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Adapting towards climate change: A whole-farm approach

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Abstract: Agricultural systems are vulnerable to climate change (CC). However, by adjustments of their management schemes farmers can minimize negative impacts of global warming on their income. One possibility of assessing adaptation options of agricultural systems to CC is the use of bioeconomic models which link process-based crop growth with economic decision models. In order to account for a wider range of possible adaptation options including changes in land-use or a farm's business activities, bioeconomic models at farm-scale are required. In this study, a whole-farm model consisting of the crop growth model CropSyst and economic decision model is used in order to assess the effects of CC and different water policies on a crop farm's total water consumption, the farmer's utility and on his management decisions with regard to land allocation as well as crop specific nitrogen and irrigation intensities. The represented farm is assumed to be located in the Broye watershed located in Western Switzerland. In this region water scarcity can already be observed in hot and dry summer months due to large water withdrawals for irrigation. In the future CC is expected to further intensify this conflict of water use. Our results show that under CC a crop's farm total water consumption will increase by more than 240% if irrigation is possible without any restrictions and assuming current water prices. However, both an increase in the water price and the introduction of a water quota would decrease the total water use significantly under current and future expected climate. As a result, the costs for significant reductions in water use of these policies are rather small, i.e. about 11% of their initial utility. Therefore, these measures should be considered by policy makers to cope with CC induced increases in agricultural water use.

***Keywords**:* Whole-Farm Model; Climate Change; Irrigation; Genetic Algorithms

1 INTRODUCTION

Climate variations are the dominant source of the overall interannual variability in agricultural production in many regions [Howden et al., 2007]. Even in European regions such as Switzerland where agriculture is highly subsidized [El Benni et al., 2012], seasonal climate conditions still have a large influence on a farmer's income [e.g. Lehmann, 2010]. In the course of global warming, climate conditions will change and thus affect production conditions in agriculture. In order to cope with climate change (CC) effects in agriculture, farmers are expected to adapt their farm

management to the changing environmental production conditions. Possible adaptation measures at the farm-scale range from changes in production practices (eg. land use, crop varieties, production intensity, irrigation, timing to operations) to farm financial programs (eg. crop insurance, crop shares and futures) and the diversification of household income sources including off-farm income and pluriactivity [Smit and Skinner, 2002]. These potential fields of adaptation show that farmers' responses to CC are of highest environmental relevance as they affect the use of natural resources such as land and water as well as the use of environmental harmful inputs such as nitrogen. Furthermore, these adaptation decisions are relevant from a societal point of view because types and amounts of agricultural production can change in response to CC.
In the last years, several studies addressed the potential of adaptation in agriculture in order to mitigate negative CC impacts [e.g. Finger et al., 2011; Holden and Berenton, 2006; Torriani et al., 2007; Tubiello et al., 2000]. However, most of these studies do not focus on more than one crop, although the adaptation potential of changes in land use and diversification of farm activities can only be taken into account if all activities of a farm are considered simultaneously. Furthermore, a whole-farm model is needed if restrictions on nutrient balance, farmers' workload and machinery are taken into account.
Our analysis addresses CC impacts and adaptation in Swiss crop production. Earlier studies have shown that besides other possible adaptation measures such as changes in production intensity [Lehmann et al., 2011], adjustment of sowing dates [Torriani et al., 2007] and changes in the optimal crop mix [Lehmann et al., 2012], particularly the use of irrigation will gain in importance for arable farms in Switzerland under CC [Finger et al., 2011; Lehmann et al., 2012]. Thus, the demand of water in the Swiss agriculture will increase in the next decades. Even Switzerland is referred as the "water tower" of Europe [Mountain Agenda, 1998], water scarcity due to irrigation can already be observed in Western Switzerland. In particular in the Broye watershed that is located in Western Switzerland in the cantons of Vaud and Fribourg, high water withdrawals for agricultural purposes led in the last years repeatedly to intolerable ecological conditions for a river's fauna in dry and hot years [Muehlberger, 2008]. In order to prevent very low water levels in rivers, water withdrawal bans are imposed by governmental institutions if a river's flow rate falls below a critical threshold (see BAFU [2000] for details). However, it is obvious that such water withdrawal bans are likely to be imposed under hot and dry weather conditions when the crops' water requirements are highest. Lehmann et al. [2012] show that this currently applied policy even increases the economically optimal irrigation amount in potato production under today's climate conditions. Since under CC these water withdrawal bans can be expected to occur more frequently in the Broye watershed, other more sustainable irrigation water withdrawal policies have to be developed.
Based on this background, we aim to model optimal whole-farm management decisions under current and future expected climate conditions applying different irrigation water policy scenarios. To this end, we use a bioeconomic whole-farm model that links the process-based crop growth model CropSyst with an economic decision model in order to optimize a crop farmer's management decisions by using genetic algorithms (GAs). The use of CropSyst allows us to simulate crop yields applying different scenarios on management decisions and conditions. The economic decision model reflects a risk-averse decision maker and evaluates different management schemes converting related profits and income risks into the farmer's utility. Finally, the use of GAs as optimization technique is required since the relations between management decisions and a farmer's utility are highly complex and nonlinear. Furthermore, the use of GAs as optimization technique enables a relatively fast optimization routine using a normal PC (Intel Pentium Core(TM) i5 at 3.33GHz).
This modelling framework allows us to assess the impact of CC and different assumed water policy scenarios on the modelled farm's total water consumption and the farmer's utility. Furthermore, we also show how farmers will adapt their management decisions to the applied changes in climatic and policy conditions. Thus, our results provide insights for environmental policy makers in which fields particular attention is needed to maintain sustainable agricultural production in

Switzerland. Furthermore, the study's outcomes can help farmers and other stakeholders to develop adaptation plans in Swiss agriculture.

2 METHODS

We use the bioeconomic whole-farm model developed by Lehmann and Finger [2012]. This model comprises the process-based crop growth model CropSyst which is linked with an economic decision model at farm scale representing a risk-averse decision maker. Using this whole-farm model a farmer's management decisions with regard to crop land use and the nitrogen fertilization intensity as well as the irrigation strategy of each crop is optimized by the application of GAs as optimization technique. Figure 1 shows the basic modeling concept used in this study.

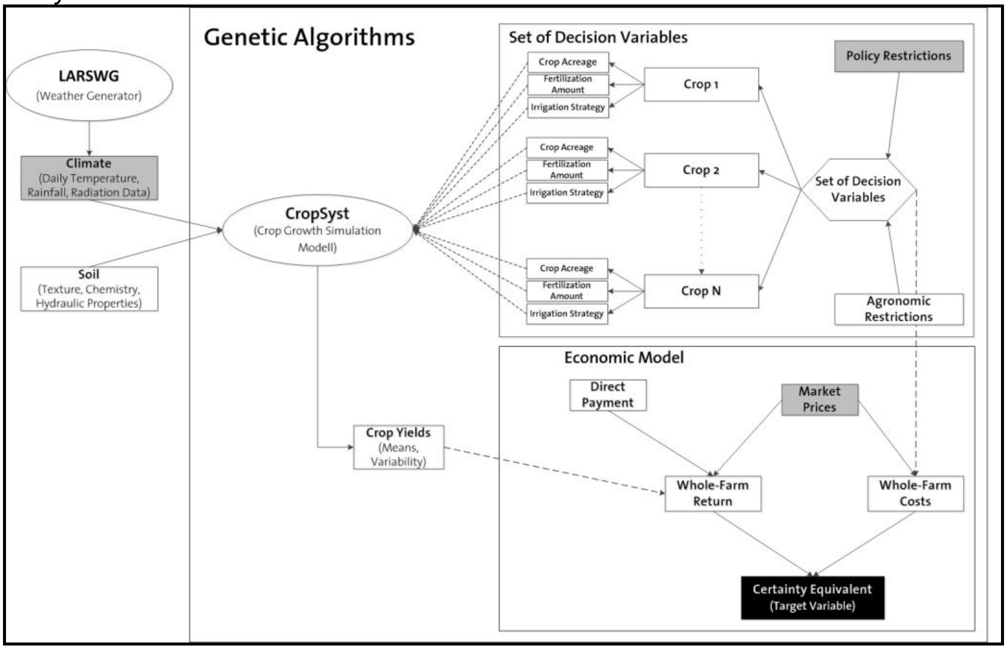

Figure 1 Basic modeling concept. Modified from Lehmann and Finger [2012].

The decision variables generated within the GAs (see upper right section in Figure 1) are passed to CropSyst (see center left section in Figure 1) which simulates the yields of the considered crops (in total we consider six different crops) using the decision variables as management input factors and applying a specific climate scenario. In order to represent production risks due to uncertain weather conditions, the yield simulation procedure for a specific set of decision variables is executed 25 times, using different weather states generated with the stochastic weather generator LARSWG. The generated crop yields are then fed into in the economic decision model (see lower right section in Figure 1) where they are used to compute the whole-farm return and the whole-farm costs taking the specific set of management variables into account. Finally, the whole-farm return and the whole-farm costs are used in order to compute the certainty equivalent (CE), which is the farmer's objective value underlying this optimization procedure.

The represented crop production farm is located in Payerne in Western Switzerland and has a total arable surface of 30 ha. The farmer can cultivate the six most important arable crops in Switzerland (winterwheat, winterbarley, winter rapeseed, grain maize, potato and sugarbeet). We implement the same restrictions of decision variables as Lehmann and Finger [2012] with regard to the maximum crop acreage, balanced supply and demand of nitrogen fertilizer, maximum working load and available field work as well as some crop specific nitrogen fertilization limits into the modeling approach. For instance, we assume a balanced nitrogen supply and demand at farm level following the official Swiss nutrient balance method "Suisse Bilanz" [BLW, 2011], which is required to receive governmental direct payments.

2.1 Set-up of Component Models

The bioeconomic whole-farm model comprises the following component models: the process-based crop growth model CropSyst [Stöckle et al., 2003], the economic decision model at farm-scale and the stochastic weather generator LARSWG [Semenov and Barrow, 1997; Semenov et al., 1998].
CropSyst is used to model the impacts of the farmer's management decisions with regard to the crop acreage, nitrogen fertilization and irrigation strategy on crop yields and yield variability under two different climate and three different water policy scenarios. For this study we use a region-specific CropSyst calibration generated by Klein et al. [2011].
LARSWG is used in order to simulate daily weather data, which are needed as input variables in CropSyst. We apply 25 weather years for a scenario referring to the region's current climate conditions (Baseline) and for a scenario referring to future expected climate conditions around the year 2050 (ETHZ-CLM). In the ETHZ-CLM climate scenario, above all, higher temperatures throughout the year and decreases in precipitation in summer months are assumed (for details see Lehmann and Finger [2012]).
The used economic decision model at farm-scale considers for all crops their revenues, direct payments and fixed as well as variables costs. In a first step the annual profit margin at farm-level for each of the 25 simulation years is computed according to (1):

$$\pi = \sum_{i=1}^{N} a_i \cdot \left(\rho_i + DP_i - c_{fix,i} - c_{irrig,i} - c_{\mathrm{var},i}\right) \qquad (1)$$

Where π is the annual profit margin at farm level, a_i is the cultivated surface of crop i, ρ_i is the revenue of the crop i and DP_i are the governmental direct payments for the crop i. $c_{fix,i}$ stands for the fixed costs (excluding irrigation systems), $c_{irrig,i}$ for the fixed costs of the irrigation systems and $c_{var,i}$ for the variable costs of the crop i.
We use crop specific prices and costs that represent currently observed levels in Swiss agriculture. Furthermore, we account for crop price variability as well as for the correlations between price levels of the considered crops are taken from (see Lehmann and Finger [2012] for details).
The expected profit margin and its variance are subsequently derived from the 25 annual profit margins and finally the farmer's CE, which is the objective function the optimization routine, can be computed as shown in (2):

$$CE = E(\pi) - \frac{1}{2} \cdot \frac{\gamma}{E(\pi)} \cdot \sigma_{\pi}^{2} \qquad (2)$$

Where E(π) is the expected profit margin, σ_π^2 is the variance of the annual profit margin and γ is the coefficient of relative risk aversion. For this study, γ is fixed at a value of 2, which corresponds to a moderate risk-averse decision maker and implies decreasing absolute risk aversion (Di Falco and Chavas 2006).

2.1 Irrigation policy scenarios

Besides two climate scenarios we further consider three different scenarios with regard to irrigation water policies as shown in Table 1. In the scenario "No Restrictions" unlimited irrigation at a water price (including costs for pumping) of 0.01 CHF/m^3 is possible. In the scenario "Higher Water Price" the water price is increased to 1.00 CHF/m^3 while in the scenario "Water Quota" the farm's annual total water consumption cannot exceed 3000 m^3.

Table 1. Water Policy Scenarios

Scenario	**Water Price (CHF/m^3)**	**Maximum Irrigation Amount (m^3/year)**
No Restrictions	0.1	unlimited
Higher Water Price	1	unlimited
Water Quota	0.1	3000

2.3 Management variables and optimization routine

In order to reduce the computation time of the optimization procedure, all decision variables are integrated as discrete values as shown in Table 2. Note that the three decision variables given in Table 2 are used for each of the six considered crops leading to totally 18 management variables at farm-scale.

Table 2. Decision Variables.

Decision variable	**Unit**	**Increment**	**Range (min-max)**
Crop Acreage of Crop i	%	1	1-50
Nitrogen Fertilization Amount of Crop i[a]	kg/ha	10	0-200
Irrigation Trigger Value of Crop i[b]	-	0.1	0-1

[a]) The maximum nitrogen amounts for potatoes and sugarbeet are restricted to 150 kg/ha and 130 kg/ha, respectively, due to losses in yield quality associated with higher application levels.
[b]) For irrigation we use the automatic irrigation option in CropSyst which triggers irrigation as soon as the soil moisture is lower than the user-defined trigger value.

For the optimization routine, the C++ based GA package Galib [Wall,1996] is used applying a steady-state GA with the following control parameters: genome size = 8 bits; population size = 300; proportion of replacement = 0.2; selection routine = roulette wheel; mutation probability = 0.25; crossover probability = 0.5; and a sigma truncation scaling has been used as fitness function. The algorithm is stopped if an optimal solution does not change for a number of 3000 generations.

3 RESULTS

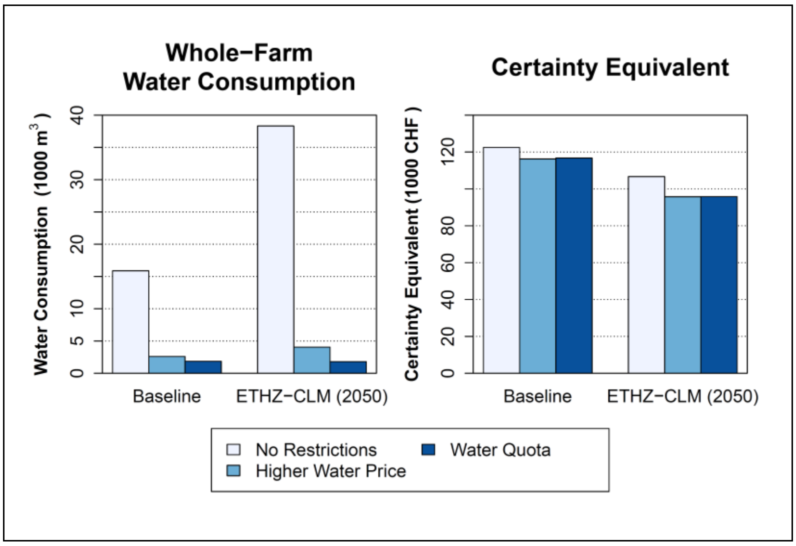

Figure 2: Whole-farm water consumption and certainty equivalent.

In Figure 2 the whole-farm water consumption and the CE for each scenario are presented. Under CC the optimal unrestricted water consumption increases more than 240% compared to the Baseline scenario, while the farmer's corresponding utility, expressed by the CE, decreases by about 13%.
Increasing the water price or implementing a water quota reduces the farm's required water amount. Under CC, for instance, a higher water price decreases the applied amount of irrigation at farm-level from more than 38'000 m^3 in the unrestricted scenario to less than 4'100 m^3. At the same time, the increased water price decreases the farmer's CE only by about 11%. The implementation of water quota reduces the farm's water consumption even more (i.e. to 1800 m^3), while the losses in the farmer's CE also amount to about 11%. Thus, significant decreases of water use can be reached at relatively low costs with both considered policy measures.

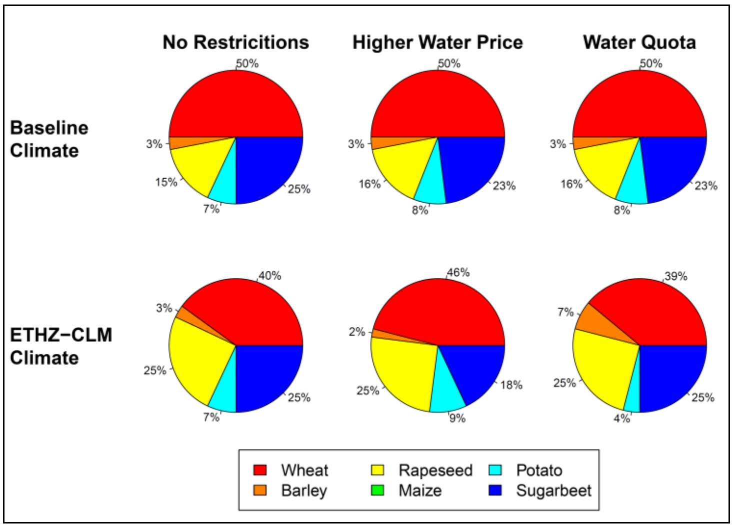

Figure 3: Optimal crop mix.

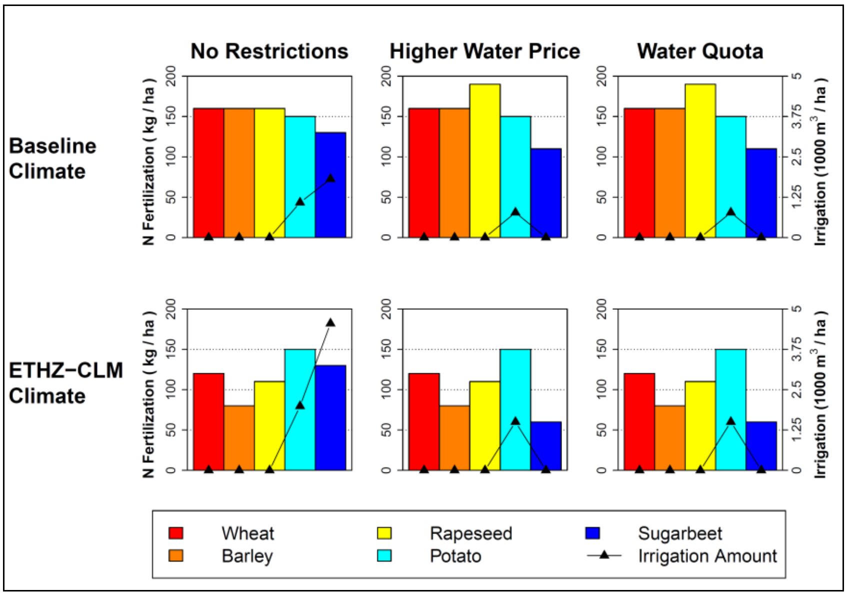

Figure 4: Crop-specific optimal nitrogen fertilization and irrigation intensity.
Figure 4 indicates for each climate and water policy scenario the crop-specific optimal nitrogen fertilization and irrigation amount. Note that grain maize is never included in an optimal crop mix.

Thus, by adjusting the management schemes a farmer can not only minimize utility losses due to CC but also due to the implementation of specific water policies. Such adjustments in the farm's crop management scheme are shown in Figure 3 and Figure 4. CC fosters the cultivation of winter rapeseed at the expense of winterwheat (see Figure 3) and decreases the optimal nitrogen amount for all crops except potato and sugarbeet (see Figure 4). Under the ETHZ-CLM scenario, the introduction of a water quota reduces the total applied nitrogen amount at farm-scale from 3627 kg in the unrestricted water policy scenario to 3027 kg. The optimal potato acreage strongly depends under the ETHZ-CLM scenario on the water policy. While higher water prices increase the optimal potato surface percentage, its acreage is reduced under the introduction of a water quota. Even if an unrestricted water policy is assumed, irrigation is only relevant in potato and sugarbeet production. Under both the current climate and CC (i.e. ETHZ-CLM) scenario, both water policy measures reduce the irrigation intensity in sugarbeet and potato production. Under these scenarios, irrigation is only applied in potato cultivation, where the additional economic benefit of irrigation is larger than for sugarbeet production and the other considered crops. Nevertheless, even under these water policy scenarios sugarbeet is still cultivated without irrigation on a surface between 15%-25% of the total arable land (see Figure 3). But, the optimal nitrogen fertilization amount in rainfed sugarbeet production is reduced significantly (by more than 50%) under the future expected climate conditions (see Figure 4).

4 DISCUSSION AND CONCLUSIONS

We find that CC will significantly increase the water demand of cropping farms in the Broye watershed if current water prices and irrigation policies are maintained. Thus, in order to reduce ecological damages caused by water withdrawals for agricultural purposes, changes in the region’s water policies are required.
Our study shows that both the increase of the water price or the introduction of a maximum annual applicable irrigation water amount are effective policy measures to decrease the region’s water consumption in agriculture. These policy measures reach the goal of reducing the agricultural water consumption not only under current but also under future expected climate conditions. Additionally, the losses in a farmer’s utility due to these water policies are rather small as farmers’ adjustments in management schemes can mitigate negative impacts of such policies on their income. Although both policies have similar impacts on the whole-farm water consumption and the farmer’s utility, they differ under the CC scenario in respect of the adjustments of the farmer’s management decisions. A higher water price, increases the optimal potato surface while the land allocated for potato production is decreased under a water quota system. Nevertheless, irrigation is considered in an optimal management scheme only in potato production under both water policies. Besides the lower required water quantity for irrigation, both water policies also reduce the applied nitrogen fertilization amount at farm-scale which is a harmful input factor for the environment. Thus, stricter water use policies have also important spill-over effects on other environmental targets.
In conclusion, our results indicate that the increasing water demand in agriculture due to CC can be effectively reduced by the introduction of a water quota or by increasing the water price for irrigation. Thus, policy makers should consider these options to cope with CC induced increases in agricultural water demand. Considering a whole-farm perspective reduces the financial burden from these policies for the farmers significantly if compared to single crop investigations because farmers can avoid high costs by switching to other crops. However, we expect that the technical implementation of both policies could create some problems since only farmers face the burdens of these policies. Therefore, future studies should also consider other policy options that allow a re-compensation of farmers for the increased ecological benefits. Furthermore, in order to verify our results, other CC scenarios and scenarios with a higher and lower assumed water price increases as well as different values for the maximum allowable annual water amount should be conducted as sensitivity analysis.

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