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Journal Article

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Publication date:
2012-06

Permanent link:
https://doi.org/10.3929/ethz-b-000049202

Originally published in:
Agricultural Water Management 109, https://doi.org/10.1016/j.agwat.2012.03.002

Citation for the original published paper:

Finger, R. (2012). Modeling the sensitivity of agricultural water use to price variability and climate change - an application to Swiss maize production. Agricultural Water Management 109: 135–143. https://doi.org/10.1016/j.agwat.2012.03.002

Modeling the sensitivity of agricultural water use to price variability and climate change – an application to Swiss maize production

Abstract

We analyze the sensitivity of crop management under current and future climate scenarios to changes in economic boundary conditions. In particular, we focus on the effects of changing price risks. We combine a bio-economic modeling approach and a crop growth model CropSyst with an economic model that represents the decision making process of a risk-averse farmer. We apply the models to irrigated maize production in Switzerland. To analyze the sensitivity of optimal water and nitrogen use to likely future states of several economic variables, we conduct sensitivity analyses with respect to changes in price variability, the price-yield correlation, water and maize prices as well as farmers' risk preferences. Results show that climate change leads to a strong increase in optimal water use for irrigation, with consequent increases in maize yields. However, our analysis also reveals that the consideration of economic drivers for farmers' irrigation decisions is indispensable. Strong effects on optimal water use are found for changes in crop (positive) and water (negative) prices. We also find strong implications of risk aversion and price variability on irrigation decisions. A doubling of price variability, which would represent a shift from the current Swiss situation to price variability levels in its neighboring countries, could reduce optimal water use by up to 40%. We conclude that investigations of water demand should consider, beyond expectations on output and input price levels, also the variability of prices.

Keywords

Irrigation, nitrogen, price risk, production risk, Switzerland

1 Introduction

Increasing competition for water resources is becoming a major challenge for food production, populations, societies and the environment (Pereira et al., 2002, IWMI, 2007, De Fraiture and Wichelns, 2010, Gordon et al., 2010). Climate change is expected to increase the pressure on water resources, either by directly shifting hydrologic cycles and the spatial and temporal availability of water for irrigation due to changes in precipitation patterns, or by increasing agricultural water demand due to temperature increases and higher frequencies of drought events (Bates et al., 2008). The relationship between climate, climate change, and agricultural water use has received particular attention in several empirical studies (e.g. De Silva et al., 2007, De Fraiture and Wichelns, 2010, Guo et al., 2010). Beyond climatic conditions, also economic considerations influence farmers' irrigation decisions and thus agricultural water use. Theoretical and empirical investigations have addressed the relationship between output, inputs, and especially water prices and the adoption of irrigation and the amount of water used (Scheierling et al., 2006, Molle and Berkoff, 2007, Brooks and Harris, 2008, Mullen et al., 2009). Furthermore, the variability of these variables is important for irrigation decisions. Agricultural production is risky; i.e., returns are not certain, but fluctuate over time. These risks, arising from volatile yields and prices, affect farmers' decisions regarding crops and technology, and input use (e.g. Hardaker et al., 1997). Similar to insurance, irrigation is an instrument to cope with production risks because irrigation makes crop production less dependent on natural rainfall patterns and thus reduces yield variability (Lin et al., 2008). Due to this relationship, the effects of production risks, irrigation technology adoption, and water demand have received particular attention in the agricultural water use literature (e.g. Harris and Mapp, 1988, Gómez-Limón and Berbel, 2000, Carey and Zilberman, 2002, Garrido et al., 2006, Gil et al., 2011, Grove and

Ossthuizen, 2010, Lavee 2010). In contrast, the influence of output price variability on agricultural water demand has received inadequate attention. Nevertheless, price variability is highly relevant for optimal water use, as farmers face uncertainty about output prices when the irrigation capacity is determined either before or early in the growing season, and also during the irrigation season (i.e. before the harvest is sold). Thus, water application can be viewed as a short-term investment that is subject to uncertain rates of return.

We present a bio-economic modeling approach that combines a biophysical model (representing the complexity of the relationships between weather, environmental conditions, crop management and plant growth) with an economic model that represents farmers' decision making with respect to crop management and irrigation. In particular, the economic model aims to look beyond average profits and thus integrates the role of production and price risks. We use the model to investigate management and irrigation decisions in maize production at the Swiss Plateau under current and future climate scenarios. The importance of irrigation is currently highly heterogeneous across European countries, in particular representing a South (high importance) to North (low importance) gradient. In Switzerland, the share of irrigated arable land is currently at about 6% (Berbel et al., 2007). However, the importance of irrigation in crop production is increasing and an intensification of this trend is expected in the next decades due to climate change (Weber and Schild, 2007, Fuhrer and Jasper, 2009). Our goal is to contribute to the quantitative analysis of the drivers of agricultural water demand by providing an analysis of water demand in maize production under current and future climate scenarios. Furthermore, we conduct a large set of sensitivity analyses with respect to price variability, price-yield correlations, water and maize prices, and farmers' risk preferences. In these sensitivity analyses we investigate likely future states of the economic boundary conditions of crop production.

2 Data and Methodology

Our bio-economic model links the process–based crop growth model CropSyst with an economic decision-making model that represents a risk-averse farmer. More specifically, CropSyst is used to simulate maize yield responses with respect to nitrogen use and irrigation intensities under different climate regimes. In order to implement information from CropSyst simulations in the economic model, we estimate production and yield variation functions that statistically describe the responses of mean yields and standard deviations to input use. Finally, the economic model that contains information on crop yield relationships, price and cost levels, and on farmers' risk preferences is used to show which levels of input use are optimal (i.e. utility maximizing) for the farmer.

2.1 Economic Decision-Making Model

A farmer's decision making process with regard to water and nitrogen use is represented using a non-linear certainty equivalent (CE) maximization approach. The CE denotes the non-random level of payoff which is rated by the farmer as equivalent in terms of utility to an uncertain (i.e. random) level of payoff. For the risk-averse decision maker, the CE is defined as the difference between the expected profit and the risk premium (RP), which is the amount of money the farmer is willing to pay to eliminate risk exposure:

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

The expected (i.e. mean) profit is defined as revenue minus fixed and variable costs. Fixed costs consist of costs for seeds, plant protection, insurance, machinery costs, costs for other inputs than water and nitrogen as well as of fixed costs of the sprinkler irrigation system. Variable costs comprise water and nitrogen costs and the cleaning and drying costs. Thus, the expected profit is defined as:

(2) $$E(\pi) = Y(N,W)p_M - C_F - Np_N - W_{P_W} - Y(N,W)p_D$$

Where $E(\pi)$ is the expected profit, $Y(N,W)$ maize yield, p_M the maize price, and C_F the fixed costs. Furthermore, N and W denote the amounts of water and nitrogen used, p_N and p_W are the prices for nitrogen and water, respectively, and p_D are the costs for cleaning and drying. The profit maximization framework is extended by assuming that profits are stochastic, due to the variability of maize yields and due to the variability of crop prices. The calculation of the variability of profits also needs to account for the correlation between crop yield and crop prices. This is motivated by the observation that low crop yields at the farm level often correlate with smaller aggregate supply and thus lead to higher crop prices (e.g. McKinnon, 1967). The resulting negative correlations between yields and prices reduce revenue variability and are thus important for farmers' decisions under yield and price risk. Following Bhornsted and Goldberger (1969), the variance of profit (σ_π^2) is defined as:

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

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. σ_{P_M} and σ_Y denote the standard deviation of maize price and maize yield, respectively. The risk premium is now defined as follows:

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

γ is the coefficient of relative risk aversion, representing the degree of risk aversion of the farmer. Risk averse behavior implies $\gamma > 0$ and a risk neutral farmer is represented by $\gamma = 0$. The relative risk premium presented in equation (4) assumes constant relative risk aversion, which implies decreasing absolute risk aversion (i.e. risk aversion decreases with increasing wealth). To derive optimal water and nitrogen allocation in this model, the certainty equivalent is maximized with respect to nitrogen and water use:

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

2.2 Production and Yield Variability Functions

2.2.1 Functional Forms

To represent the relationship between crop management and yield levels as well as yield variability, we follow Finger et al. (2011) and use non-linear Just and Pope (1978, 1979) production functions that allow inputs to influence both the mean but also the variability of crop yields:

(6) $$Yield = Y(N, W) + \sigma_{Y}(N, W)\varepsilon$$

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 (following Finger and Hediger, 2008):

$$Y(N, W) = \alpha_0 + \alpha_1 N^{0.5} + \alpha_2 N + \alpha_3 W^{0.5} + \alpha_4 W + \alpha_5 (NW)^{0.5} \tag{7}$$

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):

$$\sigma_Y(N, W) = |\hat{w}| = \beta_0 + \beta_1 N^{0.5} + \beta_2 W^{0.5} \tag{8}$$

To reduce the potential influence of outliers on the regression analyses, the production and the yield variability functions are estimated using the robust regression MM-estimator; see e.g. Finger (2010) for descriptions.

The production and yield variation function are estimated for each climate scenario independently. However, to test if these changes due to climate change are significant, both datasets are merged and dummy variables for the climate change scenario are included in the above described regressions. If the dummy variable is significant for a specific variable, this indicates significant differences of coefficients between current and future climatic conditions.

2.2.2 Data Generation

We apply the deterministic crop yield simulation model CropSyst for the eastern Swiss Plateau region to simulate maize yields for different levels of water nitrogen application. CropSyst models above- and below-ground processes such as the soil water budget, soil-plant nitrogen budget, crop phenology, canopy and root growth, and crop yield (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. These inputs are used to compute biomass accumulation and phenology at a daily time step. More specifically, we calculate biomass accumulation as the minimum of either an increment proportional to daily transpiration or an increment related to intercepted solar radiation. Phenological development is described in terms of accumulated thermal units or growing degree days (GDD) (Torriani et al., 2007a). Plant processes represented in the model are affected, for instance, by water stress and nutrient deficits. Thus, a plant's responses to crop management regarding fertilizer application and irrigation can be reflected with CropSyst. Especially relevant for this study, this model has been successfully applied to simulate the effects of irrigation on these processes (e.g. Benli et al., 2007, Torriani et al., 2007a). CropSyst model calibration, validation as well as parameters assumed for Swiss maize production are presented in Torriani et al. (2007a).

In our analysis, we employ CropSyst to simulate quasi-experiments under different climate regimes. In these experimental settings, crop yield responses to changing levels of nitrogen application and irrigation intensity are analyzed. To represent weather risk in crop yield simulation, we use different sets of daily weather data. More specifically, we use data from six meteorological stations on 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 amounts of fertilizer and irrigation water are varied randomly. The (randomly) applied nitrogen amount ranges from 0 to 320 kg ha^{-1}. Irrigation amounts are triggered by randomly choosing the intervention point (see Vico and Porporato, 2011), which represents a specific degree of soil moisture (ranging from 0, permanent wilting point, to 1, field capacity). When soil moisture falls below this intervention point, water is added in the model to shift the degree of soil moisture to 1. Irrigation is assumed to be uniformly applied over the field and the maximum application amount of irrigation water for a single irrigation event is set to 20 mm. To mimic the water use efficiency of a sprinkler irrigation system, we assume that 25% of the applied water is not usable for the plant. For each simulation (i.e. randomly chosen combination of N, W and weather), identical starting conditions regarding soil composition and soil available nutrients are used. We assume a soil texture that is characterized by 38% clay, 36% silt, and 26% sand.

The same data generation procedure is applied to derive maize observations under an exemplary climate change scenario. Our climate change scenario for Switzerland is taken from Frei (2005) and represents the period around the year 2050. These climate projections are based on simulations with two CO2 emission scenarios, four global climate models, and eight regional climate models. These simulations with a sum of 16 scenario-model combinations on a grid of 50x50 km were performed over the whole European continent within the scope of the PRUDENCE project (Christensen and Christensen, 2007). The climate projection used in this study represents the median of these ensemble simulations, and assumes temperature increases of 1.8°C and 2.7°C as well as reductions of precipitation by about 1% and 17% in spring and summer, respectively (see Table 1 for a summary).

< Table 1: Characteristics of the climate change scenario: Seasonal anomalies of temperature and precipitation >

The information on changes in climatic conditions was processed (downscaled) to the considered meteorological stations by using the weather generator LARS-WG (Semenov et al., 1998). Detailed descriptions of the downscaling approach and the weather generator are beyond the scope of this paper, but are presented in Finger et al. (2010) and Finger and Calanca (2011). In order to consider the most simple (and free of costs) adaptation option, we follow Torriani et al. (2007a) and assume a 6 day earlier sowing for the climate change scenario. The above described simulations lead to 912 yield observations for each climate scenario.

2.3 Calculations and Sensitivity Analyses

2.3.1 Cost, Price and Benefit Data

Our framework requires information on benefits, prices, risk aversion and costs. Regarding the latter, we consider fixed costs (ownership costs), that are not dependent on the level of maize yield and input used, as well as variable costs (operating costs) that are dependent on the produced level of output and the level of inputs used. More specifically, the costs for nitrogen and water as well as for cleaning and drying are assumed to be variable. Variable costs for irrigation are taken from Spörri (2011) and comprise electricity and water costs. Costs for cleaning and drying are taken from Torriani et al. (2007b), and nitrogen costs are taken from Swiss agricultural profit margin calculations (AGRIDEA and FiBL, 2009). The latter publication, presents crop-specific average price and cost levels in Swiss agriculture and is also used to specify prices, direct payments and fixed costs (including costs for seeds, plant protection, insurance, machinery costs and fertilizer costs, except for nitrogen). Fixed costs for the sprinkler irrigation system are based on a survey of irrigation projects in the Swiss Plateau region conducted by Spörri (2011). These fixed costs comprise costs for the pump, raingun, pipes, hoses, electricity connection as well as licensing costs for the water withdrawal. Price and cost levels used in our analysis represent values for the year 2008. Our analysis is based on Swiss Francs (CHF), for which the current exchange rate to US Dollars is about 1.10. All assumptions regarding costs, benefits and prices are summarized in Table 2.

The optimization presented in Equation 5 is conducted for a risk averse farmer, assuming a moderate level of relative risk aversion, $\gamma = 2$. Following Finger (2012), the variability of prices is estimated using data for 1991-2006 taken from FAO (2010). Using these data, autoregressive AR(1) models are estimated to account for the dependency structure (autocorrelation) between the price observations. We find that the coefficient of variation (CV) of Swiss maize prices is equal to 0.13. For the neighboring countries France and Germany, however, much larger CVs of 0.23 and 0.24 are found using the same approach (see Finger, 2012, for details). Price variability observed in Switzerland is much smaller than in Germany and France because trade regulations are used to larger extent to control national price levels. To estimate the price-yield correlation, we use de-trended annual national data for maize prices and yields taken from FAO (2010), leading to $corr(Y, P_M) = -0.25$. Using farm-level price and yield data from 158 farms for the period 2002-2008 (taken from Lehmann, 2010), we find a similar value for the price-yield correlation (-0.24). Thus the national level estimate is a valid assumption for farm level analysis in this specific case. More detailed descriptions of the here used approaches are presented in Finger (2012).

< Table 2. Specification of Costs and Benefits (Base Year: 2008).>

2.3.2 Sensitivity Analyses

Our goal is to investigate the sensitivity of irrigated maize production under current and future climatic conditions to expected changes in the economic boundary conditions. To this end, we conduct sensitivity analyses with respect to changes in price variability, the price-yield correlation, water and maize prices, and farmers' risk preferences. This specific set of variables has been selected for sensitivity analyses because changes in these variables are expected in the near future. Increasing price volatility may be caused by a reduction of trade barriers or by an integration of Swiss agriculture in the market of the European Union. Such an opening up of markets is also expected to reduce output price levels and to cause changes in the correlation between yields and prices. The latter is motivated by the assumption that going from the small closed country case to large open markets will reduce the marginal effect of a specific production region on price levels, and negative price-yield correlations are thus expected to disappear (Filler et al., 2010). Furthermore, variable water prices in Switzerland are currently either not charged at all or very small (about 0.02 CHF/ m^3). Thus, electricity costs are currently the most important source of variable cost in irrigation. However, increasing water prices are a frequently recommended policy measure to tackle new challenges in water demand.

Based on this background, we first analyze the sensitivity of optimal water use with respect to changes in the price variability (i.e. the CV of the maize price) as well as with respect to changes in price-yield correlations. The price CV is analyzed in a range from 0.13 to 0.27 in steps of 0.02. Thus, the analyzed levels of price variability range from the current Swiss level to the levels observed in the neighboring European countries. In addition, price-yield correlation is varied in the range of -0.25 to 0 in steps of 0.05. Finally, all possible combinations from these two variables are analyzed. All sensitivity analyses are conducted with respect to optimal (i.e. certainty equivalent maximizing) levels of nitrogen and water use, yield levels and yield variability (expressed as the standard deviation of maize yields). The results of these sensitivity analyses, i.e. the certainty equivalent maximizing input and output levels, are presented using contour plots.

Second, we conduct additional sensitivity analyses to show the influence of changes in water prices, maize prices as well as of the coefficient of risk aversion on optimal levels of water and nitrogen use, mean and variability of maize yields and profits. The effects of changing water prices (including pumping, i.e. electricity, costs) is investigated in a range from 0.7 CHF/mm to 2.2 CHF/mm (i.e. 0.07 - 0.22 CHF/m^3) in steps of 0.3 CHF/mm. To investigate the influence of changing output prices, the maize price is varied from 300 to 400 CHF/t in steps of 20 CHF/t. Finally, to investigate the role of farmers' risk preferences on irrigation decisions, the coefficient of risk aversion is varied from 0 to 4, in steps of 0.5. $\gamma = 0$ represents a risk-neutral decision maker, while $\gamma = 4$ indicates strong risk aversion of the farmer. In the sensitivity analyses with respect to water and maize prices as well as with respect to risk aversion, all other variables are kept constant at their initial values.

3 Results

By estimating production functions (Equation 6) for current and future climate, we find that both inputs nitrogen and water increase maize yields, however, with a saturating effect (Table 3). In addition, we find that there is a significant interaction between both inputs, i.e. applying additional amounts of both inputs jointly leads to higher yield increases than the separated increase of a single production factor. Estimating yield variation functions (Equation 7) we find ambiguous effects of input use: while nitrogen tends to increase yield variability, the use of water reduces yield variability and thus reduces production risks (Table 3).

By comparing production function estimates for current and future climate, we find that yield levels increase significantly due to climate change, i.e. the regression intercept of the production function increased from 6.62 t/ha to 7.03 t/ha. Furthermore, we find that climate change also increases, though not significantly, yield variability, i.e. the intercept yield variability increased from 0.42 t/ha to 0.44 t/ha.

The coefficient estimates that are presented in Table 3 are introduced in the economic certainty equivalent maximization problem (Equation 5) in a subsequent step.

< **Table 3. Coefficient Estimates of Equations 7 and 8.** >

The results of the sensitivity analysis with regard to different levels of maize price coefficients of variation as well as price-yield correlations for the BASE scenario are presented in Figure 1. Optimal levels of nitrogen use, water use, yields and yield standard deviation (SD) are presented as contour plots (numerical results are available upon request from the authors). The initial situation of price variability and price-yield correlation is indicated by a point in the graphs.

< Figure 1. Contour plots of results from sensitivity analyses with respect to price variability and price-yield correlations under current climate. >

Our results show that optimal nitrogen use decreases with increasing price variability (upper left plot in Figure 1). From initially about 88 kg/ha for current price variability (CV=0.13), optimal nitrogen levels decrease to about 74 kg/ha for a price coefficient of variation of 0.27. With increasing price variability, the return from nitrogen application (i.e. the additional revenue due to increased yield) becomes more uncertain, which causes a lower ‘investment’ in nitrogen as optimal response for a risk-averse farmer. This effect is stronger for higher levels of price variability, i.e. the lines in the contour (changes in optimal N levels) are closer to each other for high maize price coefficients of variation. A similar effect is found for the optimal use of water for irrigation (upper right plot in Figure 1): more uncertain returns caused by higher price variability reduce the optimal water application from 72 mm to about 44 mm (i.e. by more than 35%).

We find ambiguous effects of decreasing price-yield correlations on input use. For the risk increasing input nitrogen smaller price-yield correlations decrease incentives for application, while the opposite was found for the risk decreasing input water. If the revenue variability reducing (i.e. insurance-like) effect of negative price-yield correlations disappears, farmers’ react with a higher demand for the risk-reducing effect of irrigation. However, the effect of decreasing price-yield correlations on input use is much smaller than the effects of increasing price variability. For instance, optimal nitrogen use is only reduced by about 2-3 kg/ha if the correlation is set to 0 instead of -0.25.

Because both inputs are reduced for increasing price variability, yield levels consequently decrease (bottom left plot of Figure 1). Yield decreases of 0.2 t/ha are indicated if the price CV increases from 0.13 to 0.27. Again, the effect of changes in price-yield correlations is negligible compared to changes in price variability. A different pattern is found for yield variability (bottom right plot of Figure 1). Increasing price variability reduces both the risk increasing (nitrogen) and risk decreasing (water) inputs and the final influence on yield variability is thus small. In contrast, smaller price-yield correlations cause farmers to increase optimal water use but decrease nitrogen use. As a result of this change in input use, yield variability is observed to be smaller if price-yield correlations approach zero.

< Figure 2. Contour plots of results from sensitivity analyses with respect to price variability and price-yield correlations under future climate. >

Conducting the sensitivity analysis for the climate change scenario we find, in principal, the same effects described for the BASE scenario. However, optimal levels of input use are much higher in the climate change scenario. For instance, optimal nitrogen use (for the initial situation of price variability and price-yield correlation) increases from 88 kg/ha to about 109 kg/ha (upper left panel of Figure 2). This more intensive production is only possible due to the sharp increase in water use from 72 mm to 166 mm. While the effects of changes in price-yield correlations remain small, the absolute effects of increasing price variability are much higher for the climate change scenario (Figure 2): shifting maize price variability from CV=0.13 to CV=0.27 causes farmers to reduce nitrogen use to 88 kg/ha (-21 kg/ha) and to reduce water use to about 95 mm (-43%). Also because both inputs are used more intensively for the climate change scenario, maize yields are higher for this scenario (about 10.13 t/ha). Even though climate change increases (all else equal) yield variability, the higher level of optimal water use leads to lower levels of yield variability than in the BASE scenario. Thus, farmers' adaptation response to climate change can over-compensate negative effects of climate change on yield risk.

< **Figure 3. Results from sensitivity analyses with respect to water prices, maize prices and risk aversion.** >

Investigating the sensitivity analyses of optimal water use with regard to water prices, we find that water use decreases rapidly and more than proportionally if the water price increases (left panel of Figure 3). More specifically, if the water price increases from 0.7 CHF/mm to 2.2 CHF/mm, optimal water use decreases from 72 mm to 11 mm under current climatic conditions (solid line), and from 166 mm to 21 mm under future climatic conditions (dashed line). Because nitrogen and water are not independent, an increase of the water price also reduces the farmer's optimal level of nitrogen application. Consequently, increasing water prices lead to a less intensive production system that is characterized by lower maize yields. Because farmers reduce the application of water sharply for higher water prices, this causes yield variability to increase. The sensitivity responses presented in the left panel of Figure 3 clearly illustrate the nonlinearities underlying the system of climate, plants and farmers' management decisions.

Furthermore, we find that higher output prices increase input use (middle panel of Figure 3): farmers' optimal nitrogen use increases from about 70 to 96 kg/ha for the BASE scenario, and from 83 to 121 kg/ha for the climate change scenario, if the maize price increases from 300 to 400 CHF/t. These responses are found to be even stronger for the optimal amount of water application, which more than doubles for this maize price increase. The results also indicate a stronger response of water demand (in terms of water quantity) to crop prices than to water prices, which is in line with the findings of other studies (e.g. Mullen et al., 2009). Because higher maize prices cause farmers to use more inputs, they also result in higher yield levels. The effect of maize price changes on yield variability is ambiguous: for the BASE scenario no change of yield variability was found, while the sharp increase of optimal water use causes lower yield variability for the climate change scenario. Comparing the BASE and the climate change scenario, we find that input use and maize yields are higher and yield variability is lower under climate change conditions.

An additional sensitivity analysis addresses the effects of changes in the coefficient of risk aversion (right panel of Figure 3). Because nitrogen is a risk increasing input, nitrogen use decreases with increasing risk aversion. Comparing, for instance, a risk neutral ($\gamma = 0$) with a highly risk averse ($\gamma = 4$) farmer, it shows that optimal nitrogen use decreases from 93 to 83 kg/ha for the BASE scenario, and from 116to 102 kg/ha for the climate change scenario. In contrast to nitrogen, water is a risk reducing input. Intuitively, risk-averse farmers are thus expected to use more irrigation water to ensure stable yields and returns. However, both inputs are not independent from each other, i.e. high yield levels require high application rates of both inputs so that none of them is a yield-limiting production factor. Through this link, higher risk aversion leads surprisingly also to slight reductions in optimal levels of irrigation.

< **Figure 4. Influence of changes in water prices, maize prices and risk aversion on profits.**>

Finally, we investigate the influence of changes in water and maize prices, and in the degree of risk aversion on the expected profits of the farmer. We find that higher water prices decrease, but higher maize prices increase farmers' profits (left and middle panel of Figure 4). However, the expected decreases in farmers' profits due to higher water prices are much smaller than those found in other studies addressing crop production in arid environments where rainfed production is difficult (cp. e.g. Berbel and Gómez-Limón, 1999). Risk aversion, however, has not been found to have a significant influence on farmers' profits. But, profits tend to decrease slightly with increasing risk aversion because risk-averse farmers are willing to accept profit reductions in order to reduce the variability of profits. Furthermore, we find that climate change leads to a higher level of profits particularly caused by higher yield levels (Figure 4).

4 Discussion

Using the example of Swiss maize production, we present a methodological framework how interactions of climate, plants, and farmers' nitrogen use and irrigation decisions can be investigated in an integrative modeling approach. In particular, we examine the influence of risks that arise from yield and price volatility on farmers' decision making process with respect to input use. Further research should apply this approach on a larger scale of management decisions, i.e. farm-level, instead of crop specific management and irrigation decisions should be investigated. Our analysis is limited to specific soil, weather and crop characteristics. To also investigate the influence of climate change and farmers' adaptation responses on a larger spatial scale, a wider set of these characteristics should be applied, preferably in a spatially explicit modeling approach. This should also include the application of a wider set of climate change scenarios. The use of alternative risk management instruments such as insurance and forward contracts will influence the risk level faced by farmers and thus may also influence crop management and irrigation decisions (e.g. Lin et al., 2008). Therefore, alternative risk management strategies and their interdependencies with irrigation decisions should be considered.

We linked the biophysical model CropSyst with the economic model by using production and yield variation functions following the approach proposed by Just and Pope (1978, 1979). However, the estimation of coefficients and the assumption of specific (though flexible) functional forms is a source of errors for the subsequent analysis. Even though these aspects have been considered by using robust regression for coefficient estimation (Finger, 2010) and by selecting a functional form that implies low misspecification potentials (Finger and Hediger, 2008), we are aware that this estimation step might be avoided. More specifically, we think that the application of genetic algorithms (Musshoff and Hirschhauer, 2009), which avoid the estimation of coefficients, is promising.

The certainty equivalent maximization approach used in our analysis was restricted to symmetric distributions, i.e. nitrogen use and irrigation were expected to influence mean and variability of crop yields. The effect on crop yield skewness was not considered. In the agricultural economics literature, the issue of crop yield skewness (and normal distributions) remains ambiguous (Just and Weninger, 1999). However, we expect that irrigation affects crop yield skewness because irrigation will reduce the occurrence of very low yield events (i.e. negative skewness). If skewness is taken into account, it can have important effects on the decision making process under risk (Finger and Calanca, 2011). Thus, the certainty equivalent maximization approach should be expanded by implementing skewness effects in further research.

The irrigation decisions considered in our analysis were focused on the choice of the quantity of irrigation water applied in a sprinkler irrigation system. This was not considered to be a tactical (i.e. within season) decision, but rather designed as a strategic setting of specific capacities (i.e. representing on average decisions). In further research, this approach should also include farmers' choice regarding irrigation technology. Thus, it should be investigated if changes in price variability, input and output prices or changes in climatic conditions can induce switches to alternative irrigation techniques. In addition, alternative measures to reduce water requirements such as reduced tillage, the use of varieties with lower water demands or the switch to alternative crops should be considered in further research.

5 Conclusion

The consideration of farmers' responses to climatic but especially to economic incentives is indispensable if agricultural water use is analyzed. In particular, farmers' preferences regarding production and price risks should be considered when modeling irrigation decisions. We find that water use for irrigation will be much more important in Swiss maize production with changes in climate. However, sensitivity analyses reveal also a large influence of maize price variability, maize price levels, and water prices on optimal crop management. We find that increasing water prices sharply reduce optimal water and nitrogen use of farmers, thus leading to less intensive maize production. Because high yield levels in Swiss maize production can also be attained in rainfed production, no sharp decreases of farmers' profits are expected if farmers use less water due to higher water prices.

We find that higher maize prices cause farmers to increase optimal levels of input use, and thus consequently lead to higher yields. Our results also show that if maize price variability, which is currently at low levels in Switzerland, approaches currently observed levels in other European countries, a sharp decrease of optimal water use can be expected. Higher uncertainty concerning output prices reduces farmers' incentives to make short-term investments in agricultural inputs such as water. Thus, analyses of future water demand and the analysis of potential policy instruments to reduce agricultural water use should consider not only expectations on output and input price levels, but also price variability.

Acknowledgements

This work was supported by the Swiss National Science Foundation in the framework of the National Centre of Competence in Research on Climate (NCCR Climate) and the National Research Programme 61. I thank the Swiss Federal Office of Meteorology for providing access to the meteorological database, Stéphanie Schmid for CropSyst data provision, two anonymous reviewers, and Nadja El Benni, Niklaus Lehmann and Liesbeth Dries for helpful comments on an earlier version of the manuscript.

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Table 1: Characteristics of the climate change scenario: Seasonal anomalies of temperature and precipitation

	DJF	MAM	JJA	SON
Temperature	+ 1.8	+ 1.8	+ 2.7	+ 2.1
Precipitation	1.08	0.99	0.83	0.94

Anomalies of temperature in °C (absolute value) and of precipitation in relative values with respect to the climate of the year 1990. DJF: December-February; MAM: March-May; JJA: June-August; SON: September-November. CO2 concentration ranging from 495-561 (compared to 339-379ppm in the base scenario) were randomly allocated

Source: Frei (2005)

Table 2. Specification of Costs and Benefits (Base Year: 2008).

Revenue	**Initial Conditions**	**Sensitivity Analyses**
Maize price	365 CHF/t	300 – 400 CHF/t in steps of 20 CHF/t
CV maize price	0.13	0.13-0.27 in steps of 0.02
Correlation of yield and price	-0.25	-0.25 – 0 in steps of 0.05
Direct Payment	1660 CHF/ha	---
Coefficient of relative risk aversion	2	0 - 4 in steps of 0.5
Fixed costs (ownership costs)		
Seed costs	268 (CHF/ha)	---
Plant Protection	228 (CHF/ha)	---
Hail Insurance	134 (CHF/ha)	---
Machinery costs	990 (CHF/ha)	---
Other fertilizer costs	193 (CHF/ha)	---
Sprinkler Irrigation	224.6 (CHF/ha)	---
Variable costs (operating costs)		
Fertilizer	1.25 CHF/kg N	---
Water	0.7 CHF/mm	0.7 - 2.2 in steps of 0.3
Cleaning and drying	107 CHF/ tons of Yield per ha	---

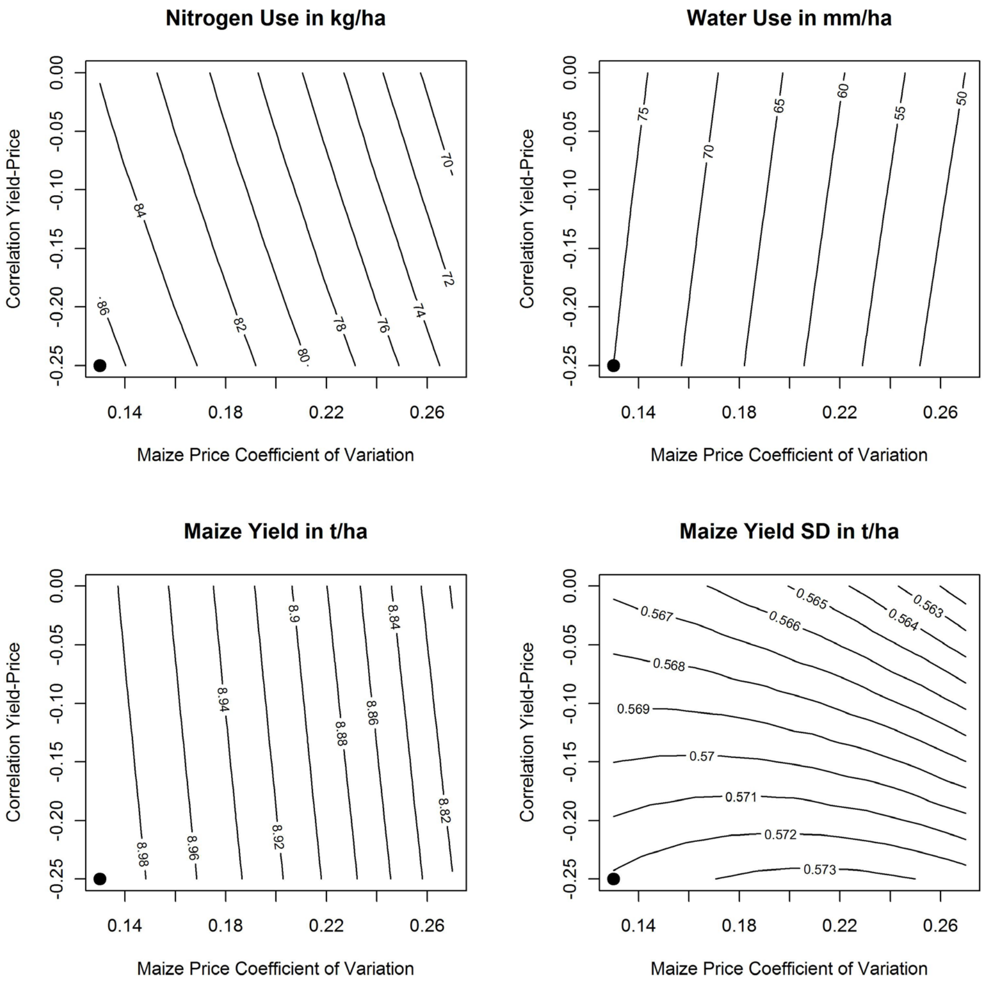
Sources: AGRIDEA and FiBL (2009), Torriani et al. (2007b), Spörri (2011). Note that the current exchange rate between Swiss Francs (CHF) and US Dollars is about 1.10 (Yahoo!Finance, accessed November 22, 2011).

Table 3. Coefficient Estimates of Equations 7 and 8.

	BASE (Current Climate)		2050 (Climate Change)	
Variable	Production Function	Yield Variation Function	Production Function	Yield Variation Function
Intercept	6.62 (153.95)***	0.42 (19.04)***	7.03 (139.31)***	0.44 (18.32)***
$N^{0.5}$	0.32 (14.69)***	0.03 (9.55)***	0.31 (12.49)***	0.03 (8.74)***
N	-0.01 (-8.42)***	---	-0.01 (-7.03)	---
$W^{0.5}$	0.05 (3.61)***	-0.01 (-4.33)***	0.07 (5.38)***	-0.02 (-6.59)***
W	-0.001 (-1.08)	---	-0.001 (-0.85)	---
$(NW)^{0.5}$	0.002 (1.99)**	---	0.003 (2.57)**	---
R^2	0.49	0.44	0.58	0.45
df	906	908	906	908

** and ***denote significance at the 5% and 1% level, respectively.

Figure 1. Contour plots of results from sensitivity analyses with respect to price variability and price-yield correlations under current climate.


Nitrogen Use in kg/ha

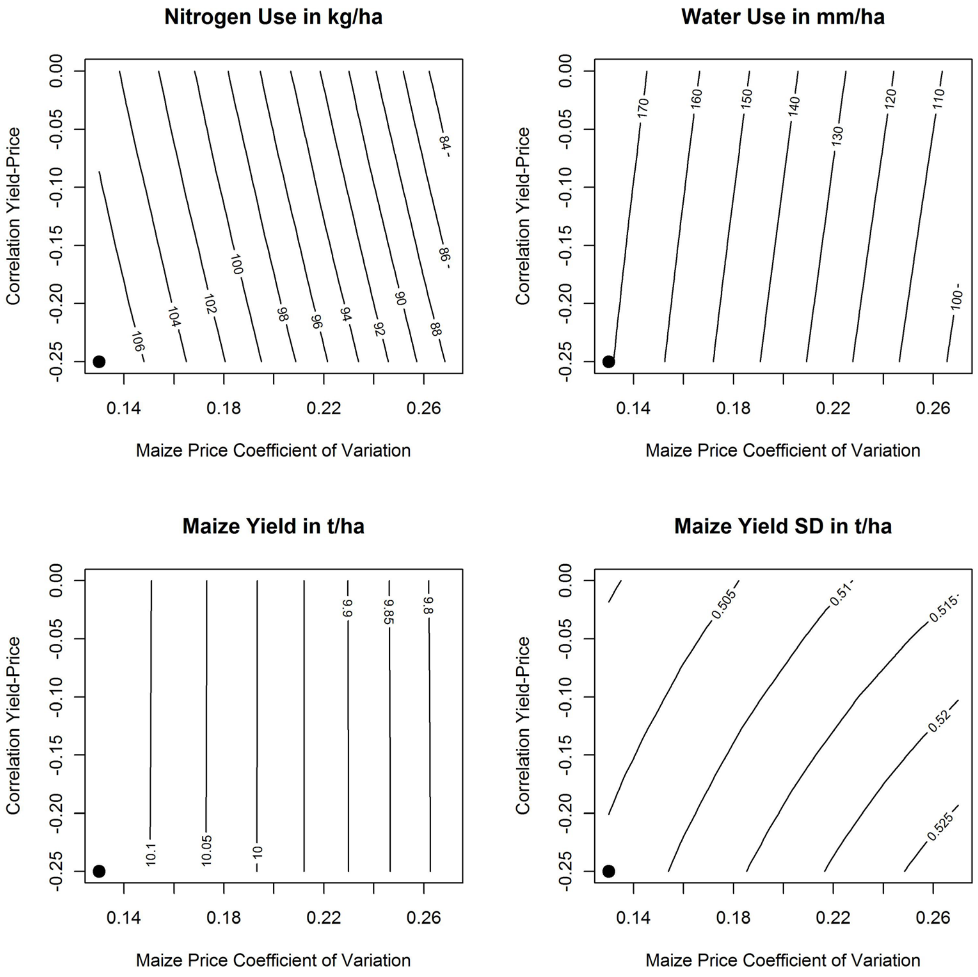
Water Use in mm/ha

Maize Yield in t/ha

Maize Yield SD in t/ha

The dot shows the position of the initial variable setting.

Figure 2. Contour plots of results from sensitivity analyses with respect to price variability and price-yield correlations under future climate.



The dot shows the position of the initial variable setting.

Figure 3. Results from sensitivity analyses with respect to water prices, maize prices and risk aversion.

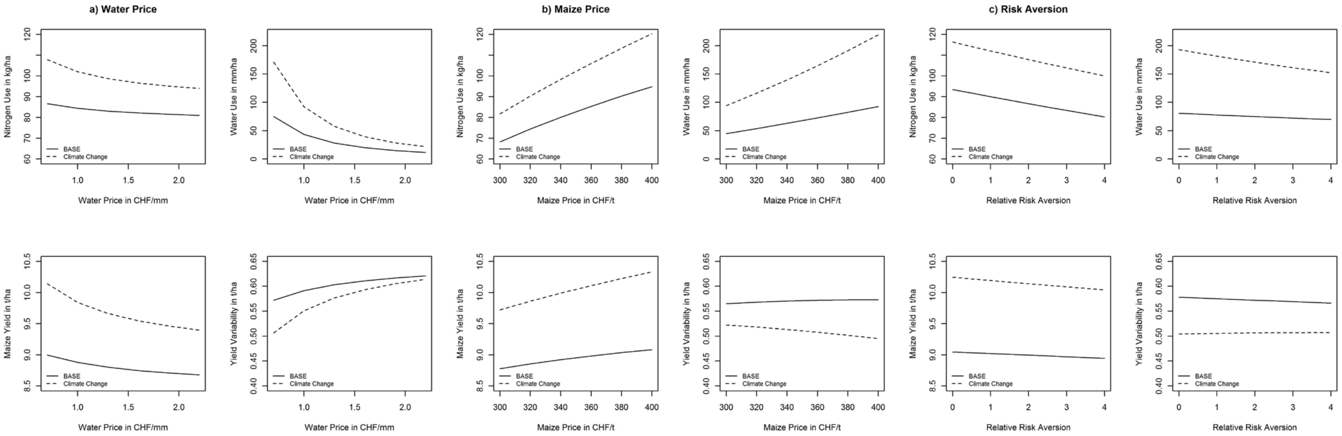


Figure 4. Influence of changes in water prices, maize prices and risk aversion on profits.