over crop-based production in Switzerland. These results are in line with outcomes obtained by applying other sector models to Swiss agriculture. Zimmermann (2008) showed that an increasing level of liberalization more strongly affects price cuts of arable products than of milk and meat, which leads to changes in relative prices and subsequently to a substitution in production structures. Flury et al. (2005) and Mack and Flury (2006) show that a decreasing level of border protection leads to a decline in open arable land while grassland area increases. Moreover, their results indicate an increase in the number of dairy cattle. A more extensive production as a farmer's response to market liberalization is also detected by Sanders (2007). He found a decline in arable land by liberalization policies. Regarding the development of GHG and nitrogen emissions until 2020, our results can be compared to those carried out by the EPA (2006b). This study by the EPA (2006b) projected the development of methane and nitrous oxide emissions for over ninety countries until the year 2020 using official National Inventory Reports (NIR) and GHG inventories that rely on IPCC methodologies. The projections reflect a business as usual scenario, incorporating achieved reductions by measures that are already in place (EPA, 2006b). However, planned measures or those in discussion were excluded. EPA (2006b) estimated methane from enteric fermentation and nitrous oxide from agricultural soils to decrease by 7% and 4%, respectively, in Switzerland between 2005 and 2020. Given our *scenario status quo*, S\_INTAGRAL results for methane from enteric fermentation and nitrous oxide from agricultural soils are in line with these estimates. The small differences in our results may be explained by the fact that current and planned changes in Swiss policies have been taken into account within S\_INTAGRAL for the

period 2007 to 2020. Thus, our *scenario status quo* and the business as usual scenario used by the EPA are not directly comparable.

The EPA (2006b) calculated both methane and nitrous oxide from manure to decline by 5% and 3%, respectively. This diminishment is consistent with results from S\_INTAGRAL while the magnitude of the decline differs. Underlying methodologies might help to explain these varying magnitudes. Projections carried out by the EPA (2006b) are based on official Swiss GHG inventories. Both methane and nitrous oxide from manure are underestimated by more than -5% with S\_INTAGRAL compared to observed data, as pointed out in more detail in the evaluation section of the results section. This leads to the discrepancy in projections between the EPA (2006b) and S\_INTAGRAL.

Applying technologies constitutes the third mitigation opportunity within S\_INTAGRAL. Our results indicate the limits of mitigation technologies in Swiss agriculture. As pointed out by Smith et al. (2008), Beach et al. (2008) and Smith et al. (2007), the effectiveness of mitigation technologies on agricultural GHGs is influenced by many factors, including climate and non-climate policies, whose impact on future conditions is unclear, and also institutional and economic restrictions. Effectiveness varies also due to heterogeneous spatial and temporal conditions. Therefore, the expected level of effectiveness of implementing mitigation measures in response to incentives is difficult to assess.

This difficulty is also true for Switzerland, as agricultural and environmental policies do not exclusively focus on reductions in GHG emissions from agriculture. Rather, policies aim to reduce nutrient losses and soil erosion or to improve water quality, for instance. Declines in agricultural GHG emissions are co-benefits, and this pairing has mostly been more effective at reducing GHG emissions than specific measures that aim to reduce GHG emissions in agriculture (Smith et al. 2007).

Nonetheless, GHG and nitrogen emissions in Swiss agriculture can be expected to contribute to mitigation to only a limited extent. This mitigation should be achieved by adjusting and improving existing measures rather than by introducing measures aimed exclusively at reducing such emissions.



## 7 Conclusion

Given the intended purpose of the model described here, S\_INTAGRAL is an appropriate tool to analyze strategies in GHG and nitrogen abatement for Swiss agriculture. This model has been designed for addressing specific research issues and for policy support. Its application guides monitoring and decision-making and provides a better understanding of the Swiss agricultural system and its behavior. The model performance is sufficiently robust and satisfactory to also project the future, even though analysis of the three mitigation opportunities - changes in production structures, changes in intensities and technique - indicates the limited ability of agriculture in Switzerland to contribute substantially to mitigation GHG and nitrogen emissions. Thus, taking both the strengths and limitations of S\_INTAGRAL into account, this model can provide scientists and policy makers with valuable information about the Swiss agricultural sector. It satisfyingly promotes the identification of cost-effective strategies to mitigate GHG and nitrogen emissions in Swiss agriculture.

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