# Reductions of Agricultural Nitrogen Use Under Consideration of Production and Price Risks

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## Abstract

Production and price risks affect optimal nitrogen use as well as the effects of nitrogen taxation if farmers' risk aversion is taken into account. Our empirical analysis for Swiss maize production shows that risk-aversion leads to lower levels of nitrogen application, and nitrogen taxes lead to higher reductions of nitrogen use for risk-averse than for risk-neutral farmers. Moreover, risk-averse farmers face lower abatement costs. Sensitivity analyses, that consider expected shocks in price and yield variability in Swiss maize production, show that these differences between risk-averse and risk-neutral farmers will increase further. Thus, agricultural policies should consider farmers' risk-preferences as well as potential increases in farmers' income risks.

## 1 Introduction

Crop production causes external effects that harm the environment. For instance, losses of applied nitrogen fertilizer, either gaseous or due to leaching, contribute to water pollution and climate relevant emissions (e.g. von Blottnitz et al., 2006, Pretty et al., 2001). In absence of governmental regulation, farmers do not have incentives to take these environmental externalities into account in their decision making process (Choi and Feinerman, 1995). Nitrogen taxes are a useful instrument to reduce nitrogen application and thus nitrogen losses to the environment (Rougoor et al., 2001).

The effects of a nitrogen tax are often evaluated with regard to farmers' income losses (abatement costs) and reductions of nitrogen application. Among others, Isik (2002), Lambert (1990), Weersink et al. (1998) and Chowdhury and Lacewell (1996) show that farmers' risk preferences affect the potential costs and environmental effects of agricultural policy measures. Ignoring risk considerations may therefore lead to erroneous predictions how farmers respond to nitrogen taxes (Chowdhury and Lacewell, 1996). Thus, including risk considerations in the ex-ante policy evaluation is a useful and necessary extension of deterministic assessment methods (e.g. Isik, 2002, Swinton and Clark, 1994, Rougoor et al., 2001). A risk considering framework implies furthermore that exogenous increases in farmers' income risks can have implications for the effectiveness of policy measures.

In this article, we demonstrate the influence of price and yield risks on the effects of a nitrogen tax using the example of maize production in Switzerland. The introduction of nitrogen tax in Swiss agriculture is considered as a relevant policy option in Switzerland if other measures do not lead to the attainment of long-term targets of reducing the loss of harmful nitrogen compounds from agriculture (Hartmann et al., 2008). Maize is chosen as a case study because it is among the crops with the highest leaching potential.

Sensitivity analyses on the influences of nitrogen taxes applied in this paper address potential shocks in farmers' income risks due to market liberalization and climate change. Currently Swiss farmers face only small income risks: Firstly, the variability of crop yields is small because climatic conditions are favourable for crop production and extreme climatic events such as droughts are rare. Secondly, price variability is much lower than in other countries because currently tariffs, quotas and other trade regulations reduce the impact of volatile world market prices on Swiss markets. However, Swiss farmers

are expected to face more risky production and market conditions in the future: Climate change is expected to increase yield variability, particularly for maize (Finger et al., 2010). Furthermore, likely market liberalization (e.g. due to a free trade agreement with the European Union) is expected to increase price variability (e.g. Mahul, 2003)[1]. Therefore, we analyse the impact of increasing yield and price risks on the effects of a nitrogen tax.

In summary, the goal of this paper is to analyse the effects of risk aversion and nitrogen taxes on nitrogen use in Swiss maize production. To this end, an economic decision model that accounts for price and yield risks is employed. Furthermore, sensitivity analyses outline the effects of potential (endogenous) shocks in price and yield variability to the effects of fertilizer taxes.

## 2 Data and Methodology

### 2.1 Economic Decision Model

In order to model farmers' decision making process with regard to nitrogen use, we use a non-linear certainty equivalent (CE) maximization approach. The CE denotes the non-random level of payoff which is rated by the farmer (in terms of utility) equivalent to an uncertain (i.e. random) level of payoff. For the risk-averse decision maker, the expected mean profit is reduced by the risk premium (RP), the amount of money the farmer is willing to pay to eliminate risk exposure:

(1) $$CE = E(\pi) - RP$$

The expected (mean) profit ($E(\pi)$) is defined as revenue (maize Yield, Y(N), times maize price, $p_M$) minus fixed ($C_F$) and variable costs. In our analysis, variable costs comprise nitrogen costs (amount of nitrogen applied, N, times nitrogen price, $p_N$) as well as cleaning and drying costs (maize yield times price for cleaning and drying, $p_D$):

(2) $$E(\pi) = Y(N)p_M - C_F - Np_N - Y(N)p_D$$

The profit maximization framework is extended by assuming that profits are stochastic due to the variability of maize yields (e.g. due to uncertain weather conditions and nitrogen application) and due to the variability of crop prices. Moreover, the correlation between crop yield and crop price has to be taken into account to calculate the variability of profits. In particular, low crop yields might imply smaller supply and thus higher crop prices (i.e. a so called "natural hedge"). Following Bhornsted and Goldberger (1969), we define the variance of profit[2] ($\sigma_\pi^2$) as follows:

(3) $$\sigma_\pi^2 = \sigma_Y^2 p_M^2 + \sigma_{P_M}^2 Y^2 + 2YP_M Cov(Y, P_M) + \sigma_Y^2 \sigma_{P_M}^2 + Cov(Y, P_M)^2$$

The covariance of yield and price is calculated as $Cov(Y, P_M) = corr(Y, P_M)\sigma_{P_M}\sigma_Y$, where $corr(Y, P_M)$ denotes the correlation between yield and price, and $\sigma_{P_M}$ and $\sigma_Y$ denote the standard deviation of maize price and maize yield, respectively.

Following Di Falco et al. (2007), the risk premium is defined as follows[3]:

(4) $$RP = 0.5\, \sigma_\pi^2\, \gamma / E(\pi)$$

$\gamma$ is the coefficient of relative risk aversion, representing the degree of risk aversion of the farmer. In particular, a risk neutral farmer is represented by $\gamma = 0$, while risk averse behavior implies $\gamma > 0$. The relative risk premium presented in equation (4) assumes constant relative risk aversion that implies

[1] Moreover, market liberalization is expected to decrease output prices, which will strongly influence the use of fertilizer (e.g. Weersink et al., 1998). However, this paper is restricted on the effects of increasing volatility on fertilizer use.

[2] I.e. the variance of a product of two correlated random variables (yield and price).

[3] In order to also address skewed distributions of profits, this approach has to be extended by downside risk aversion (e.g. Groom et al., 2008), which is beyond the scope of this paper.

decreasing absolute risk aversion (i.e. risk aversion decreases with increasing wealth). To derive optimal nitrogen allocation in this model, the certainty equivalent is maximized with respect to nitrogen use:

(5) $$\underset{N}{Max}\ CE = E(\pi) - RP$$

## 2.2 Production and Yield Variability Functions

### 2.2.1 Functional Forms

Following Finger et al. (2010), yield – nitrogen relationships are estimated using Just and Pope (1978, 1979) production functions in which inputs are allowed to influence the mean but also the variability of crop yields:

(6) $$Yield = Y(N) + \sigma_Y(N)\varepsilon$$

where $Y(N)$ and $\sigma_Y(N)$ denote the production and yield variation function, respectively, and where we further assume that $E(\varepsilon) = 0$ and $\sigma(\varepsilon) = 1$. We estimate the production function in a first step using a square root specification (Finger and Hediger, 2008):

(7) $$Y(N) = \alpha_0 + \alpha_1 N^{0.5} + \alpha_2 N$$

In a second step, the absolute values of the regression residuals associated with the production function estimation, defined as $\hat{w} = Y - \hat{Y}$, are used to estimate the yield variation function using the following specification (Finger and Schmid, 2008):

(8) $$\sigma_Y(N) = |\hat{w}| = \beta_0 + \beta_1 N^{0.5}$$

### 2.2.2 Data Generation and Coefficient Estimates

To simulate observations of maize yields for different levels of nitrogen application, the deterministic crop yield simulation model CropSyst is applied for the eastern Swiss Plateau region (Finger and Schmid, 2008). CropSyst models above- and below-ground processes (e.g. the soil water budget, soil-plant nitrogen budget, crop phenology, canopy and root growth, and crop yield) on a daily time step (see Stöckle et al., 2003, for details). In CropSyst, these processes are simulated in response to crop and soil characteristics, daily weather data, and management options. Model calibration, validation and settings for Swiss maize production are presented in Torriani et al. (2007). The stochasticity of crop yields is introduced in this model by using different sets of daily weather data, i.e. representative outcomes of current climate at the eastern Swiss Plateau for the years 1981-2003 (see Finger and Schmid, 2008). For these different sets of climate data (i.e. model runs), the total amount of fertilizer was varied randomly[4], ranging from 0 to 320 kg $ha^{-1}$. Depending on the applied amount of nitrogen, three to four fertilizer applications are made at different stages of the cropping season. These nitrogen applications are made 1, 30, and 46 days after sowing (with a 25%, 25%, 50% distribution of the total nitrogen amount), respectively, following Dubois et al. (1998). The additional fourth application (if the total annual fertilizer amount exceeds 160 kg/ha) takes place 38 days after sowing (with a 20%, 20%, 20%, 40% distribution of the total nitrogen amount on the 4 applications). For each simulation, identical starting conditions regarding soil composition and soil available nutrients are used. The assumed soil texture is characterized with 38% clay, 36% silt, and 26% sand. Soil depth amounts to 1.5 m and the soil organic

[4] In total, this leads to 394 observations.

matter content is at 2.6% weight in the top soil layer (5 cm) and 2.0% in lower soil layers, which follows Dubois et al. (1999). Further details on the simulations setup are presented in Finger and Schmid (2008). The production and the yield variability function are estimated with the MM-estimator, a robust regression technique (see e.g. Finger, 2010, for descriptions), using the 'robustbase' package of R. Coefficient estimates for Equations 7 and 8 are presented in Table 1:

**Table 1. Coefficient Estimates of Equations 7 and 8.**

| Variable | Production Function (Eq. 7) | Yield Variation Function (Eq. 8) |
|---|---|---|
| Intercept | 6.61 (143.69)*** | 0.43 (16.19)*** |
| $N^{0.5}$ | 0.33 (10.07)*** | 0.03 (6.35)*** |
| $N$ | -0.01 (-5.97)*** | ---- |
| $R^2$ | 0.38 | 0.42 |
| df | 391 | 392 |

The coefficient estimates for the production function show that nitrogen application increases maize yield, however, with a saturating effect (i.e. nitrogen shows decreasing marginal productivity). The estimates for the yield variation function show that yield variability (i.e. production risks) increase with nitrogen application.

## 2.3 Setup of the Calculations and Sensitivity Analyses

### 2.3.1 Cost, Price and Benefit Data

In order to solve the optimization problem presented in Equation (5), the assumptions with regard to costs, benefits, prices and risk aversion have to be specified. Fixed costs, including costs for seeds, plant protection, insurance, machinery costs and fertilizer costs (except for nitrogen), as well as direct payments and prices for maize and nitrogen are taken from Swiss agricultural profit margin calculations (AGRIDEA and FiBL, 2009). Variable cleaning and drying costs are taken from Torriani et al. (2008). All assumptions on costs, benefits and prices are presented in Table 2.

**Table 2. Specification of Costs and Benefits.**

| | |
|---|---|
| **Revenue** | |
| Sale of production | Price (365 CHF/t) * tons of Yield per ha |
| Direct Payment | 1660 CHF/ha |
| | |
| **Fix costs** | |
| Seeds | 268 (CHF/ha) |
| Plant Protection | 228 (CHF/ha) |
| Insurance | 134 (CHF/ha) |
| Machinery costs | 990 (CHF/ha) |
| Other fertilizer costs | 193 (CHF/ha) |
| | |
| **Variable Costs** | |
| Fertilizer | 1.25 CHF/kg N |
| Cleaning and drying | 107 CHF/ tons of Yield per ha |

Source: AGRIDEA and FiBL (2009), Torriani et al. (2008).

The maximization of CE's (Equation 5) is conducted for a risk averse as well as for a risk neutral ($\gamma = 0$) farmer. Following Finger et al. (2010), a moderate level of relative risk aversion, $\gamma = 2$, is assumed for risk averse farmers.

### 2.3.2 Estimates for Price Variability

The variability of maize prices is estimated using prices[5] from 1991-2006, taken from the FAO database (FAO, 2010). To account for the dependency structure (autocorrelation) between the observations, a time-series approach is used to estimate yield variability following Sarris (2000). Following Johnston and DiNardo (1997), we find an AR(1) specification to be most adequate. In this AR(1) model, the sample variance estimate is corrected for the dependency structure, leading to a coefficient of variation (CV) of 0.13. Compared to other countries such as France, Germany and the USA (CV of 0.23, 0.24 and 0.24, respectively - estimated using the same data source and methodology), this relative price variability is much smaller, in particular because tariffs, quotas and other trade regulations are used to control national price levels in Switzerland. To estimate the correlation between maize prices and maize yields, the correlation between detrended annual data for prices and yields (taken from FAO, 2010) is estimated, leading to $corr(Y, P_M) = -0.25$. In order to test if this correlation observed at the national level is a valid assumption for farm level analysis, we used Swiss FADN data (see Lehmann, 2010). Taking the period 2002-2008 into account, the correlation between maize prices and yields is estimated for each farm. The median of 158 available farm level correlations is -0.24, and significantly smaller than zero. This result shows that the national level estimate is, in this case, a valid assumption for farm level analysis.

### 2.3.3 Nitrogen Taxes and Sensitivity Analyses

To analyse the effects of a fertilizer tax on nitrogen use, utility and profits, the fertilizer price is increased by 10%, 20% and 30%. These assumptions on possible nitrogen taxes are within the range of observed examples of nitrogen taxes in Europe (Rougoor et al., 2001).
To analyse potential effects of shocks in farm-income risks, sensitivity analyses of the above presented optimization problems are conducted with regard to higher price and yield variability. Higher price variability is integrated in the model by assuming a doubled coefficient of variation of maize prices (CV=0.26). This sharp increase represents higher price volatility in a less protected market environment, e.g. due to a free trade agreement with the European Union, and is in the range of maize price variability in France and Germany. A second sensitivity analysis assumes higher production risks due to climate change. Finger and Schmid (2008) estimate an increase of maize yield variability of about 15%, while no effect of climate change on the relationship between nitrogen use and maize yield variability has been indicated[6]. Thus, we assume that only the intercept of the yield variation function, $\beta_0$ in Equation 8, increases by 15% from 0.43 to 0.50.

[5] Swiss farmers do not use contracts and forwards yet, so only the price after harvest is relevant – though monthly prices are available, they usually do not differ within a year (SBV, 2010). Thus annual prices are chosen for this analysis.
[6] We are aware that climate change might also affect price variability (Battisti and Naylor, 2009). This relationship is, however, beyond the scope of this paper and thus not considered.

## 3 Results

Results of the certainty maximization for risk neutral and risk-averse farmers are presented in Table 3. It shows that the results regarding, optimal nitrogen use, profits and maize yields are within the range of currently observed practices (AGRIDEA and FiBL, 2009). In comparison to risk neutral farmers (i.e. the profit maximization problem), risk averse farmers use less nitrogen fertilizer, face smaller but less variable profits and have smaller maize yields. Certainty equivalents for risk-averse farmers are markedly smaller, because income risks reduce utility levels. The risk premium (RP, Equation 4) is about 90 CHF, or about 5% in relative terms. Though risk aversion leads to a clear reduction of optimal nitrogen application, the differences for profit, profit variability and crop yields are small. A possible explanation is the fact that the production function shows only small yield decreases for reduced nitrogen applications, in particular due to the above-average available soil fertility in the here used CropSyst simulations[7]. This will restrict the quantitative results to the specific assumptions underlying this analysis, but the qualitative interpretation will be applicable without loss of generality.

**Table 3. Optimization Results for the Initial Conditions.**

| **Initial Situation** | N (kg/ha) | Profit (CHF/ha) | SD profit (CHF/ha) | CE (CHF/ha) | Yield (t/ha) |
|---|---|---|---|---|---|
| Risk Neutral | 79 | 1929.45 | 418.47 | 1929.45 | 8.45 |
| Risk Averse | 74 | 1928.93 | 416.03 | 1839.20 | 8.42 |
| **N-Tax of 10%** | | | | | |
| Risk Neutral | 75 | 1919.86 | 416.80 | 1919.86 | 8.43 |
| Risk Averse | 70 | 1919.33 | 414.28 | 1829.91 | 8.40 |
| **N-Tax of 20%** | | | | | |
| Risk Neutral | 71 | 1910.76 | 415.17 | 1910.76 | 8.41 |
| Risk Averse | 66 | 1910.21 | 412.58 | 1821.1 | 8.38 |
| **N-Tax of 30%** | | | | | |
| Risk Neutral | 68 | 1902.09 | 413.58 | 1902.09 | 8.39 |
| Risk Averse | 63 | 1901.53 | 410.93 | 1812.73 | 8.36 |

An increasing nitrogen tax, ceteris paribus, decreases nitrogen use, maize yields and profits irrespectively of farmers' risk attitudes. A 10%, 20% and 30 % nitrogen tax would reduce the nitrogen use of a risk neutral farmer by about 5.01%, 9.65% and 13.95%, respectively. For a risk-averse farmer, the effect of a nitrogen tax on nitrogen application levels is – though slightly – higher: For instance, a nitrogen tax of 30% reduces the nitrogen use of the risk-averse farmer by about 14.35%. This higher relative reduction of the applied nitrogen amount is reached with lower costs: While for the risk neutral farmer the 30% nitrogen tax induces a reduction of certainty equivalents (or profits) is 27.36 CHF, the risk-averse farmers' reduction of certainty equivalents is slightly lower, 26.47 CHF[8]. Note that the total financial welfare effects, taking into account farmers utility reduction and the revenue from the nitrogen tax, are negative. These welfare losses are higher (in absolute terms) for increasing level of the nitrogen

[7] In particular, the here assumed soil organic matter content, which follows Dubois et al. (1999), probably over-estimates average values for the Swiss Plateau region (Torriani et al., 2007).

[8] Also in relative terms (reduction from the initial wealth situation), the utility loss of risk averse decision makers is smaller.

tax and for increasing risk aversion. However, this loss of financial welfare is expected to be outweighed by reductions of external (non-financial) environmental effects of nitrogen application.

In summary, the analysis of farmers' decision making with regard to nitrogen use in Swiss grain maize production shows that a) risk averse farmer use less nitrogen fertilizer; b) the relative reduction of nitrogen use due to a nitrogen tax is larger for risk averse farmers; c) the nitrogen tax and the associated reduction of nitrogen application imply smaller abatement costs for risk-averse farmers. The latter results can be explained with a smaller value of marginal product (or a larger marginal risk premium, Ramaswami, 1992) of nitrogen for risk averse than for risk neutral farmers. However, under current yield and price risks, these differences between risk neutral and risk-averse decision makers are small.

This contrasts the results for increased price volatility, i.e. assuming an increase of the coefficient of variation of maize prices to increase from 0.13 to 0.26, which are presented in Table 4. It shows that an increase of price volatility leads to a sharp increase in the variability of profits, the coefficient of variation of profits for a risk neutral farmer increases from 0.22 in the initial situation to 0.40. This increase in the variability of returns has particular implications for the risk-averse farmers: The risk premium increases to about 314 CHF (about 19% in relative terms), and the differences between risk neutral and risk-averse decision makers with respect to nitrogen use, profits, and crop yields become much more pronounced. In contrast to the initial (current) situation, an increase of price volatility implies that risk considerations become much more relevant. For risk-averse farmers, the increase of price variability, ceteris paribus, leads to a decrease of nitrogen application of about 6 kg/ha (or 8% of the initially applied nitrogen amount).

Furthermore, the increased price variability leads to larger differences in the effects of the nitrogen tax between risk averse and risk neutral farmers. In particular, the relative reductions of nitrogen use for the risk-averse decision makers are getting larger, while the utility losses associated with the tax are getting smaller. For instance, the 30 % nitrogen tax would reduce the nitrogen use by 15.89%, reducing the CE by 25.31 CHF, compared to a reduction of nitrogen use of 14.35% and a CE reduction of 26.26 CHF in the initial situation.

**Table 4. Optimization Results for the Scenario of Increased Price Variability.**

| **Initial Situation** | N (kg/ha) | Profit (CHF/ha) | SD profit (CHF/ha) | CE (CHF/ha) | Yield (t/ha) |
|---|---|---|---|---|---|
| Risk Neutral | 79 | 1929.45 | 781.18 | 1929.45 | 8.45 |
| Risk Averse | 68 | 1926.72 | 773.97 | 1615.81 | 8.38 |
| **N-Tax of 10%** | | | | | |
| Risk Neutral | 75 | 1919.86 | 779.17 | 1919.86 | 8.43 |
| Risk Averse | 64 | 1916.88 | 771.29 | 1606.54 | 8.35 |
| **N-Tax of 20%** | | | | | |
| Risk Neutral | 71 | 1910.76 | 777.15 | 1910.76 | 8.41 |
| Risk Averse | 60 | 1907.54 | 768.64 | 1597.82 | 8.33 |
| **N-Tax of 30%** | | | | | |
| Risk Neutral | 68 | 1902.09 | 775.12 | 1902.09 | 8.39 |
| Risk Averse | 57 | 1898.65 | 766.01 | 1589.6 | 8.30 |

For the case of increased yield variability (Table 5), the results are, in general, similar to those for the increased price volatility. However, the effects of an expected 15% increase in yield variability due to climate change seem to be negligible compared to a sharp increase in price risks. Thus, agricultural

policy in Switzerland towards reductions of nitrogen applications should – in the medium-term perspective – especially take changes in price risks into account.

**Table 5. Optimization Results for the Scenario of Increased Yield Variability.**

| **Initial Situation** | N (kg/ha) | Profit (CHF/ha) | SD profit (CHF/ha) | CE (CHF/ha) | Yield (t/ha) |
|---|---|---|---|---|---|
| Risk Neutral | 79 | 1929.45 | 428.58 | 1929.45 | 8.45 |
| Risk Averse | 73 | 1928.85 | 425.79 | 1834.85 | 8.42 |
| **N-Tax of 10%** | | | | | |
| Risk Neutral | 75 | 1919.86 | 426.82 | 1919.86 | 8.43 |
| Risk Averse | 69 | 1919.25 | 423.96 | 1825.60 | 8.40 |
| **N-Tax of 20%** | | | | | |
| Risk Neutral | 71 | 1910.76 | 425.10 | 1910.76 | 8.41 |
| Risk Averse | 65 | 1910.13 | 422.18 | 1816.82 | 8.38 |
| **N-Tax of 30%** | | | | | |
| Risk Neutral | 68 | 1902.09 | 423.43 | 1902.09 | 8.39 |
| Risk Averse | 62 | 1901.45 | 420.45 | 1808.48 | 8.35 |

In summary, endogenous shocks in income risks (either due to increases yield or increases price variability) emphasize the findings for the initial situation: risk-averse farmers further reduce their nitrogen applications; a nitrogen tax leads to higher relative reductions of nitrogen application. Furthermore, endogenous shocks in income risks further reduce the abatement costs for risk-averse farmers. These effects can be explained by the fact that the higher price or yield volatility further reduces the value of marginal product (i.e. further increases the marginal risk premium) of nitrogen for risk-averse farmers.

## 4 Discussion

We find risk-averse farmers to use less nitrogen than their risk neutral counterparts, which is in agreement with other studies (e.g. Chowdhury and Lacewell, 1996, Isik, 2002). This result is based on the findings that nitrogen increases the yield variability, which is in agreement with other studies (e.g. Moschini and Hennessy, 2001). A different argumentation is used by Babcock (1992) and Babcock and Blackmer (1992), who show that in particular if soil available nutrients are unknown, applying more nitrogen than necessary can be a risk reducing strategy (following the decision rule “apply extra fertilizer just in case it is needed”, Babcock and Blackmer, 1992). In our model, soil organic matter content (i.e. available nutrients in the soil) is expected to be known by the farmer (such as proposed by Babcock and Blackmer, 1992), which weakens this argument for our analysis. Thus, our finding that risk averse farmers use less nitrogen is not in contrast to the results of Babcock (1992) and Babcock and Blackmer (1992).

More general, we assumed in our analysis that farmers are aware of expected levels of maize yield and yield variability as well as of the effect of nitrogen application on these variables. In order to validate these assumptions, further research should investigate farmers’ decision making processes with regard to fertilizer use.

The here presented analysis of relationships between maize yield and the amount of nitrogen application is based on generated data with the crop simulation model CropSyst. The here presented analysis is

restricted on the employed model- and soil-specifications. We are aware that more site specific modelling approaches are needed to account for the spatial heterogeneity of soil conditions in Switzerland, especially regarding soil fertility (BLW, 2000). Thus, further bio-economic assessment of nitrogen response functions and nitrogen taxation should be considered in a spatially explicit modelling approach.

We restricted the here presented analysis on a single agricultural activity, grain maize production, in order to clearly illustrate the effects of risk aversion and nitrogen taxes on nitrogen use. If more on- and off-farm activities would be taken into account, the introduction of risk aversion might also imply shifts towards less risky activities (e.g. Weersink et al., 1998)[9]. Moreover, also the introduction of a nitrogen tax can imply, besides reductions of fertilizer use for specific crops, adjustments in the optimal whole farm program. Thus, the biophysical spatial explicit modelling of whole farm programs, taking risk considerations and other adjustment strategies towards increasing risks and fertilizer prices (e.g. tillage intensities, fertilizer application techniques and site specific farming practices) into account, is necessary for scientifically based policy recommendations on optimal taxation of nitrogen fertilizer.

## 5 Summary and Conclusion

Using the example of Swiss grain maize production, our results show that risk-averse farmers use less nitrogen fertilizer than risk neutral decision makers. This results is based on the empirical finding that nitrogen increases yield variability and thus the value of marginal product of nitrogen is smaller (more specifically, the marginal risk premium of nitrogen is larger) for risk averse than for risk neutral farmers. Analysing optimal nitrogen allocation assuming endogenous shocks in income risks (either due to increases in yield or price variability) shows that risk-averse farmers reduce their nitrogen application further – leading to increasing differences between risk neutral and risk-averse decision makers.

Analysing the effects of nitrogen taxes, we find that a smaller tax is required to reach desired reductions of nitrogen applications for risk-averse farmers than for risk neutral agents. Moreover, the abatement costs of nitrogen reduction are smaller for risk-averse farmers. Because a high heterogeneity with regard to risk preferences among farmers within a country can be expected (e.g. Rosenzweig and Binswanger, 1993), nitrogen taxes will thus have heterogeneous effects. Moreover, spatial heterogeneity of soil fertility will further increase the heterogeneity of nitrogen tax effects. Sheriff (2005) shows that this heterogeneity can be a particular argument for a uniform nitrogen tax because reductions of nitrogen use due to the tax will be allocated across farms in a cost efficient way: For instance, those farmers that have the smallest abatement costs (e.g. due to high risk-aversion) will reduce their nitrogen applications more than those farmers that face high abatement costs. Our findings also imply that ex-ante assessments of the effects of a nitrogen tax that are based on profit-maximizing behaviour might under-estimate the nitrogen reduction and over-estimate the total abatement costs due to a tax on the national level. This ‘sorting effect’ of nitrogen reductions according to marginal costs based on heterogeneous risk preferences is furthermore an argument against a uniform nitrogen use restriction, which is currently applied in Switzerland via cross-compliance obligations (El Benni and Lehmann, 2010). Given a heterogeneous distribution of risk preferences (and marginal nitrogen abatement costs), input use restrictions might imply higher costs to reach a specific nitrogen reduction goal (Sheriff, 2005). More general, the here presented analysis underlines that farmers risk preferences should be considered in agricultural policy making processes (see e.g. Goetz et al., 2005).

[9] Also the consideration of different levels of initial wealth, reflecting the heterogeneity of the farm population, would change the here presented results but is omitted to ensure clarity of the presentation.

The analysis of endogenous shocks in income risks due to increasing yield and price variability shows that the above described effects become more pronounced because differences in optimal input allocation between risk neutral and risk-averse farmers increase. Thus, agri-environmental policy in Switzerland has to take into account effects of further market liberalization on price volatility and its implications on nitrogen use in crop production[10]. In the long run, also effects of climate change on yield variability have to be taken into account.

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