Adapting Towards Climate Change: A Bioeconomic Analysis of Winterwheat and Grain Maize

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Abstract

Climate change (CC) will alter the environmental conditions for crop growth. In order to minimize negative CC impacts on cropping systems, farmers will have to adapt their management schemes. In this paper we analyzed CC impacts and adaptation in winterwheat and grain maize production using a bio-economic modeling approach in two study regions of the Swiss Plateau, which differed in their climate and soil types. Considered adaptation options reflected the adjustment of farmers' management decisions with regard to nitrogen and irrigation strategies. To this end, we integrated the process-based crop growth model CropSyst into an economic decision model that accounted not only for the profit margin but also for production risks and thus reflected a risk-averse farmer's management decisions at field scale. Since the relations between a farmer's utility and his management decisions in cropping systems are nonlinear and highly complex we used genetic algorithms (GAs) as optimization technique. By doing so, we optimized the farmer's certainty equivalent (CE) at field scale under different climate scenarios. Our results showed that CC will foster the use of irrigation as management option in grain maize production. For winterwheat, however, irrigation did not represent an optimal solution even under a CC scenario assuming decreases in monthly precipitation sums up to 30%. Furthermore, CC reduced for both crops the optimal nitrogen fertilization amount. Taking such adaptation responses in crop management into account, negative CC impacts on farmers' utility could be partially mitigated.

List of abbreviations

CC:	Climate change
CE:	Certainty equivalent
CHF:	Swiss Franc
GAs:	Genetic algorithms
PAY:	Payerne
RP:	Risk premium
SwissMetNet:	Swiss Meteorological Network
UST:	Uster

Introduction

Recent climate trends had negative impacts on global yield levels of the six most widely grown crops (wheat, rice, maize, soybeans, barley and sorghum) (Lobell and Field, 2007). Projected future changes in global climate conditions are expected to further decrease world crop yields even taking beneficial direct effects of CO_2 fertilization and adaptation measures into account (Parry et al., 2004). In Europe, climate change (CC) impacts on agriculture are ambiguous: While for Northern Europe moderate CC may have in general positive effects on agricultural systems, the disadvantages for agriculture caused by global warming may predominate in Southern European areas (Olesen and Bindi, 2002). In both cases, however, adaptation to CC will be the key factor that shapes the severity of the impacts of global warming for both regions (Lobell et al., 2008). In particular, farmers can be assumed to pursue the goal of maximizing the returns to their land resource (Adams et al., 1998) and therefore adapt their management practices to changing environmental or market conditions. It has been shown that already small changes in agricultural management practices (i.e. tactical adaptation), like for example, adjustments of the sowing date (e.g. Torriani et al., 2007b) or in the fertilization intensity (e.g. Lehmann et al., 2011) can partially avoid negative CC impacts on cropping systems. However, the most efficient adaptation strategies to warmer climate conditions in agriculture such as the expansion of irrigation or the development of new crop varieties are costly (Rosenzweig and Parry, 1994). Breeding for e.g. more drought-tolerant cultivars that are better adapted to CC is a necessity which is pursued at the moment (Campos et al., 2004; Araus et al., 2008), but it is not sure how rapidly this progress can reach the farmer. Thus, agricultural economic considerations in the assessment of climate change impacts and adaptation are required to provide stakeholders such as farmers or policy makers with necessary information of potential options for action.

Based on this background, the goal of this study was to provide an agricultural economic investigation on CC impacts and potential adaptation measures in winterwheat (*Triticum spp. L.)* and grain maize (*Zea mays L.)* production in two study regions in Switzerland. To this end, we assessed the profitability and production risks of both crops under current and future expected climate scenarios using a bioeconomic modeling approach that took a large number of adaptation strategies into account. Although various past studies evaluated possible adaptation options in Swiss agriculture to CC by the use of crop growth models (e.g. Torriani et al., 2007a; Finger et al., 2011), they were often focused on a narrow predetermined subset of decision variables for adaptation. However, the full potential of crop growth models is only tapped when as many different management variables as possible are considered simultaneously under changing environmental or/and economic scenarios (Royce et al., 2001). To overcome this drawback, we integrated the crop growth simulation model CropSyst into a complex economic decision model, which was used to optimize on-farm management decisions of a utility maximizing, risk-averse, decision-maker taking a wide range of different adaptation options into account. We investigated two study regions located around Payerne in the cantons Vaud and Fribourg (Broye-Watershed) and the Greifensee-Watershed, which is located in the canton of Zurich in the North-Eastern part of the Swiss Plateau (see Figure 1). The two study regions were chosen due to their specific characteristics: The Broye-Watershed already faces water scarcity under current climate conditions. In this region, irrigation is currently a common management practice in cropping systems (Robra and Mastrullo, 2011). In contrast, in the more humid Greifensee - irrigation is not used (yet) in crop production. For both regions, increasing in temperatures and decreasing summer precipitation are expected for the next decades (Frei, 2004). Thus, changes in climatic conditions in both regions may increase water needs for irrigation purposes, also for currently non-irrigated crops (Finger and Schmid, 2008).

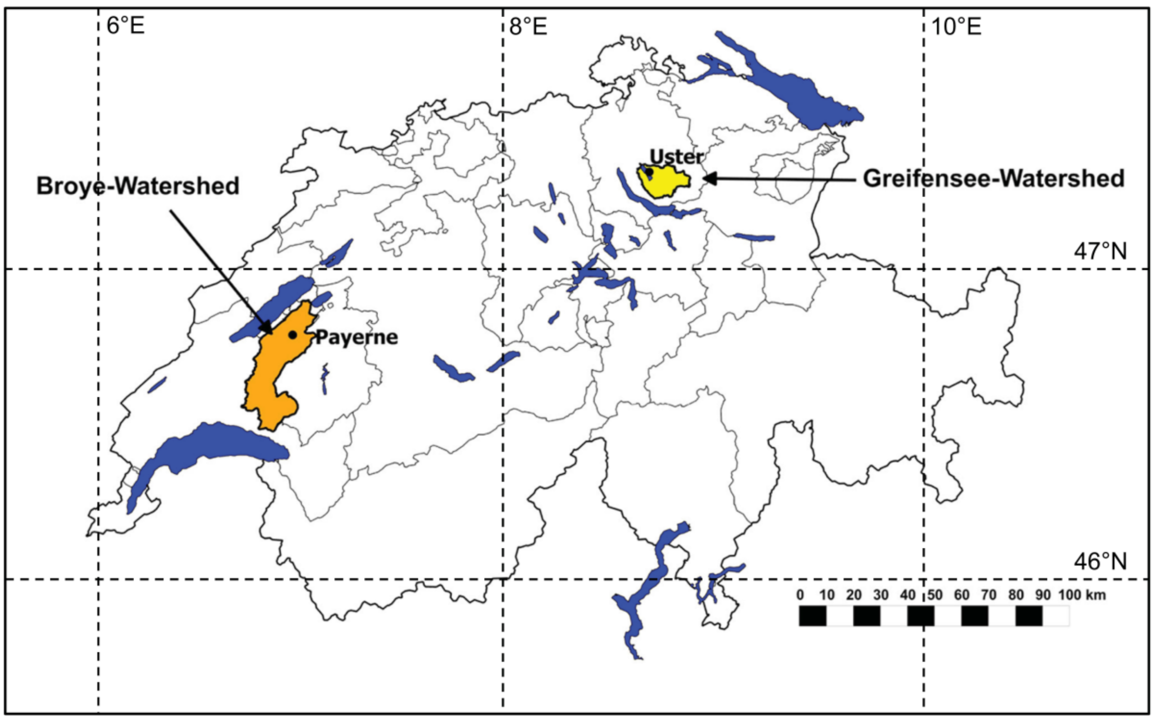

Figure 1: Map of the two study regions

Figure 1 shows the extent of the Broye-Watershed and the Greifensee-Watershed.

In our modeling approach we optimized management decisions with regard to irrigation and nitrogen fertilization strategies in winterwheat and grain maize production under different climate scenarios. We focused on winterwheat, because it is the most important cereal in Switzerland (Finger, 2010). In addition, maize has been chosen because it is the most important spring-sown cereal in Switzerland and covers about 11% of the total cereal acreage (SBV, 2010). Higher temperatures and drier weather conditions in spring and summer months are expected to decrease winterwheat yields in the Swiss Plateau if potential CO_2 fertilization effects and adaptation responses are not considered (e.g. Torriani et al., 2007a; Lehmann, 2010). With regard to maize production at the Swiss Plateau, Torriani et al. (2007b) showed that CC is likely to have a negative impact on maize yield levels, even if a positive CO_2 fertilization effect is assumed. Furthermore, the analysis of Torriani et al. (2007a) showed that the largest impacts of CC in Swiss crop production may not be changes in mean yields, but rather in yield variability, i.e. in the production risks the farmer faces.

The analysis of the two production input factors nitrogen fertilizer and irrigation water use was motivated by the fact that both inputs can be harmful for the environment and thus are of special interest for agri-environmental policy-makers (Finger and Schmid, 2008).

In our analysis, we assumed that farmers are risk averse[1] and are therefore face utility reductions due to any mean-preserving increase in the variance of income (Di Falco and Chavas, 2006).

More specifically, we applied for this study an economic model that accounted for farmers' (mean) profits as well as for production risks (i.e. profit variability) in winterwheat and grain maize production. It is important to note that expected profits and profit variability depend not only on the weather conditions during the vegetation period, but also on the farmer's crop management decisions. For instance, higher nitrogen fertilization amounts increase the expected yield of winterwheat and grain maize but they also lead to higher yield variability, i.e. higher production risks. In contrast, irrigation is expected to reduce yield variability (Finger and Schmid, 2008).

The economic model has been coupled with the mechanistic crop growth model CropSyst. CropSyst was used in this study to simulate climate and region specific crop yields applying different sets of management variables. Process-based crop growth models have been extensively used in CC impact studies in agriculture (e.g. Haskett et al., 1997; Guerena et al., 2001; Eitzinger et al., 2003; Jones and Thornton, 2003; Torriani et al., 2007a, 2007b; Finger et al. 2011), in particular because they are able to simulate crop growth under scenarios which exceed the current conditions (Finger and Schmid, 2008). This is of great importance for CC impact assessments since future climate conditions are assumed to transcend the past climate range. Yet, the main weakness of crop models is their inability to simulate adjustments in farm management depending on the prevailing market, policy and weather conditions (Risbey et al., 1999). In reality, though, farmers do not only adapt continuously their management decisions to the prevailing circumstances, but also take tactical decisions into account (Risbey et al., 1999). We overcame this drawback of crop growth models by combining the crop growth model CropSyst with an economic decision model that represent farmers' decision making process. This integrated model operates on a daily basis and is thus also able to simulate tactical responses of farmers.

Genetic algorithms (GAs) were used in this study as optimization technique in order to directly combine the biophysical crop growth model with the economic decision model (i.e. establish a live-linkage) and optimize the considered decision variables. GAs are new in agricultural economic applications (Musshoff and Hirschauer, 2009) and have shown to be highly applicable to examples of large nonlinear models where the location of the global optimum is difficult to assess (Mardle et al., 2000). In contrast to traditional optimization techniques, GAs do not require gradient information and are more likely to find the global optimum (Mahfoud and Mani, 1996). Furthermore, the here presented non-parametric approach avoids the often required intermediate step of statistical coefficient estimation of crop yield - input factor relations (e.g. Finger et al., 2011). Thus, GAs were very appropriate for this study as optimization technique since the relations between a farmer's utility and his management decisions in

[1] Evidence of farmers' risk aversion can be found in many of their actions, such as their willingness to buy insurances or that they prefer to diversify their farming systems (Hardaker et al., 1997, p.7).

cropping systems are nonlinear and highly complex. Furthermore, the simulation of crop yields based on each possible combination of management options would have been too time-consuming[2].

The remainder of the paper proceeds as follows: In the Methodology section we describe the general modeling approach and the used component models as well as the setting of the GAs. In the Results part we present the impact of different CC scenarios on the profitability and the optimal crop management in winterwheat and grain maize production in both study regions. Finally, the results are interpreted and further steps are considered in the Conclusions and Outlook section.

Methodology

We used an integrated bio-economic modeling approach linking the process-based crop growth model CropSyst with an economic decision (see Figure 2). More specifically, this modeling approach optimized decision variables with regard to irrigation and nitrogen fertilization strategies in winterwheat and grain maize production under current and future expected climate scenarios at field scale. This modeling set-up consisted of three sub-models: The mechanistic crop growth model CropSyst, an economic decision model at field scale and the generic weather generator LARS-WG. In particular, the employed modeling approach was as follows (see Figure 2 for an overview):

A set of decision variables (e.g. fertilization amount, irrigation strategy) was generated for each run within the GAs. These sets of variables are considered as potential solutions for an optimal (i.e. maximizing the farmer's utility) crop management. These decision variables were then passed to CropSyst where they were used as management input variables for climate and region specific crop yield simulations. The weather input files for CropSyst were generated by the LARS-WG weather generator. The simulated crop yields were then fed into the economic model within the GAs in order to compute the return of a specific set of management decisions. Together with the costs of production, which depended on the decision variables (e.g. fertilization amount, irrigation strategy) and the yield levels (e.g. drying costs, premium for hail insurance) as well as the consideration of the production risks, the certainty equivalent (CE) could be computed which was maximized during the optimization routine. In order to consider the above mentioned production risks coming from interannual weather variations in the crop model, we simulated for each specific set of management options crop yields during a period of 25 years. Thus, the crop growth model was not only used to derive expected yield levels, but also yield variability.

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[2] Theoretically, more than 1014 combinations of different management decisions would have been possible in our model, whereas the simulation of the crop yields of one specific combination took about 5 minutes on a normal PC (Intel Pentium Core(TM) i5 at 3.33GHz). Thus, the simulation of all possible combinations would have required a total computation time of more than 108 years.

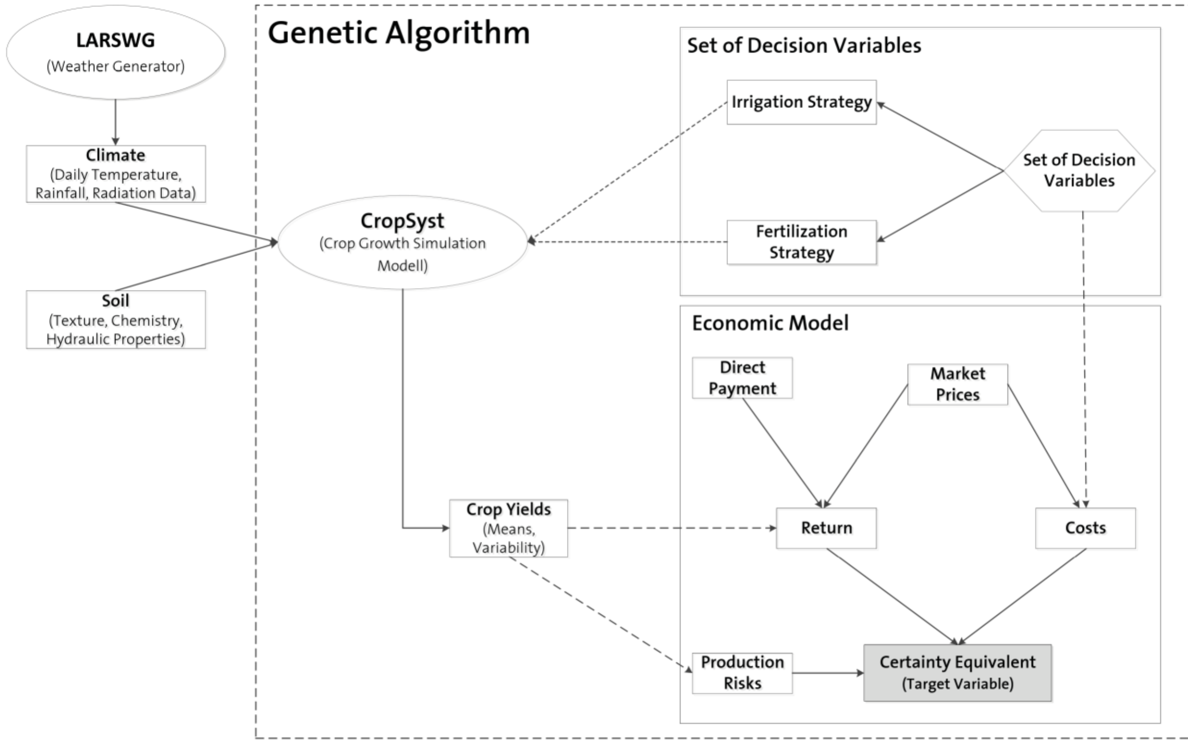

Figure 2: Overview of the modeling approach

Figure 2 gives an overview of the employed modeling approach. A set of decision variables was generated for each individual within the genetic algorithms (GAs). These decision variables were then integrated as management input factors in CropSyst, which was used to simulate crop yields. The climate scenario-dependent weather input files for CropSyst were generated by the weather generator LARS-WG. The simulated crop yields were then passed back to the economic decision model where the farmer's certainty equivalent (CE) (i.e. target variable) could be computed. This procedure was repeated until the CE converged to a maximum value.

The setting of the three sub-models and their integration in the bioeconomic model are discussed in the subsequent sections.

CropSyst

We used the generic, deterministic crop growth model CropSyst (Version 4.13.09). CropSyst is a process-based, multi-crop, multi-year cropping simulation model, which simulates biological and environmental above- and belowground processes of a single land block fragment at a daily scale (Stöckle et al., 2003). The biological and environmental processes in CropSyst are driven by daily weather data and require information of soil and crop characteristics (Stöckle et al., 2003). CropSyst has been developed based on the conceptual strengths of EPIC including a more process-oriented approach to the simulation of plant growth and its interaction with management and the surrounding environment (Stöckle et al,. 2003). Furthermore, CropSyst allows the simulation of a wide range of a farmer's management options including crop rotation, cultivar selection, irrigation, nitrogen fertilization, tillage operations and residue management (Stöckle et al., 2003). CropSyst has been applied to simulate several crops in different regions in the world (e.g. Donatelli et al, 1997; Stöckle et al., 1997; Pannuk et al., 1998; Sadras and Roget, 2004; Todorovic, 2009) and also extensively for cereals in Switzerland (e.g. Torriani et al., 2007a, 2007b; Finger and Schmid, 2008; Finger et al., 2011).

For the here presented study regions, CropSyst was calibrated against observed winterwheat and grain maize yields in the two study regions in the period 1981-2008 following the calibration method of Klein et al. (2011). Observed farm yield records came from the widely available Farm Accountancy Database Network (FADN) and were aggregated for both study areas[3].

To calibrate CropSyst, we used a proxy of water-limited yields as a reference. Important crop parameters identified by the Morris sensitivity analysis were automatically calibrated by means of an automatic parameter estimation procedure based on GAs (Klein et al., 2011).

An important input for CropSyst is the specification of soil conditions. Table 1 shows the soil profile and initial soil conditions at Payerne and Uster, representing the two study regions.

Table 1: Soil profile and initial soil conditions at Payerne and Uster

Soil parameters at Payerne					
Depth	0-0.2m	0.2-0.3m	0.3-0.7m	0.7-0.9m	0.9-1.2m
Sand (%)	56.0	57.0	60.0	57.0	65.0
Clay (%)	14.0	11.0	10.0	10.0	12.0
Silt (%)	30.0	32.0	30.0	33.0	23.0
Organic Matter (%)	2.8	2	2	2	2
NO3 (kgN/ha)	5	5	5	5	5
NH4 (kgN/ha)	5	5	5	5	5
Permanent Willting Point	0.105	0.094	0.09	0.09	0.097
Field Capacity	0.221	0.213	0.206	0.212	0.201
pH	7.1	7.3	7.7	8.0	8.2
Soil parameters at Uster					
Depth	0-0.15m	0.15-0.35m	0.35-0.76m	0.76-1.0m	1.0-1.2m
Sand (%)	52.6	59.2	58.2	74.4	86.0
Clay (%)	17.6	14.4	15.6	8.7	4.0
Silt (%)	29.8	26.4	26.2	16.9	10.0
Organic Matter (%)	2.8	2	2	2	2
NO3 (kgN/ha)	5	5	5	5	5
NH4 (kgN/ha)	5	5	5	5	5
Permanent Wilting Point	0.118	0.106	0.111	0.082	0.054
Field Capacity	0.236	0..217	0.222	0.176	0.134
pH	6.2	5.9	6.7	7.5	7.5

[3] Note that for the calibration of the crop files in the Greifensee-Watershed, FADN data of the neighboring region around the climate station Taenikon (TAE, 8°54’E, 47°29’N, 539 m a.s.l.) has been used since not enough FADN farms were available within the Greifensee-Watershed.

Regarding the initial nitrogen concentration, we assumed for both soils an initial concentration of 5 kg·ha^{-1} nitrogen in the form of nitrates (NO_3^-) and 5 kg·ha^{-1} nitrogen in the form of ammonium (NH_4^+) per soil layer (see Table 1). For the organic matter content of the soil, a spin-up of the model was conducted by running CropSyst for 300 years - turnover time of the most stable organic matter pool - with regular tillage. At equilibrium, CropSyst simulated an organic matter content of 2.8% for the top soil layer and 2% for the other layers. As these values are realistic and within the range of usual observations in Switzerland (Leifeld et al., 2003), they were used as initial organic matter conditions for both study regions investigated here.

Based on these settings, CropSyst was used to identify yield and yield variability sensitivities to weather conditions and crop management. For each simulation run - i.e. a combination of management specifications and weather conditions - identical initial soil conditions were used in order to avoid distortions due to dynamic effects.

Management options

For both crops, we considered 12 different management variables related to a farmer's nitrogen and irrigation strategy. In order to reduce the computation time, we integrated all management variables as discrete values. The ranges and increments of all considered management decision variables are given in Table 2.

We defined the temporal shift between two consecutive fertilization events to a minimum of 20 and 10 days for winterwheat and grain maize, respectively. A temporal gap of less than 20 days (for winterwheat) or 10 days (for grain maize) is not considered because each fertilization event causes costs of work and machinery equipment. Besides the timing of each fertilization application, the model optimized also the applied fraction of the total nitrogen amount for each fertilization event. Regarding the irrigation strategy, we used the automatic irrigation option in CropSyst during the whole vegetation period of winterwheat and grain maize, respectively, and considered two following decision variables: First, our analysis accounted for the irrigation trigger value. As soon as the soil moisture is lower than the user-defined value this option triggers irrigation. This user-defined value ranges from 0 (permanent wilting point) to 1 (field capacity). Second, we also considered the refill point in our model, which defines to what extent the soil water content is refilled by each irrigation application. By optimizing both variables, the irrigation trigger value and the refill point, also deficit irrigation strategies were considered as potential management option. Deficit irrigation is the application of water below the evapotranspiration requirements of the crop (English, 1990) with the purpose to maximize the economic returns and not the biological yield. We assumed an irrigation efficiency of 77%, which corresponds to the irrigation efficiency of sprinkler irrigation systems (Irmak et al., 2011). This is the most common used irrigation technique for cropping systems in the Swiss Plateau (Weber and Schild, 2007). To put it in a nutshell, we considered not only the soil moisture depending irrigation timing but also the intensity of each irrigation application. Furthermore, since we did not use a fixed irrigation amount but the total required irrigation water amount depended on a season's prevailing weather conditions, the applied irrigation amount varied considerably within a specific management scheme from year to year. In our modeling approach, the total applied nitrogen amount could be applied to the field by up to 4 temporarily different fertilization events[4].

Table 2: Considered Management Variables

Decision Variable	Management variable	Unit	Range (min-max)		Variable increment		Number of Alternatives	
			Maize	**Winter-wheat**	**Maize**	**Winter-wheat**	**Maize**	**Winter-wheat**
1	Total Nitrogen Amount	$kg \cdot ha^{-1}$	0-250	0-250	10	10	26	26
2	Number of N Fertilization events	-	0-4	0-4	1	1	5	5
3	Percentage of 1st N application	%	0-100	0-100	5	5	21	21
4	Timing of 1st N application	Days after sowing	0-150	120-220	5	5	31	21
5	Amount of 2nd N application	%	0-100	0-100	5	5	21	21
6	Timing of 2nd N application	Days after sowing	10-150	140-220	5	5	29	17
7	Amount of 3rd N application	%	0-100	0-100	5	5	21	21
8	Timing of 3rd N application	Days after sowing	20-150	160-220	5	5	27	13
9	Amount of 4th N application	%	0-100	0-100	5	5	21	21
10	Timing of 4th N application	Days after sowing	30-150	180-220	5	5	25	9
11	Irrigation trigger value	-	0-1	0-1	0.1	0.1	11	11
12	Irrigation refill point	-	0-1	0-1	0.1	0.1	11	11

The sowing date of winterwheat was fixed for all applied climate scenarios on October, 10, following currently experienced sowing dates. Since the optimal sowing date of maize is in practice highly dependent on the prevailing soil temperature, we used the conditional sowing model in CropSyst for maize. By doing so, maize was sown if the 5-day average air temperature exceeded 10°C[5].

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[4] Note that currently for both crops, winterwheat and grain maize, three nitrogen fertilization applications are recommended in Switzerland in the framework of standard fertilization procedures (Flisch et al., 2009).

[5] For maize grown in Switzerland, sowing is recommended if the soil temperature at a depth of 0.05 m is above 10°C (AGRIDEA, 2011). An analysis of observed daily mean air and soil temperature of the climate station Payerne

Simulation of Weather Data

Synthetic weather data for daily minimum and maximum temperature, rainfall occurrence and amount and daily total solar radiation, as needed on input to CropSyst, were generated for present and future climatic conditions using the LARS-WG stochastic weather generator (Semenov and Barrow, 1997; Semenov et al., 1998). LARS-WG was calibrated using weather observations at two representative stations of the Swiss Meteorological Network (SwissMetNet) (see Figure 1): Payerne (PAY, 6°57'E, 46°49'N, 490 m a.s.l.) for the Broye-Watershed and Uster (UST, 8°42'E, 47°21'N, 440 m a.s.l.) for the Greifensee-Watershed. Since the climate station UST measures only precipitation-related variables, representative temperature and solar radiation measurements for the Greifensee were obtained from the record at a nearby climate station (Zurich-Fluntern, 8°34'E, 47°23'N, 555 m a.s.l.).

25 years of synthetic weather data were generated both for a Baseline as well as for two CC scenarios addressing the nominal time frame 2036-2065 and referring to the A1B emission scenario[6].

Following Semenov (2007), for the scenarios the parameters driving the stochastic generation process in LARS-WG were modified according to changes in monthly mean climate between the baseline and future time window (see Table 3). The latter were derived from the output of two regional climate model runs performed in the context of the EU FP6 project ENSEMBLES (van der Linden and Mitchell, 2009), the first with the regional climate model maintained by the Swiss Federal Institute of Technology (ETHZ-CLM), the second with the model of the Swedish Meteorological and Hydrological Institute (SMHI-Had). For both runs, boundary conditions were obtained from global simulations with the Hadley Centre global climate model HadCM3. As seen in Table 3, both scenarios indicated for 2036-2065 a significant temperature increase. The ETHZ-CLM scenario was furthermore characterized by a large decrease in precipitation during spring and summer. Table 3 shows that under the SMHI-Had scenario monthly precipitation was expected to increase in all months except in June in the Greifensee-Watershed, whereas the projected decrease in the Broye-Watershed was significantly smaller than with the ETHZ-CLM scenario. Regarding the changes in radiation, for both regions a decrease in radiation in winter months and an increase in radiation in summer months can be observed under the ETHZ-CLM scenario. Under the SMHI-Had scenario, radiation was for both watersheds found to slightly decrease throughout the year.

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at a soil depth of 0.05 m showed that the five-day average of soil temperature is very likely to exceed 10°C if the five-day average mean air temperature is above 10°C.

[6] The emission scenario A1B expects a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies whereas a balanced use of fossil and non-fossil energy sources is anticipated (Nakicenovic et al., 2000).

Table 3: Applied changes in monthly maximum and minimum temperature, solar radiation and monthly mean precipitation

	ETHZ-CLM								SMHI-Had							
Month	**Δ Tmin (°C)**		**Δ Tmax (°C)**		**Δ Rad (%)**		**Δ Precip (%)**		**Δ Tmin (°C)**		**Δ Tmax (°C)**		**Δ Rad (%)**		**Δ Precip (%)**	
	PAY	UST	PAY	UST	PAY	UST	PAY	UST	PAY	UST	PAY	UST	PAY	UST	PAY	UST
Jan	+2.51	+2.58	+2.51	+2.6	-3	-3	-4	-4	+2.33	+2.21	+1.74	+1.67	-6	-5	+14	+8
Feb	+1.82	+1.84	+2.00	+2.07	-4	-5	-2	-2	+1.90	+1.87	+1.34	+1.37	-4	-4	+6	+6
Mar	+1.91	+1.89	+2.14	+2.28	-4	-5	-2	-1	+1.31	+1.31	+1.11	+1.05	-3	-4	+2	+8
Apr	+2.06	+2.12	+2.15	+2.24	-2	-5	-3	+3	+1.03	+1.04	+1.07	+0.90	-2	-2	-2	+8
May	+1.85	+1.92	+2.07	+1.84	+2	-2	-6	+6	+1.48	+1.54	+1.59	+1.43	+0	-2	-7	+1
Jun	+2.18	+2.11	+3.08	+2.64	+7	+5	-18	-7	+2.00	+2.10	+2.13	+2.02	+1	-1	-8	-1
Jul	+2.82	+2.67	+4.23	+3.9	+9	+9	-30	-24	+2.08	+2.21	+2.15	+2.16	+0	-1	-3	+3
Aug	+3.11	+2.96	+4.39	+4.19	+8	+9	-28	-23	+2.00	+2.12	+1.98	+2.04	-2	-2	-1	+6
Sept	+2.78	+2.7	+3.41	+3.29	+3	+5	-11	-5	+1.67	+1.72	+1.61	+1.53	-2	-3	+4	+1
Oct	+2.29	+2.36	+2.36	+2.39	+0	+1	-1	+1	+1.46	+1.43	+1.32	+1.17	-5	-6	+16	+19
Nov	+2.28	+2.44	+2.23	+2.42	+0	+1	-4	-6	+1.86	+1.77	+1.56	+1.45	-8	-8	+24	+22
Dec	+2.69	+2.8	+2.6	+2.81	-2	-1	-4	-6	+2.34	+2.21	+1.92	+1.79	-8	-7	+22	+17

Table 3 shows the absolute applied changes in the monthly mean minimum temperature (Δ Tmin), in the monthly mean maximum temperature (Δ Tmax), and the relative changes in the monthly mean radiation (Δ Rad) and in the monthly mean precipitation sum (Δ Precip) for the two used CC scenarios ETHZ-CLM and SMHI-Had.

Economic Model

Simulated yields were integrated into an economic model in order to maximize the farmer's utility depending on his management decisions in the specific cropping system. The farmer's utility was represented by the certainty equivalent (CE) (CHF · ha^{-1}) in winterwheat and grain maize production, respectively, which accounted for profits and production risks. The CE can be interpreted as the guaranteed payoff which a risk averse decision maker views as equally desirable as higher but uncertain levels of payoffs and is defined as follows:

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

Where CE stands for the certainty equivalent, E(π) for the expected profit margin (and RP for the risk premium, all of them expressed in CHF · ha^{-1}.

The RP is the sure amount of money the decision maker is willing to pay to eliminate risk exposure (Di Falco et al., 2007). The decision-maker is risk-averse, risk-neutral and risk-loving if the $RP > 0$, $RP = 0$ or $RP < 0$ (Pratt, 1964). According to Pratt (1964), the RP can be approximated by Equation 2:

$$RP \approx \frac{1}{2} \cdot \frac{\gamma}{E(\pi)} \cdot \sigma_{\pi}^{2} \qquad (2)$$

Where γ is the coefficient of relative risk aversion and σ_{π}^{2} is the variance (CHF · ha^{-1}) of the profit margin π (CHF · ha^{-1}). Values for γ between 1 and 4 represent typical forms of risk behavior (Gollier, 2001, p. 31). For this study, we assumed γ to be 2 which corresponds to a moderate risk-averse decision maker and implies decreasing absolute risk aversion (Di Faclo and Chavas, 2006). Equation 3 shows the composition of the profit margin in winterwheat and grain maize production, respectively, based on the detailed cost information given in Table 4.

$$\pi = \rho + DP - c_{fix} - c_{irrig} - c_{\mathrm{var}} \qquad (3)$$

Where π is the profit margin (CHF · ha^{-1}), ρ is the revenue (CHF · ha^{-1}) and DP are the governmental direct payments (CHF · ha^{-1}). c_{fix} stands for the fixed costs (CHF · ha^{-1}) (excluding irrigation systems), c_{irrig} for the fixed costs of the irrigation systems (CHF · ha^{-1}) and c_{var} for the variable costs (CHF · ha^{-1}) in winterwheat and grain maize production, respectively. Note that c_{irrig} = 0 if no irrigation is applied. More details of the used revenues and costs are given in Table 4.

Table 4: Revenue and costs in winterwheat and grain maize production

Revenue	**Winterwheat**	**Grain maize**
Crop yield (CHF · t^{-1}) [a]	0.51	0.365
Direct payment		
Direct payment (CHF · ha^{-1}) [a]	1680	1680
Fixed costs		
Seed (CHF · ha^{-1}) [a]	218	268
Plant protection (CHF · ha^{-1}) [a]	265	220
Plant growth regulant (CHF · ha^{-1}) [a]	41	0
Contract work and machinery costs (CHF · ha^{-1}) [a]	783	844
Fixed irrigation costs		
Irrigation system costs (CHF · ha^{-1}) [b]	447.41	447.41
Variable costs		
Nitrogen fertilizer (CHF · kg^{-1} · N^{-1}) [a]	1.4	1.4
Other fertilizer costs (CHF · kg^{-1} · N^{-1}) [a]	0.72	1.54
Hail insurance (% of Crop Yield Revenue) [a]	2.1	3.6
Cleaning, drying costs (CHF · t^{-1}) [a, c]	39.5	71.3
Other costs (CHF · t^{-1}) [a]	6.7	0
Variable irrigation costs (CHF · mm^{-1} · ha^{-1}) [b]	1.00	1.00
Interest rate (%)[a]	3.0	3.0

[a] Source: AGRIDEA and FIBL (2010)

[b] Source: Spörri (2011)

[c] Note that the cleaning and drying costs depended on the yield at harvest which had a higher water content than the final yield.

Table 4 shows that variable costs comprise fertilizer, water, insurance and capital costs as well as costs for cleaning and drying of the harvest. Since in CropSyst only nitrogen is included as fertilizer, we coupled the costs of P_2O_5, K_2O and Mg fertilizer to the chosen nitrogen fertilizer amount. After drying, the dry matter content of the winterwheat and grain maize harvest has been assumed to be 85.5% and 86%, respectively (AGRIDEA and FIBL, 2010). The expenses of the hail insurance were computed based on the expected crop yield during the simulation period of 25 years multiplied with the respective crop price. The interest claim was defined as product of the interest rate and the sum of fixed and variable costs. The considered fixed costs comprise costs for seeds, plant protection and growth regulation as well as contract work and machinery. Moreover, we considered also area-based direct payments in our analysis.

In order to account for weather related profit variability, we simulated the yields of winterwheat and grain maize for each specific set of decision variables during a period of 25 years. The expected profit margin $E(\pi)$ and the variance of the profit margin (σ_{π}^{2}) could be derived from the annual profit margins as shown in Equation 4 and Equation 5.

$$E(\pi)=\frac{1}{n}\cdot\sum_{i=1}^{n}\pi_i \qquad (4)$$

$$\sigma_{\pi}^{2}=\frac{1}{n}\cdot\sum_{i=1}^{n}\left(\pi_i-E(\pi)\right)^2 \qquad (5)$$

Where π_i is the profit margin in winterwheat or grain maize production (CHF · ha^{-1}) in the year i and n is the number of simulation years (n=25).

Thus, the target function of the optimization problem could be formulated as shown in Equation 6:

$$\max_{DV_1,DV_2,\ldots,DV_{11},DV_{12}} CE=E(\pi)-0.5\cdot\gamma\cdot\frac{\sigma_{\pi}^{2}}{E(\pi)} \qquad (6)$$

Where DV_i stand for the decision variable i (see Table 3).

Genetic Algorithms

Due to the discrete values the decision variables take in our approach, the here presented optimization problem could be interpreted as a combinatorial problem, i.e. which is characterized by a finite number of feasible solutions. In this study, though, the simple evaluation of each feasible solution was not possible because the calculation of all possible combinations would have been too time-consuming[7]. Moreover, the relations between decision variables and the target variable (CE) could not be represented by mathematical functions, since these relations had a highly complex and nonlinear nature. Therefore, our modeling approach used GAs to establish a live-linkage between the crop growth model and the economic decision model and to avoid simulation and evaluation of all possible combinations of management decisions.

[7] The presented (fast) modeling approach took more than 1 week on a normal PC (Intel Pentium Core(TM) i5 at 3.33GHz) until a stable optimal solution was found.

GAs are increasingly applied on such problems and showed great promise in experimentation and industrial applications (Gen and Cheng, 2000, p. 38). GAs are based on the biological concept of genetic reproduction (Mayer et al., 1999) and follow the concept of the "survival of the fittest" (Aytug et al., 2003). GAs work in an analogous way of natural behavior. A population of individuals, each representing a possible solution for a given problem, evolves over time by the selection of the best individuals in each generation and generating offspring for the next generation. The different decision variables are coded as binary strings of genes on a chromosome (=individual) representing a set of possible decision variables. As in genetics the term *genotype* is used in GAs for the set of decision variables represented by one specific chromosome while the term phenotype refers to the physical outcome and hence the fitness that is caused by the expression of the decision variables (De Jong, 1992). The fitter the individual, the higher is the chance of being chosen for the sexual reproduction of offspring (Beasly et al. 1993). Thus, a whole new population of possible solutions is produced by selecting the best individuals of the current population and mating them in order to generate a new set of individuals (Beasly et al. 1993). After several generations, the algorithm converges to the best individual which is either a global or a local optimum of the optimization problem (Gen and Cheng, 2000. p. 2). A GA involves at least the following three types of operators: selection, crossover and mutation (Mitchell, 1998, p. 10). The selection operator selects the chromosomes based on their fitness value in the current population for reproduction; the crossover operator randomly exchanges subsequences between two selected chromosomes in order to create offspring; and the mutation operator randomly flips some of the bits in a chromosome (Mitchell, 1998, p. 10).

For this work, we used the C++ based GA package Galib (Wall,1996) and applied a steady-state GA. The steady-state GA uses overlapping populations whereas it can be specified how much of the population should be replaced in each generation (Wall, 1996). We applied the following control parameters to the GAs: genome size = 8 bits; population size = 30; proportion of replacement = 0.2; selection routine = roulette wheel; mutation probability = 0.05; crossover probability = 0.5; and a sigma truncation scaling (Wall, 1996) has been used as fitness function. The setting of these control parameters was in line with the recommendations considering efficient parameter setting in GAs of Mayer et al. (2001). In this study, the GA stopped when a generation's best fitness value did not change for a number of 1000 generations[8].

Results

Fig. 3 shows that even though adaptation (i.e. optimal management adjustment) was considered, both climate change scenarios led to smaller yield levels in wheat and maize production in both regions. Generally, the crop yields decreased more under the more extreme climate scenario ETHZ-CLM than under the climate scenario SMHI-Had. However, in the Greifensee-Watershed the SMHI-Had scenario resulted in a larger decrease in the mean grain maize yields than under the ETHZ-CLM scenario. Furthermore, the relative decreases in winterwheat yields were highest in the Greifensee-Watershed,

[8] As a sensitivity analysis showed that the algorithm is very likely to reach the global optimal solution if a stop-criterion of no changes in the target value over 1000 generations is applied (Lehmann et al., 2011).

while relative reductions of grain maize yields were highest in the Broye-Watershed (see also Fig. 5). Fig. 3 also indicates that the variability of winterwheat increased under CC in the Broye-Watershed. In contrast, the yield variability of winterwheat was reduced in the Greifensee-Watershed. For grain maize, a large decrease in the variability of the yields could be observed in the Greifensee-Watershed under the ETHZ-CLM scenario, while the variability of grain maize yields did not change much in the Broye-Watershed under the different climate scenarios[9].

Nevertheless, since the applied modeling approach also accounted for adjustments in management decisions (i.e. adaptation), results only based on crop yields such as shown in Fig. 3 are not sufficient. Thus, financial losses and production risks, which are represented by the CE in this study, should be compared between the different scenarios. Fig. 4 shows the impact of the different climate scenarios, regions and crops on a farmer's CE at field scale.

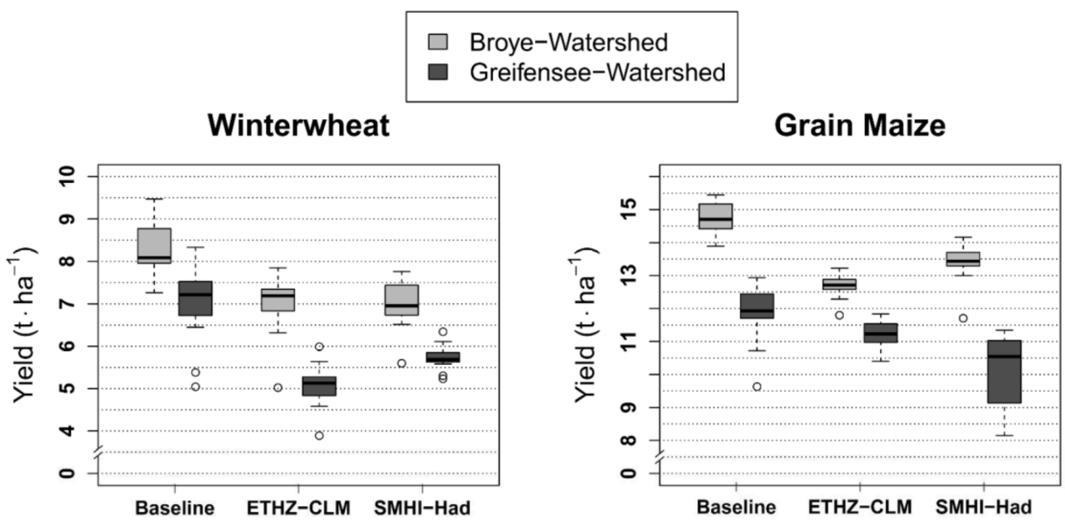

Fig.3: Climate change impacts on winterwheat and grain maize yields applying optimal management schemes

In the Fig. 3 the yield distributions of the 25 weather years for each scenario are presented applying for each scenario the specific optimal management scheme. The horizontal line denotes the median. The whiskers extend to a maximum of 1.5 times of the inter-quartile range. Note that regarding the changes in the yields' variability only for grain maize cultivated in the Greifensee-Watershed a significant decrease under the ETHZ-CLM scenario could be detected by an Ansari-Bradley test (Ansari and Bradley, 1960).

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9 Note that only for grain maize cultivated in the Greifensee-Watershed a significant change (at a significance level of $\alpha=0.05$) in the yields' variability could be detected by an Ansari-Bradley test (Ansari and Bradley, 1960) between the Baseline and ETHZ-CLM scenario. Compared to the Baseline scenario the Ansari-Bradley test resulted in a significant decrease under the ETHZ-CLM scenario for the grain maize yields in the Greifensee-Watershed.

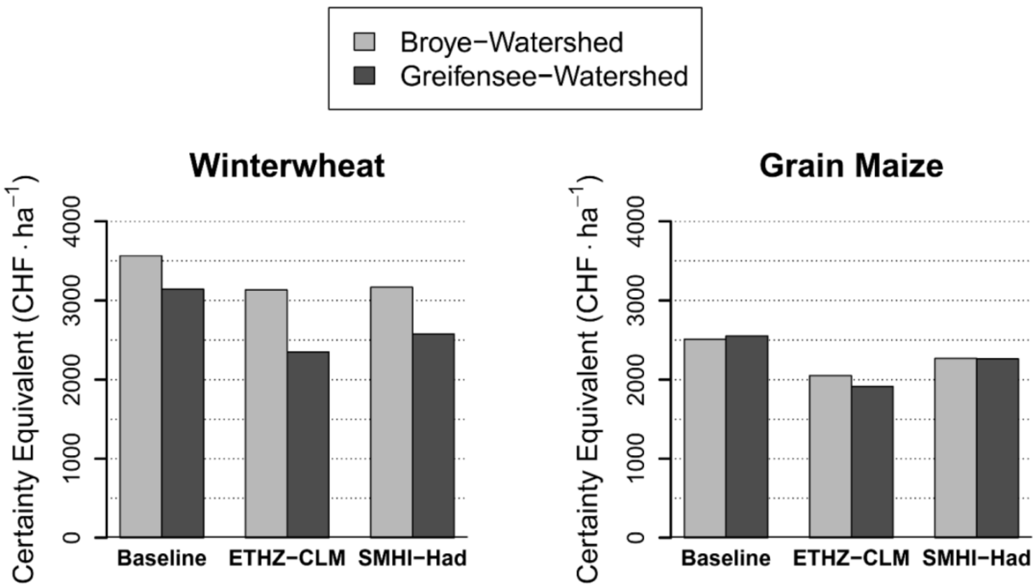

Fig.4: Climate change impacts on certainty equivalents in winterwheat and grain maize applying optimal management schemes

Fig. 4 shows the certainty equivalent (CE) in each scenario applying the optimal identified management scheme.

It shows that CC reduced farmers' CE in both regions and for both crops. For winterwheat, the CE was higher in the Broye-Watershed than in the Greifensee-Watershed under all applied climate scenarios. Applying the optimal management scheme for grain maize resulted in the Greifensee-Watershed under the Baseline scenario in a slightly higher CE than in the Broye-Watershed. Under the CC scenarios, however, a higher profitability of grain maize could be observed in the Broye-Watershed. Additionally, Fig. 5 shows the relative changes in the CE for each crop, region and CC scenario compared to the respective CE in the Baseline scenario. We found that the ETHZ-CLM scenario reduced the CE in the case of grain maize in the Greifensee-Watershed up to 25%. Applying the more moderate CC scenario SMHI-Had led for both crops and regions to much smaller decreases in the CE. For instance, the highest decrease under the SMHI-Had scenario was 18.0% (for grain maize in the Greifensee-Watershed). Furthermore, Fig. 5 also gives the relative changes in the physical crop yields (black diamonds). Except for grain maize in both regions under the ETHZ-CLM scenario and for grain maize in the Broye-Watershed under the SMHI-Had scenario, the reductions in physical crop yields were larger than the relative decreases in the corresponding CE. This indicates that by adapting the specific management scheme some of the negative CC impacts on crop farming could be mitigated.

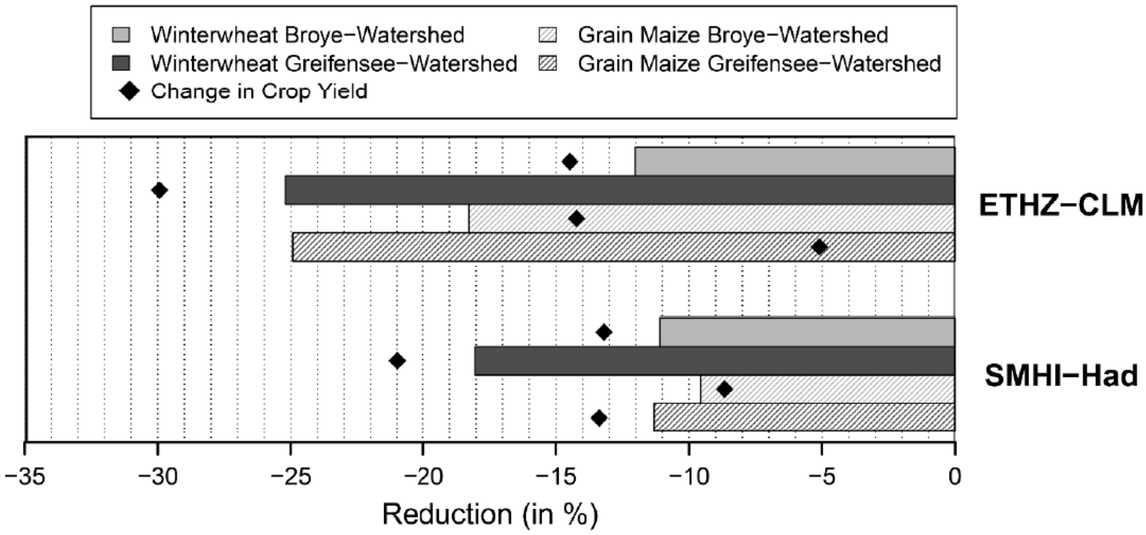

Fig.5: Relative changes of certainty equivalents and yields in winterwheat and grain maize production applying optimal management schemes

In Fig. 5 the relative reductions in the certainty equivalent (CE) compared to the CE in the Baseline scenario are shown for both climate change (CC) scenarios (horizontal bar). Additionally, the black diamonds present the relative reductions of the mean crop yields between the CC and the Baseline scenario.

To illustrate adaptation responses chosen by the farmer in more detail, Table 5 and Table 6 show the optimal (i.e. utility maximizing) management schemes for all applied climate scenarios, both regions and crops. More specifically, adaptation responses can be revealed by comparing optimal management schemes under current and potential future climate conditions. It shows that for winterwheat, even under the severe CC scenario ETHZ-CLM, irrigation was in none of the regions an appropriate adaptation measure. In contrast to irrigation, the optimal nitrogen strategy for winterwheat, however, was strongly affected by the different climate scenarios. The larger the applied increase in temperature and decrease in precipitation, the smaller was the optimal total nitrogen amount. This extensification could be observed in both regions. Under both CC scenarios in the Greifensee-Watershed and under the SMHI-Had scenario in the Broye-Watershed, total nitrogen amount was applied by only one fertilization event around the end of May. Under the ETHZ-CLM scenario in the Broye-Watershed, 95% of the total nitrogen amount was applied between the end of May and mid-June.

Table 5: Optimal management parameters for winterwheat

Management variable	**Unit**	**Winterwheat Broye-Watershed Baseline**	**Winterwheat Broye-Watershed ETHZ-CLM**	**Winterwheat Broye-Watershed SMHI-Had**	**Winterwheat Greifensee-Watershed Baseline**	**Winterwheat Greifensee-Watershed ETHZ-CLM**	**Winterwheat Greifensee-Watershed SMHI-Had**
Total N amount	$kg \cdot ha^{-1}$	150	110	120	140	80	110
Number of fertilization events	-	3	3	1	3	1	1
Percentage of 1st N application	%	45	5	100	45	100	100
Timing of 1st N application	Days after sowing	120	125	140	125	140	145
Amount of 2nd N application	%	25	70	0	45	0	0
Timing of 2nd N application	Days after sowing	140	145	-	165	-	-
Amount of 3rd N application	%	65	25	0	10	0	0
Timing of 3rd N application	Days after sowing	165	165	-	185	-	-
Amount of 4th N application	%	0	0	0	0	0	0
Timing of 4th N application	Days after sowing	-	-	-	-	-	-
Mean irrigation amount	$mm \cdot ha^{-1}$	0	0	0	0	0	0
Irrigation trigger value	-	1	1	1	1	1	1
Irrigation refill point	-	1	1	1	1	1	1

Table 6: Optimal management parameters for grain maize

Management variable	Unit	Grain maize Broye-Watershed Baseline	Grain maize Broye-Watershed ETHZ-CLM	Grain maize Broye-Watershed SMHI-Had	Grain maize Greifensee-Watershed Baseline	Grain maize Greifensee-Watershed ETHZ-CLM	Grain maize Greifensee-Watershed SMHI-Had
Total N amount	$kg \cdot ha^{-1}$	200	150	160	150	130	110
Number of fertilization events	-	4	4	4	4	3	4
Percentage of 1st N application	%	55	45	35	55	65	65
Timing of 1st N application	Days after sowing	20	10	5	5	5	5
Amount of 2nd N application	%	20	20	25	15	20	35
Timing of 2nd N application	Days after sowing	65	50	40	15	50	55
Amount of 3rd N application	%	10	20	20	10	15	0
Timing of 3rd N application	Days after sowing	85	70	65	55	80	-
Amount of 4th N application	%	15	15	20	20	0	0
Timing of 4th N application	Days after sowing	100	85	90	70	-	-
Mean irrigation amount	$mm \cdot ha^{-1}$	171 (58)	250 (56)	212 (62)	0 (0)	101 (58)	0 (0)
Irrigation trigger value	-	0.1	0.5	0.1	1	0.6	1
Irrigation refill point	-	0.7	0.8	0.7	1	0.6	1

In the case of grain maize (see Table 6), irrigation was already under current conditions (Baseline scenario) a profitable management option in the Broye-Watershed. As expected, CC increased for this region the optimal irrigation intensity, whereas the optimal total nitrogen amount was decreased. In contrast, irrigation was only profitable in grain maize production in the Greifensee-Watershed for the ETHZ-CLM scenario. Again, the optimal (i.e. utility maximizing) nitrogen amount decreased under the applied CC scenarios. Moreover, it can be observed for the Broye-Watershed that CC narrowed the time span between the first and last fertilization event. When irrigation was applied, a deficit irrigation strategy was pursued for grain maize in all scenarios, which is reflected by the observation that in the case of irrigation the optimal refill point was always smaller than one.

Conclusions and Outlook

The results of our bio-economic modeling approach showed that CC impacts on winterwheat and grain maize production in the Swiss Plateau are expected to be negative. However, our results also indicated that the magnitude of negative CC impacts will depend on the specific crop, region and the applied climate scenario considered. For instance, the reduction in farmers' utility (expressed in CE) for grain maize under the SMHI-Had scenario in the Broye-Watershed amounted only to about 10% compared to current climatic conditions (Baseline). The decrease in the CE for winterwheat in the Greifensee-Watershed under the ETHZ-CLM scenario, however, was about 25% compared to the CE in the corresponding Baseline scenario. Thus, alternative strategies to close the income gap due to climate change should be developed by farmers and other stakeholders.

Our results also showed that CC led to shorter vegetation periods of winterwheat, which reduced yield levels. However, this effect of CC may also provide opportunities for the farmer if the earlier harvest of wheat could be used to implement a second crop (e.g. grassland, maize) in the same cropping season.

By analyzing optimal adaptation responses of farmers to CC, our study clearly indicated that irrigation will gain importance in grain maize production in Switzerland. While an optimal management scheme in grain maize production already included irrigation under current climate conditions in the Broye-Watershed, irrigation became also in the Greifensee-Watershed under the ETHZ-CLM scenario a profitable management strategy for grain maize. The consideration of different irrigation strategies (in particular different irrigation intensities and different irrigation trigger values), increased the benefits of irrigation as adaptation measure to CC. Whenever irrigation was applied, it was optimal to pursue a deficit irrigation strategy, which did not maximize the physical yields but the financial profit in crop production. This increased water demand in maize production indicated by our results may cause additional problems of water allocation between agriculture and other sectors. Thus, water allocation policies should take potential effects of CC on water demand into account.

In contrast to the results for grain maize, irrigation was not profitable in winterwheat production, independently of the applied climate scenarios. This is particularly caused by two effects: On the one hand, higher winterwheat yield levels caused by supplemental irrigation cannot completely offset the arising fix costs of sprinkler irrigation systems. On the other hand, the expected decreases of monthly precipitation under climate change are highest in summer months, whereas water availability for winterwheat is particularly crucial for crop growth in spring months (Lehmann, 2010), during which reductions of precipitation is expected to be less pronounced under climate change (see Table 3). Additionally, winterwheat grown in the Swiss Plateau is more sensitive to high temperatures than to low precipitation levels in summer months (Lehmann, 2010).

Both winterwheat and grain maize showed a similar response to CC considering the optimal nitrogen fertilization amount, i.e. CC decreased the total optimal amount of nitrogen fertilizer for both crops and in both regions. In the case of winterwheat, the maximum CE strategy was to apply the whole nitrogen fertilization amount under the SMHI-Had scenario in both regions and under the ETHZ-CLM scenario in the Greifensee-Watershed in only one single application. This would further decrease variable costs in winterwheat production since only one fertilization application is required. However, because a single nitrogen application strategy may cause environmental problems compared to split applications (Hyytiäinen et al., 2011), this result may indicate need for adjustments in agri-environmental policies.

Regarding the nitrogen timing and allocation strategy for grain maize, CC narrowed the time span between the first and last fertilization event. This effect can be traced back to the shorter vegetation period of grain maize under CC. This temporal concentration of nitrogen fertilization applications combined with the increasing irrigation requirements, may increase nitrogen leaching in grain maize production under CC and underlines the potential need for policy adjustments indicated above.

In conclusion, the developed bio-economic modeling approach consisting of the biophysical crop growth model CropSyst and the economic decision model at field scale was found to be very appropriate for CC impact studies in agriculture. Due to the application of CropSyst, crop growth and its response to weather and crop management could be realistically simulated under different management and climate regimes. Furthermore, optimizing a farmer's management strategy allowed the simultaneous consideration of potential strategic (e.g. the use of irrigation) and tactical (e.g. changes in nitrogen application dates) adaptation measures to climate change. In addition, the application of GAs as optimization technique enabled a direct integration (i.e. a live-linkage) of the simulated crop yields in the economic decision model and avoided a parametric representation (e.g. production functions) of yield management relationships. Our results indicated that reliable adaptation strategies in cropping systems can only be assessed if several management variables are considered simultaneously. For instance, the application of irrigation increases the potential crop yields, which raises at the same time the level of the optimal nitrogen fertilization amount due to increasing nitrogen leaching and the higher potential yield levels. In order to assess irrigation as adaptation measure to CC from an economic point of view, our results show that input variables and their interactions have to be taken into account simultaneously.

Next steps of this research will comprise a whole-farm model based on the here presented approach, the integration of political regulations as well as of uncertainties of water supply for irrigation purposes. In our analysis, we did not consider a CO_2 fertilization effect in this study, because the exact quantification of the CO_2 fertilization effect is still highly uncertain (Körner et al., 2007). Additional research should, however, also consider different scenarios of the CO_2 fertilization effect to show the sensitivity of the results to this assumption. Additionally, also different input- and output-price scenarios should be taken into account because in Switzerland the impact of changing market conditions could potentially be of large importance for crop management and farmers income (Finger et al., 2011).

References

AGRIDEA and FIBL. 2010. Deckungsbeiträge 2010. (In German). Technical report, AGRIDEA, 2010.

AGRIDEA, 2011. Mais Saat. (In German). Available at http://www.agrigate.ch/de/pflanzenbau/ackerbau/mais/sorten/ (verified 24 October 2011), AGRIDEA, Lindau, Switzerland.

Adams, R.M., Hurd, B.H., Lenhart, S. and Leary, N. 1998. Effects of global climate change on agriculture: An interpretative review. Climate Res. 11:19-30.

Ansari, A. R. and Bradley, R. A. 1960. Rank-Sum tests for dispersions. Ann. Math. Stat. 31 (4): 1174-1189.

Araus, J.L., Slafer, G.A., Royo, C., and Serret, M.D. 2008. Breeding for yield potential and stress adaptation in cereals. CRC Crit. Rev. Plant Sci. 27(6): 377-412.

Aytug, H. and Khouja, M. and Vergara, F.E. 2003. Use of genetic algorithms to solve production and operations management problems: A review. Int. J. Ind. Eng. Prod. Res. 41(17):3955-4009.

Barrow, E.M. and Semenov, M.A. 1995. Climate change scenarios with high spatial and temporal resolution for agricultural applications. Forestry. 68(4):349-360.

Beasley, D., Martin, R.R., and Bull, D.R. 1993. An overview of genetic algorithms: Part 1. Fundamentals. University Computing. 15(2):58-69.

Campos, H., Cooper, M., Habben, J.E., Edmeades, G.O. and Schussler, J.R. 2004. Improving drought tolerance in maize: A view from industry. Field Crops Res. 90(1): 19-34.

De Jong, K.A. 1992. Are genetic algorithms function optimizers. Parallel problem solving from nature 2:3-14.

Di Falco, S., Chavas and J-P., Smale, M. 2007. Farmer management of production risk on degraded lands: The role of wheat varieties in the Tigray region, Ethiopia. Agric. Econ. Res. 36:147-156.

Di Falco and S., Chava J-P. 2006. Crop genetic diversity, farm productitvity and the management of environmental risk in rainfed agriculture. Europ. Rev. Agr. Econ. 33 (3):289-314.

Donatelli, M., Stöckle C., Ceotto, E. and Rinaldi, M. 1997. Evaluation of CropSyst for cropping systems at two locations of northern and southern Italy. Eur. J. Agron. 6 (1-2):35-45.

Eitzinger J., Stastná, M., Zalud, Z. and Dubrovský, M. 2003. A simulation study of the effect of soil water balance and water stress on winter wheat production under different climate change scenarios. Agric. Water Manage. 6(3):195-217.

English, M. 1990. Deficit irrigation. I. Analytical framework. J. Irrig. Drain. Div., Am. Soc. Civ. Eng. 116:399-412.

Finger, R. andCalanca, P. 2011. Risk management strategies to cope with climate change in grassland production: An illustrative case study for the Swiss plateau. Reg. Environ. Change. In Press (DOI: 10.1007/s10113-011-0234-9).

Finger, R., Hediger, W. and Schmid, S. 2011a. Irrigation as adaptation strategy to climate change - A biophysical and economic appraisal for Swiss maize production. Climatic Change. 105:509-528.

Finger, R. 2010. Evidence of slowing yield growth - The example of Swiss cereal yields. Food Pol. 35(2):175–182, 2010.

Finger, R. and Schmid, S. 2008. Modeling agricultural production risk and the adaptation to climate change. Agr. Finance Rev. 68 (1): 25-41.

Flisch R., Sinaj S., Charles R. and Richner W. 2009. Grundlagen für die Düngung im Acker- und Futterbau (GRUDAF) 2009. (In German with English abstract). Agrarforschung 16(2):1-97.

Frei, Christoph. 2004. Die Klimazukunft der Schweiz – Eine probabilistische Projektion. MeteoSwiss. (In German). Zürich.

Gen, M. and Cheng, R. 2000. Genetic algorithms and engineering optimization, Wiley-Interscience, USA.

Gollier, C. 2001. The economics of risk and time. The MIT Press, Cambridge, MA.

Guerena, A., Ruiz-Ramos, M., Diaz-Ambrona, C.H., Conde, J.R. and Minguez, M.I. 2001. Assessment of climate change and agriculture in Spain using climate models. Agron. J. 93(1):237-249.

Hardaker, J.B., Huirne, R.B.M., Anderson, J.R. and Lien, G., 2004. Coping with risk in agriculture. 2nd ed. CABI Publishing. Cambridge, USA.

Haskett, J.D. and Pachepsky, Y.A. and Acock, B. 1997. Increase of CO2 and climate change effects on Iowa soybean yield, simulated using GLYCIM. Agron. J. 89(2):167-176.

Hyytiäinen, K., Niemi, J.K., Koikkalainen, K., Palosuo, T. and Salo, T., 2011. Adaptive optimization of crop production and nitrogen leaching abatement under yield uncertainty. Agric. Syst. 104: 634-644.

IPCC. 2007. Climate change 2007: The physical science basis. Cambridge University Press Cambridge.

Irmak, S., Odhiambo, L.O, Kranz, W.L and Eisenhauer, D.E. 2011. Irrigation efficiency and uniformity and crop water use efficiency. Available at http://elkhorn.unl.edu/epublic/live/ec732/build/ec732.pdf. (verified July 26, 2011). Institute of Agriculture and Natural Resources at the University of Nebraska-Lincoln.

Jones, P.G. and Thornton, P.K. 2003. The potential impacts of climate change on maize production in Africa and Latin America in 2055. Global Environ. Change. 13(1):51-59.

Klein, T., Calanca, P. Holzkämper, A., Lehmann, N., Rösch, A. and Fuhrer J. 2011. Using farm accountancy data to calibrate a crop model for climate impact studies. Agricultural Systems, In Press.

Körner, C., Morgan, J. and Norby, R. 2007. CO2 fertilization: When, where, how much? p. 9-21. In Canadell, J.G. et al. (ed.). Terrestrial ecosystems in a changing world, global change - The IGBP Series. Springer, Berlin, 2007.

Lehmann, N., Finger, R. and Klein, T. 2011. Optimizing wheat management towards climate change: A genetic algorithms approach. IASTED International Conference on Applied Simulation and Modelling. 22-24 June 2011, Crete, Greece.

Lehmann, N. 2010. Regional crop modeling - How future climate may impact crop yields in Switzerland. Master Thesis, ETH Zurich, Switzerland.

Leifeld, J., Bassin, S., Fuhrer, J. 2003. Carbon stocks and carbon sequestration potentials in agricultural soils in Switzerland. Schriftenreihe der FAL 44.

Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P. and Naylor, R.L. 2008. Prioritizing climate change adaptation needs for food security in 2030. Science. 319 (5863):607-610.

Lobell, D. and Field, C. 2007. Global scale climate–crop yield relationships and the impacts of recent warming. Environ. Res. Lett. 2(1).

Mahfoud, S. and Mani, G. 1996. Financial forecasting using genetic algorithms. Applied Artificial Intelligence. 10:543-566.

Mardle, S.J., Pascoe, S. and Tamiz, M. 2000. An investigation of genetic algorithms for the optimization of multi-objective fisheries bioeconomic models. Intl. Trans in Op. Res. 7:33-49.

Mayer, D.G. Belward, J.A. and Burrage, K. 2001. Robust parameter settings of evolutionary algorithms for the optimisation of agricultural systems models. Agric. Syst. 69(3): 199-213.

Mayer, D.G. Belward, J.A. and Widell, H. and Burrage, K. 1999. Survival of the fittest--genetic algorithms versus evolution strategies in the optimization of systems models. Agric. Syst. 60(2):113-122.

Mitchell, M. 1998. An introduction to genetic algorithms. The MIT press,

Nakicenovic N., Alcamo J., Davis G., de Vries B., Fenhann J., Gaffin S., Gregory K., Grbler A., Jung TY., Kram T., La Rovere EL., Michaelis L., Mori S., Morita T., Pepper W., Pitcher H., Price L., Raihi K., Roehrl A., Rogner HH., Sankovski A., Schlesinger M., Shukla P., Smith S., Swart R., van Rooijen S., Victor N. and Dadi Z. 2000. IPCC special report on emissions scenarios. Cambridge University Press, Cambridge.

Olesen, J.E. and Bindi, M. 2002. Consequences of climate change for European agricultural productivity, and land use and policy. Eur. J. Agron. 16 (4):239-262.

Pannkuk, C.D., Stockle, C.O. and Papendick, R.I. 1998. Evaluating CropSyst simulations of wheat management in a wheat-fallow region of the US Pacific Northwest. Agric. Syst. 57(2):121-134.

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M. and Fischer, G. 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Global Environmental Change 14(1): 53-67.

Pratt, J.W. 1964. Risk aversion in the small and in the large. Econometrica. 32(1-2):122-136.

Robra, J.P. and Mastrullo, J.. 2011. Evaluation d'irrigation dans la Broye des besoins en eau. (In French). Technical Report.

Roger, H.H., Runion, G.B and Krupa, S.V. 1994. Plant responses to atmospheric CO2 enrichment with emphasis on roots and the rhizosphere. Environ. Pollut. 83:155-189.

Rötter, R. and Van De Geijn, S.C. 1999. Climate change effects on plant growth, crop yield and livestock. Climatic Change. 43:651-681.

Rosenzweig, C. and Parry, M.L. 1994. Potential impact of climate change on world food supply. Nature. 367:133-138.

Royce, R.S., Jones, J.W. and Hansen, J.W. 2001. Model-based optimization of crop management for climate forecast application. Transactions of the ASAE 44(5):1319-1327.

Risbey, J., Kandlikar, M., Dowlatabadi, H., and Graetz, D. 1999. Scale, Context, and Decision Making in Agricultural Adaptation to Climate Variability and Change. Mitig. Adapt. Strat. Global Change. 4(2): 137-165.

Sadras, V.O. and Roget, D.K. 2004. Production and environmental aspects of cropping intensification in a semiarid environment in Southeastern Australia. Agron. J. 96:236-246.

SBV. 2010. Statistische Erhebungen und Schätzungen über Landwirtschaft und Ernährung. (In German). Schweizer Bauernverband (SBV, Swiss Farmers' Union), Brugg, Switzerland.

Semenov, M.A. 2007. Development of high-resolution UKCIP02-based climate change scenarios in the UK. Agricultural and Forest Meteorology 144 (2007) 127–138

Semenov, M.A. and Brooks, R.J. 1999. Spatial interpolation of the LARS-WG stochastic weather generator in Great Britain. Climate Res. 11:137-148.

Semenov, M.A. and Barrow, E.M. 1997. Use of a stochastic weather generator in the development of climate change scenarios. Climatic Change. 35:397-414.

Semenov, M.A., Brooks; R.J., Barrow, E.M. and Richardson, C.W. 1998. Comparison of the WGEN and LARS-WG stochastic weather generators for diverse climates. Climate Res. 10:95-107.

Sinclair, T.R. and Muchow, R.C. 1999. Radiation use efficiency. Adv. Agron. 65:215-265.

Spörri, M. 2011. Economic efficiency of irrigation strategies for arable crops under current and future climate scenarios, Bachelor Thesis, ETH Zurich, Switzerland.

Stöckle, C.O., Donatelli M. and Nelson, R. 2003. CropSyst, a cropping systems simulation Model. Eur. J. Agron. 18(3-4):289–307.

Stöckle, C.O., Cabelguenne, M. and Debaek, P. 1997. Comparison of CropSyst performance for water management in southwestern France using submodels of different levels of complexity. Eur. J. Agron. 7: 89-98.

Todorovic, M., Albrizio, R., Zivotic, L., Saab, M.T.A., Stöckle, C. and Steduto, P. 2009. Assessment of AquaCrop, CropSyst, and WOFOST models in the simulation of sunflower growth under different water regimes. Agron. J.101(3):509-521.

Torriani, D.S., Calanca, P., Schmid, S., Beniston, M. and Fuhrer, J. 2007a. Potential effects of changes in mean climate and climate variability on the yield of winter and spring crops in Switzerland. Climate Res. 34(1):59-69.

Torriani, D.S., Calanca, P., Lips, M., Ammann, H., Beniston, M. and Fuhrer, J. 2007b. Regional assessment of climate change impacts on maize productivity and associated production risk in Switzerland. Reg Environ Change. 7:209-221

van der Linden P. and Mitchell, J.F.B. (ed.). 2009. Summary of research and results from the ENSEMBLES project. Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK.

Wall, M. 1996. A C++ Library of Genetic Algorithm Components. Technical report, Massachusetts Institute of Technology.

Weber, M. and Schild, A. 2007. (In German). Stand der Bewässerung in der Schweiz – Bericht zur Umfrage. (In German). Technical report, Federal office for agriculture, Bern, Switzerland.