Doctoral Thesis

Economic analyses of strategies to mitigate greenhouse gas and nitrogen emissions in Swiss agriculture

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Economic analyses of strategies to mitigate greenhouse gas and nitrogen emissions in Swiss agriculture

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presented by

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Summary

Agriculture is not only a basis to provide for food. Over the last few decades other benefits such as energy supply and environmental services in the form of wildlife habitat and landscape amenity have been increasingly appreciated. However, the intensification of farm production and the aggregation of farming processes have adverse effects, such as the pollution of air and water. Thus, negative impacts caused by nutrient surpluses, leaching and denitrification have to be considered when regarding greenhouse gas (GHG) and nitrogen emissions and their relationship to the climate and environment.

There is an increasing interest in developing effective and socially attractive strategies for the sustainable use of scarce resources and in minimizing the related external costs. This requires a better understanding of the impact of legal policies and the search for alternative production techniques to reduce GHG and nitrogen emissions. For the Swiss agricultural sector a comprehensive economic outline as to what extent agriculture could efficiently contribute to the mitigation of GHG and nitrogen emissions is missing. Filling this gap has been the aim of this study.

Therefore, an economic model has been applied, which mimics the structure of Swiss agriculture in combination with important features that are linked to GHG and nitrogen emissions. Cost-effective strategies have been obtained from the integrated linear programming model S_INTAGRAL. Its integrated character combines both economic and environmental aspects of GHG and nitrogen emissions. Therefore, its normative approach might provide scientists and policy makers with valuable information about the Swiss agricultural sector. However, both the strengths and limitations of such approaches need to be taken into account to validate the information.

As a primary effect of the current Swiss agricultural policy, GHG emissions decreased by 14% between 1990 and 2000. It is expected that they will further decline by about 12% by 2010. In contrast, targeted incentives and soil carbon sequestration will only marginally contribute to the reduction in GHG emissions.

Emissions of environmentally relevant nitrogen are calculated to decline by 12% (scenario “EU2010”) or remain constant (scenario “AP2011”) between 2000 and 2013. As the policy stipulated a reduction of these losses by 23% between 1994 and
2005, it is assumed that the present policy measures are not sufficient to meet the target, not even by eight years later than the original target.

In conclusion, a further reduction of the level of GHG and nitrogen emissions can be expected in the near future. Such a reduction is primarily caused by changes in both agricultural policy and economic conditions rather than changes in climate policy. However, this will most probably be linked to high income losses in Swiss agriculture.
Zusammenfassung


Als eine Folge der gegenwärtigen Agrarpolitik der Schweiz verringerten sich die landwirtschaftlichen THG Emissionen zwischen den Jahren 1990 bis 2000 um 14%.
Eine weitere Reduktion um 12% bis zum Jahr 2010 wurde modelliert. Hingegen spielen gezielte Anreize zur Vermeidung von THG und die Sequestrierung von Kohlenstoff in diesem Zeitraum nur eine untergeordnete Rolle.


Abschliessend kann festgehalten werden, dass eine weitere Reduktion der THG- und Stickstoffemissionen zu erwarten ist, die auf Änderungen in der Agrarpolitik und anderen ökonomischen Bedingungen zurückzuführen ist und weniger auf die aktuelle Klimapolitik. Diese Verringerung der Emissionen kann aber teilweise mit grossen Einkommensrückgängen in der Agrarwirtschaft verbunden sein.
1 General introduction

1.1 Environment and agriculture

Agriculture is not only a basis to provide for food. Over the last few decades other benefits of agriculture, such as energy supply, and environmental services, such as wildlife habitat and landscape amenity, have received increasing attention. This development became evident, though agricultural activities provide more than goods and services that are perceived by society as positive and normal. Agricultural activities can also cause a severe impact on the environment, such as pollution of the atmosphere and the hydrosphere. Thus, when considering agricultural practices, people have raised concerns about healthy nourishment, food security, the environment, the quality of nature and the use of scarce resources. Although the reasons concerning the environment are many and not exclusively related to agriculture, the intensification of farm production and the aggregation of farming processes have adversely affected the environment. The negative impact caused by nutrient surpluses, leaching and denitrification, among others, have to be considered due to their environmental impact, such as greenhouse gas (GHG) and nitrogen emissions, even though agricultural practices have evolved over time. However, the interdependencies among agricultural processes and their impact on both the environment in general and the climate in particular are very complex. The above-mentioned issues have led to an increasing interest in developing effective and socially attractive strategies for the sustainable agricultural use of scarce resources, thus lowering their negative environmental impact. This first of all requires a better understanding of both the effects of current legal policies and the applied technologies available for the mitigation of GHG and nitrogen emissions by agriculture. It further requires an analysis of how to adjust or change policies and technologies to mitigate GHG and nitrogen emissions in a cost-effective manner.

1.1.1 Greenhouse Gases

From a global viewpoint, carbon dioxide (CO$_2$) caused by the use of fossil fuels and deforestation is the most important anthropogenic GHG, representing about 77% of the total anthropogenic GHG emissions in the year 2004. Methane (CH$_4$) and nitrous
oxide (N\textsubscript{2}O) are also crucial GHGs accounting for about 14% and 8%, respectively, of the total anthropogenic GHG (IPCC, 2007a). About 60% of nitrous oxide and about 50% of methane emitted are associated with agricultural activities, such as raising livestock and soil cultivation (IPCC, 2007a).

Although methane and nitrous oxide have an overall low contribution to the total anthropogenic GHG emissions, they are more effective than carbon dioxide in absorbing radiation and thus contribute more to global warming on a per molecule basis. To account for such differences, the concept of the global warming potential (GWP) has been introduced. By this figure, the future climatic impact of the emissions of several greenhouse gases is compared. On a physical basis, the GWP concept, as recommended and applied by the Intergovernmental Panel of Climate Change (IPCC), compares the contributions from the emissions of various components to climate change for a specified time period (e.g., 100 years as taken in the Kyoto Protocol). The GWP metric provides a framework to compare the trade-offs between emissions to allow for the determination of comprehensive and cost-effective policies for implementation.

Thus, applying the GWP allows policy makers to rank the emissions of the different GHGs. Within the GWP concept, as applied by IPCC, each gas emitted is compared with the reference gas carbon dioxide, which is set to 1 for several time horizons. Thus, the GWPs for methane and nitrous oxide are defined relative to CO\textsubscript{2} for several given time horizons. Referring to the Second Assessment Report of the IPCC, the GWPs for methane and nitrous oxide are 21 and 310, respectively, calculated for a time period of 100 years, as in the Kyoto Protocol. Thus, one unit of methane has the same impact on the climate as 21 units of carbon dioxide (Table 2.14 in IPCC, 2007b).

The Fourth IPCC Assessment Report indicated that there is no doubt that anthropogenic activities are having a discernible impact on the observed changes in climate by anthropogenic emissions of GHGs (IPCC, 2007a). Therefore, the reduction of or at least a limitation on these emissions is an important target not only for agriculture but also for almost all sectors of the economy throughout the world.

### 1.1.2 Nitrogen

Nitrogen (N), as well as phosphorus and potassium, does play a key role as a major nutrient necessary for agricultural crop and grassland production. Concomitantly,
plant-derived nitrogen provides the basis for human and livestock diets. The nitrogen cycle is dynamic and complex, and includes several nitrogen compounds, such as ammonium ($\text{NH}_4^+$), ammonia ($\text{NH}_3$), nitrate ($\text{NO}_3^-$) and nitrite ($\text{NO}_2^-$), that are derived from various conversion processes. Nitrogen is taken up by plants primarily from the soil in the directly utilizable forms of ammonium and nitrate. Upon application of both organic and mineral fertilizers, as well as through symbiotic N-fixation and atmospheric deposition, nitrogen accumulates in the soil. The mineralization of organic nitrogen in soils results in the release of ammonium and ammonia, some of which is taken up by plants. In the process of nitrification, part of the remaining ammonium is oxidized via nitrite to nitrate, which is also taken up by plants.

However, an increasing intensification of agricultural processes strongly affects the above-mentioned natural fluxes of nitrogen. Nitrogen that is not taken up by the plant or immobilized in soil organic matter can be lost to the atmosphere or hydrosphere. Nitrate can easily leach down into the ground water depending on both the quantity of the groundwater flux and the nitrate concentration. In the process of denitrification, nitrite and nitrate can be reduced to nitrous oxide, which may be further reduced to dinitrogen ($\text{N}_2$), and lost to the atmosphere (McNeill and Unkovich, 2007). Thus, ammonium and nitrate additions act as an indirect source of a GHG.

Thus, agricultural activities involve the use of substances that have detrimental effects on the environment. The emissions of GHGs and nitrogen, i.e., methane and nitrous oxide as well as ammonia and nitrate, are strongly related to livestock farming and plant production. In turn, agriculture is affected by both climatic changes and environmental pollution as well (cf. Fuhrer, 2006; Fuhrer et al., 2006; Finger, 2009). However, this is beyond the scope of this thesis.

### 1.2 International and national efforts referring to GHG and nitrogen emissions

As GHG and nitrogen emissions have a mostly irreversible impact on the environment, the international community enforces commitments and establishes adequate policy instruments to mitigate them. These international efforts will act in the long run. They are briefly described in chapters 1.2.1 (GHGs) and 1.2.2 (nitrogen). Impli-
cations of these international efforts on national policies and objectives in Switzerland are briefly presented in chapter 1.2.3.

### 1.2.1 International commitments to reduce GHG emissions

On a global level, negotiations and efforts are mainly pursued within the scope of the United Nations Framework Convention on Climate Change (UNFCCC) and the related Kyoto Protocol.

A resolution from 1992, passed at the UNFCCC at The Earth Summit in Rio de Janeiro, was a first step towards stabilizing GHG emission levels to prevent the continuous and dangerous anthropogenic interference with the climate system. Although it already became effective in 1994, no precise quantitative targets or legally binding commitments for individual countries were included to reduce or at least limit anthropogenic GHG emissions. Such limits were set for the first time in the Kyoto Protocol, entered into force in February 2005. The Kyoto Protocol provides the first important step in achieving a long-term objective for the stabilization of GHG concentrations at a level that alleviates climatic change. Its signatories committed themselves to reducing their emissions of the six GHGs, *i.e.*, carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆), within the first commitment period (2008 - 2012) by specific amounts below the reference level in 1990. Further arrangements have already been initiated in 2005 in the internationally coordinated post-Kyoto climate policy as the Kyoto Protocol will expire in 2012. The ratifying parties of the Kyoto Protocol adopted and agreed upon precise topics and time schedules for a prospective climate change policy at the United Nations Climate Change Conference of Parties in Bali (COP13) in 2007. Besides a further reduction of GHG emissions, the so-called Bali Road Map focuses on adaptation and development as well as the transfer and financing of technologies. Among a number of forward-looking decisions, one aim of the Bali Road Map is to negotiate the new process during the United Nations Climate Change Conference of Parties in Copenhagen in 2009 (COP15), which will come into force in 2013.
1.2.2 International commitments to reducing nitrogen emissions

Several international conventions to limit and decrease transboundary nitrogen emissions in surface, ground and marine waters as well as in the atmosphere exist. Two conventions have to be mentioned in this context: The UN/ECE Convention on Long-Range Transboundary Air Pollution (UNECE, 2000 and 2004) and the Convention for the Protection of the Marine Environment of the North-East Atlantic (the “OSPAR Convention”) (OSPAR, 2003). The first convention and its related Gothenborg Protocol to abate acidification, eutrophication and ground-level ozone included the substantial reduction of both nitrogen oxide and ammonia emissions to below their level in 1990 by 2010. The OSPAR convention scheduled the committed reduction of nitrogen discharges to 50% of the level fed into the North Sea in 1985.

1.2.3 Implications of international commitments to reduce GHG and nitrogen emissions on Switzerland’s national policies

With the ratification of the Kyoto Protocol, Switzerland committed itself to reducing its GHG emissions by 8% below the reference level of 1990 until the first commitment period (2008-2012). This goal is reflected in the national CO₂ Law (1999), which only prescribes a reduction of energy-based CO₂ emissions until 2010 by 10% below the level of 1990. However this law does not address agricultural GHG emissions. The current situation shows that the measures hitherto are not sufficient to meet the national reduction goal (BAFU, 2006). As a consequence, the Swiss Parliament approved in March 2007 the concept of a CO₂ tax on combustibles that is implemented in 2008 and shall increase in three steps from initially 12 CHF/t CO₂ to 36 CHF/t CO₂ in 2010. This constitutes an additional instrument besides the so-called “climate cent”, which has been established in 2005 as a voluntary measure by the Swiss industry with a charge levied on all imports of petrol and diesel at a rate of 1.5 cents per litre.

According to the requests of the international commitments (OSPAR, Gothenborg Protocol) to reduce environmentally relevant nitrogen emissions, Swiss agriculture is obligated by national objectives. In Switzerland, an official task force has been mandated to elaborate a national strategy aimed at solving the environmental problems caused by the emissions of harmful nitrogen compounds (BUWAL/BLW, 1996). Supported by scientific studies, the task force defined a long-term target of reducing
the loss of harmful nitrogen compounds from agriculture by 50% below the baseline of 1994. Furthermore, an intermediate goal of reducing these nitrogen losses by 23% until 2002 (originally) and 2005 (finally) was formulated.

1.3 A brief outline of aspects concerning agricultural, environmental and resource economics

1.3.1 Impact on the environment from a theoretical point of view

Agriculture uses natural resources to provide benefits and services. The particular effect of agriculture on the environment varies substantially due to the heterogeneity and uncertainty of natural resources as well as to the applied production conditions. Indeed, climate, topography and geology affect crop productivity and the pattern of input use.

From an economic perspective, environmental benefits and services of agriculture are noticed by humans as positive externalities. In contrast, the impact on both climate and the environment are considered as negative externalities.

An externality occurs when the utility of one individual A depends on activities of another individual or institution. In fact, the utility of individual A include a range of nonmonetary variables, whose values are chosen by others without particular attention to the effects on A’s welfare. The existence of such externalities is associated with an inefficient resource allocation. That is the person or institution, whose activity affects other’s utility levels, does not receive or pay compensation equal to the resulting (marginal) benefits or costs to others (Baumol and Oates, 1975; Buchanan and Stubblebine, 1962).

On one hand, the supply of agricultural output to private markets exceeds that of a socially-favored optimum. On the other hand, the supply of environmental quality is below that of a socially-favored optimum. This discrepancy reveals a market failure, and it points to the following: (1) Farmers do not adequately pay for the additional input of nutrients and pesticides into both surface and ground waters. (2) Farmers cannot charge for the landscape amenity they provide for passersby. A theoretical solution to minimizing the negative externalities on both the environment and climate is their internalization. However, this process is far from taking place automatically. The main reason for this is that property rights for relevant resources are hard to define as
many externalities appear as public goods. Environmental problems caused by agriculture commonly underlie these market failures that claim a more effective market in terms of environmental quality (Carlson et al., 1993; Lichtenberg, 2002; Hendrikse, 2003).

Applying an individual instrument or an instrument mix, effectiveness can be related to both costs and the environment (OECD, 2007). From a national economic point of view, the commitments from both international and national agreements for the mitigation of GHG and nitrogen emissions, for instance, have to be achieved at the lowest possible marginal costs. Cost-effectiveness therefore means to exploit abatement opportunities with minimal costs, by either focusing on a specific sector or covering all sectors within an economy. Covering all sectors, in particular, can lead to the identification of alternative cost-effective solutions. In contrast, focusing on a specific sector requires the comparison of its marginal abatement costs to those of other sectors of an economy. The result of these comparisons provides the basis for decision makers to decide to what extent and to what costs each individual sector can contribute to meeting both international and national objectives in climate policy in a cost-effective manner.

Unlike cost-effectiveness, when effectiveness is related to the environment, the marginal environmental benefit should be as high as possible (environmental effectiveness). In an ideal case, sectoral mitigation targets will succeed in reaching a particular target for that sector only. Yet, no mitigation from other sectors of an economy is necessarily induced. For example, this means that a reduction of GHG and nitrogen emissions in sector X will not necessarily induce a reduction in sector Y. Moreover, sectoral target agreements may change the competitive relationship between various sectors. This might cause the transfer of services or products from one sector to another or to a region with less or no restrictions. This has to be taken into account particularly when the mitigation potential of agricultural GHG and nitrogen emissions is examined.

### 1.3.2 Instruments to achieve environmental objectives

A variety of instruments exist to achieve international commitments and national objectives related to the environment. Environmental effectiveness (see chapter 1.3.1) and economically efficiency constitute important criteria for the capability of instru-
ments to achieve a given environmental objective. Carlson et al. (1993) distinguish between first-best and second-best solution instruments. First-best instruments act directly on factors that cause environmental problems and include regulatory incentives that are based on economical aspects. These include, for instance, levies on emissions, trading with emission certificates and subsidies for abating emissions (Perman et al., 1999, UNFCCC, 2008). Applying levies raise the question of the level at which they should be imposed. Furthermore, an adjustment and re-adjustment of the fee has to be considered to realize a certain environmental objective. Therefore, production conditions as well as biological or chemical factors have to be considered. The heterogeneity of agricultural practices and local conditions are prerequisites for trading emission permits due to the differences in the costs of pollution mitigation between different areas. For example, as European agriculture is heterogeneous, so are its marginal abatement costs (EPA, 2006a; Pérez Domínguez, 2005). Three ways to get emission permits are distinguished. Either, the polluter directly pays for the permit when they are auctioned off. Or, the polluter validates its own emissions and sells it to other polluters if the polluter received the permits free of charge by a one-time distribution, or a combination of both (Cropper and Oates, 1992). An emission trading system might be of particular interest, as it might reduce the distributional effects that occur from agriculturally-related environmental policies. The selling of permits might compensate for income losses related to shifts in production, while a yield increase may at least partially cover the costs for a permit. A market for emissions permits might, therefore, be a feasible option to minimize high-income losses. With using trading permits, such losses cannot be excluded, but they are minimized (Egenhofer and Legge, 2002; OECD, 2004).

However, the implementation of first-best instruments in agriculture is difficult for several reasons. Sources of agricultural emissions are numerous and dispersed; thus, they form non-point sources. In addition, agricultural and naturally occurring emissions can hardly be distinguished from each other. This, in particular, complicates their identification and raises the monitoring costs, which leads to increasing transaction costs for implementing the first-best instruments.

In contrast, second-best instruments act indirectly on causes of environmental problems. These instruments include regulatory measures, voluntary agreements and international programs, among others (Lipsey and Lancaster, 1956-1957; Perman et al., 1999; UNFCCC, 2008; OECD, 2007). The main factors of regulatory measures are
the limitation or guidance of input uses, charging fees for input uses, including subsidies to maintain landscape amenities, regulating the application of best management practices and cross compliance (Lichtenberg, 2002). Voluntary agreements predominantly cover soil management practices, while international programs might support the global sharing of innovative technologies.

Second-best instruments, however, may suffer from a decline in efficiency as their impact on a given environmental objective is only indirect, which leads to increasing costs. Furthermore, the feasibility of second-best instruments varies for several reasons: (1) a variation in cropping patterns, such as the use of fertilizers and yield variation, (2) differences in the topography and slope of land, and (3) the particular characteristics and texture of soils. Depending on whether the implementation of second-best instruments can be monitored, additional costs may emerge. Finally, the decision makers must be able to observe the compliance.

1.3.3 Analysis of agricultural impact on the environment: The application of models

The international commitments to reduce GHG and nitrogen emissions as mentioned in chapter 1.2 are often adopted into national policies, such as those for the environment, energy or agriculture. National policies, however, do not exclusively focus on the reduction in GHG and nitrogen emissions from one sector. These policies rather strive for a multitude of objectives. The Swiss Federal Office for the Environment (FOEN) mainly pursues the sustainable use of natural resources (land, water, air, climate, biological diversity) and the protection of the public against harmful substances (FOEN, 2009). The Swiss agricultural policy promotes a multifunctional agricultural system for the following reasons: (1) to ensure food supply for the population with regard to ecological standards, (2) to maintain both natural resources and the rural landscape, and (3) to maintain rural areas through a decentralized arrangement (FOAG, 2004). Therefore, the impact of policies other than climate policy on agricultural mitigation of emissions should not be underestimated.

The analysis of environmental aspects in general and appropriate domestic strategies to mitigate GHG and nitrogen emissions from agriculture in particular, require considering comprehensively the implications of both climate and non-climate policies as well as environmentally related technologies. This necessitates an adequate approach
that enables the analysis of the agricultural use of natural resources from an economic point of view. This means that an approach to improve the understanding and management of agricultural natural resources is essential. Moreover, such an approach should enable a proper definition of the issues relevant to the analysis of environmental aspects. Furthermore, it is required to indicate which and to what extent several measures, such as policies and technologies, have and will contribute to the mitigation of GHG and nitrogen emissions over a certain time period.

Analytical models have been proven as adequate approaches to analyze complex real world problems, such as the impact of agriculture on the environment (Burrell et al., 1995; Heckelei et al., 2001; Bauer and Henrichsmeyer, 1989). Models represent simplifications of complex real world problems by integrating several types of information, experiences and thoughts as well as both economic descriptions and explanations. Thus, they constitute abstractions. With this approach, they enable the user to simultaneously interrelate many factors that help to identify crucial inputs, outputs and framework conditions (Hazell and Norton, 1986). Therefore, they are regularly applied to support the decision making process. The application of a model necessitates the reduction of the real world problems to their essentials. This particularly refers to questions that include the following: (1) which aspects of reality have to be included in the model and which can be ignored, (2) what assumptions can and should be made, and (3) which type of model has to be used. Agricultural impact on the environment can be analyzed by assessing the farm level impact on the environment (van der Werf and Petit, 2002) or by evaluating the impact at a regional or sectoral level (Payraudeau and van der Werf, 2005). Models applied to analyze agricultural impact can refer to biophysical or economical aspects. Biophysical aspects include the simulation of yields, the estimation of nutrient losses, or the consideration of substance fluxes. Torriani et al. (2007) used the simulation model CropSyst to study the effects of climate on the productivity of cropping systems for perennial and non-perennial crops. Lazzarotto et al. (2009) investigated the dynamics of the co-existence of grass and clover by applying the dynamic model PROGRASS. They assessed the role of root development in controlled grass and clover interactions in a temperate, rotational grassland. Riedo et al. (1998) simulated the impact of cutting and fertilization on the annual dry matter production of a mixed perennial meadow using the pasture simulation model (PaSim), which considers the fluxes of carbon, nitrogen and water as well as energy. Menzi et al. (2003) applied the N-flux model DYNAMO to calculate am-
monia emissions on an annual basis. They estimated the nitrogen flow from excretion by considering animal housing, grazing and manure storage and applying different livestock categories and manure types. The ammonia emissions were calculated with standard emissions factors expressed as the percent of the N present at a given stage of the manure handling chain. Brugger (2008) applied the biophysical model EPIC for the estimation of yield, soil and nutrient losses depending on the crop, weather, soil characteristics and cultivation techniques.

In contrast, aspects of economic models focus on the income and/or market facets of agriculture, for which both positive and normative approaches are distinguishable (Grafton et al., 2004). A positive model describes and explains facts and relationships. It is characterized by questions such as “what is?” or “what would be?” A normative model, on the other hand, leads to economic or political recommendations in order to define a specific objective, and thus, it refers to the question “what should be?” As concluded by Spedding (1987), improvements in environmental quality through agricultural activities can only be achieved when the agricultural system is holistically analyzed, and not by the sole change of a single component.

An integrated perspective is useful for the analysis of the measures and policies that are applied to the environmental aspects of complex systems. Computer-aided integrated assessment models provide the opportunity to take both the biophysical and economic elements into account. An integrated assessment model is a simplified and schematic representation, which omits several feedbacks and cross-links (cf. Janssen, 1998; McCarl and Schneider, 2001; Schneider and Lane, 2005). Knowledge from various disciplines, such as plant and livestock production or economics, is combined in one framework. This enables the analysis of important biophysical and economical elements to be done in one system. Thus, it maintains consistency in definitions and identities at different levels of aggregation. An integrated model framework is also crucial for managing the huge amount of data that is needed for this type of analysis. It allows for an easy and reproducible computation of solutions that are based on different sets of assumptions (Barker, 2003 and 2001; IPCC, 2001). Integrated model outputs not only offer valuable information for decision makers concerning how different measures (such as policies and technologies) affect the costs of meeting environmental objectives, but they also provide the basis for a time-dependent implementation of emissions cuts (Schneider and Lane, 2005).
In addition to the integrated assessment models, linking models or model chains provide another opportunity to take both biophysical and economical elements into account. Linking models or model chains, in particular, refer to the parameterization of agricultural sector models by biophysical or special trade models, for instance (Offermann, 2008; Britz, 2008; van Ittersum et al., 2008; Jansson, 2008; Leip et al., 2007; Helming et al., 2005). This is realized by either enriching the components or by adding new tools to existing models. This enables the user to focus on upcoming issues that agriculture is confronted with, such as environment or rural development. Linking several models rather than building a very complex model allows for flexibility in methodological and technical solutions as well as for the parameterization and the use of versatile underlying data. The advantage lies in a developmental flexibility and in an increase of applications and maintenance. Moreover, the combination of various model types can lead to results or spatial resolutions that are of higher quality than that of the model upon which they have been primarily based. The linked model approach, however, also faces a number of challenges. The compatibility of models from different disciplines has to be assured, e.g., aspects of definition, units of measurements and data sources. Models with several levels or scales require a certain level of theoretical consistency. Financial and human resources have to ensure the effective and sustainable maintenance of linked models. Often, a lack of transparency may occur that results from the huge amount of information produced. This can lead to a reduced acceptance of computed results by policy makers (Offermann, 2008; Britz, 2008).

In general, the information content of a model does not exceed the purpose it was intended for. A political decision solely based on models will never completely consider the complexity of the problem, as each mathematical model is a simplified representation of reality (see above). Thus, models can not replace decision makers as calculated results do not necessarily provide “optimal solutions” free of human subjectivity and error. The model solution simply presents the best solution to the problem that is modeled under the aspects and assumptions chosen. The optimal or near-optimal solution derived from such a model is at least significantly better than the policy or procedure that it is meant to replace (Ackoff and Sasieni, 1968; Ravindran et al., 1987).

In summary, quantitative estimates derived from models provide the basis for policy makers to determine how changes in agricultural production or policy can affect envi-
1 General introduction

Ronmental quality and what consequences can result from such changes. A normative approach aims to optimize agricultural production in relation to its technical or political options, while reducing its environmental impact. Mathematical programming and quantitative methods have proven to be a powerful tool for the analysis of the optimal allocation of scarce resources at the sector level when considering the environmental aspects of agricultural practices.

1.4 Framework and scope of the analysis

As mentioned above, monitoring the role of agriculture as a source of GHG and nitrogen emissions is of high relevance to society. To address this, a keen knowledge of the specific contributions of the agricultural sector to these emissions is required. This particularly refers to the assessment of domestic strategies for the reduction of GHG and nitrogen emissions.

For the Swiss agricultural sector in particular, a comprehensive economic outline of the extent to which agricultural practices might efficiently contribute to the mitigation of Swiss GHG and nitrogen emissions is missing. This study provides valuable information to impact this field by applying an economic model that mimics the structure of Swiss agriculture in combination with important features that are linked to GHG and nitrogen emissions. The three main objectives of the present study are as follows:

#1: Identification of Swiss agriculture's contribution to climate and nitrogen policies

- What are the international and national objectives related to GHG and nitrogen emissions to which Switzerland is committed?
- To what extent have GHG and nitrogen emissions from agriculture decreased since 1990?
- What is the economic value of this contribution to climate policy?
1 General introduction

#2: Expectations of future reductions in GHG and nitrogen emissions

- What is the economic value of additional reductions in GHG and nitrogen emissions when considering different agricultural policies?
- What economic values can be identified in comparison to other national sectors (e.g., energy consumption sector)?
- What are the costs for the agricultural sector to reach a specific reduction target?

#3: Evaluation and recommendations for environmental policies in the future

- What is the impact of the obtained results on future policies?
- What kinds of policies may contribute to a further reduction in emissions from the agricultural sector?
- Which additional policies might be considered from the results presented?
- How a certain reduction target can be optimally achieved?

1.5 Structure of the thesis

The structure of the thesis is based on the objectives mentioned above. As chapter 2, 3 and 4 have been published, they are presented as self-contained papers.

In chapter 2, the focus lies on the linear programming model S_INTAGRAL and its evaluation as this model has been applied to the objectives and the related questions presented in chapter 1.4. Chapter 3 applies this model to GHG emissions emerging from Swiss agriculture, and it contrasts the costs of mitigation of both the agricultural and energy consumption sectors using a meta-analytical framework. In chapter 4, nitrogen emissions as well as the costs and effectiveness of different nitrogen taxes are examined by adapting the S_INTAGRAL model. Chapter 5 presents concluding remarks, including answers to the questions outlined above, and relates these results to further research issues.
2 Strategies to mitigate greenhouse gas and nitrogen emissions in Swiss agriculture: the application of an integrated sector model

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

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

2.1 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 (CO₂) 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 (CH₄) and nitrous oxide (N₂O) constitute crucial non-CO₂-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 (CO₂) (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 (NH₄⁺) or ammonia (NH₃). In the process of nitrification, ammonium is oxidized via nitrite (NO₂⁻) to nitrate (NO₃⁻). 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 Unkovitch, 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, Povellato 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.

2.2 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 aggre-
2 Strategies to mitigate greenhouse gas and nitrogen emissions in Swiss agriculture: the application of an integrated sector model

gated 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 bio-physical/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.
2.3 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 avail-
able 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.

2.4 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.

2.4.1 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.

\[
\text{Max } Z = \sum_{y} Y_{y} p_{y} + \sum_{x} X_{x} d_{x} - \sum_{x} X_{x} c_{x}^{\text{var}} - \sum_{x} X_{x} c_{x}^{\text{fix}} - \sum_{x} X_{x} l_{x} - \sum_{x} AK_{x} l_{a_{x}}
\]

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]
  - \(l_{a_{x}}\) = labor costs [CHF/hour]

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.

2.4.2 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 additional to general direct payments, farmers can get ecological direct payments, e.g., for organic farming, extensive production and for particularly animal-friendly conditions.

2.4.3 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).
Two strategies to mitigate greenhouse gas and nitrogen emissions in Swiss agriculture: the application of an integrated sector model

Figure 2: Incremental price function with two steps.

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.

\[
p_{\text{domestic}} \text{ if } Y \leq Y_{\text{domestic}} \\
p_{\text{foreign}} \text{ if } Y > Y_{\text{domestic}}
\]

with:

\[
Y_{\text{domestic}} = (K_{\text{domestic}} \cdot P_{\text{domestic}}) - \text{IMP}
\]

with:

\[
\begin{align*}
\text{variables} & \\
\text{indices} & \\
p & \text{producer price [CHF]} \\
Y & \text{supply of livestock and plant products [t]} \\
K & \text{consumption per capita at farmgate [kg/capita]} \\
P & \text{population [population]} \\
\text{IMP} & \text{imports [t]}
\end{align*}
\]

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.
2.4.4 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>
<thead>
<tr>
<th>index</th>
<th>description</th>
<th>details</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>zone</td>
<td>n = 3</td>
</tr>
<tr>
<td>b</td>
<td>soil type</td>
<td>n = 2</td>
</tr>
<tr>
<td>bb</td>
<td>soil cultivation</td>
<td>n = 2</td>
</tr>
<tr>
<td>k</td>
<td>crops</td>
<td>n = 13</td>
</tr>
<tr>
<td>i</td>
<td>intensity</td>
<td>n = 3</td>
</tr>
</tbody>
</table>

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).

\[
\sum_k X_{area}^k \cdot F_{Ff}^k \geq 0; \quad F_{Ff}^k = \begin{cases} 
(1 - F_{Ff}^{max}) \cdot -1, & k \in \text{ff} \\
F_{Ff}^{max}, & k \not\in \text{ff}
\end{cases} \quad (3)
\]

with:

- **variables**
  - \(X_{area}^k\) = land use decision [ha]
  - \(F_{Ff}^k\) = coefficient for crop rotation [%]
  - \(F_{Ff}^{max}\) = maximum share of acreage of (grouped) crops ff [%]

- **indices**
  - \(k\) = crop
  - ff = (grouped) crops (e.g., cereals)

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 \(F_{Ff}^{max}\)). For example, the share of wheat on crop acreage is re-
2 Strategies to mitigate greenhouse gas and nitrogen emissions in Swiss agriculture: the application of an integrated sector model

stricted 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.

Table 2: Specifications for livestock production.

<table>
<thead>
<tr>
<th>index</th>
<th>description</th>
<th>details</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>zone</td>
<td>n = 3, plain, hill, mountain</td>
</tr>
<tr>
<td>ti</td>
<td>animal type</td>
<td>13, dairy cattle, suckler cattle, fattening calf, fattening bullock, rearing cattle, fattening swine, breeding swine, piglet, sheep, lamb, pullet, laying hen, broiler</td>
</tr>
<tr>
<td>s</td>
<td>house system</td>
<td>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)</td>
</tr>
<tr>
<td>g</td>
<td>house size</td>
<td>n = 7, 15 places, 25 places, 40 places, 100 places, 200 places, 500 places, 4000 places</td>
</tr>
<tr>
<td>l</td>
<td>livestock efficiency</td>
<td>n = 8, 5000_kg, 7000_kg, 9000_kg, Natura_Beef, low, high, standard, profi</td>
</tr>
<tr>
<td>kf</td>
<td>concentrate</td>
<td>n = 3, 0%, 20%, 40% (of dry matter-ratio)</td>
</tr>
<tr>
<td>a</td>
<td>management style</td>
<td>n = 5, no pasture, part-time pasture, full pasture, run, no run</td>
</tr>
</tbody>
</table>

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.
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\[
(1 - \eta) \cdot X_{cattle}^{(t-1)} \leq X_{cattle}^t \leq (1 - \eta) \cdot X_{cattle}^{(t-1)} + \alpha \cdot R_{(t-1)} \tag{4}
\]

with:

<table>
<thead>
<tr>
<th>variables</th>
<th>indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X_{cattle}) = dairy and suckler cattle activity [livestock unit]</td>
<td></td>
</tr>
<tr>
<td>(\eta) = culling rate of cattle [1/life expectation]</td>
<td></td>
</tr>
<tr>
<td>(\alpha) = survival rate of cattle [%]</td>
<td></td>
</tr>
<tr>
<td>(R) = rearing cattle &gt; 2 years [livestock unit]</td>
<td></td>
</tr>
</tbody>
</table>

The total number of dams (denoted by \(X_{cattle}^t\)) 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):

\[
X_{cattle}^t \leq B_t \text{ with } B_t \leq (1 - \delta) \cdot B_{(t-1)} + I_t \tag{5}
\]

with:

<table>
<thead>
<tr>
<th>variables</th>
<th>indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X_{cattle}) = dairy and suckler cattle activity [livestock unit]</td>
<td></td>
</tr>
<tr>
<td>(\delta) = constant depreciation [%]</td>
<td></td>
</tr>
<tr>
<td>(B) = existing house systems</td>
<td></td>
</tr>
<tr>
<td>(I) = investment [CHF]</td>
<td></td>
</tr>
</tbody>
</table>

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 \(X_{cattle}^t < B_t\)). 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 (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 \(\sigma\)).
\[ X_{\text{young stock}} = X_{\text{dam}} \times \mu \times (1 - \sigma) \]  

with:

variables

- \( X_{\text{young stock}} \): number of young stock [livestock unit]
- \( X_{\text{dam}} \): 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 is shown in eq. (7), which demonstrates the procedure for nutrients. The nutrient balance additionally forms a legal requirement for receiving direct payments.

\[
\sum_k X_{\text{area}} \times Nb \leq NS + \sum_{kd} KD \times g \leq (1 + To) \sum_k X_{\text{area}} \times Nb
\]

with:

variables

- \( X_{\text{area}} \): 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

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.

**2.4.5 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 pro-
Strategies to mitigate greenhouse gas and nitrogen emissions in Swiss agriculture: the application of an integrated sector model

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.

Table 3: Modeled indicators for GHG emissions.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>source in S_INTAGRAL</th>
<th>depending on/affected by in S_INTAGRAL</th>
<th>based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{CH}_4 ) methane</td>
<td>• enteric fermentation</td>
<td>feed absorption, digestibility, animal specific methane rate</td>
<td>IPCC (1997); UNFCCC (2000, 2003); NIR (2008); Minonzio et al. (1998)</td>
</tr>
<tr>
<td></td>
<td>• manure management</td>
<td>animal specific amount of digestible excrements, methane formation capacity, a housing specific amount of manure</td>
<td></td>
</tr>
<tr>
<td>( \text{N}_2\text{O} ) nitrous oxide</td>
<td>• manure management (direct)</td>
<td>livestock population, house system, management style, storage and deploy of slurry and manure, storage time</td>
<td>IPCC (1997); NIR (2008); Schmid et al. (2000); Schmid et al. (2001)</td>
</tr>
<tr>
<td></td>
<td>• agricultural soils (direct)</td>
<td>N-leaching crops, N-loss grassland, fertilizer, N-fixation, crop residues, organic soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• indirectly</td>
<td>from emissions of ammonia, nitrate and nitrogen oxide</td>
<td></td>
</tr>
<tr>
<td>( \text{CO}_2 ) carbon dioxide</td>
<td>machinery fuel consumption</td>
<td>fuel consumption for plant activities depending on zones and performance</td>
<td>IPCC (1997); Ammann (2007)</td>
</tr>
<tr>
<td>potential for C-sequestration in agricultural soils</td>
<td>• coefficients</td>
<td>no-till farming, conversion arable to permanent pasture</td>
<td>Leifeld et al. (2003)</td>
</tr>
</tbody>
</table>

Note:  

\( ^a \) 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.
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).

\[
NLP = \sum_{\text{env}_{-}\text{relevant}} \text{nitrogen emission} + \sum_{\text{env}_{-}\text{harmless}} \text{nitrogen emission} \tag{8}
\]

with:

\[
\text{nitrogen emission}_{\text{env}_{-}\text{relevant}} = \text{NH}_3 + \text{NO}_3^- + \text{N}_2\text{O} + \text{NO}_x
\]

\[
\text{nitrogen emission}_{\text{env}_{-}\text{harmless}} = \text{N}_2
\]

with:

\begin{align*}
\text{variables} & \quad \text{indices} \\
\text{NLP} = \text{nitrogen loss potential} & \quad \text{env}_{-}\text{relevant} = \text{environmentally relevant nitrogen emission} \\
\text{NH}_3 = \text{ammonia} & \quad \text{env}_{-}\text{harmless} = \text{environmentally harmless nitrogen emission} \\
\text{NO}_3^- = \text{nitrate} & \\
\text{N}_2\text{O} = \text{nitrous oxide} & \\
\text{NO}_x = \text{nitrogen oxide} & \\
\text{N}_2 = \text{dinitrogen} &
\end{align*}

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.
### Table 4: Modeled indicators for nitrogen emissions.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>source in S_INTAGRAL</th>
<th>depending on/affected by in S_INTAGRAL</th>
<th>based on</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH$_3$ ammonia</td>
<td>livestock</td>
<td>animal type, house system, manure storage and deploy, livestock efficiency, management style</td>
<td>Reidy and Menzi (2005); Reidy et al. (2008)</td>
</tr>
<tr>
<td></td>
<td>deploy fertilizer</td>
<td>fertilizer specific nutrient content</td>
<td></td>
</tr>
<tr>
<td></td>
<td>agricultural soils</td>
<td>share on crop acreage and crop specific factors</td>
<td></td>
</tr>
<tr>
<td>NO$_3^-$ nitrate</td>
<td>agricultural soils</td>
<td>share on crop acreage and crop specific factors</td>
<td>Braun et al. (1994)</td>
</tr>
<tr>
<td></td>
<td>management (direct)</td>
<td>livestock population, house system, management style, storage and deploy of slurry and manure, storage time</td>
<td>Schmid et al. (2000); Schmid et al. (2001)</td>
</tr>
<tr>
<td>N$_2$O nitrous oxide</td>
<td>manure management (direct)</td>
<td>N-leaching crops, N-loss grassland, fertilizer, N-fixation, crop residues, organic soils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>agricultural soils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO$_x$ nitrogen oxides</td>
<td>manure and fertilizer</td>
<td>livestock population, amount of manure and fertilizer</td>
<td>Schmid et al. (2000)</td>
</tr>
</tbody>
</table>

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

#### 2.4.6 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.
2.4.7 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.

2.4.8 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.

2.5 Results

This section presents results from both evaluation and application of the S_INTAGRAL model.

2.5.1 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.

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.

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

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%.

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

<table>
<thead>
<tr>
<th>GHG emissions</th>
<th>CH$_4$ from enteric fermentation</th>
<th>CH$_4$ from manure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>100</td>
<td>24</td>
</tr>
<tr>
<td>2000</td>
<td>105</td>
<td>25</td>
</tr>
<tr>
<td>2001</td>
<td>110</td>
<td>26</td>
</tr>
<tr>
<td>2002</td>
<td>115</td>
<td>27</td>
</tr>
<tr>
<td>2003</td>
<td>120</td>
<td>28</td>
</tr>
<tr>
<td>2004</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>31</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>N$_2$O from agricultural soils</th>
<th>N$_2$O from manure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>5</td>
</tr>
<tr>
<td>2000</td>
<td>6</td>
</tr>
<tr>
<td>2001</td>
<td>7</td>
</tr>
<tr>
<td>2002</td>
<td>8</td>
</tr>
<tr>
<td>2003</td>
<td>9</td>
</tr>
<tr>
<td>2004</td>
<td>10</td>
</tr>
<tr>
<td>2005</td>
<td>11</td>
</tr>
<tr>
<td>2006</td>
<td>12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nitrogen emissions</th>
<th>Environmentally relevant N emissions total</th>
<th>Ammonia from agriculture total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>2004</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>2005</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>46</td>
<td></td>
</tr>
</tbody>
</table>
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 CH₄/head/year) as the factor for rearing cattle (2 kg CH₄/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 N₂O-N/kg N) is nearly twenty times that factor for liquid manure (0.001 kg N₂O-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%.

2.5.2 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.
2 Strategies to mitigate greenhouse gas and nitrogen emissions in Swiss agriculture: the application of an integrated sector model

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

tion (-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 CO2eq mitigated by technology is introduced. This incentive for using mitigation technologies successively rises from 0 to 5000 CHF/t CO2eq. 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$_2$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$_2$eq. At costs less than 100 CHF/t CO$_2$eq, manure coverage might contribute between 80 to 100 kt CO$_2$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$_2$eq at maximum, but only if the incentive exceeds 1000 CHF/t CO$_2$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.

### 2.6 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.
2.6.1 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.
2.6.2 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 NH3 gap”, as an increase in measurement of nitrogen emissions does not confirm the decline of inventory calculations.

2.6.3 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.

### 2.7 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.
3 How much should Swiss farmers contribute to greenhouse gas reduction? A Meta-analytical approach

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Abstract

The debate about future climate policy involves the question about the contribution of agriculture in meeting overall greenhouse gas mitigation targets. From an economic perspective, this calls for assessing and equalizing marginal mitigation costs across different sectors. To this end, we employ a meta-analytical approach that is based on results from different studies, and that allows us to assess the optimal level and economic value of agriculture’s contribution to meeting national policy targets.

A numerical example for Switzerland shows that, even without any legal commitment to greenhouse gas emissions reduction, Swiss agriculture will contribute 17 to 28 % to the national Kyoto target until 2010. This reduction corresponds to an economic value in the range of 30 to 106 Mio CHF/year and diminishes the expected total abatement costs in the rest of the economy in the same magnitude. This is primarily an effect of the current agricultural policy, whereas targeted incentives and soil carbon sequestration may only marginally contribute within the same time frame. Moreover, the results of our meta-analytical assessment underline that it would be efficient to participate in international emissions trading.

From a methodological point of view, our analysis explicates how the results about greenhouse gas mitigation costs from a highly detailed allocation model of the agricultural sector and those from an energy model of the overall economy can be connected in a meta-analytical framework.

Keywords: agriculture, climate policy, greenhouse gas emissions, abatement costs, economic evaluation.

JEL classification: Q1, Q4, Q5, D61

3.1 Introduction

The stabilization of greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system is the objective in the United Nations Framework Convention on Climate Change (UNFCCC) which entered into force in 1994. It “should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not
threatened and to enable economic development to proceed in a sustainable manner.” However, the UNFCCC does not include quantitative goals or legally binding commitments for countries to reducing or at least limiting their anthropogenic greenhouse gas (GHG) emissions. These are set in the Kyoto Protocol of 1997, which entered into force in February 2005 and defines the frame of reference of current climate policy for its signatories. It constitutes an important first step towards achieving the long-term goal of stabilizing GHG concentrations at a level which shall avoid dangerous climatic change. Accordingly, more stringent emission reduction targets must be agreed in the negotiations for the second commitment period and a new international framework that needs to be in place when the Kyoto Protocol expires in 2012. On national level, this involves the need of revising current legislation and reconsidering climate policy measures and instruments. Amongst others, this brings in the question about how much agriculture - and particularly livestock-based production - should contribute to meeting a country’s climate policy targets. From an economic perspective, this calls for an integrated assessment of mitigation options and comparison of marginal abatement costs across different sectors. Indeed, economic efficiency requires marginal costs of mitigation being equalized across the different measures to either reduce GHG emissions at their source or to sequester carbon in soils and biomass, respectively. The equalization of marginal mitigation costs must be achieved both within agriculture and in the economy as a whole.

In this article, we utilize a meta-analytical approach that puts together the results of two different, but complementary studies that provide information about marginal greenhouse gas mitigation costs. The aim is to present a conceptual framework for integrated climate policy appraisal and, in particular, to address the question about how much the agricultural sector should contribute to reaching climate policy targets in a small country like Switzerland. For illustrative purposes, we use the results of existing studies by Bahn and Frei (2000), who studied policy options of mitigating energy-based CO₂ emissions in Switzerland for the year 2010, and Hediger et al. (2004), who assessed marginal costs of GHG reduction in the agricultural production sector with the same time horizon. This allows us to calculate, for different policy and price scenarios, economically optimal levels of GHG mitigation for Swiss agriculture and to assess the economic value of agriculture’s contribution to climate policy in
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Switzerland since 1990 and the expected emission reductions until 2010. To this end, the paper is organized as follows.

In Section 2, we briefly review the state of the art in the economics of agricultural GHG mitigation. Section 3 gives an outline of the Swiss climate policy framework and relevant options of GHG mitigation in the agricultural sector. Section 4 portrays our methodological approach, and Section 5 gives a selection of base-run modeling results for the period 2000 to 2010. Building on this background and using a meta-analytical framework, Section 6 is devoted to the assessment of the economic value of agriculture’s contribution to climate policy within the first commitment period of the Kyoto Protocol. Finally, Section 7 concludes with an outlook on considerations about agriculture’s prospective role in post-Kyoto climate policy.

3.2 On the economics of agricultural GHG mitigation - a brief review

In the Kyoto Protocol of 1997 industrialized countries committed themselves to reducing their emissions of the six GHGs carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆) by specified amounts below the reference level of 1990 until the first commitment period 2008 - 2012. To comply with these targets, countries must not only reduce energy-intensive activities and invest in clean technologies through adequate policy measures in their countries. They can also make use of international measures through means of joint implementation, clean development mechanisms and emissions trading. Moreover, countries can use biological sinks in vegetation and agricultural soils to remove CO₂ from the atmosphere. By various commentators, the latter is propagated as a prospective way of CO₂ mitigation and as an interesting new option for income support in agriculture, through either receiving government subsidies or participation in a carbon trading scheme (Sandor and Skees, 1999; Marland et al., 2001; Lal, 2004).

In the economics literature of the 1990s carbon sequestration has primarily been addressed with regard to forestry measures and afforestation on agricultural land, while carbon sequestration in agricultural soils only gained attention in recent years (cf. Antle and McCarl, 2002). Based on integrated assessments using biophysical simulation and econometric process models, Pautsch et al. (2001) and Antle et al. (2001,
2003) investigated specific options of soil carbon sequestration in Iowa and Montana, and compared the cost-effectiveness of different policy schemes that would encourage farmers to adopt targeted sequestration techniques on their land. The estimated costs indicate that, at least in Montana, carbon sequestration in agricultural soils would be competitive with measures to reduce GHG emissions in other sectors.

Antle et al. (2001) report marginal costs of C sequestration by converting cropland to permanent grassland (PG) in the range of 50 US$/t C to over 500 US$/t C, and for the alternative case of conversion to continuous cropping without set aside (CC) marginal costs in a range of 12 to 140 US$/t C. The main reason for this difference may be a consequence of fundamental differences in the two policy scenarios, rather than due to an effective difference in marginal costs of sequestration. Under the PG policy scenario, a fixed annual per hectare payment is given to producers for C sequestration, under the premise that all cropland and pasture land is eligible. In contrast, under the CC scenario, farmers are paid on a per hectare basis only for fields switched to continuous cropping. This has a similar effect as the distinction between payments to all adopters and new adopters only in the study of Pautsch et al. (2001).

A different approach with respect to methodology and research question has been used by McCarl and Schneider (2000, 2001). They analyzed various options for reducing GHGs in US agriculture by introducing alternative carbon prices in the Agricultural Sector and Mitigation of Greenhouse Gas (ASMGHG) model (Schneider, 2000), and conclude that, from an economic perspective, the contribution of C sequestration in agricultural soils exceeds that of reducing agricultural methane and nitrous oxide emissions. This means that for a given carbon price (marginal cost) the economic potential of GHG reductions by C sequestration is higher than the potential of reducing agricultural GHG emissions. But, McCarl and Schneider also emphasize the existence of more cost-effective measures for elevated carbon prices above 100 US$/t C-equivalent. These measures include C sequestration through afforestation on agricultural land and the use of bio-fuels as CO2-neutral energy source (Schneider and McCarl, 2003).

These findings go in line with the results of De Cara and Jayet (2000) for French agriculture that is based on an analysis with a set of farm-unit linear programming models. They show that afforestation on set-aside land would be the cost-effective solution for curtailing net GHG emissions. In contrast, Lehtonen et al. (2006) conclude
that significant GHG reductions can be reached with little decrease in national agricultural incomes, by restricting the cultivation of peatland in Northern Finland. They apply the dynamic regional sector model of the Finnish agriculture DREMFIA to simulate agricultural production and markets for the period 1995 to 2020.

Using the recursive dynamic linear optimization model S_INTAGRAL, Hediger et al. (2004) found much lower economic potential for soil carbon sequestration in Swiss agriculture and rather high cost of GHG mitigation from agricultural land use and livestock production. The deviation in results from the above studies is explained by the subsequent facts:

(a) the share and area of cultivated peatland is much smaller in Switzerland than in Finland;

(b) due to lack of adequate data, Hediger et al. (2004) did not consider the restoration of cultivated peatland despite the relatively high physical potential estimated by Leifeld et al. (2003);

(c) caused by the agricultural policy reform since the early 1990s, Swiss agriculture has already reduced its GHG emissions (mainly methane and nitrous oxide) by about 10% between 1990 and 2000, whereas total GHG emissions in Switzerland are still around the reference level of 1990 (BAFU, 2006);

(d) the existence of a highly integrated agricultural production system with strong links between livestock and land use that has been historically developed and causes relatively high cost of agricultural GHG mitigation in Switzerland.

Numerous studies - in particular from the USA and Canada - reveal that the economic potentials of C sequestration in agriculture and forestry are significantly smaller than biophysical potentials, and that carbon sequestration can only provide a limited contribution to achieving national Kyoto targets. Moreover, the economic assessment of GHG mitigation costs and potentials cannot be restricted to soil carbon sequestration. Rather, it must consider the various sources of agricultural GHG emissions and the related costs of mitigation through changes of land and livestock management. McCarl and Schneider (2001) observed that interdependencies of crop and livestock management affect the costs and potential for agricultural GHG emission mitigation in different ways. Accordingly, agriculture must be seen as a complex system with various interrelated nutrient cycles (nitrogen and carbon) that exhibit their own inter-
nal dynamics (Hediger, 2006). It is the resulting production structure (size and composition of livestock population and land use patterns) and the intensity of cultivation (especially the manure and fertilizer application rates) that, according to scientific studies and IPCC guidelines, determine agricultural emissions of methane and nitrous oxide.

From a methodological point of view, the various studies illustrate the relevance of an integrated modeling approach for the economic analysis of agricultural GHG-reductions. Such an approach particularly allows for consideration of synergies and trade-offs among separate measures in a systematic way, even if interdependencies are not always obvious.¹

All in all, it is essential to consider the above insights for the development of further economic analyses that aim at evaluating alternative measures and potentials of GHG mitigation through emissions abatement and carbon sequestration in agricultural production systems. Finally, from an economic perspective, any assessment of agricultural GHG mitigation options must include a comparison with marginal GHG abatement costs in other sectors. Indeed, different measures in reducing GHG emissions and their cost-effectiveness in achieving national Kyoto targets can only be evaluated by comparing marginal abatement costs across the various sectors. To this end, we employ a meta-analysis that puts together the results from different sectoral studies.

¹ It is increasingly acknowledged in the literature that the evaluation of agricultural and environmental policy measures asks for an integrating perspective across different disciplines (Antle and Capalbo, 2001; Braat and van Lierop, 1987; Hediger, 1999; Jakeman and Letcher, 2003; Morgan and Dowlatabadi, 1996). In particular, if complex systems and their interactions are considered, an integrated assessment approach is needed (Janssen, 1998; McCarl and Schneider, 2001; Schneider and Lane, 2005). According to Barker (2001, 2003) such approaches are required to incorporate scientific knowledge in different areas, to manage the huge amounts of data needed for modeling, to maintain consistency in definitions and identities at different levels of aggregation and to allow for easy and reproducible computation of solutions based on different sets of assumptions. Furthermore, Spedding (1987) emphasises that improvements for the agricultural system have to be sought for the system as a whole and cannot be achieved by changes in one component, and not without regard to the rest of the system. This is particularly relevant when a problem involves economic and environmental aspects of circular nutrient flows, such as the interconnection of forage and manure production and use that is central for the assessment of GHG mitigation options in agriculture.
3.3 Swiss climate policy and national options for agricultural GHG reduction

With the ratification of the Kyoto Protocol, Switzerland committed itself to reducing its GHG emissions by 8% below the reference level of 1990 until the first commitment period (2008-2012). This goal is reflected in the national CO₂ Law (1999), which only prescribes a reduction of energy-based CO₂ emissions until 2010 by 10% below the level of 1990, but does not address agricultural GHG emissions. In this legal framework, subsidiary targets are set for combustibles that shall be reduced until 2010 by 15% and transport fuels (not including aviation fuel for international flights) by 8% below their 1990 levels. These reductions shall primarily be achieved by means of energy, transport, environmental and fiscal policy, and, most importantly, by voluntary measures in the manufacturing and service industries. If the reduction target cannot be accomplished by these measures the CO₂ Law prescribes the introduction of a CO₂ tax on fossil fuels.

The current situation shows that the measures hitherto are not sufficient to meet the national reduction goal. Emissions from combustible fuels decreased by about 6% from 1990 until 2005, whereas emissions from transport fuels increased by 9% over the same period (BAFU, 2006). As a consequence, the Swiss Parliament approved in March 2007 the concept of a CO₂ tax on combustibles that is implemented in 2008 and shall increase in three steps from initially 12 CHF/t CO₂ to 36 CHF/t CO₂ in 2010. This constitutes an additional instrument besides the so-called “climate cent”, which has been established in 2005 as a voluntary measure by the Swiss industry with a charge levied on all imports of petrol and diesel at a rate of 1.5 cents per litre. The estimated receipts of about 100 million CHF per annum shall be invested in GHG reduction projects in Switzerland and abroad. This instrument must prove its effectiveness until the end of 2007. Otherwise the Federal Council may also introduce a CO₂ tax on petrol.

In contrast, Swiss agriculture has already provided a contribution of 14% to the national Kyoto target, even though there is no explicit commitment, neither in the Kyoto protocol nor in the CO₂ Law. The entire sector causes about 12% of the national GHG emissions. It is the major emitter of methane with 67% and nitrous oxide with 72%, but only contributes 1.7% of the national CO₂ emissions (BUWAL, 2004). Since 1990, Swiss agriculture has reduced its methane and nitrous oxide emissions by more than 10%, as a result of reforms in agricultural policy that particularly forced
livestock reduction and improved fertilizer management. Beyond that, further reductions of agricultural GHG emissions are expected until 2010 by continuing the current agricultural policy (Bundesrat, 2002).

Given the magnitude of methane and nitrous oxide as the major sources of agricultural GHG emissions, the most obvious GHG mitigation options are directly linked with a reduction of these emissions and thus with the farmers’ interrelated decisions on livestock, manure and land use management. This accounts for the fact that, methane emissions are mainly caused by enteric fermentation of ruminants (mainly milk cows) and manure management, whereas nitrous oxide is due to manure management, fertilizer application and land use patterns. These emissions are reported on an annual basis in the national GHG inventory (cf. SAEFL, 2004), which is compiled in accordance with the requirements of the Climate Convention (UNFCCC, 2000, 2003). They are calculated according to methodological guidelines recommended by the IPCC (1997) and under consideration of specific conditions in Switzerland. The latter are documented in special reports on methane and nitrous oxide emissions from Swiss agriculture (Minonzio et al., 1998; Schmid et al., 2000).

Another option of GHG mitigation in agriculture is the sequestration of carbon in soils and biomass. Yet, carbon sinks have hitherto only been considered in the GHG inventory as far as they are due to GHG removals (biomass accumulation) by land-use change and forestry. Carbon stocks in agricultural soils have not yet been included, due to the lack of internationally approved reporting guidelines. These are described in the Good Practice Guidance of the IPCC (2003) and have been approved by the Conference of Parties of the UNFCCC for preparing annual inventories due in 2005 and beyond (UNFCCC, 2004: 31).

A first assessment of carbon stocks and sequestration potentials in agricultural soils in Switzerland is provided by Leifeld et al. (2003). This constitutes a scientifically based prerequisite for the assessment of carbon sinks in Swiss agriculture. Together with previous studies on methane and nitrous oxide emissions in Swiss agriculture (Minonzio et al., 1998; Schmid et al., 2000) and a state-of-the-art review by Fischlin et al. (2003) on carbon sequestration options in agriculture and forestry, it establishes a valuable basis for an economic appraisal of measures to reduce GHG emissions and to enhance soil carbon stocks by Swiss agriculture. Leifeld et al. (2003) show that the most important options of soil C sequestration in Switzerland are the adoption of no-
till farming or the conversion of cropland to permanent pasture, and the restoration of the rather small area with organic soils (see also Hediger, 2004, 2006).  

Altogether, scientific studies indicate that the realization of sequestration potentials in Swiss agriculture would require fundamental changes of agricultural structures, while expected sequestration potentials in agricultural soils are relatively small compared to those in forests. Furthermore, the existence of systemic interdependencies of land use and animal production through the forage-and-manure cycle indicates, that an integrated approach is required for the economic appraisal of carbon sequestration options in agriculture. It will imply simultaneous consideration of all agricultural GHG emissions (CO₂, CH₄ and N₂O) as well as assumptions about the development of economic conditions and the agricultural policy framework. Apparently, this implies an allocation problem of finding the optimal (i.e., cost-minimizing) mix of mitigation measures.

### 3.4 Methodology

On the Swiss national level, the medium-term target for reducing GHG emissions is determined by the commitment in the Kyoto protocol. In the sense of an efficient use of scarce resources, this target should be achieved at the least cost for the Swiss economy within the time frame of the first commitment period (2008-2012). Building on this background, the potential contribution of Swiss agriculture shall be analyzed with regard to the achievement of the national Kyoto target in a cost-effective way. The institutional framework for this analysis is given by:

1. the Kyoto target which, as mentioned above, is translated in the Swiss CO₂ Law into a 10 % reduction of energy-based CO₂-emissions until the year 2010, and
2. the fact that, so far, there is no commitment for agriculture to reduce its emissions of methane and nitrous oxide within the legal frame of Swiss climate policy.³

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² Notice that induced N₂O emissions in case of C sequestration in mineral soils has not been quantified by Leifeld et al. (2003), and can therefore not be considered in our analysis. Moreover, existing data on land use management are not sufficient to include the restoration of organic soils in the economic assessment.

³ This could change in the second commitment period, if the Swiss parliament should decide to also include specific reduction targets for methane and nitrous oxide emissions that mainly stem from agriculture. However, this would not change the analytical approach that searches to equalize marginal abatement costs across sectors and mitigation measures.
Thus, under the current legislation, property rights are arranged in such a way that the „energy consumption sector“ (ECS), which consists of manufacturing and service industries, private households and transport, is legally obligated to reduce its emissions, whereas agriculture is free of any obligation to reduce its GHG emissions. However, this does not imply that it would be economically reasonable for agriculture not to reduce its emissions. Rather, from an economic point of view, each sector should contribute to achieve the Kyoto target in a cost-effective manner. In other words, agriculture should reduce its GHG emissions and provide carbon sinks as long as it can be realized at lower marginal cost than GHG abatement in the ECS. Apparently, this calls for an economic analysis which allows us to calculate and compare marginal abatement costs for different options of GHG mitigation in agriculture and the ECS. Theoretically, this could be calculated within the framework of one single model that includes all relevant activities and mitigation options.

Yet, to keep a model as simple as possible and as comprehensive as necessary, we use a meta-analytical approach that combines estimates of sectoral mitigation costs from different studies, such as described below. Given the complexity of the agricultural production system, this must allow for consideration of synergies and trade-offs among separate measures in a systematic way, even if interdependencies are not always obvious. Moreover, the prevailing institutional arrangements and policy framework must also be taken into account in both the modeling and the economic meta-analysis.

Building on a study that evaluates GHG abatement and carbon sequestration options from an economic perspective (Hediger et al., 2004), we use a three-stage procedure for the monetary assessment of Swiss agriculture’s contribution to meeting the national Kyoto target. Applying the recursive dynamic optimization model S_INTAGRAL (Swiss INTegrated AGRicultural ALlocation model), we first assessed the expected development of agricultural GHG emissions and income for the period 2000 to 2010 for two price scenarios. With the same model, we then calculated the marginal cost of reducing GHG emissions in Swiss agriculture in the target year 2010. However, on this basis, one cannot conclude whether and to which extent agriculture should reduce its GHG emissions. Rather, the marginal abatement costs in other sectors must also be considered.
To this end, we also use results of a study by Bahn and Frei (2000) who investigated different strategies to reduce energy-based CO₂ emissions in the framework of a computable general equilibrium (CGE) model of the Swiss economy and its interaction with the energy system. In particular, they estimated for a unilateral and a multilateral strategy the specific carbon tax that would have been required to realise by 2010 a 10% cut in CO₂ emissions below the 1990 base level. Using this information, we approximate the marginal abatement cost function for the ECS and compare in a meta-analysis the results for the agricultural sector with those for the ECS. On this basis, we assess the optimal levels of GHG abatement for the ECS and the agricultural production sector. Moreover, we calculate the total GHG abatement cost for the ECS and the cost reductions it can benefit, under the Kyoto protocol, due to agricultural GHG mitigations. These are the benefits to the national economy, as the agricultural contribution lowers the remaining abatement efforts required from the ECS and thus the total GHG mitigation cost of the economy, such as illustrated in Figure 3, below.

3.4.1 The model S_INTAGRAL

S_INTAGRAL is a recursive-dynamic linear optimization model which maximizes the aggregate annual income (labor income plus land rents) of Swiss agriculture under consideration of cropping constraints, plant nutrient requirements, manure production, forage and fertilizer balances, as well as structural constraints and dynamic adjustment processes of the system. It provides an analytical tool for economic appraisals of GHG abatement strategies in the agricultural sector for different price and policy scenarios, and, in particular, to assess marginal GHG abatement costs at different points in time and for different scenarios.

Since the GHG inventory constitutes the official reference for evaluating national policy achievements, we based the model on the same methodology as the GHG inventory and used the latter as benchmark for the validation. In other words, all factors that determine agricultural GHG emissions and carbon sequestration are considered in the model, and therefore determine the structure of the economic allocation model that has been particularly developed for the purpose of analyzing agricultural GHG emissions and carbon sequestration from an economic perspective. Options consid-

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4 A detailed description and validation of the model are available from the authors.
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ered in the model are no till (direct drilling) and the conversion of cropland into per-
manent grassland. These constitute, according to Leifeld et al. (2003), the two alterna-
tives for soil carbon sequestration in mineral soils. In contrast, the renaturation and 
extensification of cultivated organic soils is not included in the model, due to lack of 
spatially differentiated data that would be required to investigate this option. 
Moreover, S_INTAGRAL includes the most important activities of Swiss agriculture 
with regard to revenue, land use, livestock population and GHG emissions. It is di-
vided into three major production zones (plains, hills and mountain area) and is based 
on the three production modules “livestock”, “grassland” and “cropland”. As stylized 
in Figure 1, these modules are integrated through balances between production and 
use of forage (grass and crop forage) and livestock manure. The latter must be applied 
within the zone of origin, while forage exchange between regions is allowed in the 
model, but implies transportation costs.

Fig 1. The structure of the model S_INTAGRAL [adapted from Hediger et al. (2004)]

The model also includes constraints for crop rotations that are compatible with the 
legal requirements for receiving direct payments, as well as with recommendations for 
minimum nutrient inputs for different levels of intensity in crop and forage produc-
tion. Furthermore, a characteristic feature of our linear programming model is the 
consideration of different technology options of mechanization (different types of 
machinery) and livestock management (different types and sizes of stables, manure
management systems, and different shares of grazing time and concentrated feed), as well as different options for forage production (grazing, fresh grass, dry grass, silage, forage crops) and final products (cash crops and animal products) that are sold on the market. In the numerical solution, the model determines the conditionally optimal use of these options together with the optimal allocation of the land (cropland, grassland, crop rotation, as well as the intensity of cultivation and the option of land retirement) and the optimal development of livestock populations and animal holding systems.

Given the fact, that Switzerland is a small open economy with an agricultural sector that is in transition from border protection to market liberalisation, producer prices are assumed exogenous. This may be criticised from a general equilibrium perspective. However, despite of its analytical and theoretical strengths, the latter also suffers from stylised assumptions - such as perfect competition, single-output sectors, vertical integration of production, et cetera - that cannot be maintained in many situations.\(^5\) Agricultural and food markets, for instance, are not fully integrated as assumed in the standard Walrasian framework. Rather, they are characterised by large retailers and manufacturers who exercise market power, which leads to distortions between producer and consumer prices, and distortions in the price transmission from consumers to producers and vice versa. In other words, changes on the consumer markets do not, in general, result in immediate changes of producer prices, but may rather affect future prices and expectations.

Accordingly, producer prices are taken exogenous in the agricultural production model S_INTAGRAL, but with a differentiation between domestic and foreign prices. That is, Swiss farmers can sell their products on the domestic market at a more or less fixed price within bounds of the established market capacities, while a decrease in domestic supply may not lead to higher producer prices but rather to more imports. In contrast, excess products can only be sold on the much larger European market, where (for most products) a lower price level applies that cannot be influenced by Swiss producers. Together with constraints that reflect observed absorption capacities of domestic markets, this differentiation between domestic and foreign price levels eliminates the overshooting of single activities.\(^6\)

\(^5\) See also McKenzie (1998).

\(^6\) Notice that only producer prices, but no consumer prices are considered in S_INTAGRAL.
The recursive-dynamic connection of consecutive production years is another characteristic element which helps to avoid the extreme behavior (“bang-bang” or “flip-flop”) that is typical for linear programming models. It allows us, at the same time, to take existing structures and costs of structural changes into account and to conditionally forecast the development of the agricultural production system with sequential calibration to the structural variables (livestock population, stable capacities, and machinery stock) of the previous year. Altogether, these issues are important for assessing the mitigation cost and evaluating the different options of GHG reduction in a realistic way. Flexibility is built in through a procedure of depreciation of existing capacities and investments in new ones, which can result in a gradual shift from original activities to an increase in other ones (structural change). Livestock populations are dealt with in a similar way, whereas dynamic considerations are formalized and translated into adequate constraints (cf. Hediger, 2006) to eliminate extreme and unrealistic changes. Due to this recursive dynamic formulation, our model is more robust against exogenous shocks and comes closer to reality than an aggregation of farm-level optimization models would.

The basis for the economic evaluation of agricultural measures is provided by a recursively related set of model runs for the time period 2000 to 2010. Starting from the results of these base runs, we can impose and gradually tighten a constraint on net GHG emissions (emissions minus sequestration rates) in our model. As a consequence, the solution space is increasingly confined and the value of the objective function (the total agricultural income) decreases with the GHG constraint. The loss of income (the difference to the income without GHG constraint) represents the total cost of GHG mitigation at a given (predetermined) level of GHG reduction. These model-based results can then be used to assess mitigation cost functions for Swiss agriculture and to get estimates of the marginal abatement costs by differentiation of the total cost functions with respect to the level of additional GHG mitigation.

### 3.4.2 Data

The calibration of the model is based on statistical data for the year 1999 and validated over the period 2000 to 2002 under consideration of agricultural statistics and

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7 Further details are available from the authors.

8 www.agr.bfs.admin.ch
the national GHG inventory. Carbon and nitrogen flows are formalized and parameterized on the basis of scientific studies and synthesis reports (Minonzio et al., 1998; Schmid et al., 2000; Leifeld et al., 2003; Hediger, 2004) for Switzerland as well as on international guidelines (IPCC, 1997) for the preparation of national GHG inventories. The corresponding equations allow us to determine the feed energy requirement and manure production of animals, to assess related GHG emissions from various sources and to evaluate different options of emissions control and soil carbon sequestration.

For simplicity we only consider to two different scenario settings in our analysis: (a) the unilateral case of climate policy with continued border protection for agriculture and related price development; and (b) the multilateral case with international cooperation in climate policy, opening of agricultural markets and adequate prices. For the time period 2000 to 2005 only one agricultural price scenario (“base-scenario”) is used, whereas for the period 2005-2010 a “Swiss price scenario” (scenario “CH”) and an “EU price scenario” (scenario “EU”) are distinguished. In the official “Swiss price scenario” of the Federal Office of Agriculture producer prices are expected to decline in a range between 10 and 30 % for most of the crop and livestock products between 2005 and 2010. In contrast, in the “EU price scenario” a continuous decline and approximation of the EU price level until 2010 is assumed for both agricultural outputs and tradable inputs. This implies a decline of 20-40 % for livestock and 60-70 % for crop products between 2005 and 2010. Thus, future producer prices are considerably lower in this alternative scenario than in the official one, while the prices for domestic inputs may decline less rapidly due to institutional capture and market imperfections. Table 1 illustrates the reference prices in 2000 and scenario assumptions for selected products in the years 2005 and 2010.

Tab. 1: Reference levels and scenarios of producer prices for selected products and years

<table>
<thead>
<tr>
<th>Products</th>
<th>Units</th>
<th>Year and scenario</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>winter wheat</td>
<td>CHF/ton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>base</td>
<td>base</td>
<td>CH“</td>
<td>CH“</td>
<td></td>
</tr>
<tr>
<td>winter barley</td>
<td>CHF/ton</td>
<td>750</td>
<td>470</td>
<td>445</td>
<td>179</td>
<td></td>
</tr>
<tr>
<td>rape</td>
<td>CHF/ton</td>
<td>750</td>
<td>421</td>
<td>359</td>
<td>154</td>
<td></td>
</tr>
<tr>
<td>sugar beets</td>
<td>CHF/ton</td>
<td>112</td>
<td>110</td>
<td>90</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>potatoes</td>
<td>CHF/ton</td>
<td>440</td>
<td>341</td>
<td>304</td>
<td>173</td>
<td></td>
</tr>
<tr>
<td>milk</td>
<td>CHF/kg</td>
<td>0.77</td>
<td>0.67</td>
<td>0.56</td>
<td>0.47</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2005</td>
<td>2010</td>
<td>2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>calf</td>
<td>CHF/kg</td>
<td>11.30</td>
<td>11.31</td>
<td>10.41</td>
<td>7.36</td>
<td></td>
</tr>
<tr>
<td>beef</td>
<td>CHF/kg</td>
<td>7.30</td>
<td>6.21</td>
<td>5.72</td>
<td>4.15</td>
<td></td>
</tr>
<tr>
<td>“Natura Beef”</td>
<td>CHF/kg</td>
<td>9.65</td>
<td>9.26</td>
<td>8.52</td>
<td>8.23</td>
<td></td>
</tr>
<tr>
<td>fattening pigs</td>
<td>CHF/kg</td>
<td>4.80</td>
<td>4.18</td>
<td>3.72</td>
<td>2.11</td>
<td></td>
</tr>
<tr>
<td>lamb</td>
<td>CHF/kg</td>
<td>8.88</td>
<td>8.70</td>
<td>8.25</td>
<td>6.20</td>
<td></td>
</tr>
<tr>
<td>milk cows</td>
<td>CHF/kg</td>
<td>3.60</td>
<td>3.42</td>
<td>2.84</td>
<td>3.01</td>
<td></td>
</tr>
</tbody>
</table>

In all scenarios, EU prices are assumed for excess production that cannot be absorbed by the domestic market and therefore must be exported at a lower price.

3.4.3 A CGE analysis of curbing energy-related CO₂ emissions in Switzerland

To investigate different strategies to reduce Swiss CO₂ emissions, Bahn and Frei (2000) implemented the applied general equilibrium model GEM-E3 to the case of Switzerland. It provides details on the macro-economy and its interaction with the environment and the energy system.

GEM-E3 is a recursive-dynamic model that contains of one economic and one environmental module. The model considers four economic agents (producers, one representative household, government and foreign sector), 13 consumption categories, and 18 production sectors using capital and labour as the two primary production factors. Thus, land is not considered in GEM-E3 Switzerland, and agriculture is highly aggregated (one single production sector), which does not allow for calculating agricultural GHG emissions according to the requirements of the national GHG inventory (IPCC guidelines). However, GEM-E3 has been designed and implemented to conduct policy analysis in the economy-energy-environment sphere, rather than to investigate greenhouse gas mitigation options in agriculture. Accordingly, the model distin-
guishes among electricity, natural gas and crude oil or oil products as the primary energy resources. The related CO₂ emissions are computed in linear relation to the use of fossil fuels (using fixed emission factors according to the specific carbon contents) within the environmental module.¹⁰ The time period considered for calculations was from 1990 (base year) forward to the year 2010 in steps of 5 years.

Within the frame of GEM-E3 Switzerland, Bahn and Frei (2000) investigated two strategies that are either based on a national carbon tax (the unilateral case, or what they call “the ‘tax only’ strategy”), or the combination of a carbon tax with the buying of CO₂ emission permits on the international market (the multilateral case, or “permits & tax” strategy). For both strategies, they further considered a low and high growth variant, reflecting the assumption about technical progress and economic growth in the rest of the world. In their analysis, they particularly calculated the CO₂ taxes that would be required to satisfy the 10 % reduction target of the CO₂ law until 2010. In equilibrium, these imputed prices correspond to the marginal CO₂ abatement costs under the different scenarios. These results are subsequently used to approximate the marginal abatement cost curve for the ECS and to compare in a meta-analytical framework the marginal CO₂ abatement costs of the ECS and the agricultural production sector.

3.4.4 Meta-analysis

Meta-analysis is a research method to synthesise previously obtained research results. It is usually seen as a statistical approach towards reviewing and summarising the literature (Florax et al., 2002). However, in more general terms, meta-analysis is referred to summarising, comparing, averaging, evaluating and apprehending common elements in other studies. In this regard, van den Bergh and Button (1997) emphasise that meta-analysis - or, more adequately, a meta-analytical framework and the use of meta-analytical tools and techniques - can help to improve our understanding of environmental economic analysis. In this sense, we apply in the subsequent section a meta-analytical approach to compare the marginal GHG mitigation costs across different sectors and gases, and to assess the economic value of Swiss agriculture’s contribution to the national Kyoto target. The advantage of this approach is the integra-

¹⁰ The economic and environmental databases have been developed on the basis of an existing Social Accounting Matrix and official statistics (see Bahn and Frei, 2000, for details).
tion of results from complementary studies in an economic meta-analysis at the interface of the respective studies, using information that cannot be transmitted within the frame of the respective models due to restricted research questions and simplifying assumptions. The key issue here is the comparison of marginal GHG abatement costs that have been calculated in different sector-specific models for the energy and agricultural sector, respectively.

3.5 Base results for the period 2000-2010

The results of the base runs with the agricultural allocation model S_INTAGRAL reveal the expected decline of agricultural income under the current agricultural policy regime and for a decline of producer prices to the EU level (cf. Figure 2). Furthermore, the decline of agricultural GHG emissions until 2010 is, as illustrated in Table 2, quite similar for both price scenarios. This indicates that Swiss agriculture can be expected to further reduce its GHG emissions in about the same range of magnitude as between 1990 and 2000, even without specific climate policy incentives. Moreover, the results show, in contrast to those from the USA and Finland, that cost-effective measures to reduce GHGs in Switzerland will be mainly achieved by means of emission reductions, rather than carbon sequestration in agricultural soils.\(^\text{11}\)

![Agricultural Income Graph](image)

**Fig. 2:** Changes in agricultural income 2000-2010 according to calculations with S_INTAGRAL.

\(^{11}\) Reasons that explain these differences are given in Section 2.
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Tab. 2: Changes of agricultural GHG emissions and C sequestration (kt CO₂eq/year)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions</td>
<td>132.6</td>
<td>124.2</td>
<td>121.9</td>
<td>117.8</td>
</tr>
<tr>
<td>CH₄ emissions</td>
<td>2572.7</td>
<td>2525.4</td>
<td>2220.9</td>
<td>2227.9</td>
</tr>
<tr>
<td>N₂O emissions</td>
<td>2016.8</td>
<td>1961.2</td>
<td>1828.8</td>
<td>1801.6</td>
</tr>
<tr>
<td>GHG emissions totally</td>
<td>4722.1</td>
<td>4610.8</td>
<td>4171.0</td>
<td>4147.3</td>
</tr>
<tr>
<td>Reduction of emissions</td>
<td>—</td>
<td>111.3</td>
<td>551.1</td>
<td>574.8</td>
</tr>
<tr>
<td>C sequestration</td>
<td>11.5</td>
<td>15.6</td>
<td>19.4</td>
<td>26.0</td>
</tr>
<tr>
<td>Total GHG reduction</td>
<td>—</td>
<td>126.9</td>
<td>570.5</td>
<td>600.8</td>
</tr>
</tbody>
</table>

As illustrated in Table 3, the results of our model-based calculations suggest that one could expect for both price scenarios a decline of GHG emissions until 2010 by about 12% compared to the year 2000. This is apparently higher than the 3 to 4% that are expected by the Federal Council (Bundesrat, 2002). This difference can, to a certain extent, be explained by the fact that Swiss agriculture is considered in the model as one single enterprise. It offers more flexibility to the overall system than individual farmers effectively will have in their decisions, given the existence of farm level constraints. Hence, the results of the model-based expectations for future GHG reductions under the current agricultural policy must be considered as over estimations. Thus, our results indicate an upper limit, while the reductions expected by the Federal Council represent a lower limit for the future development of GHG emissions under the current agricultural policy.

Tab. 3: Changes of expected GHG emissions compared to 2000 (in percent)

<table>
<thead>
<tr>
<th>year and scenario:</th>
<th>2005 base</th>
<th>2010 “CH”</th>
<th>2010 “EU”</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ emissions</td>
<td>- 6.4 %</td>
<td>- 8.1 %</td>
<td>- 11.1 %</td>
</tr>
<tr>
<td>CH₄ emissions</td>
<td>- 1.8 %</td>
<td>- 13.7 %</td>
<td>- 13.4 %</td>
</tr>
<tr>
<td>N₂O emissions</td>
<td>- 2.7 %</td>
<td>- 9.3 %</td>
<td>- 10.7 %</td>
</tr>
<tr>
<td>GHG emissions</td>
<td>- 2.3 %</td>
<td>- 11.7 %</td>
<td>- 12.2 %</td>
</tr>
</tbody>
</table>

The main reasons for the estimated decline in the emissions of all three GHGs are a further decrease of livestock populations and manure production until 2010, and the related effects on land management tending to more open cropland with a reduction in forage production and lower intensity of cultivation (see also Hediger et al., 2004, p.
This development is primarily due to the assumed development of agricultural prices. However, apart from the level of total agricultural income (cf. Figure 2), these results do not show significant differences in real variables (livestock populations and land allocation) between the two price scenarios. This also explains why there is no substantial difference in our projections of GHG emissions for the year 2010. The development of the real variables that determine agricultural GHG emissions is driven by relative prices (the allocation problem), rather than by the price level. On the contrary, the difference in the level and decline of agricultural income is directly explained by the differences in the absolute prices.

3.6 The economic value of agriculture’s contribution to Swiss climate policy

As mentioned in Section 3, Switzerland committed itself in the Kyoto Protocol to reducing its GHG emissions until the commitment period by 8% below the level of 1990. This corresponds to a reduction of 4.25 Mt CO\textsubscript{2}eq/year. However, until 2002, total GHG emissions in Switzerland only marginally declined by 0.88 Mt CO\textsubscript{2}eq/year (or 1.7%) below the 1990 level (BUWAL, 2004; SAEFL, 2004). In contrast, Swiss agriculture reduced its GHG emissions over the same time interval by 0.6 Mt CO\textsubscript{2}eq/year. This corresponds to 14% of the Swiss reduction commitment according to the Kyoto protocol.

The economic value of this contribution to Swiss climate policy can only be determined from an efficiency point of view which reflects the above mentioned allocation problem of equalizing the marginal abatement costs across GHG mitigation measures and sectors. This value is optional, as it refers to reduced abatement costs for the ECS in the commitment period of the Kyoto protocol, and it is conditional to assumptions about the institutional framework. The latter can either be represented by a unilaterial policy, which means all reductions must be realized in Switzerland, or a multilateral policy, which also includes reductions generated abroad through international emissions trading and investment in specific mitigation projects (joint implementation and clean development mechanism) that are principally permitted under the Kyoto protocol.
3.6.1 Value of previous GHG reductions in agriculture

The following considerations are based on assessments of implicit CO₂ prices for the energy consumption sector (ECS) as reported in a study by Bahn and Frei (2000) who used a computable general equilibrium (CGE) model of the entire Swiss economy, but without specific consideration of the agricultural production system. They calculated marginal costs for reducing energy-based CO₂ emissions by 5 % until 2005 and by 10 % until 2010. In the case of a unilateral policy the estimated CO₂ price for the year 2010 ranges between 83 and 103 CHF/t CO₂. In case of participation in a European emissions trading system, the estimated price is 42 CHF/t CO₂.

These results of Bahn and Frei determine the reference framework for our evaluation of GHG mitigation options in Swiss agriculture, which includes the assessment of the economically efficient levels of GHG reduction by agriculture and its conditional value to society. To this end, the marginal abatement costs of the energy consumption sector (ECS) and the agricultural sector must be compared. This is schematically illustrated in Figure 3, which shows in stylized form the marginal abatement costs of both sectors as increasing functions of the respective GHG mitigation efforts. The latter are represented with opposing orientation on the horizontal axis. On the one hand, it shows an increasing level of GHG reductions by the ECS from the left to the right. On the other hand, it uses the Kyoto target Q₀ as point of reference for the evaluation of GHG reductions by the agricultural sector. Even without any legal commitment, the latter contribute to fulfilling the national Kyoto target and thus reduce the need to curbing GHG emissions in the ECS. In Figure 3, the agricultural GHG reductions therefore point in the opposite direction than those in the ECS. The vertical axis refers to the marginal abatement cost for the ECS (MAC_E) and agriculture (MAC_A), respectively, as well as to the related CO₂ prices.
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Fig. 3: Optimal allocation of GHG reductions in a two sector representation

The reference point of our analysis is given by the national Kyoto target of reducing GHG emissions, which is equivalent to the 10% reduction of CO₂ emissions that shall be achieved according to the CO₂ Law until 2010. The economic value of agriculture’s contribution to fulfilling the Kyoto target is equal to the induced reduction in total abatement costs for the rest of the economy, which is represented here by the ECS.

Taking a linear approximation of the MACₐ curve,¹² using the upper value of 103 CHF/t CO₂ from Bahn and Frei (2000) and the Kyoto target Q₀ = 4.25 Mt CO₂eq/year, the total abatement costs for the ECS would be nearly 220 Mio CHF/year averaged over the commitment period 2008-2012. This calculation refers to the re-

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¹² Since Bahn and Frei (2000) only provide the above mentioned estimates for a 10% reduction in 2010, we do not have full information for the assessment of the MACₐ curve and therefore use a linear approximation, as represented in Figure 3. Given the theoretical convexity of the abatement cost function and additional estimates by Bahn and Frei for the year 2005, this approximation may represent a slight overestimation of the MACₐ curve.
quirement of the CO₂ Law that the Kyoto target shall be achieved by reducing energy-based CO₂ emissions by 10 % until 2010.

Yet, the Kyoto protocol does, in contrast to the Swiss CO₂ Law, not only address CO₂ but also other anthropogenic GHG emissions. Correspondingly, agriculture’s mitigation efforts can be accounted for in this framework, such that the remaining requirement to reducing emissions by the ECS declines by the respective amount. Taking into account the reduction of agricultural GHG emissions between 1990 and 2002 by 0.60 Mt CO₂eq/year (R₁ in Figure 3), the remaining commitment for the ECS reduces to Q₁ = Q₀ – R₁ = 3.65 Mt CO₂eq/year. In relation to this, the expected annual abatement cost for the ECS diminish by 57.1 Mio CHF, or 26 % of the original value. This corresponds to the area Q₀B₀B₁Q₁ in Figure 3, and quantifies the economic value of the agricultural GHG reduction between 1990 and 2002.

The resulting CO₂ price goes down from p₀ = 103 CHF/t CO₂eq to p₁ = 88.56 CHF/t CO₂eq (see also Table 4).

3.6.2 The value of further GHG reductions until 2010

3.6.2.1 The unilateral case

As presented in Section 5, further reductions of GHG emissions from agriculture can be expected if the current agricultural policy is continued and if price relations develop as assumed in official scenarios of the Swiss Federal Office for Agriculture and without specific climate policy measures and obligations imposed on agriculture. These reductions (including carbon sequestration) are estimated between 0.12 and 0.50 Mt CO₂eq/year (R₂ − R₁) for the period 2002-2010. They further reduce the ECS’s total abatement cost by about 10 to 40 Mio CHF/year (area Q₁B₁B₂Q₂ in Figure 3), which determines the economic value of additional GHG reductions by agriculture. Another effect, which is visualized in Figure 3, is the decline of the marginal costs for the ECS and of the related CO₂ price that would be in the range of 76 to 86 CHF/t CO₂eq (cf. rows C and D in Table 4).

All in all, previous and further GHG reductions that can be attributed to the current agricultural policy accumulate to an estimated economic value of about 67 to 99 Mio CHF/year in the commitment period of the Kyoto protocol. This value corresponds to 30 to 45 % of the originally calculated abatement costs for the ECS of 220 Mio
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CHF/year. This will be enabled by Swiss agriculture without having to bear effective GHG abatement costs. Indeed, losses of farmers’ aggregate income that are caused by agricultural policy measures and changes in economic conditions (prices) cannot be attributed to climate policy, and must therefore not be considered as GHG mitigation costs. Nonetheless, they are relevant for addressing socio-economic aspects of both agricultural and climate policy.

Tab. 4: GHG reductions and economic value of agriculture’s contribution until 2010 with a unilateral policy and Swiss price scenario

<table>
<thead>
<tr>
<th>GHG reduction by agriculture Mt CO₂eq/year</th>
<th>Remaining commitment for the ECS Mt CO₂eq/year</th>
<th>Equilibrium CO₂ price CHF/t CO₂eq</th>
<th>Abatement costs for the ECS Mio CHF/year</th>
<th>Value of agricultural contribution Mio CHF/year</th>
<th>Abatement costs agriculture Mio CHF/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>4.25</td>
<td>103.00</td>
<td>218.9</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0.60</td>
<td>3.65</td>
<td>88.56</td>
<td>161.8</td>
<td>57.1</td>
</tr>
<tr>
<td>C</td>
<td>0.72</td>
<td>3.53</td>
<td>85.61</td>
<td>151.2</td>
<td>67.7</td>
</tr>
<tr>
<td>D</td>
<td>1.10</td>
<td>3.15</td>
<td>76.32</td>
<td>120.2</td>
<td>98.7</td>
</tr>
<tr>
<td>E</td>
<td>1.20</td>
<td>3.05</td>
<td>73.86</td>
<td>112.6</td>
<td>106.4</td>
</tr>
</tbody>
</table>

A = Kyoto target (commitment to reduce GHG emissions)  
B = effective decline of agricultural GHG emissions 1990-2002  
C = expected decline of agricultural GHG emissions 1990-2010 with a continuation of current agricultural policy (assumption: 3% reduction compared to emissions in 2000; source: Bundesrat 2002)  
E = maximal reduction of agricultural GHG emissions in 2010 with additional incentives for GHG reduction (according to model-based assessments with S_INTAGRAL)

Additional GHG reductions might be expected from agriculture if targeted economic incentives would be introduced. In this case, an additional GHG reduction of 2.5% in the year 2010 would be efficient, under the assumption of a unilateral policy and the Swiss price scenario. This is determined by the intersection of the MACₐ and MACₐ curves in Figure 3, and would result in an estimated CO₂ price of 73.86 CHF/t CO₂eq. The costs involved amount to 2.2-2.5 Mio CHF/year for the agricultural sector (cf. row E in Table 4, area Q₂*B* in Figure 3). Compared to savings in abatement costs for the ECS of about 7.5 Mio CHF/year (difference between rows D and E in Table 4), it proves to be economically efficient to further reduce agricultural GHG emissions beyond the reference level in 2010 (row D in Table 4). However, it must also be considered that, due to transaction costs that are eventually incurred with the imple-
mentation of a system of policy measures and incentives to reduce agricultural emissions of methane and nitrous oxide and to sequester carbon in agricultural soils, the net benefit to society may be smaller than estimated or even negative.

3.6.2.2 The multilateral case - participation in international emissions trading

With the participation of Switzerland in international emissions trading and thus in a multilateral policy, both GHG abatement costs for the ECS as well as the economic value of the agriculture’s contribution will decline. Given the price \( p_{EU} = 42 \text{ CHF/t CO}_2 \), assessed by Bahn and Frei (2000), the total cost for the Swiss economy to achieve the Kyoto commitment fall from 120 to 151 Mio CHF/year (cf. Table 4) into the range of 94 to 112 Mio CHF/year (cf. Table 5). This elucidates the social benefit of following a multilateral climate policy. In turn, the value of agriculture’s contribution also decline from the range of 67 to 99 Mio CHF/year to the level of 30 to 48 Mio CHF/year in the base-line projections for the year 2010. This still corresponds to about 20 to 33 % of the ECS’s total CO\(_2\) abatement cost. However, the agricultural contribution that could be induced by specific economic incentives and under assumption of the EU price scenario will be almost negligible with only 5 kt CO\(_2\)eq/year.

Tab. 5: GHG reductions and economic value of agriculture’s contribution until 2010 in the multilateral case with participation in international emissions trading and EU prices

<table>
<thead>
<tr>
<th>GHG reduction by agriculture (Mt CO(_2)eq/year)</th>
<th>Remaining commitment for the ECS (Mt CO(_2)eq/year)</th>
<th>CO(_2) price (according to Bahn and Frei, 2000) (CHF/t CO(_2)eq)</th>
<th>Total costs for the ECS (incl. certificates) (Mio CHF/year)</th>
<th>Value of agricultural contribution (Mio CHF/year)</th>
<th>Abatement costs agriculture (Mio CHF/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>4.25</td>
<td>42.00</td>
<td>142.1</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0.53</td>
<td>3.72</td>
<td>42.00</td>
<td>119.8</td>
<td>22.3</td>
</tr>
<tr>
<td>C</td>
<td>0.72</td>
<td>3.53</td>
<td>42.00</td>
<td>112.0</td>
<td>30.2</td>
</tr>
<tr>
<td>D</td>
<td>1.13</td>
<td>3.12</td>
<td>42.00</td>
<td>94.6</td>
<td>47.5</td>
</tr>
<tr>
<td>E</td>
<td>1.14</td>
<td>3.11</td>
<td>42.00</td>
<td>94.4</td>
<td>47.8</td>
</tr>
</tbody>
</table>

For explanations about A to E, see Table 4
3.7 Summary and conclusion

Since 1990, Swiss agriculture has reduced its GHG emissions by 0.67 Mt CO$_2$eq, whereas methane and nitrous oxide as the most important gases decreased by about 10%. This contribution corresponds to about 16% of the national Kyoto commitment. It is primarily a consequence of changes in economic conditions and agricultural policy reform, but has not been induced by climate policy measures. Therefore, agricultural income losses cannot be attributed to climate policy (no effective abatement costs), even though agriculture has provided a valuable contribution on the way to achieving the national Kyoto target. Moreover, it cannot be concluded that Swiss agriculture has already fulfilled its commitment to reduce GHG emissions. Indeed, the Kyoto protocol does only specify national commitments for GHG reduction, but no sectoral targets.

Yet, the effort of each sector, such as agriculture, cannot solely be evaluated on the basis of quantities. Rather, it is necessary to consider different options and costs for reducing GHGs in different sectors. This can be realized by calculating and comparing marginal abatement costs across sectors, which also allows for the determination of an economically efficient allocation of mitigation efforts. From an economic point of view, this may require targeted incentives to agriculture, such as compensation payments according to the marginal abatement costs (CO$_2$ prices) that are reported in Tables 4 and 5 for additional GHG reductions. However, the establishment of an exclusively efficiency-oriented climate policy with targeted incentives to agriculture may also induce presumably high costs of monitoring and implementation.\textsuperscript{13} Therefore and under consideration of the relatively small contribution that can be expected from such a policy in the short run (i.e., within the first commitment period of the Kyoto Protocol), we cannot recommend the introduction of additional incentives to induce Swiss agriculture to further reduce its GHG emissions beyond the expected level under the current agricultural policy. Nonetheless, we can attribute the base-level reductions as a result of the ongoing agricultural policy reform.

Under the given institutional situation and implicit assignment of property rights, the assessment of marginal abatement costs also provides the analytical framework for

\textsuperscript{13} These transaction costs are generally assumed to be higher than those for measures aimed at reducing CO$_2$ emissions from fossil fuels, where emission coefficients only depend on their carbon contents. In contrast, agricultural GHG emissions of methane and nitrous oxide are determined by numerous factors that are due to farmers’ decisions (cf. IPCC, 1997).
assessing the economic value of Swiss agriculture’s contribution to achieving the national Kyoto target. In case of a unilateral policy, this value amounts to 67 to 107 Mio CHF/year for expected GHG reductions in the year 2010. It corresponds to about 30 to 50 % of the total abatement costs the Swiss economy would have to bear to unilaterally achieve the Kyoto target with a policy exclusively based on measures to reducing energy-related CO₂ emissions.

From an economic perspective, however, it would be efficient to participate in international emissions trading (multilateral climate policy). This would reduce, on the one hand, the total abatement cost of the energy consumption sector in the commitment period from about 220 Mio CHF/year to estimated 142 Mio CHF/year. On the other hand, the value of agriculture’s overall contribution would also diminish to about 30 to 48 Mio CHF/year. This can be achieved without effective abatement costs for agriculture.

With targeted measures and economic incentives, agriculture could further reduce its emissions. In this case, farmers would have to bear effective abatement costs. This has been analyzed by means of incremental GHG constraints in our optimization model. The results show that cost-effective potentials for additional GHG reductions by agriculture exist, but that - at least within the first commitment period - they are rather small compared to the estimated base-level reductions. Moreover, the results indicate that soil carbon sequestration may only constitute a moderate option in the short term.

This leads to the advice of renouncing targeted measures for additional GHG mitigation in agriculture under the current policy framework. However, an active policy might be adequate in the longer term, since future options may include the production of biofuels and the use of new technologies. These have not been included in the present analysis. Given the current structures and market conditions of regenerative energy sources, no significant contribution from the use of biofuels can be expected in Switzerland until the commitment period 2008-2012.

The fact that our results are partly different from those received in other countries, such as the USA and Finland, underlines the necessity of carefully designed analyses and policies that account for national circumstances. For instance, the relatively steep slope of the marginal GHG abatement curve for Swiss agriculture is primarily due to the historical development of a highly integrated agricultural production system with a nearly closed forage-manure cycle. Finally, from a methodological point of view,
our analysis shows how the results from a highly detailed allocation model of the agricultural sector in a small open economy can be combined with those from an energy-allocation model of the overall economy by using the framework of a meta-analytical approach. This particularly allows us to integrate results from different models with different degrees of disaggregation, different levels of detail, and different simplifying assumptions. This is not only important for the ex-post evaluation presented in this article, but especially for the ex-ante appraisal and a well-informed design of future climate policies. Our approach particularly allows for careful evaluation and discussion of agriculture’s role in future GHG mitigation strategies, while using information gained from carefully designed and targeted studies on GHG mitigation costs in different sectors.

On the basis of the present analysis and with updated estimations of marginal GHG mitigation costs for different sectors or domains, the answer about how much agriculture should contribute to climate policy can also be answered in a prospective manner for the upcoming decade. From a theoretical perspective, the answer is straightforward. Each sector should contribute to achieving a national GHG reduction target as long as its own marginal abatement costs are lower than those of other sectors. Thus, additional assessments about the marginal abatement costs in the different sectors are required before a final answer and policy recommendation can be drawn.
4 Reducing nitrogen losses from Agricultural systems - an integrated economic assessment

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Abstract

The loss of reactive nitrogen from agriculture into the environment is a major threat to the global environment and a challenge for agri-environmental policy. We therefore investigate the problem of reducing nitrogen losses from agriculture into the environment from an economic perspective. Based on a recursive-dynamic linear programming model, our study reveals that the above difficulty is primarily due to the rigidities associated with the nutrient-forage cycle and existing production structures. Moreover, we assess the cost and effectiveness of different nitrogen taxes for the case of Switzerland. Our results show that a tax on fertilizers only exhibits the best performance in terms of cost-effectiveness.

Keywords

agri-environmental policy, integrated assessment, land use, nitrogen tax.

4.1 Introduction

Nitrogen is a natural element, which is essential for plants to grow and animals to thrive. As a vital factor, it is added in reactive forms to agricultural production processes with animal feedstuffs and fertilizers applied to crops and pastures, or fixed through biological processes by certain plants. On the output side, nitrogen leaves the agricultural system as a component of marketable products, or it is released into the environment in reactive forms - such as nitrate (NO₃⁻), ammonia (NH₃), and nitrogen oxides (NOₓ and N₂O). These compounds cycle through the air, aquatic systems and soils, and can cause a cascade of detrimental effects on human health and ecosystems through surface and ground water eutrophication, air quality degradation, acidification of soils, and enhancement of global climate change. Therefore, nitrogen pollution is a major threat to the global environment and an important policy challenge in both industrialized and developing countries (Galloway et al., 2002; Kaiser, 2001; Fields, 2004).

Recognizing this challenge, many nations established goals and policies to reduce nitrogen emissions from agriculture and energy use. Moreover, international conventions aim at limiting and reducing transboundary nitrogen emissions into surface and ground water, marine waters and the atmosphere. These agreements include the
UN/ECE Convention on Long-Range Transboundary Air Pollution and the related Gothenborg Protocol to abate acidification, eutrophication, and ground-level ozone. For example, the Gothenborg Protocol implies the Swiss obligation of reducing its NO$_2$ and NH$_3$ emissions until 2010 by 52% and 13%, respectively, below the reference levels of 1990. On the level of the European Community these reduction targets have been set to 49% and 15% of NO$_2$ and NH$_3$ losses into the environment below the respective reference levels.

Moreover, Contracting Parties to the Convention for the Protection of the Marine Environment of the North-East Atlantic (the “OSPAR Convention”) are committed to reducing their discharge of nitrogen into the North Sea by 50% below the levels of 1985. But no country has reached the committed reduction target on nitrogen losses, and – apart of Sweden and the Netherlands – no country expects itself to meet the target before 2020. According to OSPAR Commission (OSPAR, 2003, p. 4), this “inability to reach the 50% reduction target for nitrogen is primarily because the measures to reduce the diffuse losses from the agriculture sector are progressing much slower than expected, and because the measures in many cases are either inadequate or inadequately implemented”. Indeed, regulatory measures but hardly any economic incentives to curtailing nitrogen emissions have been already implemented as a rule by individual countries. Only Sweden uses a nitrogen tax on mineral fertilizer which is set at about 30% of the nitrogen price (Brady, 2003; Larsson et al., 2005).

Recognizing this problem, the aim of this article is to investigate from an economic perspective the problem of reducing nitrogen losses from agriculture into the environment. For the empirical work, we take Switzerland as the case of a country that currently experiences the difficulty of meeting national and international emission reduction targets, and where the prospective employment of a nitrogen tax is an issue. In Switzerland, a parliamentary motion of January 1994 requests the introduction of incentive taxes on mineral fertilizers, surplus manure and plant protection products if the introduced environmental and agricultural policy instruments fail to have the intended effect (SAEFL, 2005). As a consequence, an official task force has been mandated to elaborate a national strategy aimed at solving the environmental problems caused by the emissions of harmful nitrogen compounds (BUWAL/BLW, 1996). Supported by scientific studies, the task force defined a long-term target of reducing the loss of harmful nitrogen compounds from agriculture by 50% below the baseline.
of 1994, and formulated an intermediate goal of reducing these nitrogen losses by 23% until 2002. However, recent analyses show that the latter target is far from being achieved (BLW, 2004; Hediger, 2005; SAEFL, 2005; Peter et al., 2006). This development indicates that existing policy measures and regulations are inadequate to deal with the complexity of the nitrogen cycle and do not give farmers the right incentives to reduce their nitrogen surplus. This indicates that additional policy measures, such as a tax on nitrogen inputs might be required to realize the committed emission reduction targets. To assess the cost and effectiveness of different nitrogen taxes, we apply an integrated agricultural allocation model (Hediger, 2006) which we improved to fully represent the nitrogen cycle within the agricultural production system.

Accordingly, the article is organized as follows. First, the method and data used are described in Section 2. Then, selected results are presented in Section 3 which illustrates the development of the agricultural system and nitrogen emissions under different price scenarios over the next decade. In addition, we examine the impact of hypothetical taxes on nitrogen in 2005. Finally, Section 4 concludes.

4.2 Methodology

The use of nitrogen in agricultural production systems is a typical allocation problem that has been analyzed in the agricultural, resource and environmental economics literature in various contexts of production and policy analysis. With regard to nitrogen losses, economic analyses mainly focused on problems of agricultural water pollution from nonpoint sources (e.g., Horan and Shortle, 2001) and the reduction of nitrogen surplus on farm level (e.g., Polman and Thijsen, 2002). However, there is a lack of comprehensive approaches using integrated assessment models that capture the complexity of nitrogen-management problems (Galloway et al., 2002) and provide economic appraisals of policies that jointly address the various nitrogen compounds emitted into the environment. In contrast, economic assessments of costs and options of agricultural greenhouse gas mitigation on the national scale (McCarl and Schneider, 2001; Hediger et al., 2004) reveal the need and advantage of modeling approaches that integrate the various interdependencies of crop and livestock management together with greenhouse gas (GHG) emissions and sinks.
4.2.1 The model

To assess the cost for reducing nitrogen losses from Swiss agriculture and evaluate alternative policy options on the national scale, we adapted and improved the agricultural allocation model S_INTAGRAL (Swiss INTegrated AGricultural ALlocation model), which originally has been developed for the economic evaluation of carbon sequestration potentials and agricultural GHG mitigation strategies (Hediger, 2006; Hediger et al., 2004). The use of this model to investigate the nitrogen problem is straightforward since the carbon and nitrogen cycles are strongly interrelated. For instance, scientific studies indicate a strong relationship between carbon sequestration and the nitrogen cycle (cf. Hungate et al., 2003). Moreover, nitrous oxide (N₂O) is the second most important agricultural GHG. This directly links the climate and nitrogen problem. Finally, N losses from agriculture are triggered by external N inputs to the system with feed stuffs and fertilizers, and depend on agricultural land use and livestock farming decisions. Thus, measures to control the different forms of environmentally harmful N emissions (NH₃, NO₃⁻, NOₓ and N₂O) are most usefully analyzed from an agricultural systems perspective, rather than independent of each other.

Given the fact, that Switzerland is a small open economy in transition from high protection towards opening agricultural markets, prices are taken exogenous. Another feature of our approach, which helps to avoid the typical extreme behavior of linear programming models, is the recursive-dynamic connection of consecutive years. This allows us to mimic the development of the agricultural production system with sequential calibration using the state variables (livestock population, capacities of animal holding, and machinery) of the previous year. Flexibility is built in with the depreciation of existing capacities and investments in new ones.

For instance, the population of dairy cows \( S_{izt} \) of type \( i \) in zone \( z \) at time \( t \) is restricted to the number of surviving cows \( S_{iz(t-1)} \) from the previous year and the maximum population that could be achieved by comprising all the two-year-old cattle \( Y_{iz(t-1)} \) from the previous year, with \( \eta_i \) and \( \alpha_i \) denoting the survival rate of cows and of cattle, respectively:

\[
S_{izt} \geq (1 - \eta_i) S_{iz(t-1)} \quad \text{and} \quad S_{izt} \leq (1 - \eta_i) S_{iz(t-1)} + \alpha_i Y_{iz(t-1)}
\]

(1)

The share of this population cannot exceed the current capacity \( K_{jzt} \) of animal holding systems of type \( j \) in zone \( z \) at time \( t \):

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4 Reducing nitrogen losses from Agricultural systems - an integrated economic assessment

\[ S_{ijzt} \leq K_{ijzt} \quad \text{with} \quad S_{izt} = \sum_j S_{ijzt} \]  

This capacity depreciates at a rate \( \delta_j \) and can be enhanced with adequate investments \( I_{ijzt} \):

\[ K_{ijzt} \leq (1 - \delta_j) K_{ijz(t-1)} + I_{ijzt} \]  

With this recursive dynamic formulation, we avoid the extreme and unrealistic behavior that is characteristic for more conventional linear programming models (for elaborated model details cf. Peter et al., 2006).

4.2.2 Data sources

The calibration of the model is based on statistical data for the year 1999 and validated over the period 2000 to 2004 under consideration of existing agricultural and market statistics and the national GHG inventory. Product and factor prices for the years 2000 to 2004 are taken from annually updated publications, while price assumptions for 2005 onwards are based on two official price and policy scenarios of the Federal Office for Agriculture, referred to as “AP2011_pure” and “AP2011_WTO”, respectively. They are distinct with regard to prices after 2008, to reflect slightly different degrees of market opening.

For the purpose of sensitivity analysis, we use two additional price scenarios. The “CH2004” scenario assumes constant prices and direct payments on the 2004 level. In contrast, the “EU2010” price scenario provides a lower benchmark for our analysis. It assumes a gradual decline to the EU price level over the period 2004 and 2010, but continuation of the current agricultural policy reform and farmers’ support program in Switzerland (Peter et al., 2006).

4.3 Results

Starting with initial values of livestock populations, estimated stable and machinery capacities for the calibration year 1999, the first optimization run provides the optimal factor allocation that would have been maximizing the total agricultural income in the year 2000. It also determines the initial values of livestock, stable and machinery capacities for 2001. Using the same procedure year for year, we run the model in a recursive dynamic manner for the above mentioned scenarios over the period 2000 to
2013 to assess the conditional development of the agricultural production system and nitrogen (N) emissions.

### 4.3.1 Development until 2013

On the economic side, our model results indicate a decline of the expected agricultural income in Switzerland from 3 billion CHF in 2000 to about 2 and 2.5 billion CHF in the year 2013 for the “AP2011_WTO” and “AP2011_pure” scenarios, respectively. Furthermore, the benchmark scenarios “CH2004” and “EU2010” reveal the strong impact of the price level upon the resulting income. In contrast, the real variables do not have this strong reaction on price changes. They are determined by relative rather than absolute prices.

As a consequence of the development in the sphere of livestock production, Figure 1 shows an initial increase of the total amount of nitrogen in animal manure (liquid and solid) until 2003, followed by a slight decline of about 3% until 2013 for the two official AP2011 scenarios and the upper benchmark case “CH2004”. This decline is mainly attributed to a continuous decline in suckler cow and rearing cattle populations.

With regard to the total of environmentally relevant nitrogen losses, our results only reveal a minor reduction of 12% between 2002 and 2013 for the “EU2010” scenario while for the other three scenarios a stabilization on the current level of about 88 kt N/year is assessed. Given the original policy target – a reduction of the potentially harmful nitrogen load into the environment from 94 kt N/year to 74 kt N/year between 1994 and 2005 (BUWAL/BLW, 1996) – our results reveal that current policy measures will not be sufficient to meet this target, even within the time frame of one further decade.
Hence, additional measures are required to the regulations on maximum stocking rates and nutrient inputs per area. Candidates are economic incentives, such as levies on nitrogen surplus and fertilizer use, as discussed in the literature (Fontein et al., 1994; Helming, 1998; Lansink and Peerlings, 1997; Polman and Thijsen, 2002; Vatn et al., 1996; Vermersch et al., 1993).

4.3.2 Nitrogen taxes

In Switzerland, the use of economic instruments is envisaged in a parliamentary request for a bill on the introduction of incentive taxes on fertilizers and pesticides,
should current agricultural and agri-environmental policy instruments fail to have the intended effects. Under consideration of recent studies (e.g. Peter et al., 2006) and the above results, we investigate for the year 2005 the effects of three different taxes on the nitrogen content of animal manure (liquid and solid) and synthetic fertilizers:

a) a tax on all nitrogen in animal manure and synthetic fertilizers,

b) an exclusive tax on nitrogen in animal manure, and

c) an exclusive tax on nitrogen in synthetic fertilizers.

The idea of these hypothetical instruments is to generate economic incentives by changing relative prices and production costs, such that farmers change behavior and reduce N emissions in a cost-effective manner.

In our model-based assessment, we compare the consequences which N taxes would have had 2005 upon total agricultural income, land use and livestock production, and on the different forms of environmentally relevant N emissions. The results in Figure 2 reveal the highest cost-effectiveness of an exclusive tax on synthetic nitrogen fertilizers. In contrast, a tax imposed on nitrogen in animal manure performs inferior with regard to both the effectiveness in terms of environmentally relevant nitrogen losses and the cost measured in terms of forgone agricultural income. Moreover, Figure 2 shows only for prohibitively high taxes of more than 12 CHF/kg N a significant cut down in total nitrogen losses for the two options that involve a tax on synthetic fertilizers. To compare, the current price of nitrogen in synthetic fertilizers is in the range of 1.60 CHF per kg N.
On the production side, a nitrogen tax exclusively imposed on animal manure does not affect land use – which is visualized in Figure 2 with the almost constant grassland area. But, it would have a slight effect on livestock populations and animal holding systems, which results in a 2.6% reduction of nitrogen in animal manure and 5.5% decline in ammonia emissions. As a consequence, a nitrogen tax on animal manure
would only marginally effect emissions of nitrate and nitrous oxides, and result in a stabilization of total nitrogen losses at about 96% of the reference level without tax. In contrast, a tax on synthetic fertilizers would result in a reallocation of cropland to grassland, but hardly effect animal populations and manure production. A combined tax on both manure and fertilizers would have impact on both land allocation and manure production. Thus, either a tax on synthetic fertilizers or a tax on all nitrogen applied to the land would induce considerable reductions in nitrate (NO$_3^-$) and nitrous oxide emissions (N$_2$O and NO$_x$), but only if the tax rate exceeds the above mentioned 12 CHF per kg N.

For the year 2005, the total amount of environmentally relevant nitrogen losses without any tax on nitrogen is estimated at 87.7 kt N/year. A tax on all nitrogen in manure and fertilizers of 12 CHF/kg N would induce a 4% reduction to 84 kt N/year, and a tax of 15 CHF/kg N a reduction to 78 kt N/year. Altogether, this reveals that even extremely high taxes on nitrogen fertilizers and manure would not be sufficient to comply with the agri-environmental policy target of reducing the total of environmentally harmful nitrogen losses to 74 kt N/year. As illustrated in Figure 2, this would go along with a hardly acceptable decline of total agricultural income of 89% compared to the pre-tax level. In contrast, a tax exclusively imposed on synthetic fertilizers would only cause a 20% decline of agricultural income.

From this perspective, a pure fertilizer tax is clearly preferred over a combined tax on manure and fertilizers, at the cost of almost unaffected ammonia emissions. Yet, as illustrated in Figure 3, the income effect of a nitrogen tax could be substantially reduced by reimbursing the tax revenue to the farmers.

**Figure 3:** The estimated fiscal effect of taxing nitrogen in 2005
In this case, the net income effect would be minus 8% and minus 9% for the pure fertilizer tax and the combined tax on manure and fertilizer, respectively. In other words, the major part of a tax on all nitrogen in manure and fertilizers is a pure fiscal or distribution effect; that is, revenue absorbed by the tax authority.

From this revised perspective, a tax imposed on all nitrogen could be preferable, since it exhibits about the same cost-effectiveness with respect to the total of environmentally relevant nitrogen loss, and performs much better with respect to ammonia emissions.

4.4 Discussion and conclusions

The reduction of agricultural nitrogen losses to desired levels – that have been agreed in international agreements or set as national policy targets – prove to be difficult in many countries. However, there is a lack of scientific analyses that comprehensively address the complex problem of nitrogen use and emission control with a system-oriented economic approach.

Filling into this gap, we developed an integrated agricultural allocation model to evaluate agri-environmental policy measures to curb nitrogen losses from agriculture and assess mitigation costs on a national level. Taking the case of Switzerland, our model-based analysis reveals the limitation of the current regulation of livestock units and nitrogen application rates per hectare as means to achieve the desired nitrogen reduction targets (Peter et al., 2006). These targets have originally been implemented in accord with the requests of the OSPAR Convention and the Gothenborg Protocol. Moreover, they have been evaluated on the basis of agri-environmental studies and an economic approach using linear programming models for different farm types in a comparative static way by the official task force (BUWAL/BLW, 1996). Yet, recent investigations show that the traditional modeling approach used by the Swiss task force group was not adequate for taking rigidities into account that are immanent to the overall system. These stringencies include structural constraints imposed by livestock populations and agricultural production capacities, the cost of related adjustment processes, and the linkage between livestock production and agricultural land use through the integrated nutrient-forage cycle. Another crucial issue is the sensitiv-
ity of the model-based results to assumptions about relative prices that have not sufficiently been taken into consideration in previous studies.

From a methodological point of view as well as with regard to policy analysis, these insights about the rigidity of the agricultural system due to the interdependence of land and livestock-based production (forage-manure cycle) and the sensitivity to changes in relative prices might also help to better understand the problem of reducing nitrogen emissions in many countries. Accordingly, we suggest the use of integrated assessment models that adequately reflect the nutrient cycles within the agricultural system as the most appropriate tool for policy analysis. This is supported by McCarl and Schneider’s (2001) emphasis on the crop-livestock management interdependencies on the costs and potential for agricultural greenhouse gas mitigation. Since nitrogen plays an important role in agricultural production and as a direct and indirect determinant of greenhouse gas emissions, this argument must be logically extended to the problem of reducing nitrogen emissions from agriculture into the environment.

The present analysis, for which we employed a recursive-dynamic and integrated approach on the national level of agricultural production in Switzerland, indicates that the target of reducing agricultural nitrogen losses cannot be met without fundamental policy changes. First, our analysis shows that, by continuing the current agricultural policy, total nitrogen losses would be reduced until 2013 in the range of only 9% (both “AP2011” scenarios) to 19% (scenario “EU2010”), respectively, below the 1994 level. This is in contrast to the 23% reduction target that originally has been envisaged for the year 2002 and finally should have been achieved by 2005. Even with an enforced reduction of output prices to the EU price level, this target cannot be achieved within the time frame of the next decade. One reason for the rather slow decline of nitrogen losses lies in the systemic rigidities of a highly integrated agricultural production system, such as that in Switzerland. These rigidities are determined by the various interdependencies between livestock production and agricultural land use (the forage-manure cycle) and the high cost of mitigating nitrogen losses through livestock reduction. Altogether, this calls for additional, more incentive-based measures to achieve the national and international policy targets. Hence, the use of incentive-based instruments must be reconsidered.

For the year 2005, we examined in our model the costs and effectiveness of hypothetical nitrogen taxes imposed on either fertilizers, or manure, or both. Our results
clearly reveal the highest cost-effectiveness of a tax on N fertilizers only, due to a much lower impact on agricultural income. It shows about the same environmental performance as a combined tax on all nitrogen in fertilizers and manure. However, our investigation shows reductions of more than 4% below the reference level for tax rates of more than 12 CHF/kg N, only. This would be extremely high compared to the current fertilizer price of 1.60 CHF/kg N.

Given the persistent resistance against tax-based solution in most countries and the negative impact upon farmers’ income, a reimbursement of nitrogen tax revenues to the farmers could help to improve acceptance and thus make incentive-based instruments other than subsidies more fashionable amongst polluters and policy-makers. As our results show, the reimbursement of nitrogen tax revenues to the farmers would substantially reduce the net income loss. A candidate vehicle is a flat rate area payment on both cropland and grassland. Since this can be interpreted as a subsidy on land, the question arises about the optimal level of land-based payments to the farmers. Theoretically, this goes in line with the combination of a nitrogen tax and a land-use tax or subsidy, such as proposed by Goetz et al. (2006), and requires consideration in future research that also must take into account the linkages between livestock production and agricultural land use through the forage-manure cycle.

Consequently an effective policy to reduce agricultural nitrogen losses must jointly address nitrogen inputs and land use. This general conclusion is not restricted to the situation in Switzerland, but applies all countries and regions where the land is both used to feed animals and to discharge animal waste. Together with the theoretical request for charging all pollution-relevant inputs (Griffin and Bromley, 1982), it calls for the combination of a nitrogen tax with a differentiated land-use tax and a land-based reimbursement of nitrogen tax revenues. Yet, this would imply a fundamental change of the current system with uniform land-based direct payments. It would have substantial equity effects, and therefore be difficult to implement. Hence, further options must be explored that might help to reduce nitrogen losses without curtailing agricultural income too much. This might involve consideration of ambient based instruments, such as proposed by Segerson (1988) and Xepapadeas (1995), and voluntary environmental agreements (Segerson and Miceli, 1998). In addition, incentives may be required to support the development and implementation of manure treatment technologies that separate nutrients and produce bio-energy, and thereby break up the
rigidity of the forage-nutrient cycle, provide a substitute for synthetic fertilizers and fossil fuels and avoid the spreading and discharge of manure without effective use of various components of this valuable resource. Current studies show that these technological options are not competitive in Switzerland. The costs of agricultural bio-fuel production are much higher than in the EU, even with current Swiss government support per unit of CO$_2$-equivalent avoided (Steenblik and Simón, 2007). Nonetheless, manure treatment technologies may constitute a valuable option for mitigating both nitrogen and GHG losses in the upcoming decades, and will therefore be considered in future research with longer time horizons.
5 Synthesis and concluding remarks

The emissions of greenhouse gases (GHG) and nitrogen from agriculture are relevant for climate change and environmental damage. Thus, facilitating their mitigation has been one of the major concerns of both scientists and policy makers over the last 20 years. In addition, there is an increasing societal demand to provide information on the relative efficiency of policies dealing with the environment and agriculture. Politicians are in charge of evaluating the impact of alternative policy choices on agriculture and the environment as well. Thus, it needs to be determined which set of policy designs and technologies are suitable for the agricultural sector to achieve a favored or required level of climate relevant gas mitigation at the lowest costs.

The aim of this study was to analyze Swiss agriculture's contribution to environmental objectives from an economic point of view with the focus lying on GHG and nitrogen emissions. Cost-effective strategies, presented in the chapters 2 to 4, were obtained from the integrated linear programming model S_INTAGRAL. This analytical tool (see chapter 2) enables both scientists and politicians to identify cost-effective strategies to mitigate GHG and nitrogen emissions from Swiss agriculture in order to achieve a given level of GHG and nitrogen emissions. The model performance can be described as sufficiently robust and satisfactory. S_INTAGRAL is appropriate to economically evaluate GHG and nitrogen emissions arising from Swiss agriculture. This model has been and is successfully applied to both research issues and policy support. The results that have been obtained and that refer to the three main objectives given in chapter 1.4 can be summarized as follows:
### #1: Identification of Swiss agriculture's contribution to climate and nitrogen policies

- What are the international and national objectives related to GHG and nitrogen emissions to which Switzerland is committed?
- To what extent have GHG and nitrogen emissions from agriculture decreased since 1990?
- What is the economic value of this contribution to climate policy?

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Results obtained:</th>
</tr>
</thead>
</table>
| 3       | - By ratifying the Kyoto Protocol Switzerland is committed to reduce its GHG emissions by 8% below the reference level of 1990 within the first commitment period (2008-2012).
|         | - Agricultural GHG emissions are not addressed in the national climate policy as the CO₂ Law prescribes a reduction of energy-based CO₂ emissions by 10% below the level of 1990 until 2010.
|         | - Agricultural GHG emissions have decreased by 14% between 1990 and 2002.
|         | - The economic value of the reduction of agricultural GHG emissions between 1990 and 2002 corresponds to 57 Mio CHF/year. |
| 4       | - The Gothenborg Protocol obligates Switzerland to reduce its NH₃ emissions by 13% below the reference level of 1990 by 2010.
|         | - A Swiss national strategy defines both a long-term and an intermediate target for the reduction in the emissions of harmful nitrogenous compounds from agriculture:  
  
  - long-term target: 50% below the baseline level in 1994  
  - intermediate target: 23% below this baseline by 2005.  
|         | - Recent analyses show that the intermediate target is far from being achieved. |
5 Synthesis and concluding remarks

#2: Expectations of future reductions in GHG and nitrogen emissions

- What is the economic value of additional reductions in GHG and nitrogen emissions when considering different agricultural policies?
- What economic values can be identified in comparison to other national sectors (e.g., energy consumption sector)?
- What are the costs for the agricultural sector to reach a specific reduction target?

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Results obtained:</th>
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</table>
| 2       | • Technical opportunities to mitigate GHG emissions contribute only to 8% of the modeled GHG emissions in 2020.  
         | • This amount is largely linked to monetary incentives higher than 1,000 CHF/t CO₂eq reduced. |
| 3       | • GHG emissions from agriculture can be expected to decline further between 0.12-0.5 Mt CO₂eq/year without any new specific climate policy measures until 2010.  
         | • The economic value of additional GHG reductions is about 10 to 45 Mio CHF/year.  
         | • The introduction of targeted economic incentives might lead to an additional GHG reduction (ca. 2.5 %) in the year 2010 accompanied by additional annual costs (ca. 2.2-2.5 Mio CHF) for the agricultural sector (unilateral case). |
| 4       | • Emissions of environmentally relevant nitrogen are calculated to decline by 12% (scenario “EU2010”) or remain constant (scenario “AP2011”) between 2002 and 2013.  
         | • The income loss decreases from 3 billion CHF in 2000 to about 2.5 billion CHF in 2013 (scenario “AP2011”).  
         | • The introduction of a hypothetical tax leads to reductions in nitrate and nitrous oxide emissions only if the tax rate exceeds 12 CHF/kg N.  
         | • The tax on nitrogen leads to a decline in total agricultural income of 20% to 89% compared to the pre-tax level.  
         | • Reimbursing the tax revenue to the farmers reduces the net income effect by 8% to 9%. |
#3: Evaluation and recommendations for environmental policies in the future

- What is the impact of the obtained results on future policies?
- What kinds of policies may contribute to a further reduction in emissions from the agricultural sector?
- Which additional policies can be considered from the presented results?
- How a certain reduction target can be optimally achieved?

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Results obtained:</th>
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| 2       | • Swiss agriculture can be expected to contribute marginally to the mitigation of GHG and nitrogen emissions.  
          • These reductions arise by adjusting and improving existing policies rather than introducing specific measures. |
| 3       | • Recent and additional GHG reductions are a result of agricultural policy reforms and their continuation.  
          • Reductions in GHG emissions from Swiss agriculture due to the introduction of specific incentives are expected to be small compared to other sectors within the first commitment period of the Kyoto Protocol (2008-2012).  
          • The introduction of specific incentives induces presumably high monitoring costs.  
          • Participation in an international emissions trading system would be economically efficient due to a reduction in total abatement costs. |
| 4       | • Current policy measures were not sufficient to reach a 23%-reduction of agricultural nitrogen losses by 2005, not even within the time frame of one additional decade.  
          • Existing policies and regulations are inadequate to deal with the complexity of the nitrogen cycle, and they do not give farmers the right incentives to reduce their nitrogen surplus.  
          • An effective policy towards reducing agricultural nitrogen losses must jointly address nitrogen inputs and land use. |
5 Synthesis and concluding remarks

As the conclusions presented in the chapters 2 to 4 focused on a particular task each, in this chapter 5 the argumentation follows an overall perspective. First, reflections on the model S_INTAGRAL are summarized in chapter 5.1. Then, more general conclusions on policy impact are drawn in chapter 5.2, while chapter 5.3 gives an outlook for future research issues.

5.1 Reflections on the model approach S_INTAGRAL

The recursive-dynamic integrated model S_INTAGRAL has been developed for the economic evaluation of political and technological opportunities for the mitigation of GHG and nitrogen emissions for the agricultural sector in Switzerland. It combines environmental and economic parameters, which enables the consideration of the dynamics and interconnectedness of the agricultural process that can be managed to mitigate such emissions. The S_INTAGRAL 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.

Although models, by definition, are imperfect abstractions of the complex reality (see chapter 1.3.3), they provide valuable information on a specific problem. However, each model has restrictions that result from the assumptions and simplifications made to abstract a complex problem. The appropriate use of data derived from such a model thereby requires the definition and analysis of its restrictions as well.

5.1.1 Strengths of the applied model framework S_INTAGRAL

The integrated model approach S_INTAGRAL provides an analytical tool for economic appraisals of abatement strategies, and, in particular, to assess marginal abatement costs at different points in time and for different price and policy scenarios. It combines both economic and environmental aspects of agricultural production in Switzerland. Interactions between agricultural practices and their impact on the environment are analyzed with a focus on the current political and economical conditions. This comprehensive view enables the user to assess and identify cost-effective strategies for the mitigation of GHG and nitrogen emissions. As S_INTAGRAL is characterized by a modular structure, it allows for the easy adjustment to emerging research
questions in the context of the environment and structure of the Swiss agricultural system. In addition, the explicitly described parameters enable a clear and user-friendly employment of S_INTAGRAL. The use of recursive-dynamic elements decisively reduces the typically jumpy behavior of pure linear programming models that results from overspecialization. These recursive elements are justifiable from an agricultural point of view as they enable to adequately model the dynamics and structural changes. Recursive programming provides a suitable alternative to a time-dependent adjustment of agricultural structures. Thus, the endogenous modeling of investments for buildings (including sunk costs) and machinery is taken into account as is the development of the livestock population.

5.1.2 Limitations of the applied model framework S_INTAGRAL

Despite its strengths for displaying a complex problem, the sole use of highly aggregated data may be seen as a limitation of S_INTAGRAL. This leads to only roughly spatially explicit results. Therefore, S_INTAGRAL, as applied in this study, is not suitable to extract farm- or disaggregated spatially explicit information. However, this is termed to be appropriate for the evaluation of cost-effective strategies to mitigate GHG and nitrogen emissions in Swiss agriculture. Another restriction of S_INTAGRAL is that possible interactions between the agricultural sector and other sectors within the Swiss economy are not considered. Producer prices are taken as exogenous, as Switzerland is a small open economy that does not have any impact on the world market prices but does provide a well-equipped system of tariffs. Thus, no impact on the market is indicated. However, to roughly consider these factors within S_INTAGRAL, an incremental function of demand (two steps) is implemented that emerges as a proper solution in the context of an adequate analysis of policy (see chapter 2). Finally, S_INTAGRAL is limited by disregarding technical progresses, as it considers a short to middle-term computational period only.

5.1.3 Applying S_INTAGRAL to support policy and recent research issues

Peter et al. (2009) applied S_INTAGRAL to analyze strategies for the mitigation of GHG emissions from Swiss agriculture. Within that recently finished study, several policy scenarios and technological opportunities are assessed.
Hediger et al. (2004) provided the basis for Swiss agricultural policy discussions related to GHG emissions by assessing the reduction of GHG emissions since 1990 (ex-post) and the expected reduction until 2010 (ex-ante). Applying S_INTAGRAL, this study in particular looked at the possibility of carbon sequestration in agricultural soils to achieve the Swiss aims of the Kyoto protocol. They demonstrated that the economic potential for that is relatively small, accompanied by overall high monitoring costs. Moreover, marginal abatement costs (MAC) have been calculated by considering both constraints to reducing emissions and their stepwise reduction. The results have been visualized in a MAC curve for Swiss agriculture.

Peter et al. (2006) applied S_INTAGRAL to the assessment of the nitrogen emissions from the Swiss agricultural sector. This study analyzed the current situation for environmentally relevant nitrogen emissions and considered the expected development until the year 2013. Evidence is provided suggesting that the sole continuation of the current agricultural policy will not substantially reduce environmentally relevant nitrogen emissions. Further economic and technologic measures are a prerequisite to realize the desired reductions in the targets instead.

Applying S_INTAGRAL, Peter et al. (2008) assessed the potential of Swiss agriculture to serve as supplier of a crop-based production of bio-energy from an economic point of view. They evaluated the interdependence between food and energy production as well as the impact on Swiss agriculture in terms of its significance for area, energy and income. The authors concluded that the energy-related significance of biofuel production will remain at no more than 8% of the total fossil energy consumption in Switzerland.

The studies described above have been assigned by the Swiss Federal Office for the Environment (FOEN) and the Federal Office for Agriculture (FOAG). Apart from these studies, the analytical tool S_INTAGRAL has been applied to other research projects as well.

An ongoing project (Huber, 2008) investigates the jointness between agricultural production and ecosystem services. It includes the assessment of economies of scope, considering the provision of ecosystem services by non-agricultural competitors as well. For that purpose, the spatially explicit adaptation of S_INTAGRAL was stressed.

Within the recently started project “Mountland” (CCES, 2008), the S_INTAGRAL framework will be applied for an integrative approach. This work aims to investigate...
5 Synthesis and concluding remarks

the dynamics of an ecosystem under the particular considerations of global change, socio-economic impact and policy implications.

The findings presented in the chapters 2, 3 and 4 as well as the above-mentioned applications, as far as the projects have been completed, indicate that S_INTAGRAL is appropriate to analyze agricultural impact on the environment as well as to evaluate policies and measures for the mitigation of environmental impact. In conclusion, this model provides scientists and policy makers with valuable information regarding the Swiss agricultural sector. It satisfyingly promotes the identification of cost-effective strategies to mitigate GHG and nitrogen emissions in Swiss agriculture.

5.2 Reflections on policy implications

By ratifying the Kyoto Protocol, Switzerland has committed to reducing its GHG emissions by 8% below the reference level of 1990 by the first commitment period (2008-2012). However, neither in this international commitment nor in the national climate policy are agricultural GHG emissions explicitly addressed (see chapter 3).

As indicated in chapter 4, Swiss agriculture is obligated indirectly by international commitments (OSPAR, Gothenborg Protocol) and directly by national commitments to reduce environmentally relevant nitrogen emissions. The national objectives have been implemented according to the requests of international commitments defined for both a long-term and an intermediate perspective. While in the long-term, the loss of harmful nitrogen compounds from agriculture has to be reduced by 50% below the level in 1994, the intermediate target has scheduled a reduction of 23% by 2002 (originally) and 2005 (finally).

Primarily, as a consequence of the reforms in agricultural policy, agricultural GHG emissions decreased between 1990 and 2006 (see chapters 2 and 3). It can be expected that they will decline further between 0.12-0.5 Mt CO₂eq/year under the current agricultural policy reforms and without the implementation of new specific climate policy measures until 2020.

In contrast, Peter et al. (2006) demonstrated that the stipulated reduction of environmentally relevant nitrogen emissions by 23% by 2005 (intermediate target) is far from being achieved. This is despite the fact that livestock units and nitrogen application
rates per hectare have been regulated as means to reach the nitrogen reduction targets. The results presented in chapter 4 indicate a decline in environmentally relevant nitrogen emissions between 2000 and 2013 provided that the output prices for agricultural products are substantially reduced. Otherwise, the level of these emissions remains constant in this period. Thus, the intermediate target in Switzerland can be achieved neither within the next decade nor without essential changes in the policy. Decreases in livestock production and changes in land use have mainly been associated with the observed and computed reduction in GHG and nitrogen emissions (see chapter 2, 3 and 4). This emphasizes the interdependencies in crop-livestock management (forage-nutrient cycle), particularly based on the costs of and the potential for the mitigation of these emissions, and thus, on the rigidity of the agricultural system. The application of an integrated assessment model, such as S_INTAGRAL, provides an appropriate tool for the analysis of various policies. The application of varying scenarios within S_INTAGRAL affects real variables, such as numbers of livestock, the area of cultivation and the income generated. The latter shows a strong impact when the producer prices being less than the present ones. Striking income losses will primarily endanger the constitutional objectives of Swiss agriculture to society (Bundesverfassung Art. 104, 1999): (1) to secure the food supply, (2) to conserve and preserve nature and the cultivated landscape, and (3) to contribute to peripheral settlement. High marginal abatement costs for Swiss agriculture would subsequently occur (see chapter 3). In contrast, the relative reduction in GHG emissions induced by climate policy is low compared to that of other sectors. If the Swiss agricultural sector is obliged to reduce its GHG emissions, a market for emissions permits might be a feasible option (see chapter 1.3.2). High income losses cannot be excluded, but they can be minimized by the use of tradable permits. In contrast, the real variables do not have this strong impact of price changes. They are determined by relative rather than absolute prices.

In conclusion, the results of this study reveal that recent agricultural policy reforms comprise an effective way to reduce GHG emissions. However, the achievement of national and international policy targets of environmentally relevant nitrogen emissions requires additional and concrete economic incentives and technologies. These include, for instance, rigorous programs for the use of natural resources, voluntary environmental agreements and manure treatment technologies. The latter enable a
break from the rigidity of the forage-nutrient cycle. Thereby they provide a substitute for synthetic fertilizers and avoid the spreading and discharging of the manure without an efficient use of the various components of this valuable resource. This is especially true for the ammonia and nitrate that make up the principal share of the environmentally relevant nitrogen losses from Swiss agriculture.

### 5.3 Prospects and Outlook

Applying models for policy makers on the one hand and for the scientific community on the other hand usually leads to a compromise. In either case, the chosen model is required to focus on the particular questions of one of the two target groups. In the worst case, the computed results are useless to both of them. The major difference is that modeling for the scientific community should bring up novel ideas/answers for current research questions rather than “just” applying existing ones. Modeling for a policy support must be geared towards the stakeholders. This means that applying an existing model approach seems to have a big advantage in terms of their confidence in the results. Moreover, the generation of consistent and accepted assumptions and scenarios appears also to inspire confidence. The application of S_INTAGRAL for policy analysis in Switzerland is increasingly accepted. This has arisen not only because of the studies presented above (see chapter 5.1.3) but also due to the ongoing and concretely planned studies assigned by Switzerland’s Federal Office for the Environment (FOEN) and Federal Office for Agriculture (FOAG) that reveal their confidence in the results obtained with S_INTAGRAL.

Projects to which S_INTAGRAL has been or is applied led to improvements and adjustments of the model. This not only results in the adaptation to the particular research question but also to a continuous updating of the methodologies included. Therefore, new scientific findings are continuously reflected in S_INTAGRAL. However, the significance of modeled results is often limited as it strongly depends on the data used. For instance, Menzi et al. (2006) refer to a “Swiss NH3 gap” as an increase in the measured nitrogen emissions does not correlate with the decline of Swiss inventory calculations. The latter are also implemented in S_INTAGRAL. Thus, even though a huge amount of data exists, it is necessary to survey and collect additional data. There is still a lack of adequate regional disaggregated data on agricultural man-
agement options that considers site-specific production conditions. Moreover, as ex-
emplified by the technical opportunities to mitigate GHG or nitrogen emissions, it
needs to be deciphered whether an effect tested in the laboratory is additive to already
existing measures.

Model improvements based on remedies to issues like those mentioned above would
not only improve the results that have generally been obtained by integrated assess-
ment models. They would also subsequently improve the support for policy analysis
by research-provided feasible approaches and solutions. This especially refers to re-
search dealing with broad and complex issues like biodiversity, rural development or
food security. Integrated approaches are feasible to analyze how to efficiently use
nutrients in agricultural ecological systems, and this approach is not only restricted to
Switzerland. Sharing knowledge by diffusing the best practices is possible only when
several aspects are considered. The latter comprise aspects and interactions of: (1)
local, regional and global food systems, including the knowledge of the respective
consumer behavior, (2) political systems, (3) economical systems, and (4) environ-
mental systems.

In conclusion, integrated model approaches can make an important contribution to
comprehending and understanding interactions between agricultural, environmental,
economical and political systems both on a regional and a global scale. They provide
a scientific basis for the analysis of the global and regional food security and quality
issues through the sustainable use of scarce natural resources.
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