REDUCING NITROGEN LOSSES FROM AGRICULTURAL SYSTEMS – AN INTEGRATED ECONOMIC ASSESSMENT

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Michael Hartmann, Werner Hediger† and Simon Peter**

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.

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 (NO_3^-), ammonia (NH_3), and nitrogen oxides (NO_x and N_2O). 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.

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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.

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.

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 (N_2O) 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 (NH_3, NO_3^-, NO_x and N_2O) are most usefully analyzed from an agricultural systems perspective, rather than independent of each other.

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 the dynamics of the system. It provides an analytical tool for economic studies of GHG and different forms of nitrogen emissions from the agricultural sector. The model includes all important activities with regard to income generation, land use, livestock production, as well as GHG and nitrogen emissions on the national level. It is divided into the three major production zones (plains, hills and mountain area), and is based on the two production modules “livestock production” and “plant production”. Those are integrated through balances between production and use of forage (grass and crop forage) as well as livestock manure production and application, such as illustrated in Figure 1.

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 η_i and α_i denoting the survival rate of cows and of cattle, respectively:

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

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:

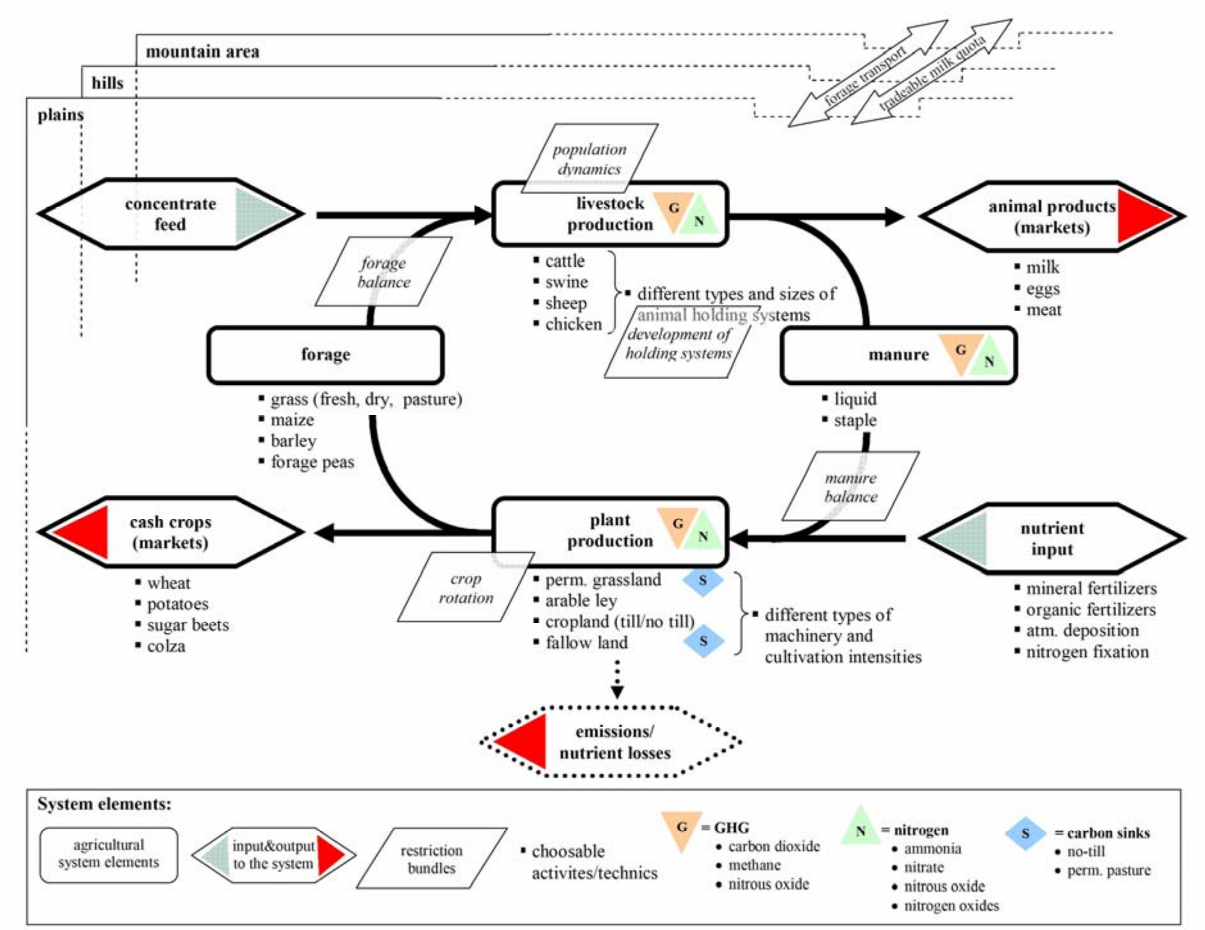
$$S_{ijzt} \leq K_{jzt} \quad \text{with} \quad S_{izt} = \sum_j S_{ijzt} \tag{2}$$

This capacity depreciates at a rate δ_j and can be enhanced with adequate investments I_{jzt}:

$$K_{jzt} \leq (1-\delta_i)K_{jz(t-1)} + I_{jzt} \tag{3}$$

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).

Figure 1: Schematic representation of the agricultural system in S_INTAGRAL model



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).

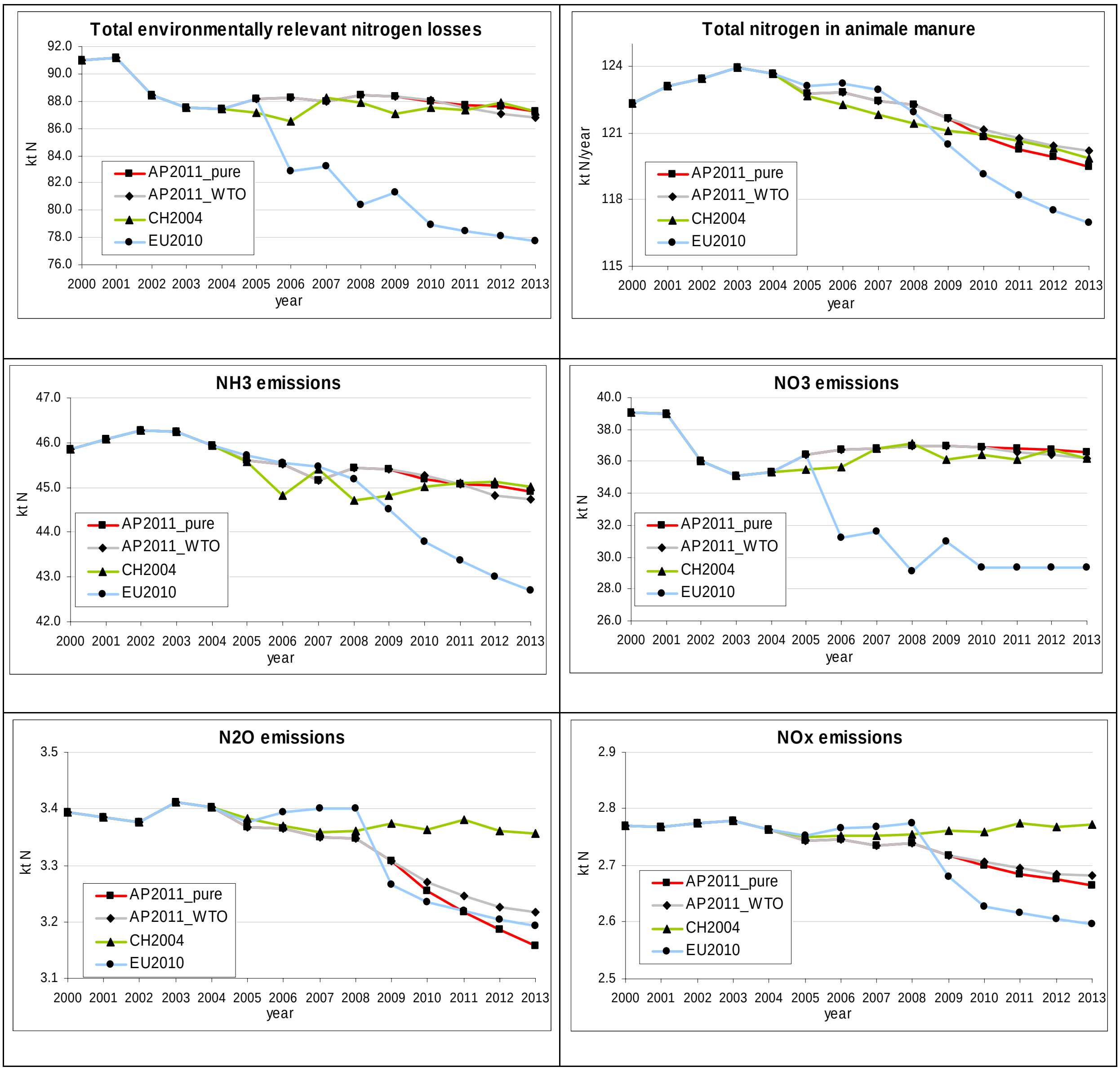
3 Results

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.

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.

Figure 2: Development of environmentally harmful nitrogen losses 2000 to 2013



As a consequence of the development in the sphere of livestock production, Figure 2 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).

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

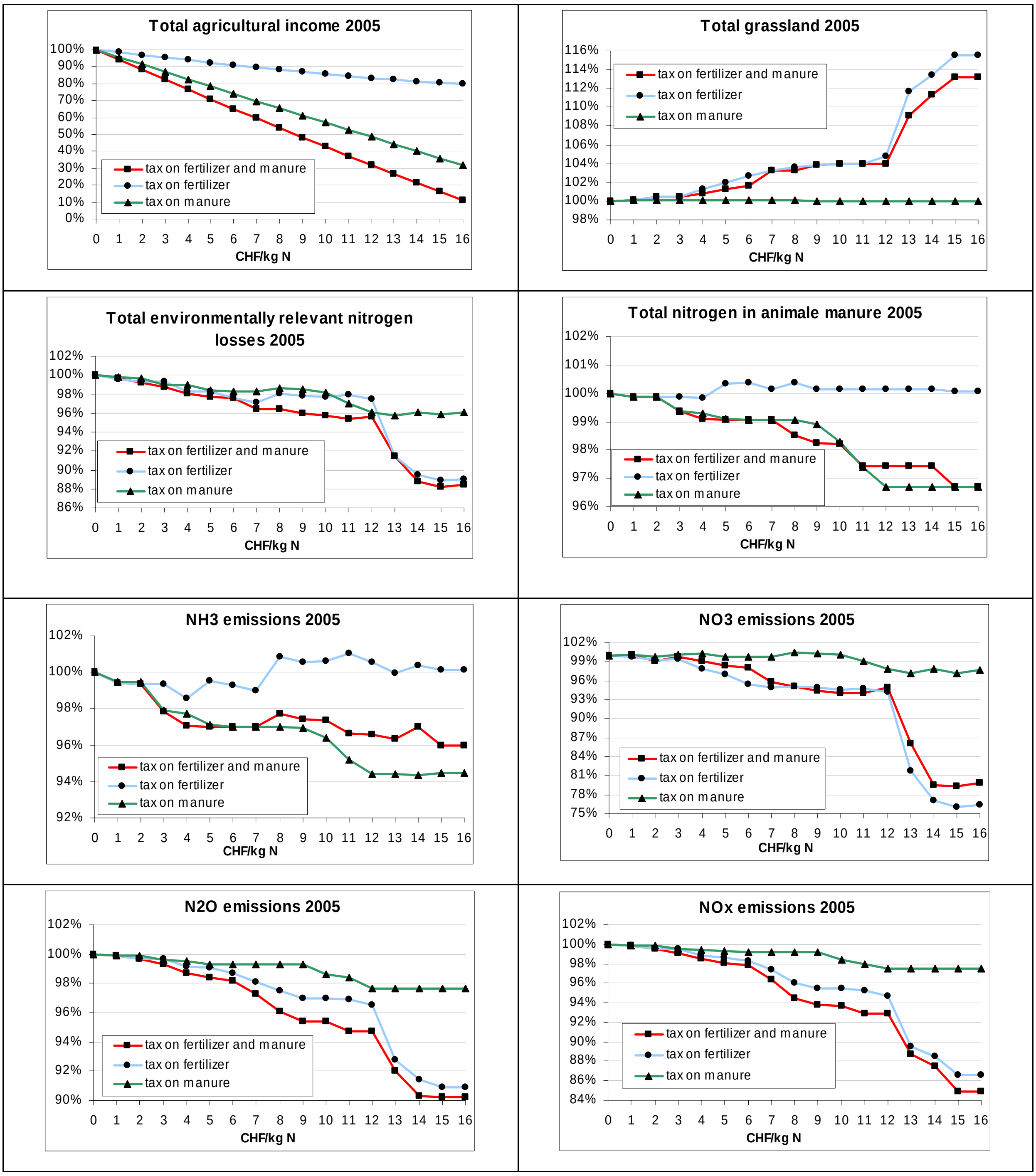
c) an exclusive tax on nitrogen in synthetic fertilizers.

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 3 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 3 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 3 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_2O and NO_x), but only if the tax rate exceeds the above mentioned 12 CHF per kg N.

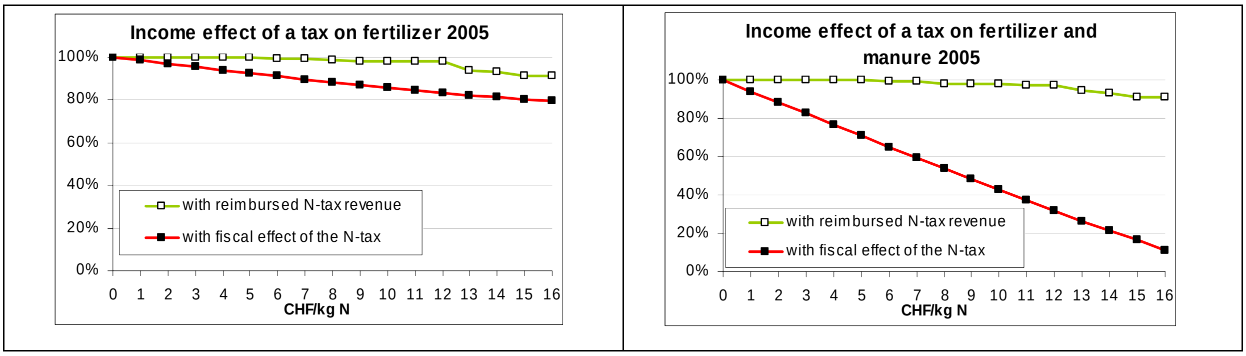
Figure 3: Estimated effects of a nitrogen tax in 2005



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 3, 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 4, the income effect of a nitrogen tax could be substantially reduced by reimbursing the tax revenue to the farmers.

Figure 4: 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 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 sensitivity 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; HEDIGER, 2003). 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.

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