# Adapting agricultural land management to climate change: A regional multi-objective optimization study

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

vorgelegt von

**Tommy Klein**

von Lüttich (Belgien)

Leiter der Arbeit:
Prof. Dr. Jürg Fuhrer
Universität Bern, Oeschger Center for Climate Change Research
Head of Air Pollution and Climate Group at Agroscope Reckenholz-Tänikon

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# List of Acronyms

| | |
|---|---|
| **AGWAM** | Water Demand in Swiss Agriculture, and Sustainable Adaptive Options for Land and Water Management to Mitigate Impacts of Climate Change |
| **ETH** | *ETHZ-CLM* (climate scenario) |
| **FADN** | Farm Accountancy Data |
| **GA** | Genetic Algorithm |
| **MPY** | ‘Meteorologically Possible Yield’ |
| **RCM** | Regional Climate Model |
| **RUSLE** | Revised Universal Soil Loss Equation |
| **SMHI** | *SMHIRCA-HadCM3Q3* (climate scenario) |
| **SOMs** | Self-Organizing Maps |
| **WG** | Weather Generator |

# Chapter 1: Summary

Climate change is likely to alter agroclimatic conditions with distinct regional patterns, which necessitates adaptation measures that are adjusted to local characteristics. The multifunctionality of agriculture needs to be included in the development of suitable adaptation options that maintain agricultural production while preventing continued degradation of natural resources.

The objective of this thesis is to identify agricultural land management adaptation measures for a mesoscale catchment in western Switzerland with regard to indicators reflecting major aspects of four important agricultural functions: crop yield (food and fiber production function), soil erosion by water (soil preservation function), nutrient leaching (clean water provision function), and water use (water saving function). To this end, relevant drivers (i.e., local conditions, agricultural practices) that explain high proportions of variance of productivity, erosion, and leaching are first identified. Then, impacts of climate change on the indicators are assessed, with a special focus on emerging trade-offs between the latter. At last, a wide range of measures are generated for adapting (i) the spatial distribution of agricultural land use types and (ii) local cropping practices (i.e. irrigation and fertilization levels, crop rotation choice, tillage, and residue operations) with the goal to minimize negative effects of climate change on the different indicators.

The method relies on the integration of the generic crop model CropSyst within a spatial optimization routine that combines the four indicators in a performance criterion. First, CropSyst has been calibrated for Swiss conditions based on a novel calibration method relying on the widely available Farm Accountancy Data (FADN) as reference. The calibration procedure includes the Morris method for parameter screening and a genetic algorithm for automatic parameter estimation. Second, CropSyst has been coupled with empirical functions to account for livestock production in terms of fodder consumption, nutrient loads and water intake. The crop model in connection with the livestock model were applied to test a multitude of management scenarios under different conditions including soil type, slope, or current and future climate. Third, by integrating these models into a multi-objective spatial optimization routine, a series of optimum trade-off scenarios for regional adaptation strategies were produced by varying weights of each indicator.

The study region is the Broye catchment that exhibits a wide range of local conditions and a steep elevation gradient. Under current climate conditions, northern plains are appropriate for intensive cultivation of arable crops while southern hilly parts are mostly used for livestock and fodder productions. The Broye is characterized by relatively low precipitation levels, and irrigation is a common management strategy for certain crops. Water resources for irrigation are mainly withdrawn from surface water bodies, and water scarcity in rivers is regularly a serious issue in this catchment.

Results of this thesis indicate a trend for median productivity to decrease by $2-3\%$, for median erosion to increase by $25-30\%$ due to shorter crop growth cycles and increased rainfall intensity in fall/winter, and for median nutrient leaching to increase by $43-52\%$ as a consequence of higher mineralization rates in a warmer and sufficiently wet climate. A trade-off exists among agricultural productivity and environmental impacts, and results show that this trade-off aggravates with climate change.

Without changes in agricultural land management (status-quo scenario), mean regional productivity of crops in the Broye catchment is expected to decrease by $0-10\%$ for the time horizon 2050, in parallel with an increase in water needs by $20-50\%$. In contrast to those moderate changes in productivity, impacts of climate change on erosion and nutrient leaching are expected to be largely negative (increase by $30-45\%$ for leaching and $25-35\%$ for erosion).

Results demonstrate that even under an extreme climate scenario effective adaptation options are possible; the latter outperform the status-quo scenario in terms of productivity, erosion and leaching. In contrast, water saving cannot be improved, and water needs are expected to be 4 to 5 times higher than today, but without exceeding future surface water availability on average. Necessary management changes to reach those options include (i) adjustments of crop shares, i.e. increasing the proportion of early harvested winter cereals at the expense of irrigated spring crops, (ii) widespread use of conservation soil management, (iii) allocation of irrigated areas to soils with low water-retention capacity at lower elevations, and (iv) conversion of some pre-alpine grasslands ($> 700$ m) to croplands.

Overall, this thesis shows that negative climate change impacts on agroecosystems in the Broye catchment around 2050 can be limited to a large extent by adaptation. However, such adaptation measures are expected to cause a sharp increase in the region's agricultural water demand.

# Chapter 2: Introduction

## 2.1 Context

### 2.1.1 Observed changes in Europe

Indications that climate change is already taking place have been repeatedly reported in recent studies. In Europe, an increase in surface air temperature of 0.9 °C in annual mean temperature over the entire continent has been observed during the period 1901-2005 (Alcamo et al., 2007), with a more pronounced warming in the last decades (Moberg and Jones, 2004). It has been shown that trends are higher in central and northern Europe (in particular in mountainous regions), and more pronounced in summer (Alcamo et al., 2007). In Switzerland, Ceppi et al. (2012) found seasonal positive and highly significant trends towards an increase in temperatures, with an average annual warming rate of 0.35 °C /decade during 1959-2008 and of 0.46 °C /decade in summer. They also highlighted the altitude dependence of surface temperature trends, which is likely to be influenced by changes in atmospheric circulation, snow-albedo feedback effects, and other local processes.

Changes in the rainfall pattern are less obvious and more complex. Nevertheless, previous studies indicate a global increase in precipitation over the last 50 years, mostly resulting from an increase in very wet and extremely wet days (Alexander et al., 2006). In Europe, a similar trend towards higher precipitation extremes was suggested (Klein Tank and Können, 2003; van den Besselaar et al., 2012). In terms of rainfall amount, no change in summer precipitation has been detected in northern Europe during 1951-2010, while a slight increase in winter precipitation by 5 mm/decade was found to be significant for 30% of the stations (van den Besselaar et al., 2012). In recent decades, trends towards drier summer conditions in central Europe have been observed, as a consequence of increased summer temperatures rather than precipitation changes (Briffa et al., 2009).

In western Europe the potential yields of main crops have been found to be stable and almost not affected by the changing temperature and radiation patterns (Supit et al., 2010b). However, yields have continuously and considerably increased in all European countries (Olesen et al., 2011) as a consequence of improved technologies. Nevertheless, despite the fact that genetic progress has not declined, yield increases have leveled off appreciably during the past 10-20 years, which is attributed to rising temperatures (Brisson et al., 2010). In Switzerland, changes in legislation in favor of low inputs have also largely contributed to the stagnation of crop yields (Finger, 2010).

Short-term adjustments of agricultural practices have been observed during the recent decades, mainly earlier sowing of spring crops - which is sometimes contested (see e.g. van Oort et al., 2012) - and adoption of longer season cultivars in Europe (Olesen et al., 2011), as well as in other regions of the world (Sacks and Kucharik, 2011). Also, cultivation techniques to better manage soil resources have become progressively more important. For instance, the use of reduced or no tillage in Switzerland in order to reduce soil erosion has increased from a few hectares in the 1980s to about 12,000 ha in 2006 (Ledermann and Schneider, 2008).

### 2.1.2 Vulnerability of agriculture to climate change

Agriculture is among the economic sectors that are most vulnerable to climate change. Vulnerability can be defined as a function of the degree of exposure to climate hazards, the sensitivity to changes in climate, and the adaptive capacity of the system (IPCC, 2007).

In Switzerland, the exposure of agriculture to climate hazards is expected to increase in the future, partly due to an increase in drought risk in a warmer climate (Calanca, 2007). Climate projections with the A1B emission scenario show a significant rise in temperature increasing from $0.9-1.4$ °C by 2035 (depending upon the region and season) to $2.0-2.9$ °C by 2060, while significant changes are expected towards drier summers, which are, however, subject to large uncertainties (Fischer et al., 2012).

Climate change during the next decades is first expected to lead to positive effects on agriculture in cool and temperate regions of Europe through the lengthening of the growing season and the expansion of suitable areas for crop cultivation (Alcamo et al., 2007). However, the combination of increased air temperature, changes in the amount and distribution of precipitation, and increasing drought during the cropping season are likely to increase the number of unfavorable years, which may cause more frequent crop loss, yield instability, and make areas less suitable for traditional crops (Olesen and Bindi, 2002). Furthermore, extreme weather events can dramatically reduce crop yields when occurring during sensitive phases (e.g. flowering), and such events are likely to become more common under climate change (Challinor et al., 2006).

Autonomous adaptation options include adjustments of crop rotations (e.g. shifting from high to low water-demanding crops), changes in production intensities, use of reduced tillage, integration of cover crops, or adoption of irrigation with higher efficiency. Key to the ability of farmers to adapt to climate change will be (i) access to relevant knowledge and information (Challinor et al., 2007), and (ii) sufficient access to capital and technologies (Easterling and Apps, 2005). Other drivers that are expected to determine the adaptive capacity of farmers are (i) socio-economic conditions and farm characteristics (Reidsma et al., 2007), and (ii) the degree of climate change awareness (Marshall et al., 2013) which emphasizes the need to improve the climate change knowledge and that institutions communicate this information to farmers on a regular basis (Howden et al., 2007). Adaptation to climate change must be considered in the context of other driving forces, such as market, policy and technological development, which may reshape the farming landscape even more than climate change itself (Mandryk et al., 2012). To evaluate the adaptive capacity of agroecosystems to climate change, Iglesias et al. (2011b) proposed an index with three major components that characterize the economic capacity, human and civic resources, and agricultural innovation. In addition to autonomous adaptations, planned adaptations are expected to play a major role too (Easterling et al., 2007), mostly by developing infrastructure (e.g. water reservoirs or introduction of suitable landscape elements to reduce runoff), but also building the capacity to adapt in the broader user community by putting in place institutional and macro-economic conditions that support and facilitate adaptation at different levels of decision. Adequate policies and subsidies schemes are expected to be important drivers to foster the development of agricultural systems (Nelson et al., 2009).

### 2.1.3 NRP61 Research Program and AGWAM project

This dissertation has been conducted in the framework of the National Research Program 61 on sustainable water use (NRP61) within the project entitled ‘Water Demand in Swiss Agriculture, and Sustainable Adaptive Options for Land and Water Management to Mitigate Impacts of Climate Change (AGWAM)’.

The main objective of AGWAM is to develop sustainable recommendations (i) to optimize the use of water, while maintaining economic profitability and environmental standards, under scenarios for climatic, socio-economic and political development, and (ii) to identify regulatory actions needed to facilitate implementation of adaptive measures (Fuhrer et al., 2009).

Specifically, the AGWAM project aims to investigate the following three research questions (Fuhrer et al., 2009):

1. *What is the water consumption by agriculture in two selected regions (catchments) under present and future conditions (considering climate, economy and agricultural policy), and how large is the risk to agricultural production due to reduced water availability?*
2. *How can we optimize strategies for water conservation in agricultural land use (forage, crop and livestock production) at the regional (catchment) scale, and at*

*the scale of individual farms, and what are the environmental impacts of such strategies?*

3. *What recommendations for management and policy measures can be made to implement sustainable water use in Swiss agriculture considering a range of possible climate change scenarios?*

In the project, two decision levels are considered: the regional scale (this Ph.D. thesis) and the farm scale (Ph.D. thesis by Lehmann, 2013). The identified adaptation at both scales are then analyzed via a Life Cycle Assessment method to explore wider environmental implications (Ph.D. thesis by Tendall, in preparation). Two different regions are investigated: (i) the Broye catchment in western Switzerland (results presented in this thesis), and (ii) the Greifensee catchment in the region of Zurich (results not shown).

## 2.2 Overall objectives

This thesis aims to assess expected impacts of climate change in the Broye catchment for the time horizon 2050 and to explore spatially-explicit adaptation options to maintain agricultural productivity to the current level with minimal water use and minimal environmental impacts (i.e. erosion and nutrient leaching). The development of guidelines for adapting Swiss agriculture to climate change with regard to multiple objectives considering local conditions (e.g. soil and weather) is a top priority as stated in the last 'Federal Council's strategy on Adaptation to climate change in Switzerland' (FOEN, 2012a).

More specifically, this thesis addresses the following research questions:

1. *How can a crop model be calibrated in data-limited situation for climate impact studies?*
2. *Which agricultural practices have the greatest potential for adaptation of multifunctional agriculture?*
3. *What are the trade-offs resulting from adaptation?*
4. *What are the benefits of regional adaptation compared to the status-quo scenario?*
5. *Which guidelines can be provided based on this work for adapting agricultural land management in the Broye catchment around 2050?*

The method relies on the use of the generic crop model CropSyst (Stöckle et al., 2003). The first question raised above is related to the tuning of the model for Swiss conditions. After CropSyst calibration, it was coupled with empirical functions to represent livestock production (i.e. fodder consumption, water intake, and nutrient loads). The model was then integrated within a spatial optimization routine, and applied in combination with climate scenarios to investigate other questions.

## 2.3 Structure of the thesis

This thesis consists of three main parts. The first part provides the necessary background information on the main aspects addressed in this dissertation (Chapter 3). At first, the concept of multifunctionality of agriculture is introduced. Second, a state of the art knowledge on expected impacts of climate change on agroecosystem functions is presented. Third, an overview of potential adaptations to climate change is provided, with references to recent quantitative studies based on modeling approaches. In particular, the importance of the choice of the spatial scale, and the link with decision-making support are emphasized. Fourth, a review of recent studies where optimization methods have been applied to solve complex agricultural problems is presented. Fifth, the main gaps and shortcomings of previous studies are summarized, and the motivations for the development of new tools are highlighted. At last, the study region (Broye catchment) is introduced, with a special focus on important drivers and the current/future importance of irrigation in the region.

The second part is structured according to four self-contained publications, three of them that form the backbone of this thesis, and one by Lehmann et al. (2013) realized in the framework of AGWAM and for which I was involved. The first article (Chapter 4) describes the automatic calibration procedure that has been developed and applied to the model for subsequent climate impact studies. The originality of the approach is that it relies on Farm Accountancy Data (FADN) as reference, which means that the method can be used at many locations where this dataset is available. The second paper (Chapter 5) addresses the sensitivity of CropSyst after calibration to climate change, a wide range of agricultural practices, and local soil conditions. The goal of this paper is to explore which agricultural practices and combinations of them are relevant for adaptation to climate change with regard to multiple agroecosystem functions, and considering two soil types as local constraints. In addition, simple adaptation options are envisaged focusing separately on the different functions, and the resulting trade-offs are analyzed. The third paper (Chapter 6) presents the main results of the spatial multi-objective optimization routine developed here and applied to the Broye catchment. More specifically, benefits of adaptation as compared to the status-quo scenario are examined. Compromise adaptation options avoiding trade-offs are extracted and analyzed to provide guidelines for suitable agricultural land management to achieve those options. A last paper (Chapter 7) by Lehmann et al. (2013) applied the calibration of CropSyst derived from the first paper (Chapter 4) to investigate adaptation to climate change at the field level with economic considerations.

In the third and final part of this thesis (Chapter 8), results of the three main articles are summarized and discussed in the context of the present research questions. In addition, main implications of modeling limitation and uncertainties are discussed. At last, a short outlook summarizes perspectives for further work, in particular possible ways to deal with the identified uncertainties in a future implementation of this modeling framework.

# Chapter 3: Background

## 3.1 Multifunctional role of agriculture

The concept of multifunctionality of agriculture was first mentioned in the Agenda 21 documents of the Rio Earth Summit in 1992 (UNCED, 1992). It refers to the fact that, besides its primary role of producing food and fiber, agriculture also has relevant effects on several other functions, such as the management of renewable natural resources, landscape, conservation of biodiversity and contribution to the socio-economic viability of rural areas.

The concept of multifunctional agriculture has attracted many scientific contributions from different disciplines, and led to the development of a wide range of conceptual approaches and prospects (for a review see Renting et al., 2009). The multifunctionality of agriculture may be structured according to four main categories based on the degree of attention and the level of analysis (Caron et al., 2008):

1. market regulation approaches: central attention to economic aspects and to governance mechanisms for structuring markets;
2. actor-oriented approaches: focus on issues at the farm level, in particular to decision-making of actors in the social construction of multifunctional agricultural practices;
3. public regulation approaches: particular attention to institutional and policy aspects;
4. land use approaches: focus on spatial issues related to the multifunctionality of agriculture and rural areas. This category originates from natural scientific disciplines (e.g. landscape/conservation ecology, geography, land use planning) and constitutes an intensively researched and heterogeneous set of approaches for analyzing natural resource use and climate change mitigation and adaptation (Renting et al., 2009). In the literature, numerous studies in connection with land use approaches can be found either to assess agricultural ecosystem services at the regional scale (e.g. Ausseil et al., 2013; Koschke et al., 2013) or to explorative trade-offs between economic and environmental goals (for a review see Rossing et al., 2007).

Throughout this thesis, four different agricultural functions will be investigated: (i) food and fiber production, (ii) soil conservation, (iii) clean water provision and (iv) water saving. Those functions were found to be strongly affected by climate change in previous studies (Bindi and Olesen, 2010; Nearing et al., 2004; Olesen and Bindi, 2002) and are particularly important in the context of adaptation in Switzerland (FOEN, 2012a). To analyze those functions, diverse indicators reflecting the main aspects were defined (see Table 3.1).

**Table 3.1:** List of agricultural functions considered in this dissertation and, for each of them, the indicator that was analyzed, and associated units.

| **Agricultural function** | **Indicator** | **Unit** |
|---|---|---|
| Productivity | Crop yield | scaled between max and min possible yields and averaged over the rotation |
| Soil conservation | Erosion | t $ha^{-1}$ $yr^{-1}$ |
| Clean water provision | Nutrient leaching | kg N $ha^{-1}$ $yr^{-1}$ |
| Water saving | Irrigation and water intake by livestock | $m^3$ $ha^{-1}$ $yr^{-1}$ |

## 3.2 Expected impacts of climate change on agroecosystems

Agriculture exhibits known observed responses to inter-annual, monthly and daily distribution of climate variables, such as temperature, radiation, precipitation, water vapor pressure in the air and wind speed (Easterling et al., 2007). Changes in seasonal precipitation and temperature patterns are of major importance (Olesen and Bindi, 2002). Higher temperatures are expected to accelerate crop development yielding in short periods of biomass accumulation and lower yields (Rötter and Van de Geijn, 1999). Changes in the variability and frequency of extreme events are also likely to be determinant factors as crops can exhibit highly non-linear and threshold responses (Porter and Semenov, 2005).

In recent years, many studies have been conducted assessing climate change impacts on agroecosystem functions in different regions of the world, mostly based on simulation models (see Section 3.2.1). Key results of earlier studies are summarized in the following sections, in order to give some insights into understanding how climate change is expected to affect agricultural systems, with a special focus on Switzerland. Besides effects of climate change on productivity (Section 3.2.2), which corresponds to the variable analyzed in climate impact studies most often (White et al., 2011), the main trends of expected impacts of changing climate on erosion (Section 3.2.3), nutrient leaching (Section 3.2.4) and water needs (Section 3.2.5) are also presented since they are central aspects in this thesis.

### 3.2.1 Simulation models

Efforts to investigate the effects of climate change on agriculture are primarily based on simulation models (Challinor et al., 2009). Two main types of models can be distinguished: dynamic system models and response-based models. Dynamic crop models represent processes underlying crop growth and development with much simpler representations, allowing one to study the evolution of the overall crop-soil system. Response-based models analyze the effect of input variables on response variables based on statistical regressions. They have been occasionally used to assess impacts of climate change (e.g. Iglesias et al., 2011a, 2010) but their validity is limited to conditions for which they have been calibrated as opposed to dynamic equations (Wallach et al., 2006).

For this thesis, the dynamic crop growth model CropSyst (Stöckle et al., 2003) is used. It is a multi-year, multi-crop cropping system model, which operates on a daily time scale. It has the ability to simulate effects of local conditions (i.e. soil, slope, weather) and a wide range of management options (crop rotation, cultivar selection, irrigation, N fertilization, tillage operations, and residue management) on cropping systems and the environment. Outputs from CropSyst include soil water and nutrient budgets, crop phenology, canopy/root growth and biomass production, final crop yield, residue production and decomposition, soil erosion by water, and salinity. CropSyst has been used in the context of climate impact studies in Europe (see e.g. Moriondo et al., 2010a; Tubiello et al., 2000), in Africa (see e.g. Tingem et al., 2008), and at some occasions in Switzerland (see e.g. Torriani et al., 2007).

Crop models such as CropSyst contain many parameters, and a critical problem is obtaining the values of those parameters. It is well known that model calibration has implications for the overall reliability of simulations (Challinor et al., 2009) and is indispensable to improve the accuracy of predictions in climate change studies (Jagtap and Jones, 2002). However, the amount of experimental data for calibration is in general limited because experimentation on crop systems is lengthy and expensive in terms of land, equipment and manpower (Wallach et al., 2006). Another important aspect is that the larger is the number of parameters, the greater is the risk of reproducing observations without representing the processes involved correctly, which decreases the reliability of the model when it is run with climate change data (Challinor et al., 2007). Therefore, the number of parameters to be calibrated needs to be reduced in order to prevent computational problems (Confalonieri, 2010; Janssen and Heuberger, 1995; Tremblay and Wallach, 2004; Wallach et al., 2011).

### 3.2.2 Agricultural productivity

Europe is one of the world's largest and most productive suppliers of food and fiber, accounting for 19% of global meat production and 20% of global cereal production in 2008 (Olesen et al., 2011). Under present climate, drivers and limiting factors differ across regions. For instance, it has been shown that yields in northern Europe are limited by cool temperatures (Holmer, 2008), whereas yields in southern Europe are limited by high temperatures and low rainfall (Reidsma and Ewert, 2008). Changing climate conditions could cause significant shifts in agroclimatic zones in Europe (Trnka et al., 2011) and impacts are expected to depend on crops and regions (Supit et al., 2012). Northern Europe may first benefit from climate change through the expansion of suitable areas, but the positive effects are likely to be reversed at temperature increases exceeding 4 °C for cereal production (Rötter et al., 2011b). In contrast, disadvantages of global warming are found to predominate in the South, already with moderate climatic changes (Iglesias et al., 2011a).

In Swiss agriculture, negative impacts on productivity are expected by the end of the century, together with an increase in production risks (Fuhrer et al., 2006; Torriani et al., 2007). Torriani et al. (2007) suggest in their projections for the end of the 21st century without $CO_2$ fertilization effect that rainfed mean yields will decrease by 34, 26 and 46% for maize, winter wheat and canola, respectively. They found that $CO_2$ fertilization could compensate crop losses and even lead to an increase in wheat productivity in the future. Holzkämper et al. (2012) fitted a statistical model to CropSyst simulations to investigate effects of temperature/precipitation changes in mean values and variability on maize yields. They found that an increase in mean temperature will lead to increased maize yields as maize growth is currently limited by sub-optimum temperatures in Switzerland during early phases (Holzkämper et al., 2013), while an increase in temperature variability will lead to decreased productivity. In terms of rainfall, a decrease in mean precipitation will reduce yield considerably, while an increase in precipitation variability (i.e. extension of dry spells, shortening of wet spells) will have only small negative effects on yield levels. Calanca and Fuhrer (2005) analyzed grassland production under projected climate change scenarios and concluded that, with moderate climatic changes, grassland production in Switzerland will benefit from elevated atmospheric $CO_2$ concentrations and more favorable temperature and radiation conditions, resulting in an increase in total grassland production of about 50%. Similar results were obtained by Finger et al. (2010) when $CO_2$ fertilization effect was considered while grassland yields decreased when this effect was excluded.

### 3.2.3 Erosion

In most studies, a trend towards soil loss increase with changing climate was modeled (Nearing et al., 2005; Yang et al., 2003). Rainfall amounts and storm intensities are certainly the most direct and important factors controlling erosional changes under climate change (Nearing et al., 2004). 1% increase in precipitation is expected to lead to $1.5 - 2\%$ increase in erosion rates (Nearing et al., 2004). Michael et al. (2005) showed that precipitation intensities increase alone would have impacts on soil loss ranging from $+22$ to $+66\%$ in Saxony (Germany) depending on the slope steepness. Some studies found opposite trends towards decreased erosion under climate change. For example, Scholz et al. (2008) predicted a decrease in erosion rates by 11 to 24% on sugar beet fields in central Europe in tillage systems, because of a decrease of rainfall amounts in erosion sensitive months and an overall increase of rainfall in less-prone-to-erosion periods. In addition to changes in rainfall pattern, changes of plant biomass will also play a major role to control soil loss as plant canopies reduce soil erosion by weakening the power of rain, roots stabilize soils, and crop residues reduce sediment transportation (Lotze-Campen and Schellnhuber, 2009).

In general, Switzerland is moderately susceptible to soil erosion, but some soil types such as those formed of alluvial deposits have proved to be prone to erosion (Mosimann, 1990). It has been suggested that soil erosion rates are likely to increase because of more frequent and intense rainfalls (Fuhrer et al., 2006). Wanner (2013) tested the sensitivity of CropSyst to different climate scenarios, crop choice, soil management for diverse locations and concluded that, overall, soil loss rates are expected to increase with climate change in Switzerland (up to $+54\%$ in northern parts of the Alps), mainly due to changes in rainfall erosivity, soil cover, and seasonal rainfall patterns.

### 3.2.4 Nutrient leaching

Impacts of climate change on nutrient leaching remain difficult to predict as not yet fully understood, but predictions suggest that leaching rate may increase under future climate scenarios (Stuart et al., 2011). Higher temperatures are likely to accelerate the decomposition of organic matter due to stimulation of microbial activity, leading to higher soil nutrient supply. If mineralization exceeds plant uptake, which primarily occurs during winter time when plant demand is low or plants are absent, then nutrient leaching will be the consequence. However, the overall effect of climate change on organic matter mineralization will depend on how climate change affects soil moisture (Leirós et al., 1999). Indeed, decomposition should be faster in regions where temperature increases greatly and soil moisture remains high enough to allow decomposition (e.g. North and East Europe), but does not become faster where the soil becomes too dry, despite higher temperatures (Smith et al., 2005).

Dueri et al. (2007) conducted a Swiss case study based on a modeling approach to analyze how climate change will affect N losses in crop and livestock farming, with current and longer cycle crops. Temperature changes ranging from $+2$ to $+5$ °C were tested, in combination with precipitation change from $+5$ to $-20\%$. The results of their study show that, without adaptation, N losses in the form of leaching will decrease by 12/21% for crop / dairy farm under climate change, while other sources of N loss (denitrification, ammonia volatilization) will become substantially higher.

### 3.2.5 Water needs

No trend towards an increased water demand in Swiss agriculture has been detected over 1981-2010 (Fuhrer and Jasper, 2012), but irrigation requirements in drier sub-regions may be substantially higher than those estimated with larger-scale models. Water demands in extreme years (e.g. 2003) were found to be several times higher than in ‘average’ years, exceeding the limits of surface water availability (Fuhrer and Jasper, 2012).

In the coming years, climate change will further increase water requirements for irrigation in agriculture (Fuhrer and Jasper, 2009) and water shortages are, therefore, assumed to become even more frequent. Based on surveys sent to farmers and considering a future decrease of rainfall by 25%, Robra and Mastrullo (2011) estimated that irrigation amounts will be 5 times higher in the future in the Broye.

Projected hotter summers may also mean that livestock needs to be housed to reduce problems from heat stress or because pastures may not remain productive (Iglesias et al., 2011c). In addition, it has been shown that environmental factors including climatic conditions can affect drinking behavior of livestock (Cardot et al., 2008). For instance, in a 4 °C warmer climate, water intake by dairy cows will increase by 30% (McDonald et al., 2011). However, it should be noted that water consumption by animals is generally negligible compared to irrigation water needs.

## 3.3 Adaptation options

According to Smith (2002), agricultural adaptation options can be grouped into four main categories: (i) technological improvements (e.g. the development of new crop varieties or new irrigation systems), (ii) government programs and insurance (e.g. government income stabilization programs), (iii) farm production practices (e.g. crop substitution, production intensification, or crop mix), and (iv) financial management of farms (e.g. crop insurance). However, categories are often interdependent; for example, government programs to develop financial incentives or new technologies might be adopted to modify farm production practices. Martin et al. (2012) make a distinction between two types of adaptation: (i) exploitative innovations (incremental) designed to improve existing farming systems in order to achieve clearly identified new goals to better cope with the changing world and (ii) exploratory innovations (more radical) designed to meet emerging aspects of the production context or create new production outputs. However, previous modeling approaches rarely attempted the development of exploratory innovations, despite the acknowledged strong need for it (Howden et al., 2007).

### 3.3.1 Current state of knowledge

A gap between potential and actual yields is observed in many regions of the world. It has been shown that the average yield in rainfed systems is commonly 50% or less of yield potential, suggesting ample room for improvement (Lobell et al., 2009). Mueller et al. (2012) reported that adapting nutrient management could close yield gaps in most agricultural areas across the world, except for drier regions in East Africa where irrigation plays a more important role.

Previous studies generally ignored interactions between different ecosystem functions (Betts, 2007). However, results of such studies can be misleading since it is known that adaptation strategies for improving crop yield may lead to new conflicts or aggravate existing ones with other agricultural functions (Schröter et al., 2005). Typically, a trade-off exists between food production and regulating functions, but, recent studies suggest that this trade-off is not inevitable (Power, 2010). For instance, Mueller et al. (2012) found that opportunities exist to reduce the environmental impacts of agriculture by eliminating nutrient overuse while still allowing an approximately 30% increase in production of major cereals. To prevent degradation of natural resources while maintaining decent yield levels, there is a need to carry out impact studies that consider interactions between multiple functions (Betts, 2007). Moreover, policy will need to support the adaptation of agriculture while considering the multifunctional role of agriculture to strike a balance between economic, environmental and social functions (Olesen and Bindi, 2002).

Most of quantitative studies on the vulnerability of agricultural systems to climate change focus on impacts, while adaptation strategies are often highly simplified (Reidsma et al., 2007), although the latter is a key factor that will alter impacts of climate change (Iglesias et al., 2011c; Lobell et al., 2008). Thanks to their ability to explore large sets of management options, biophysical models are used more and more often to examine options for adaptation as evidenced by a large number of recent studies (Iglesias et al., 2011a; Moriondo et al., 2010a; Rötter et al., 2011b; Ruane et al., 2013; Thaler et al., 2012; Ventrella et al., 2012). Several studies suggest great potential of short-term adaptations associated with low costs, such as change in crops (Kurukulasuriya and Mendelsohn, 2008), changing cultivation practice (e.g. planting date, see e.g. Tubiello et al., 2000), adjustment of fertilization intensity (e.g. Van Ittersum et al., 2003), change in irrigation intensity (e.g. Ventrella et al., 2012), use of alternative tillage practices (e.g. Scholz et al. (2008) for erosion, Thaler et al. (2012) for productivity and leaching). Longer-term adaptations with higher technical difficulties and higher costs have also been tested occasionally (Iglesias et al., 2011c), such as the introduction of irrigation to rainfed areas (e.g. Moriondo et al., 2010a), or the development of climate change resilient crops (for instance later maturing new cultivars to take advantage of longer growing seasons, see e.g. Tingem et al., 2008).

Crop-simulation studies are often incomplete with respect to the crops investigated (often only one) and the number of agricultural practices considered (Table 3.2). Typically, only one cropping practice is tested, sometimes two, but rarely more than three. To the latter category belongs the

**Table 3.2:** Number of climate impact papers (literature review) that tested specific cropping practices as a potential for adaptation and the total number of practices that were varied per paper (from White et al., 2011).

| Practice | No adaptation | 2-4 options | 5 or more options | Automatic regime |
|---|---|---|---|---|
| Planting date | 119 | 34 | 37 | 31 |
| Fertilization | 186 | 17 | 10 | 8 |
| Tillage practices | 197 | 10 | 1 | 0 |
| Irrigation | 23 | 28 | 3 | 19 |
| Cultivar | 157 | 32 | 14 | 18 |
| Rotation choice | 209 | 9 | 3 | 0 |

| | None | 1 | 2 | 3 | >3 |
|---|---|---|---|---|---|
| Total practices varied per paper | 55 | 73 | 59 | 26 | 8 |

study by Ruane et al. (2013) who investigated the effect of season length, planting date, fallow period, soil type, cultivar choice and fertilizer use on maize growth in Panama. They found that planting dates and soil types are important drivers of maize yield. Planting date and use of cultivar with a longer/shorter growth cycle were the most frequently varied options in the literature, while tillage and crop rotation choice have almost never been tested (Table 3.2). Effects of tillage and residue management remain difficult to simulate with generic crop models (Sommer et al., 2007), while changes in crop rotations are complicated to implement because of (i) the lack of empirical data for a proper representation of crop rotations (Schönhart et al., 2011) and (ii) the fact that models need to be calibrated specifically for every crop involved in the rotation. In general, modeling studies exploring effects of climate change and potential for adaptation focus on impacts on economic yield (Table 3.3), neglecting other functions. However, exceptions can be found in the literature. This is for example the case of Van Ittersum et al. (2003) who assessed impacts of climate change and agricultural practices on numerous variables connected to biomass and N allocation. Soil erosion and nutrient leaching were analyzed in relatively few cases.

A few quantitative studies have been addressing possibilities for adaptation to climate change in Swiss agriculture, in particular to minimize yield decreases. Torriani et al. (2007) found that early sowing and use of crops with longer growth cycle greatly offset negative impacts of climate change on maize yields, and can even lead to higher yields than under present climate. Moriondo et al. (2010a) showed that longer growth cycle was an efficient adaptation strategy to reduce vulnerability to climate change in sunflower, soybean, spring/winter wheat. Wanner (2013) investigated adaptation options to mitigate erosion on Swiss agricultural lands and found that soil conservation practices are effective methods to control soil erosion under climate change, especially the use of mulching or catch crops. The efficiency of direct seeding is expected to decrease in a warmer climate due to faster decomposed residues, but it remains nevertheless the most effective way to reduce erosion (Wanner, 2013). Dueri et al. (2007) found that slower maturation crops would have

**Table 3.3:** Number of climate impact papers (literature review) that assessed climate change impact for a given crop, environmental or socio-economic variable (from White et al., 2011).

| **Assessment of impact in terms of:** | **Completeness of assessment** | | | | |
|---|---|---|---|---|---|
| | Full | Partial | Semi-quantitative | Qualitative | Speculative |
| Economic yield | 175 | 11 | 1 | 3 | 0 |
| Biomass | 32 | 6 | 0 | 2 | 0 |
| Yield quality (e.g., grain nitrogen conc.) | 9 | 4 | 0 | 3 | 0 |
| Yield components (e.g., mass/grain) | 11 | 0 | 0 | 2 | 0 |
| Phenology (flowering, maturity) | 62 | 12 | 1 | 6 | 0 |
| Harvest date | 17 | 2 | 2 | 1 | 0 |
| Water use or evapotranspiration | 45 | 6 | 6 | 4 | 0 |
| Water use efficiency | 22 | 1 | 0 | 1 | 0 |
| Water stress index (of simulation model) | 6 | 0 | 0 | 0 | 0 |
| Soil water level or groundwater recharge | 18 | 2 | 0 | 1 | 0 |
| Runoff | 13 | 1 | 1 | 0 | 0 |
| Nitrogen use or uptake | 17 | 2 | 0 | 0 | 0 |
| Nitrogen use efficiency | 0 | 0 | 0 | 0 | 0 |
| Soil nitrogen level | 4 | 1 | 0 | 0 | 0 |
| Soil carbon | 4 | 1 | 0 | 0 | 0 |
| Greenhouse gas emissions | 5 | 1 | 0 | 0 | 0 |
| Soil erosion | 13 | 0 | 0 | 0 | 0 |
| Salinity | 2 | 0 | 0 | 0 | 1 |
| Geographic distribution of crop | 10 | 8 | 4 | 4 | 1 |
| Net economic return | 11 | 2 | 1 | 1 | 0 |
| Regional or global markets | 2 | 1 | 0 | 0 | 0 |
| Other impacts[a] | 40 | 5 | 1 | 0 | 1 |

[a] Aridity, Bowen ratio, Climate class, Economic indicators, Fractional leaf area, Harvest index, Irrigation use efficiency, Land area suitable for bench terracing, Leaf blast disease progress, Maximum leaf area index, Net US grain production, Net primary productivity, Nitrate leaching, Nitrogen loss, Safe planting date, Sea level rise, Surface pesticide loss, Water stress index, Water stress, Water temperature, Water yield (watershed scale), Water yield, Yield loss.

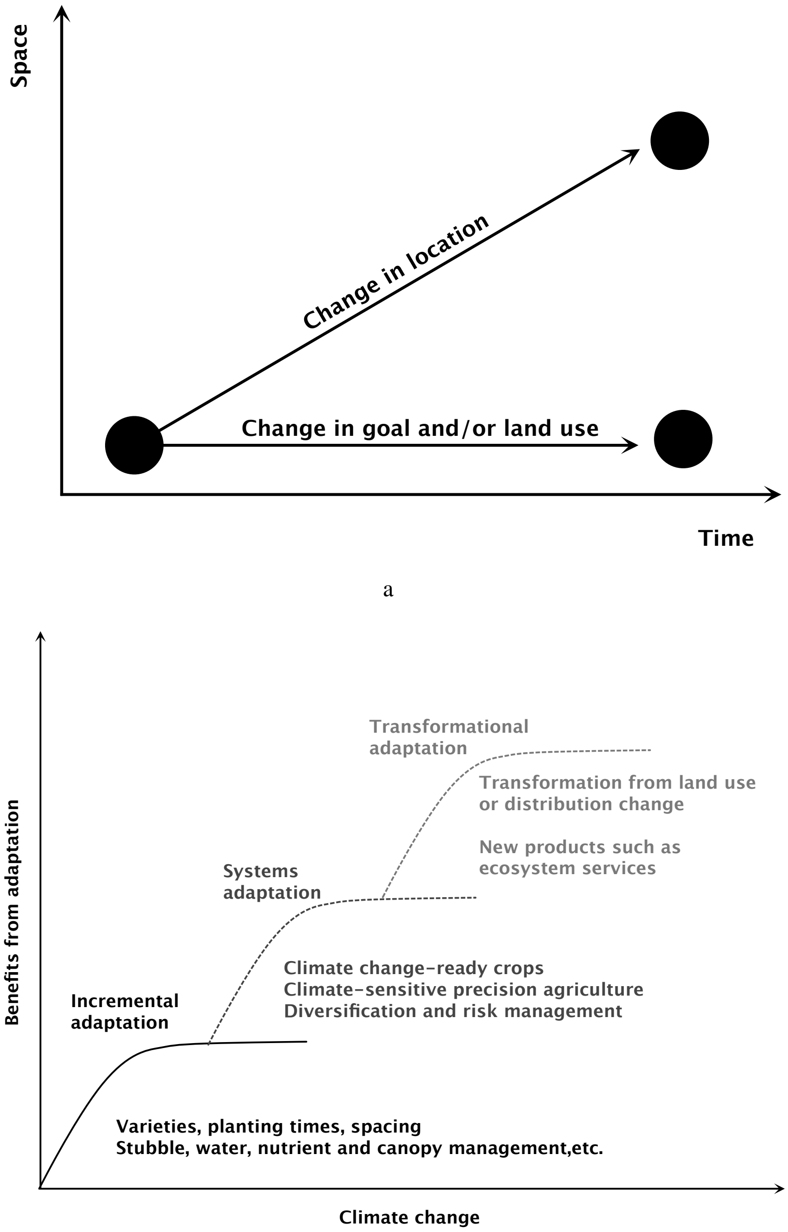
a positive effect on leaching (up to −34% for dairy farm and −31% for crop farm), but impacts on denitrification and ammonia volatilization were found to be negligible.

### 3.3.2 Spatial scale

The scale at which climate adaptations are developed and assessed is of major importance and responses at different decision levels should be considered. To support decision-making, the choice of the scale is particularly important and typically involves trade-offs among the following factors (Van Delden et al., 2011): (i) the scale at which end users or policy makers require information; (ii) the scale at which processes take place and the representation of those processes in a single model; (iii) the way to integrate model components representing processes occurring at different scales; and (iv) the limitations posed by practical restrictions such as data limitations and computation speed. In the context of AGWAM, two relevant decision levels are considered (Fuhrer et al., 2009): the regional scale, which is relevant for planners and decision-makers (Chapter 6), and the farm scale (Chapter 7), where changing economic and political pressures play important roles. A large majority of studies of impacts and adaptation to climate change in agriculture have been conducted at the field or farm level so far. There is a considerable need for an increased number of regional studies since effects and responses are depending on local conditions and interactions with soils, climate, and cropping systems (Olesen et al., 2011). Moreover, considering the spatial heterogeneity is crucial to test so-called ‘transformational adaptation’ options. Transformational adaptation is a new concept (Rickards and Howden, 2012) that focuses on two major types of change: changes in the goals (e.g. change of land use or function) and/or changes in location (Fig. 3.1a). The costs of transformational adaptation are expected to be high (Rickards and Howden, 2012), but may become profitable as the severity of climate change increases (Fig. 3.1b). To the best of my knowledge, no attempt has been undertaken to analyze quantitatively the benefits of transformational adaptation so far.

## 3.4 Optimization techniques

To define most appropriate management practices, traditionally, a number of management scenarios are formulated and fed into the model, then outputs are compared, and the management of the scenario that fits the requirements best is selected. The most straightforward method is to realize those three operations manually (see e.g. Gaydon et al., 2012), which can become a considerable effort as the number of scenarios increases. Another approach is to perform the search by means of an optimization algorithm that connects the scenarios, the model run and the computation of the scenarios’ performances criterion (so-called goal function or objective function) that should be maximized or minimized to reach the desired state (Seppelt and Voinov, 2002). The main advantage of optimization methods is that the search is executed automatically and in a systematic way



a

b

**Figure 3.1:** Concepts of transformational adaptation: (a) schematic diagram of the two main forms of transformational adaptation in agriculture (modified from Rickards and Howden, 2012) and (b) levels of adaptation in relation to benefits from adaptation actions and degree of climate change with illustrative examples (modified from Howden et al., 2010).

over the whole space defined by all possible combinations of management practices. The downside is that optimization procedures require substantially higher computational complexity than scenario techniques.

Objective optimization methods in connection with biophysical models have shown great potential. For instance, Whittaker et al. (2009) coupled SWAT with a Pareto-optimization approach for analysis of trade-offs between profits from land use and chemical pollution from farm production. Similarly, Bryan and Crossman (2008) elaborated a regional optimization-based planning approach to determine geographic priorities for management actions that need to be taken to meet multiple natural resource management goals. Higgins and Hajkowicz (2007) applied a multi-objective programming model, in combination with objective functions standing for biodiversity, water run-off and carbon sequestration.

In recent years, numerous studies have applied optimization techniques to solve agriculture-related complex problems (see Table 3.4 for a review). Those studies can be sorted into three different categories based on their primary goal:

1. landscape planning studies (upper part of Table 3.4) that aim to find trade-offs between multiple goals to ensure efficient land use from economic as well as environmental perspectives. For example, Groot et al. (2007) developed a framework to explore conflicts between financial returns from agriculture, landscape quality, nature conservation and environmental quality, and to generate alternative solutions to support discussions with stakeholders on various topics. Landscape planning approaches focus on a wide range of ecosystem services and not only agricultural functions; hence, the representation of agronomic processes is often oversimplified (e.g. crop development omitted, final yield depending on a few land use classifications, see e.g. Makowski et al., 2000), and offering limited possibilities in terms of management practices (Koschke et al., 2013);
2. agronomic studies (middle part of Table 3.4) whose goal is to identify optimal combinations of agricultural practices with regard to one or several goals, usually at the farm-level (a recent review of farming system design optimization can be found in Martin et al., 2011);
3. climate change adaptation studies (bottom part of Table 3.4) that aim at developing adaptation strategies, in that sense similar to mainstream adaptation studies mentioned in Section 3.3, but considering a very large number of management options requiring the use of an optimization algorithm. For instance Lehmann et al. (2013) applied a bioeconomic modeling approach in combination with a genetic algorithm to find options that maximize the certainty equivalent of farmers in the Broye (paper embedded in this thesis, see Chapter 7).

**Table 3.4:** Literature review of studies involving biophysical models within an optimization routine to find optimum agricultural land management with regard to (multiple) objective(s).

| **Study** | **Management option(s)** | **Objective(s)** | **Spatially-explicit** | **Climate change adaptation** |
|---|---|---|---|---|
| Makowski et al. (2000) | regional ('where'), crop ('what') and technical ('how') aspects | min nitrogen loss with constraints on area, water use, product balances, and manure balances | partly | |
| Seppelt and Voinov (2002, 2003) | land use, fertilizer | crop yield, N-leaching, fertilizer costs, nutrient outflow, surface base flow | ✓ | |
| Koo and O'Connell (2006) | 7 different agricultural land uses | economic return, nitrate diffuse pollution | ✓ | |
| Groot et al. (2007) | land use, occupation of field borders | max gross margin from agricultural production, min loss of nutrients, max nature value of fields and borders, max variation the landscape | ✓ | |
| Meyer et al. (2009) | farming systems (rotation, fertilization) and land use elements | min nitrogen leaching while maintaining income | ✓ | |
| Sadeghi et al. (2009) | land use | max income, min erosion | ✓ | |
| Gao et al. (2010) | land use, land cover | control of soil erosion, appropriate utilization of water resources, soil and water conservation investment, economic output | ✓ | |
| Kuo et al. (2000) | water demand, crop shares | profit | | |
| Lu et al. (2004) | crop rotation, soil conservation measures, terracing type, mechanization level | min soil loss, min cropping area, max employment, max net return, min production costs, min fertilizer, min biocide, max crop production, min N loss | | |
| Dogliotti et al. (2005) | soil type, mechanization level, crop protection, irrigation, inter-crop activities | max gross margin, max family income, min erosion, max rate of change organic matter, min N surplus, min exposure to pesticides | | |
| Xevi and Khan (2005) | crop mix, level of groundwater pumping, allocation of water for irrigation and environment | max net returns, min variable cost, min total supplementary groundwater pumping requirements | | |
| Latinopoulos (2007) | types of crops (e.g. perennial, irrigated, rainfed, etc.) | socio-economic and environmental criteria (9 options) | | |
| Mayer et al. (2008) | proportion of crops, conditions (e.g. planting time) | crop yields, operating return and chance of loss, water use efficiency | | |
| Hyytiäinen et al. (2011) | fertilization (splits) | min costs, min N-leaching | | |
| García-Vila and Fereres (2012) | irrigation management | farm income | | |
| Groot et al. (2012) | areas of cultivated crops, destination of crop products, livestock management | max income, min labor resources, max organic matter balance, min nitrogen soil losses | | |
| Schuetze and Schmitz (2010) | irrigation schedule | crop yield | | ✓ |
| Lehmann et al. (2013) | irrigation and fertilization strategies (12 options) | farmer's certainty equivalent | | ✓ |

## 3.5 Shortcomings of earlier studies

This section summarizes all the gaps that have been highlighted throughout this chapter and formulates approaches proposed in this thesis to circumvent the latter. The main shortcomings identified earlier are:

1. the lack of established methods to calibrate crop models in data-limited situations;
2. mainstream adaptation studies often neglect important aspects: (i) included agricultural practices represent a small subset of possible adjustments (e.g. tillage operations and crop rotation choice as adaptation options are rarely tested, see Table 3.2), (ii) adaptation strategies focus on impacts of climate change on crop yields (see Table 3.3) omitting the multifunctionality of agriculture and possible trade-offs among ecosystem functions, and (iii) benefits of transformational adaptation has yet to be explored in regional studies;
3. spatially-explicit multi-objective approaches such as those developed in the field of landscape planning have great potential to circumvent shortcomings of mainstream adaptation studies. However, those methods currently have two major limitations: (i) relevant agronomic processes are extremely simplified and (ii) the number of agricultural management options is limited.

**Lack of empirical data to calibrate crop models.** Here the FADN database is used as reference for crop model calibration. To account for the lack of management information, the concept of ‘Meteorologically Possible Yield’ (MPY) is introduced, which represents yields obtained under optimal nutrient and pests management.

**Gaps of the mainstream adaptation studies.** The approach is based on a generic crop model that allows simulating a wide range of management options including cropping practices that are rarely tested for climate change adaptation, such as tillage operations and crop rotations. Here, a multi-objective optimization is applied to account for trade-offs between several relevant agricultural functions in the context of climate change. Most previous studies focused on incremental adaptation (e.g. planting date, fertilization) and, to a limited extend, to systems adaptation (e.g. climate change-ready crops with longer maturation) at the farm level. In this thesis spatial heterogeneity is considered in order to test transformational adaptation that implies changes of location or goals (see Fig. 3.1) in addition to ‘usual’ local adjustments of cropping practices.

**Tuning of existing optimization approaches.** The complexity of an optimization task depends on two factors (Seppelt and Voinov, 2002): the complexity of the simulation model (e.g. number of state variables, degree of non-linearity) and the spatial complexity (size of the study area, grid cell size, number of spatially interacting processes). To ensure that a solution to a given optimization problem is found within a reasonable computation time, simplification or aggregation are required (see Fig. 3.2). Here, the spatial complexity is reduced by applying a so-called ‘local optimization’, which neglects interactions between neighboring cells (for an application of this approach, see Seppelt and Voinov, 2002, 2003). In contrast, a very high degree of modeling complexity is maintained by embarking in the optimization routine the generic crop model CropSyst that can simulate most relevant processes of agroecosystems. The spatial scale considered in this thesis is the mesoscale (catchment) with a grid of 500 m by 500 m. High spatial resolution is required since crop models are designed to run at the field scale and input data (i.e. management, soil, and weather) are often not available at larger scales, which makes large scale simulations not reliable (Challinor et al., 2006). It is possible to partly circumvent those limitations with the application of various downscaling and upscaling procedures (Hansen and Jones, 2000). An alternative is to design models that operate on higher scales that reduces the complexity and omit farm-level relationships (Challinor et al., 2004), but a good understanding of (i) the sensitivity of those models to various levels of detail (Adam et al., 2011) and (ii) impacts of calibration strategies on simulation results (Angulo et al., 2012) are crucial. However, the use of regional crop models is not an option in this thesis as farm-level adaptation strategies cannot be tested.

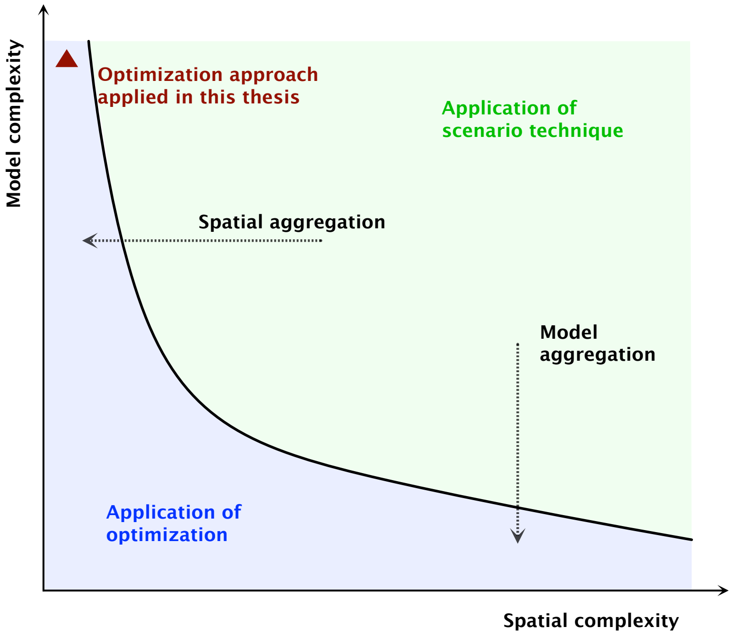


**Figure 3.2:** Complexity of regional optimization approaches (modified from Seppelt and Voinov, 2002) and relative location of the optimization method employed in this thesis.

## 3.6 The Broye catchment

The study region is the Broye catchment (Fig. 3.3), which is located in western Switzerland in the canton of Fribourg and Vaud. Agriculture covers more than 70% of the region, which corresponds to about 42,750 ha of agricultural areas (BFS, 2010). The northern plain of the region is dominated by arable farms, while mixed farms with livestock, as well as crop production, prevail in the region's hilly southern part at elevations above 700 a.m.s.l. Major crops are (FOAG, 2011): winter wheat ($\sim$ 30%), silage/grain maize ($\sim$ 15%), winter barley ($\sim$ 9%), sugar beet ($\sim$ 7%), winter rapeseed ($\sim$ 5%), and potato ($\sim$ 5%). Main livestock types that can be found in the region are dairy cows and cattle breeding, accounting for more than 80% of the total animal production.

The Broye region covers of wide range of climate conditions due to a steep North-South elevation gradient. Annual average precipitation is 900 mm at Payerne (North of the Broye, 490 a.m.s.l.), while precipitation is substantially higher in the South (1535 mm on average at Semsales, 866 a.m.s.l.). A strong temperature gradient is also observed in the catchment as a consequence of elevation differences (mean temperatures of 9.6 °C and 7.1 °C in Payerne and Semsales, respectively).

Due to drier climate conditions in the northern parts, and the relatively large crop shares of high value crops, irrigation is already a common practice in those areas, with a yearly average of 1.13 $10^6$ $m^3$ applied to 1,377 ha (Robra and Mastrullo, 2011). Irrigation is used for potato (50%), maize (15%), tobacco (15%), and sugar beet (8%). Most of irrigation water is pumped from the Broye, the principal river in the catchment that originates from the Prealps at an elevation of about 1000 a.m.s.l. and flows into the Lake of Murten ($\sim$ 500 a.m.s.l.). The Broye catchment is already facing water scarcity and water needs occasionally exceed surface water availability (e.g. in summer 2003, Fuhrer and Jasper, 2012). In the future the situation is expected to further aggravate (Fuhrer and Jasper, 2009), leading to potential conflicts in water utilization.

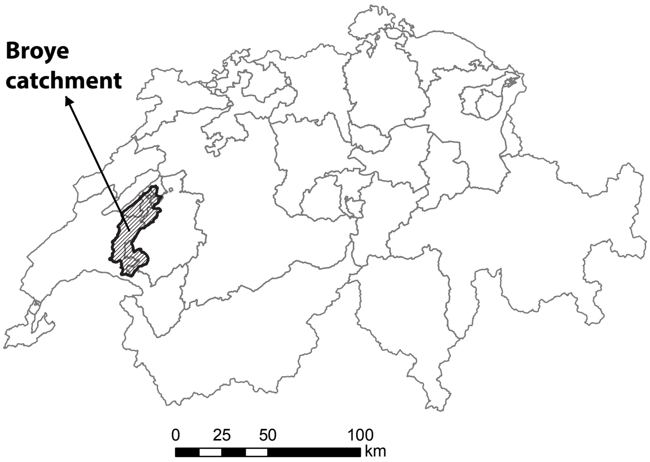


**Figure 3.3:** The Broye catchment is located on the western part of the Swiss Central Plateau and covers an area of 850 $km^2$.

# Chapter 4

# Using farm accountancy data to calibrate a crop model for climate impact studies

*Published as*:
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## Abstract

Process-based crop models are widely used in decision support systems or to assess impacts of climate change on agriculture at different spatial scales. They include crop and/or cultivar-specific parameters that need to be calibrated. However, the availability of reference data is often limited. An alternative is to use yield records from widely available Farm Accountancy Data (FADN). The goal of this study was therefore to propose and test a crop model calibration procedure that makes use of FADN data. To account for the lack of management information in the FADN databases, the concept of 'Meteorologically Possible Yield' (MPY) was adopted. This concept is particularly relevant in the context of climate impact studies as MPYs are by definition only driven by climate variability. As an example, the procedure was applied to calibrate the generic crop model CropSyst for a region located in north-eastern Switzerland. Validation using data from a long-term field trial with detailed information on fertilizer applications showed that the proposed procedure provides robust simulation results and is therefore suitable for climate impact studies in regions where detailed experimental data are scarce. In a case study application, the transferability of the local calibration to a site with drier conditions was tested and simulation results for this new site were compared to results obtained using local recalibration. Results showed that predicted yields can differ substantially and the differences can be strongly amplified when impacts of climate change are considered. This highlights the need for adjusting model calibrations to local site conditions and for considering parameter uncertainties in climate impact studies.

**Keywords** Crop yield modeling - Farm Accountancy Data - Meteorologically Possible Yield - Model calibration - Parameter uncertainties

## 4.1 Introduction

Generic crop models can be applied for a large variety of different crops providing useful decision support for farmers or technical advisors (Stöckle et al., 2003). Since the last decade, they have also been widely used to assess climate impacts on crop yields at various scales (e.g. Moriondo et al., 2010b; Olesen et al., 2007; Supit et al., 2010b). Mechanistic crop models are based on sets of equations that describe soil-plant-atmosphere processes generally at the field level. Specific parameters are set to represent differences between crops and varieties, but their exact values are seldom known. Crop model performance based on default values alone is often poor (Guillaume et al., 2011), especially as the characteristics of crops and varieties can vary substantially in space and time (Supit et al., 2010b). Local calibration is therefore a crucial step for many model applications. In this context, the efficiency of the calibration procedure and the availability of reference data play particularly important roles.

Arguably the best reference for crop model calibration are data from field trials in which crops are grown under controlled conditions (e.g. Bechini et al., 2006; Bellocchi et al., 2002; Donatelli et al., 1997; Guillaume et al., 2011; Pannkuk et al., 1998; Wallach et al., 2011). However, the availability of such data is limited as field experiments are time-consuming and expensive (Wallach et al., 2006). Alternatively, census data can be used, such as those available from the Farm Accountancy Data (FADN), a European system of surveys conducted every year to collect structural and accountancy data on farms. It is particularly useful because it refers to spatial scales compatible with those addressed by crop models. Although FADN is the primary source of farm yield records at the European level, surprisingly few cases are documented in which this database was used in combination with crop models. Reidsma et al. (2009) compared regional yield simulated by WOFOST (Van Diepen et al., 1989) with data from FADN and identified factors that explained differences between observed and simulated yields. Torriani et al. (2007) used Swiss FADN data to validate CropSyst (Stöckle et al., 2003) after calibration with experimental data. Therond et al. (2011) used information from FADN to upscale simulated yields with APES (Donatelli et al., 2009). Godard et al. (2008) constructed crop nitrogen (N) response curves for EU regions based on information from FADN using STICS (Brisson et al., 1998). To the best of our knowledge, no attempt has been undertaken to date to employ information from FADN for crop model calibration.

The primary goal of our study was therefore to develop an approach to crop model calibration relying on FADN as reference. The concept of 'Meteorologically Possible Yield' (MPY; Karing et al., 1999) was adopted to represent maximum rainfed yields under non-limiting nutrient availability and optimal pest/disease management. By definition MPY's temporal variability can be assumed to be exclusively driven by climatic variations and, therefore, MPY is a useful concept for climate impact studies. However, as FADN data reflect a wide spectrum of managements, the approach to obtaining reliable estimates of the MPY from FADN is not obvious. In our study we estimated the MPY as a statistic of the upper tail of yield distribution, defining the latter with respect to a threshold that was adjusted to provide results that were both plausible (in relation to what can be expected based on expert knowledge) as well as robust.

The calibration procedure included parameter screening based on sensitivity analysis and an automated parameter estimation of the selected parameters by means of a Genetic Algorithm (GA). The procedure was applied to the calibration of the model CropSyst (Stöckle et al., 2003) using data collected in north-eastern Switzerland. After calibration, the model was validated with data from a field trial conducted in an area close to the calibration site, in which rotations with four crops where grown under optimal management. For this field trial, we compared the performance of CropSyst with the newly determined parameters to the performance based on earlier calibration for Switzerland by Torriani et al. (2007).

The calibrated model was applied at a site with drier conditions to test its transferability and simulation results for this new site were compared to simulation results obtained after local recalibration. Discrepancies between the two calibrations were analyzed in terms of identified crop parameters and simulated impacts of climate change. With that, we also explored the implications of parameter uncertainties for climate change impact assessments.

## 4.2 Methods and data

In the following we define the study areas of the case study application and describe the crop model together with the implementation settings. Then we present the overall calibration approach adopted for this study as illustrated in Fig. 4.1. It included three main steps: (i) FADN data preprocessing to derive a proxy of MPY, (ii) parameter screening using the Morris (1991) method and (iii) parameter estimation based on a GA.

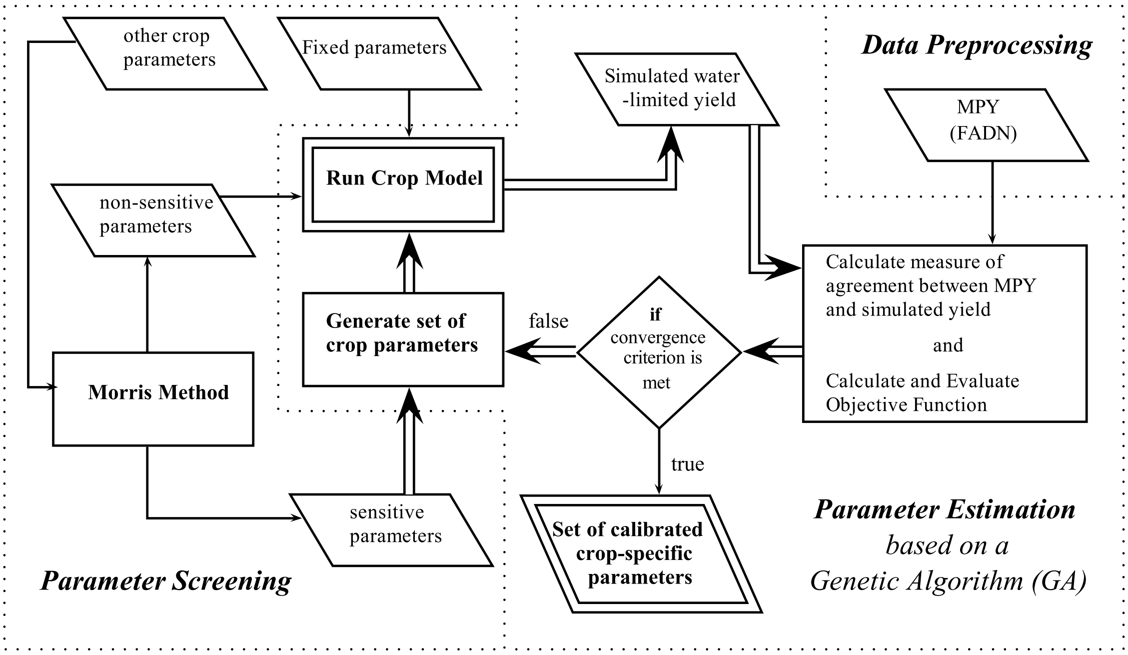

**Figure 4.1:** Scheme of the calibration procedure. Double arrows indicate the automatic calibration loop - from parameter set generation to evaluation of goodness of fit between simulated yield and meteorologically possible yield (MPY).

### 4.2.1 Study areas

The calibration approach was developed and tested with respect to a region located in the north-eastern part the Central Plateau in Switzerland, about 10 km to the west of the city of Zurich and 10 km south of the German border, and centered on the meteorological station of Taenikon (47.48 N, 8.90 E and 539 a.m.s.l.). Taenikon was selected for two main reasons: first, a sufficiently large number of yield records was available from the FADN database for calibration; second, independent data for model validation was available from a long-term field trial carried out at Chaiblen (Dubois et al., 1998), a site close to the meteorological station. In this field experiment, intensive management was applied, which can be assumed to provide optimal pest/disease and nutrient conditions. Information was collected on (i) final yields for different crops in a rotation (i.e. silage maize, winter barley, winter wheat and winter rapeseed), (ii) sowing and harvest dates, (iii) fertilizer applications (amount, type and timing), and (iv) tillage operations (i.e. plowing and harrowing).

A second region centered on the meteorological station of Payerne 46.81 N, 6.94 E and 490 a.m.s.l.), located in the south-western part of the Swiss Central Plateau, was considered to test the validity of a model calibration for a larger area. Compared to Taenikon (annual rainfall $\sim$ 1125 mm), the climate at Payerne is characterized by lower precipitation amounts (annual rainfall $\sim$ 845 mm), especially during late spring and summer. Moreover soils exhibit a higher proportion of sand (56%, as opposed to 28% at Taenikon/Chaiblen).

For both locations, daily weather data as needed to drive CropSyst were obtained from the monitoring network of the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss). Soil data for Taenikon/Chaiblen were derived from Sturny (1987) and soil data for Payerne were derived from the Swiss Soil Monitoring Network (NABO).

As a basis for testing climate impacts, the stochastic weather generator LARS-WG (Semenov and Barrow, 1997) was used to generate 50 years of synthetic daily weather data for a baseline period corresponding to 1981-2010 and a climate scenario representing the period 2036-2065. The climate change signal used to modify the generation parameters of LARS-WG was extracted from a Regional Climate Model (RCM) simulation carried out in the framework of ENSEMBLES (van der Linden and Mitchell, 2009) with the *ETHZ-CLM* regional climate model. The climate change signal suggests precipitation decrease during the summer months ($\sim$ 25% in July and August), and a very marked temperature increase up to $+3.75$ °C in August.

### 4.2.2 Crop model description and implementation

CropSyst (version 4.13.04) is a multi-year, multi-crop, daily time step cropping systems simulator developed to serve as an analytical tool to study the effects of climate, soils, and management on cropping systems and the environment (Stöckle et al., 2003). It simulates soil water and N budgets, crop phenology, canopy/root growth and biomass production, final crop yield, residue production and decomposition, soil erosion by water, and salinity. Management options include crop rotation, cultivar selection, irrigation, N fertilization, tillage operations, and residue management. CropSyst has successfully been applied to several crops and regions (e.g. Badini et al., 2007; Bechini et al., 2006; Bellocchi et al., 2006; Djumaniyazova et al., 2010; Donatelli et al., 1997; Pannkuk et al., 1998; Peralta and Stöckle, 2002; Stöckle et al., 1997; Torriani et al., 2007).

In CropSyst, the length of phenological stages is expressed in terms of thermal time. Thermal time units, so-called growing degree days (*GDDs*), are calculated for each day as the temperature above a certain threshold (base temperature, $T_{base}$) and limited by a cutoff temperature ($T_{cut-off}$). The biomass accumulation calculation in the model relies on the determination of potential biomass growth based on crop potential transpiration and on crop intercepted radiation. The potential growth is then corrected by water and N limitations, to compute actual daily biomass gain. Key parameters for computing potential biomass accumulation are the biomass to transpiration coefficient (*BTR*) and the light to biomass conversion (*RUE*). *RUE* is corrected to account for temperature stress when temperature is lower than the mean daily temperature that limits early growth ($T_{opt}$). The increase of leaf area during the vegetative period is a function of accumulated biomass and is controlled by two parameters, a specific leaf area index (*SLA*, leaf area per kg of dry matter) and a partition coefficient (*SLP*, fraction of biomass apportioned to leaves). Leaf senescence occurs after reaching *GDDs* of leaf duration, but can be accelerated in case of water stress.

Potential crop evapotranspiration is determined by multiplying reference evapotranspiration by a crop coefficient (*Kc*); the partitioning into potential crop transpiration and potential soil evaporation depends on the leaf area. Root growth in CropSyst is described in terms of root depth and root density. Root depth is synchronized with leaf area growth, until reaching a specified maximum value. The root distribution is driven by the curvature of root density distribution parameter. Low values of the latter give a nearly linear root distribution with depth, whereas high values yield a large proportion of roots close to the surface.

CropSyst does not simulate the storage organs growth and the final yield is obtained by multiplying the total above ground biomass by a factor, the harvest index, which can be reduced in case of water and/or N stress during critical phenological stages such as flowering. All CropSyst crop/genotype specific parameters are listed in Table 4.1. A more detailed description of the structure of CropSyst and of the main modules can be found in Stöckle et al. (2003).

For this study, the following submodels were deactivated: freezing and snowpack, salinity and erosion. N limitation was disabled for the calibration process to make simulated yield comparable to MPY, but was enabled for validation with experimental field data. We used the new crop transpiration model (V. 4.1) and the Penman-Monteith evapotranspiration scheme. The cascade daily infiltration model was selected and runoff was determined as a function of current soil moisture content, static soil conditions, and management practices (Soil Conservation Service curve number). Multiple organic matter pools were considered (incorporated residues, microbial, labile, meta-stable, and passive).

Since several crop genotypes are expected to be grown within the study regions and information on exact genotypes was lacking in the FADN dataset, we had to assume an ‘average’ variety. Approximate dates for main phenological stages of this ‘average’ variety were provided by field experts. Sowing dates were kept constant throughout the simulation period and we assumed that harvest occurred 5 days after reaching physiological maturity, except if maturity was reached past a fixed end date. Initial water content was set to field capacity for all soil layers. A value of 12 kg N ha$^{-1}$ ($\mathrm{NO_3}-N+\mathrm{NH_4}-N$)

**Table 4.1:** Presentation of CropSyst crop modules and description of crop parameters; parameter ranges used for the parameter screening and the parameter estimation are provided, together with references to sources of information; all parameters were subjected to calibration, excepted those describing the length of phenological stages and the harvest index (values in italics); PAR: photosynthetically active radiation; LAI: leaf area index; LWP: leaf water potential; AT/PT: ratio of actual to potential transpiration; ET: evapotranspiration; GDD: growing degree days.

| Parameter | Description | Unit | Bounds | Source* |
|---|---|---|---|---|
| **Attainable growth** | | | | |
| $BTR$ | Transpiration to biomass coefficient | Pa | $[6, 8.5]$ | 1 |
| $T_{opt}$ | Mean daily temperature that limits early grow | °C | $[15, 25]$ | 2 |
| $RUE$ | Light to biomass conversion PAR | g MJ$^{-1}$ | $[3.5, 4]$ | 1 |
| **Canopy growth** | | | | |
| $LAI_{init}$ | Initial green LAI | m2 m$^{-2}$ | $[0.001, 0.025]$ | 3 |
| $LAI_{max}$ | Maximum LAI | m2 m-2 | $[4, 7]$ | 1 |
| $SLA$ | Specific LAI | m2 kg$^{-1}$ | $[15, 25]$ | 1 |
| $LAI_{mat}$ | Fraction of maximum LAI at physiological maturity | $[0, 1]$ | 1 | |
| $SLP$ | Stem/leaf partitioning coefficient | $[2.5, 4]$ | 9,4 | |
| $LWP_{red}$ | LWP reduction of canopy expansion | J kg$^{-1}$ | $[-880, -720]$ | 8 |
| $LWP_{stop}$ | LWP stop canopy expansion | J kg$^{-1}$ | $[-1320, -1080]$ | 8 |
| **Root** | | | | |
| $Root_{depth}$ | Maximum root depth | m | $[1.5, 2]$ | 1 |
| $Root_{mass}$ | Root length per unit root mass | km kg$^{-1}$ | $[72, 108]$ | 8 |
| $Root_{density}$ | Maximum surface root density at full rooting depth | cm cm$^{-3}$ | $[4.8, 7.2]$ | 8 |
| $Root_{distrib}$ | Curvature of root density distribution | $[0.0001, 6.0]$ | 1,5 | |
| $Root_{AT/PT}$ | AT/PT ratio limiting root expansion | $[0, 1]$ | 1 | |
| **Harvest** | | | | |
| $HI$ | Harvest Index | | 0.45 | 7 |
| $Stress_{W\&N}$ | Sensitivity to water and N stress during flowering | | $[0, 1.5]$ | 1 |
| $GF_{dur}$ | Duration of grain filling period (unstressed) | days | $[24, 36]$ | 8 |
| $Stress_{T}$ | Sensitivity to temperature stress during flowering | | $[0.5, 1.5]$ | 1 |
| **Transpiration** | | | | |
| $K$ | Light extinction coefficient | $[0.35, 0.65]$ | 1 | |
| $Kc$ | ET crop coefficient | | $[1, 1.2]$ | 1 |
| $Wupt_{max}$ | Maximum water uptake | mm day$^{-1}$ | $[7, 13]$ | 1 |
| $C_{xylem}$ | Critical xylem water potential | J kg$^{-1}$ | $[-1200, -930]$ | 1 |
| $W_{xylem}$ | Wilting xylem water potential | J kg-1 | $[-1800, -1400]$ | 1 |
| **Senescence** | | | | |
| $LAD_{stress}$ | Leaf area duration sensitivity to water stress | $[1, 3]$ | 1 | |
| $GDD_{sen}$ | GDD for leaf duration | ° days | $[800, 1400]$ | 6,4 |
| **Thermal time accumulation** | | | | |
| $T_{base}$ | Base temperature | ° | 6 | 2 |
| $T_{cut_{off}}$ | Cut-off temperature | ° | 23 | 2 |
| $GDD_{em}$ | GDD for emergence | ° days | 100 | 9 |
| $GDD_{root_max}$ | GDD for maximum root depth | ° days | 700 | 9 |
| $GDD_{peak_LAI}$ | GDD for end vegetative growth (peak LAI) | ° days | 930 | 9 |
| $GDD_{flo}$ | GDD for flowering | ° days | 900 | 9 |
| $GDD_{fil}$ | GDD for grain filling | ° days | 1225 | 9 |
| $GDD_{mat}$ | GDD for maturity | ° days | 1850 | 9 |

* 1: Stöckle and Nelson (2000);2: Supit et al. (2010a);3: Confalonieri and Bechini (2004); 4: Peralta and Stöckle (2002);5: Jackson et al. (1996);6: Bellocchi et al. (2006);7: Stöckle and Debaeke (1997); 8: centered on default value; 9: Expert knowledge

was assumed for initial soil mineral N in the top 30 cm (Weisskopf et al., 2001). Soil hydrological properties such as permanent wilting point, field capacity, bulk density or hydraulic conductivity were estimated from texture by CropSyst. For the organic N, a spin-up of the model was conducted by running CropSyst for 300 years (corresponding to the turnover time of the most stable organic matter pool) with regular tillage. At equilibrium, CropSyst simulated an organic matter content of 2.89% for the first soil layer and 2% for 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 conditions. The bypass coefficient which defines the fraction of water in the soil layer that is bypassed during the infiltration process (Stöckle and Nelson, 2000) was set to 0.5, i.e. the average value recommended by Corwin et al. (1991).

### 4.2.3 Preprocessing of FADN yield data and derivation of MPY

The data used for the current study are retrieved from the Swiss FADN, which is managed by the Farm Economics Research Group of Agroscope Reckenholz-Tänikon Research Station. The survey comprises detailed farm-level information on cost accounting, farming system and structural aspects. These include in particular crop areas and crop yields per ha. Unlike many other European countries, Switzerland uses a non-financial criterion to define the target population. The target population of the reference farms is delimited by minimum physical thresholds, e.g. 10 ha of utilized agricultural area or farming activities involving at least six cows.

Stratification is used to increase sampling efficiency and to control the allocation of sample to the strata. The current stratification scheme for the Swiss FADN is based on three criteria: farm size, type of farming and regional area. The regional area is subdivided into three levels: ‘mountain’, ‘hill’ and ‘plain’. Further, five size classes and eleven farm types are distinguished. In contrast to the EU system, the Swiss farm typology is more differentiated and classification is carried out on the basis of land use and production characteristics rather than economic criteria.

The reference farms can be considered as a non random sample of the target population, a random sample has not been considered to be feasible so far. The non-random FADN sample includes detailed information on cost accounting from approximately 3300 farms. The sample size differs spatially and over time, e.g., the number of farms within a 20-km radius around Taenikon ranged from 12 to 104 in the period 1981-2008. Due to data protection laws, individual farms can only be allocated to municipalities.

For use as a reference in crop model calibration, the FADN database presents two major limitations. First, it only provides information on total fertilizer costs, which is not sufficient to quantify types and amounts of fertilizers. Second, it does not provide information on the occurrence of pests and diseases, which can have major effects on observed yields but cannot be simulated with common process-based crop models. For these reasons the derivation of MPY estimates from FADN data is not obvious.

One way to overcome these limitations is to specify management based on expert knowledge, as done by Therond et al. (2011), or based on recommended practices (e.g. Jagtap and Jones, 2002). However, these approaches do not account for the discrepancy between observed and simulated yields due to pests and diseases. In the presented approach we tried to account for this gap by inferring estimates of the MPY from aggregated yield data from a specific region, assuming that for a sufficiently large region, at least some farms operated close to a production optimum in terms of fertilizer application and pest management. We further assumed that in this case, the MPY can be evaluated as the mean value of the upper tail of the regional yield distribution, defining the latter in terms of an appropriate quantile ($Q_y$) chosen as to provide a sufficiently large sample.

In our study, robustness of MPY estimates with respect to location, size of the region and spatial distribution of the census data within the region was verified by repeating the calculations for varying area of aggregation and choice of $Q_y$. These tests were supplemented by an examination of the time series of the associated standard errors. Data processing was carried out using the statistical software R (R Development Core Team, 2012).

### 4.2.4 Parameter screening

If the model contains a large number of crop parameters, which is the case with CropSyst, the number of parameters to be calibrated needs to be reduced in order to prevent computational problems (Confalonieri, 2010; Janssen and Heuberger, 1995; Tremblay and Wallach, 2004; Wallach et al., 2011). In our case, we first eliminated parameters that did not require calibration either because reliable values could be found in the literature or because accurate estimates could be provided by field experts. For all other parameters, a sensitivity analysis was conducted to identify those parameters that have the greatest influence on simulated yields.

The so-called ‘Morris method’ (Morris, 1991), as revised by Campolongo et al. (2007), was used because this is a robust approach to screen a subset of relevant parameters, which requires low computational costs compared to global variance-based methods (Confalonieri, 2010; Saltelli et al., 2007). In this method, the experimental plan is composed of individually randomized 'one factor-at-a-time' experiments, in which the impact of changing the value of each of the parameter is estimated in turn. The method relies on evaluating so-called 'elementary effects' for $r$ trajectories (successions of points starting from a random base parameter set in which two consecutive elements differ only for one parameter value) and operates on $p$ levels. In our application, $r$ was set to 7 and $p$ to 4 (12.50th, 37.50th, 62.50th and 87.50th quantiles of the parameter initial distributions). After assessment of the elementary effects, parameter screening is based on two sensitivity measures: (i) $\mu^*$, the average of the distribution of the absolute values of the elementary effects related to a given parameter (a measure of the overall importance of a parameter); and (ii) $\sigma$, the standard deviation of the distribution of elementary effects (a measure of how a parameter interacts with others and of nonlinearity of model response to the parameter).

All calculations were carried out with Simlab, a free software package for global uncertainty and sensitivity analyses developed at the Joint Research Center of the European Commission in Ispra (SimLab, 2004). Crop parameters and their ranges that were considered in the sensitivity analysis for both Taenikon and Payerne are listed in Table 4.1. The Morris method was conducted based on samples drawn from uniform distributions within parameter bounds that were defined based on literature data (see Table 4.1 for references).

As the Morris method only gives a ranking of the parameters, an additional criterion was introduced for completing the selection. Based on the assumption that in many circumstances $\mu^*$ can be treated as a proxy of Sobol's (1993) sensitivity index, an estimate of the percentage of explained variance for single parameters (Campolongo et al., 2007), we selected the $m$ most important parameters out of all $n$ parameters included in the sensitivity analysis through the following steps:

1. Computation of $\sum_{i=1}^{n} \mu_i^*$;
2. Normalization of individual $\mu^*$ by their sum: $\eta_i = \mu_i^* / \sum_{i=1}^{n} \mu_i^*$;
3. Ranking $\eta_i$ in decreasing order;
4. Finding the minimum $m$ for which $\sum_{i=1}^{m} \eta_i > 0.9$ and selecting the $m$ parameters accordingly;
5. Checking the plausibility of the choice e.g. by examining a scatter plot of $\mu^*$ vs. $\sigma$ (Morris, 1991).

## 4.3 Parameter estimation

Sensitive crop parameters identified through the parameter screening were calibrated using an automated procedure based on a GA. GAs are based on the theory of evolution and aim at finding optimum solutions to complex combinatory problems, even where relations between independent variables and target values are highly non-linear and complex (Goldberg, 1989). GAs have been widely employed for calibration of hydrological and ecohydrological models (Cheng et al., 2002; Seibert, 2000; Whittaker et al., 2009; Zhang et al., 2009) and also for calibration of crop models (Bulatewicz et al., 2009; Dai et al., 2009; Pabico et al., 1999).

We applied a steady-state GA with overlapping populations as provided by the C++ package GAlib (Wall, 1996). A solution is represented as a ‘genome’ (here a set of crop parameters). The procedure starts with a random initial ‘population’ (group of ‘genomes’) with a specific size *nPop*. At each iteration, ‘genomes’ are evaluated using a user-defined objective function. The ‘fittest’ are selected while others are excluded, and newly generated offspring are added to the population to make a new ‘generation’. The amount of overlap between generations is specified by the *pRepl* parameter, which is the percentage of the population to be replaced in each generation. As convergence criterion, the algorithm uses the ratio between the best individual of the *nConv*-th previous generation and the best current individual, and it terminates if this ratio is greater than *pConv*. For our application, we kept the default specifications for: $nPop = 30$, $pRepl = 0.25$, 0.9 crossover probability, $pConv = 0.99$, Roulette-wheel selection algorithm and linear scaling. We increased the mutation probability to 0.03 (0.01 by default) and *nConv* to 50 (20 by default) in order to reduce the probability of convergence to a local optimum. These values are in line with Kuo et al. (2000) and Mayer et al. (2001) who investigated robustness of GA parameters for agricultural system models.

The normalized index $d$ (Eq. 4.1) was chosen as performance criterion for the objective function. Willmott (1981) proposed $d$ as a measure of fit to overcome the two main weaknesses of the well known and widely used relative root mean squared error (*RRMSE*). The first improvement is that $d$ is bounded (0 = no fit, 1 = perfect fit), while *RRMSE* is not. Also, $d$ has proved to be more stable than *RRMSE* when $\hat{Y}$, $\sigma_{\hat{Y}}$, and/or $N$ are small (Willmott, 1981), by using the mean squared error (*MSE*) as numerator in combination with a denominator reflecting the variability in observed ($Y_i$) and in calculated values ($\hat{Y}_i$) over the $N$ years used for calibration.

$$d = 1 - \frac{\sum_{i=1}^{N}(Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{N}(|\hat{Y}_i - \overline{Y}| + |Y_i - \overline{Y}|)^2} \tag{4.1}$$

As GAs are stochastic search algorithms, results can differ between calibration runs. We performed multiple GA runs from different random initial populations not only to control whether the GA successfully converged, but also to identify several 'optimum' parameter sets of equal performance. To make sure that the model parametrizations represented climate effects without bias we performed an analysis of residuals similar to the approach of White et al. (2007). GA runs for which unexplained (residual) variations exhibited significant correlations (p-value$< 0.05$) with the temperature and/or precipitation sums over the growing season were eliminated. As suggested by Beven and Freer (2001), prediction uncertainties were assessed by considering all acceptable parametrizations.

## 4.4 Results and discussion

In the following, we present results for the three steps involved in the calibration procedure for the example of grain maize in Taenikon (Sections 4.4.1 - 4.4.3). Validation results are presented for the Chaiblen experiment (Section 4.4.4). Next we consider results of a model application to a site characterized by different climatic conditions, and discuss the importance of local recalibration. Finally, we show results of a climate impact case study application of the calibrated model (Section 4.4.5).

### 4.4.1 Input preparation and preprocessing

In our study, yield data were extracted from the FADN database for all years from 1981 to 2008. To compute the MPY we used all records from municipalities with geographic centroids located within a 20-km radius around the climate stations of Taenikon and Payerne. The sensitivity of MPY estimates with respect to the aggregation radius was tested by repeating the calculations for a smaller radius of 15 km but little differences were found. Analysis of the results further suggested that for an aggregation radius of 20 km the choice of $Q_y = 0.9$ provided acceptable estimates of the MPY.

For some crops, the application of the Mann-Kendall test to the MPY time series indicated the presence of a significant trend (p-value $< 0.05$), which we assumed to be the consequence of breeding improvements. Where necessary the time series were therefore detrended using locally weighted regression (Cleveland and Devlin, 1988). Non-linear detrending was applied to account for step-changes evolution in agricultural policy that led to a leveling-off of national crop yields after 1994 (Finger, 2010). In theory, detrending should be based on the understanding of influences of technology and agricultural policy, as trends in time series of yield may also be influenced by climate change. However, in our case the effects of trends in climate may be excluded as potential yield was found to remain stable over the last 30 years in the majority of regions in Europe, especially for maize and sugar beet, in spite of changing temperature and global radiation patterns (Supit et al., 2010b).

At Taenikon, the distributions of grain maize yields within the aggregation radius were, in most years, positively skewed (see Fig. 4.2). For some years, the upper tail was very long leading to high standard errors (e.g. 1985). In rare cases, the tail was relatively short and associated with low standard errors. This was likely due to the fact that fewer farms with near-optimum management were sampled in these years implying that MPY was probably underestimated.

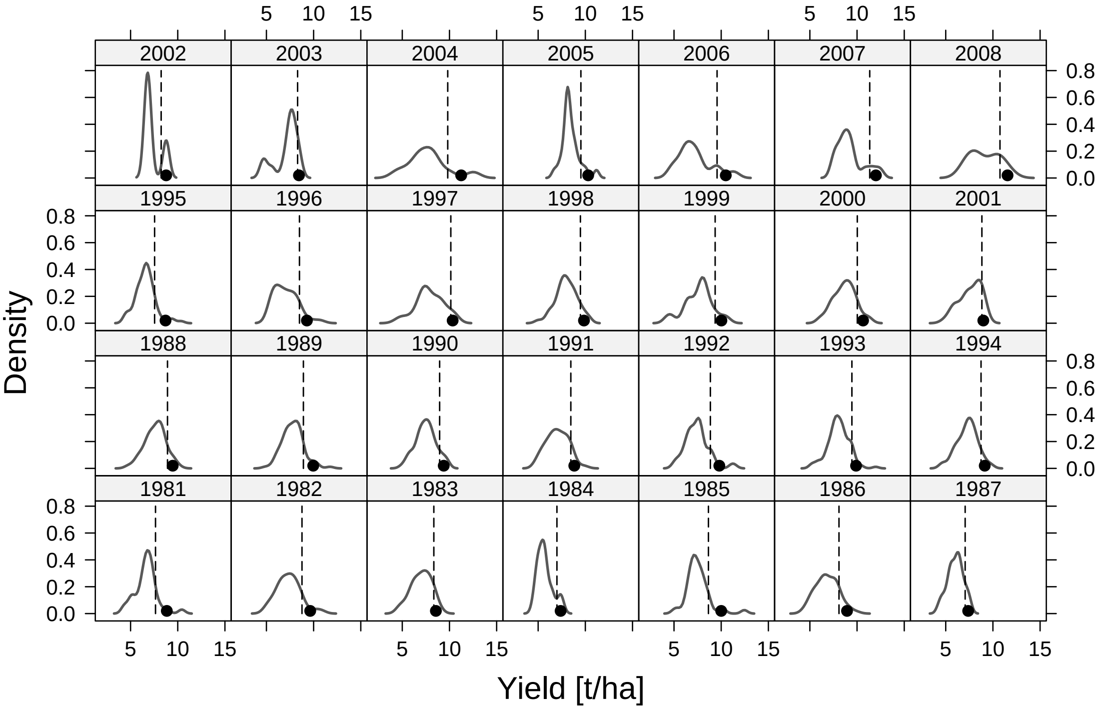

**Figure 4.2:** Distribution of grain maize yield records for the period 1981-2008 within a 20-km radius around the station of Taenikon; $Q_{0.9}$ value is represented as a dashed line and meteorologically possible yield as a point symbol.

A potential source of bias in the estimation of MPY is the decrease in temporal variability as the aggregation radius increases, a problem which is expected to appear unless yield time series at different farms are perfectly correlated (Hansen and Jones, 2000). In our case, however, a comparison of yield distributions showed no considerable decrease in variability as the aggregation radius was increased from 15 to 20 km.

Given the large uncertainties, we tested the plausibility of MPY by considering the ratio between MPY and the regional mean yield (mean of all yields within the area), assuming the latter to also reflect farms that do not operate in an optimal way. Based on the information available from Richner et al. (2010), this ratio should be of 1.25 (winter wheat), 1.5 (winter barley) and 1.15 (winter rapeseed). In our simulations almost equivalent ratios for winter wheat (1.27), slightly higher for winter rapeseed (1.28) and slightly lower for winter barley (1.36) were obtained from the FADN data, indicating that estimates of MPY were realistic. Unfortunately, we could not make the comparison for maize as the maximum possible yield in Switzerland is not well documented.

### 4.4.2 Parameter screening

Fig. 4.3 shows the results of the sensitivity analysis. Based on the Morris method we found for both Taenikon and Payerne that only a few parameters had a strong influence on final yield (high $\mu^*$ values), in agreement with results of Confalonieri (2010). In most cases parameters with high $\mu^*$ also exhibited high $\sigma$, indicating that these parameters interacted with others. For Taenikon the selected parameters were: $T_{opt}$, $BTR$, $K$, $SLA$, $Root_{distrib}$, $GDD_{sen}$, $LAI_{init}$, $SLP$, $RUE$ and $K_c$. With a few exceptions, screening returned a similar set of parameters for Payerne. Of the sensitive parameters identified for Taenikon, only $RUE$ was not selected for Payerne, but two more parameters related to water stress were selected instead (i.e. $LAD_{stress}$, $Stress_{W\&N}$).

Importantly, parameters related to radiation-intercepted biomass growth ($RUE$ and $T_{opt}$) were more sensitive at Taenikon, while parameters related to the water availability (e.g. Rootdistrib) and crop response to water stress (e.g. $LAD_{stress}$, $Stress_{W\&N}$) had higher $\mu^*$ at Payerne. This highlighted climatic differences between the two locations and suggested that maize yield at Taenikon is more radiation- and temperature-limited, while water availability plays a more important role at Payerne.

### 4.4.3 Parameter estimation

Fig. 4.4 presents the simulation results based on 10 automatic parameter estimation runs using $d$ as performance criterion in the goal function. The high $d$ indicated that simulated and observed MPY were well in line after GA parameter estimation. Standard deviation across the 10 different GA runs was relatively low, suggesting that the GA converged successfully in all 10 runs.

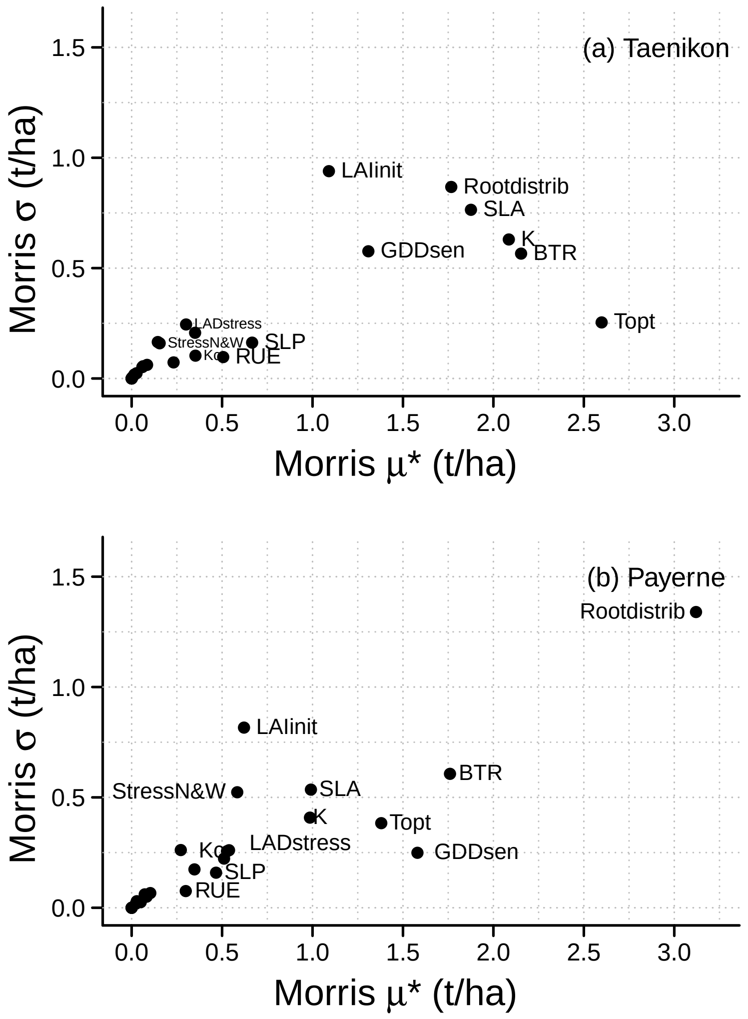

**Figure 4.3:** Results of the sensitivity analysis: Morris $\mu^*$ and $\sigma$ for maize in (a) Taenikon and in (b) Payerne.

Simulated yield exceeded estimated MPY on short-tailed years (e.g. 1984, 1997 and 2001, see Fig. 4.4), possibly because MPY was underestimated on such occasions (see Section 4.4.1). In contrast, negative deviations between simulations and MPY occurred for some long-tailed years (e.g. 1982, 1985, 2004), possibly because the sample of farm records used to derive MPY included farms that had more favorable production conditions (e.g. soil, climate) than those used to drive CropSyst. For our simulations, we used a single set of soil and weather data, assuming that soil and weather conditions were representative for the entire aggregation area. However, local weather and soil conditions are expected to vary spatially within the aggregation radius and this incomplete representation of spatial variability of inputs is likely to alter the prediction quality (Hansen and Jones, 2000).

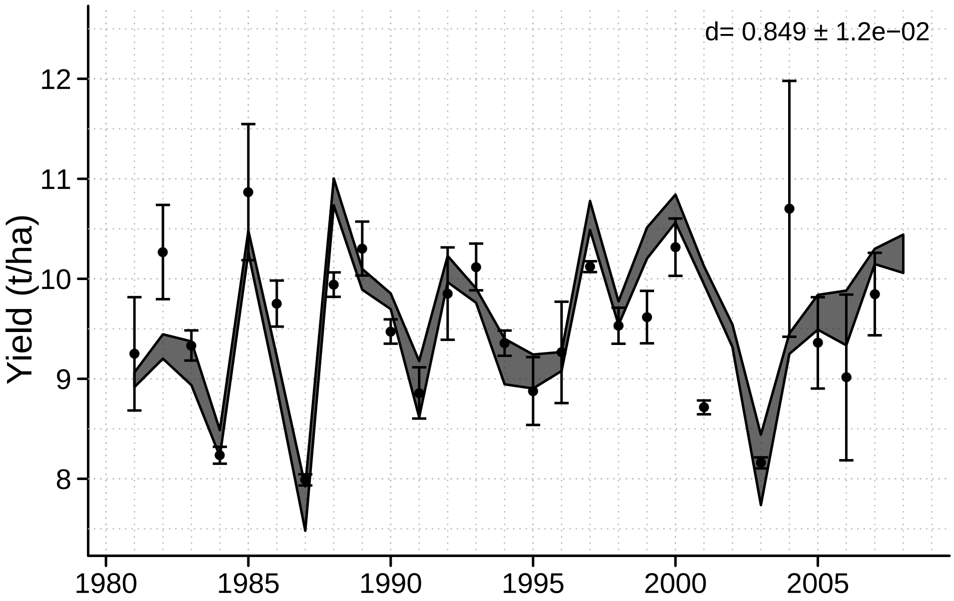

**Figure 4.4:** Ranges of CropSyst simulations for maize using the best genomes of each calibration run based on the Willmott index (*d*) as performance criterion in the goal function; constructed maize meteorologically possible yield (MPY, black dots) in Taenikon is represented together with the yearly standard error; yields are expressed in dry matter assuming a 15% water-content for maize (Flisch et al., 2009); mean ± standard deviation of *d* are also displayed.

The GA-based parameter estimation worked efficiently, requiring only short run times. On average, calibrating 10 CropSyst parameters with $nPop = 30$, $pRepl = 0.25$, $pConv = 0.99$ and $nConv = 50$ required 600 runs (80 generations) to attain convergence.

One might question whether similar performances could be achieved with simpler parameter estimation approaches. Tests were conducted by adjusting sensitive parameters sequentially in a two-iteration setup. Therefore, parameter ranges were divided into 20 intervals. Each parameter was calibrated in turn by running the model for each of the 21 discrete values and picking the best one based on $d$, while other parameter values were kept constant at the center value of their range during a first iteration and at the optimum values from the first iteration during a second iteration. We found out that the performance of the model, after the sequential parameter estimation, was almost as good as after the GA parameter estimation. However, sequential calibration approach can be risky as potential interactions between parameters cannot be considered. Therefore, the GA-based parameter estimation was preferred. The choice of GA was also motivated by the possibility to identify several parameter sets with very similar performances, which made it possible to represent parameter uncertainties.

Fig. 4.5 shows box plots of all parameter values identified as optimum in the 10 GA runs for Taenikon and Payerne. Note that in this figure the Y-axis limits correspond to the boundaries of the parameter ranges specified a priori for use in the parameter screening and GA parameter estimation. Parameter uncertainties were generally low, particularly for sensitive parameters such as $T_{opt}$, *BTR* and $GDD_{sen}$ (Fig. 4.5, compare with Fig. 4.3). However, the overall uncertainty of some parameters was still large since different combinations of parameters values were equally reasonable, a phenomenon generally known as ‘equifinality’(Beven and Freer, 2001). Indeed, several parameters interacted with each other, which was e.g. the case for those related to the leaf area development during the vegetative period such as *SLA*, *SLP* and $LAI_{init}$.

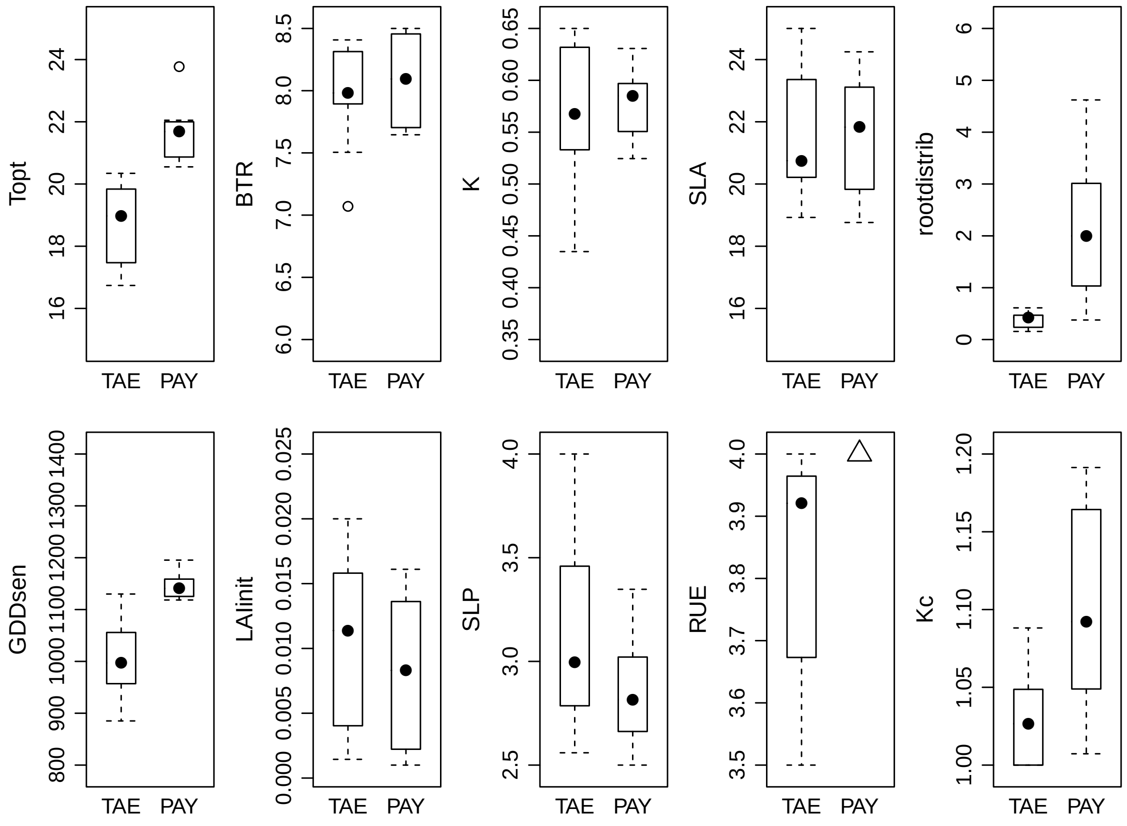

**Figure 4.5:** Box plots of all crop parameters resulting from 10 GA runs in Taenikon (TAE) and Payerne (PAY); Y-axes cover the initial ranges of parameter values used for the sensitivity analysis and the parameter estimation; *RUE* was not calibrated in Payerne due to low sensitivity (point symbol); a complete description of CropSyst crop parameters can be found in Table 4.1.

It seems obvious that fixing parameters introduces bias for estimating other parameters. However, it is crucial to reduce the complexity of the optimization problem as much as possible by limiting the number of parameters to be calibrated and by defining relatively narrow initial parameter distributions as the risk of model overfitting is high with large numbers of parameters and limited sample sizes (Holzkämper et al., 2012); it is very likely that all 25 CropSyst crop parameters which were subject to parameter screening could not be properly calibrated with ‘only’ 28 years of reference data.

### 4.4.4 Validation

To validate the calibration for Taenikon, data from a field trial in Chaiblen were used. We conducted the calibration approach not only for maize, but also for the other crops occurring in the rotation and compared simulated yields for this rotation to the observed yields. The performance that could be achieved with the presented calibration approach was compared against the performance achieved with the CropSyst calibrations by Torriani et al. (2007), who had calibrated CropSyst for four crops in Switzerland based on data obtained from three field trials. Their calibration was carried out in two steps, by adjusting first the phenology and then the biomass accumulation. Fig. 4.6 summaries the validation results for the reference calibration of Torriani et al. (2007) and the calibration presented here.

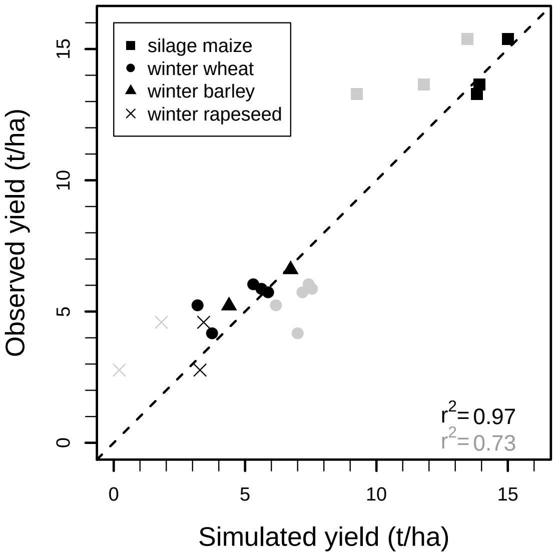

**Figure 4.6:** Model validation using data from an independent long-term field experiment in Chaiblen (nearby Taenikon): comparison between simulated and observed yields; the performance of the parameter set resulting from the best GA run (black symbols) was compared to the parametrization proposed by Torriani et al. (2007) (gray symbols) for each crop in the rotation.

With the MPY-based calibration approach, CropSyst reproduced observed yields very satisfactorily. This was a key result as it not only validated the model calibration but it also indicated that estimated MPY were realistic. In comparison to the calibration of Torriani et al. (2007) the predictive power was increased from $r^2$ of 0.73 to 0.97.

### 4.4.5 Testing the model parametrizations under different climate conditions

To assess the performance of the calibrated model under different climatic conditions and soil properties, we simulated grain maize growth at Payerne with the parameter values as determined for Taenikon (denoted *pTAE*). We found that at Payerne yields were systematically underestimated, with large deviations in years characterized by conditions departing more substantially from those represented by the climate at Taenikon (e.g. 2003 and 2006). Because at Payerne growth limitation is mostly related to transpiration, while at Taenikon radiation has also a limiting effect, CropSyst was not able to realistically simulate the sensitivity of crop growth to climate at Payerne without local recalibration. These results highlight the importance of calibrating and validating a crop model specifically for the area of interest (see e.g. Timsina and Humphreys, 2006). The importance of local recalibration is stressed by Fig. 4.7, which compares the model predictive ability in Payerne based on *pTAE* and locally adjusted sets of parameters (*pPAY*).

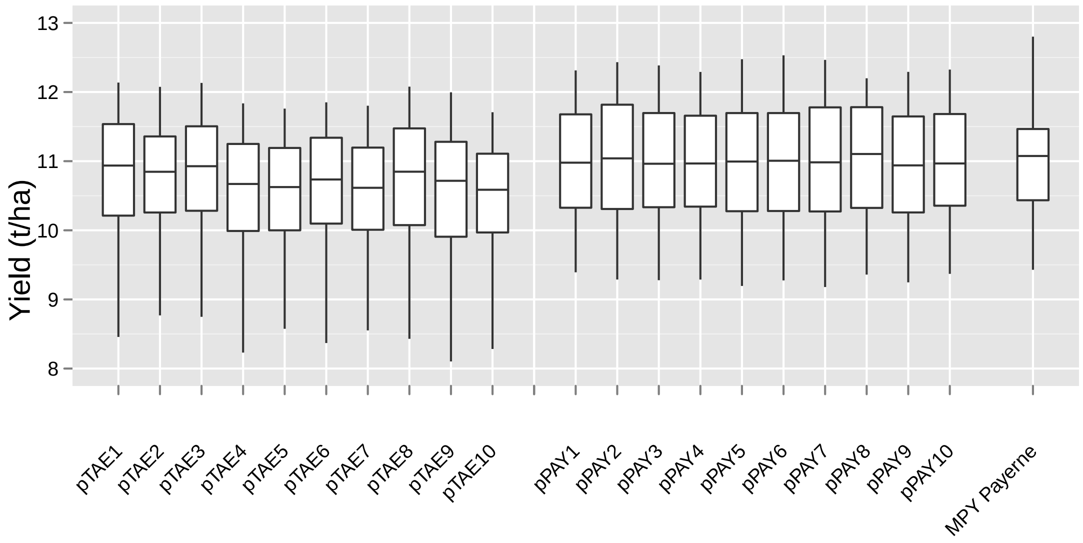

**Figure 4.7:** Box plots of simulated and observed yields at Payerne: simulated using the 10 GA parametrizations derived at Taenikon (*pTAE*), simulated based on the 10 GA local recalibrations at Payerne (*pPAY*) and observed meteorologically possible yields (MPY) used as reference for the local recalibrations *pPAY*.

To explain the differences between *pTAE* and *pPAY* on simulated yield, those two parametrizations were examined in terms of parameter values. $T_{opt}$ was lower in *pTAE* in order to increase radiation-dependent biomass accumulation which is limited when the air temperature is below $T_{opt}$ (see Fig. 4.5). Higher *SLA* but lower *SLP* in *pPAY* increased the leaf area with positive feedback on intercepted solar radiation and transpiration which was further increased by higher *Kc*. In addition, a higher value of $GDD_{sen}$ in *pPAY* allowed leaf senescence to occur later than with *pTAE*, further increasing the gap between total biomass accumulation at maturity.

Difficulties in reproducing the sensitivity to climate without recalibration can have severe implications for climate change impact assessment. To illustrate this problem, the comparison between *pTAE* and *pPAY* was extended by considering in addition a crop model application with an illustrative climate scenario for 2050. Fig. 4.8 presents box plots of relative changes in mean yield between 1981-2010 and 2035-2065, as obtained for Taenikon with the 10 parameter sets *pTAE*, and for Payerne with both the 10 parameters sets *pTAE* as well as the parameter sets *pPAY*. The figure suggests that climate change had a similar impact on yield at both locations if local calibrations were used, with a yield decrease by about 0.75 t ha$^{-1}$. Thus local GA parameter sets simulated the yield reduction consistently, with few exceptions in Payerne where one parameter set led to negligible decrease and another one to a decrease by more than 1 t ha$^{-1}$. Simulations in Payerne with *pTAE*, on the other hand, showed that yield would decrease by 1.5-2 t ha$^{-1}$ under climate change, indicating a much higher, but likely unrealistic sensitivity to the assumed decrease in summer precipitation with *pTAE* than with *pPAY*. Our results emphasize the importance of considering parametrization uncertainties when applying a crop model for climate change impact studies, which is often missing, as pointed out in several publications (Beven and Freer, 2001; Janssen and Heuberger, 1995; White et al., 2011).

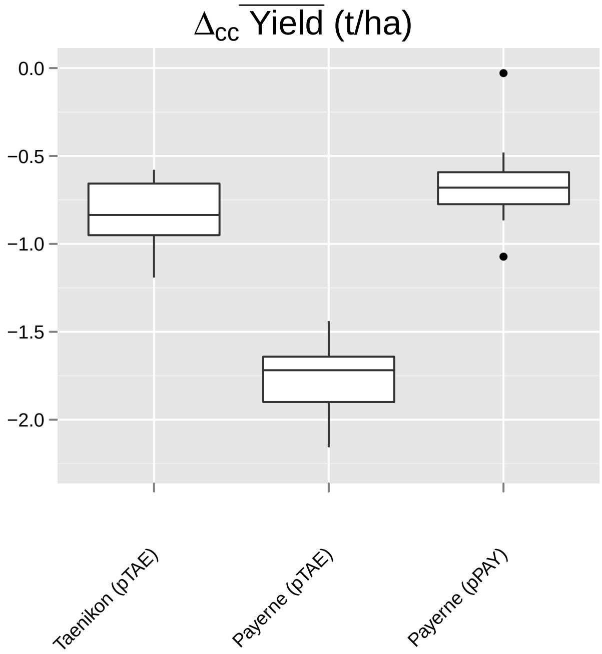

**Figure 4.8:** Box plots of mean yield reductions with the climate change scenario (*ETHZ-CLM* scenario for horizon 2050) for three situations: simulated in Taenikon with local calibration in Taenikon (*pTAE*), simulated in Payerne with *pTAE* and simulated in Payerne with local recalibration in Payerne (*pPAY*).

## 4.5 Conclusions

We showed that a generic crop model (CropSyst) can be successfully calibrated based on FADN data, provided that subset of the latter are selected in such a way as to reflect the specific research questions. In our case we were interested in climate-crop interactions, and proposed therefore to use so-called ‘Meteorologically Possible Yields’ (MPYs) as a basis for model calibration. We derived robust estimates of MPY from FADN data by specifying thresholds that allow defining an upper tail of the distribution of yields recorded in FADN. Estimated MPY were then used as a reference in an objective automated parameter estimation procedure for water-limited yield simulations. Our results suggested that FADN data are a valuable source of information for crop model calibration in areas where more detailed information from experimental field trials in controlled conditions is not available.

From a technical point of view, our study indicated that the GA-based automated calibration procedure was feasible at low-computation costs. While not always superior to simpler approaches, such as sequential calibration, parameter screening following Morris (1991) and GA parameter estimation proved to be powerful tools for calibration of crop models in which non-linear interactions between various processes and parameters are the rule rather than the exception.

We showed that local recalibration of crop parameters is needed to account for differences in site conditions, even for locations that are in geographic terms relatively close to each other. In the context of our study, simulations without local readjustment of the parameter values failed e.g. to properly capture the sensitivity of crop growth to summer drought, leading in a climate change impact assessment to effects of decreasing summer precipitation that were clearly overrated when compared to simulations relying on a local parametrization. These findings highlight the strong necessity for adjusting model calibrations to local site conditions and for considering parameter uncertainties in climate impact studies. The need for local recalibration could be relaxed if e.g. parameter values were estimated based on pooled data from locations with different climate conditions. Further work is needed to explore this possibility. Other sources of model uncertainties should also be considered, such as uncertainties in model inputs (soil data and parameters, weather data, climate change scenarios and emission scenarios) and model structure, which are expected to lead to even larger biases than parametrization uncertainties (Ceglar and Kajfež-Bogataj, 2012).

## Acknowledgements

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# Chapter 5

# Adaptation options under climate change for multifunctional agriculture - a simulation study for western Switzerland

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## Abstract

Besides its primary role in producing food and fiber, agriculture also has relevant effects on several other functions, such as management of renewable natural resources. Climate change may lead to new trade-offs between agricultural functions or aggravate existing ones, but suitable agricultural management may maintain or even improve the ability of agroecosystems to supply these functions. Hence, it is necessary to identify relevant drivers (i.e. cropping practices, local conditions) and their interactions, and how they affect agricultural functions in a changing climate. The goal of this study was to use a modeling framework to analyze the sensitivity of indicators of three important agricultural functions, i.e. crop yield (food and fiber production function), soil erosion (soil conservation function) and nutrient leaching (clean water provision function), to a wide range of agricultural practices for current and future climate conditions. In a two-step approach, cropping practices that explain high proportions of variance of the different indicators were first identified by an ANOVA-based sensitivity analysis. Then, most suitable combinations of practices to achieve best performance with respect to each indicator were extracted and trade-offs were analyzed. The procedure was applied to a region in western Switzerland, considering two different soil types to test the importance of local environmental constraints. Results showed that the sensitivity of crop yield and soil erosion due to management is high, while nutrient leaching mostly depends on soil type. We found that the influence of most agricultural practices does not change significantly with climate change; only irrigation becomes more relevant as a consequence of decreasing summer rainfall. Trade-offs were identified when focusing on best performances of each indicator separately, and these were amplified under climate change. For adaptation to climate change in the selected study region, conservation soil management and the use of cropped grasslands appear to be the most suitable options to avoid trade-offs.

**Keywords** Multifunctional agriculture - Climate change adaptation - CropSyst - Trade-offs

## 5.1 Introduction

Agriculture is among the economic sectors that are most sensitive to climate change. In Europe, the combination of increased air temperature and changes in the amount and distribution of precipitation could cause significant shifts in agroclimatic zones (Trnka et al., 2011). More frequent droughts and extreme weather events during the cropping season are likely to increase the number of unfavorable years, which may cause enhanced yield instability and make current agricultural areas less suitable for traditional crops (Olesen and Bindi, 2002), with differential climate change impacts depending on crops and regions (Supit et al., 2012).

In Switzerland, projections for 2050 indicate a temperature increase ranging from $+1.5$ to $+3.5$ °C , with precipitation changes ranging from $-15$ to $+15\%$ in winter and from $-5$ to $-25\%$ in summer relative to 1980-2009 (CH2011, 2011). An increase in air temperature in combination with a marked shift in the seasonality of precipitation may increase drought risk on the Swiss Central Plateau (Calanca, 2007; Fuhrer et al., 2006). Such changes are likely to have negative impacts on agricultural productivity and to significantly increase production risks toward the end of the century (Fuhrer et al., 2006; Torriani et al., 2007). Hence, adaptations of cropping practices, such as changes in crop choice or irrigation, seem unavoidable in order to reduce the vulnerability of crop production to climate change.

Besides its primary role of producing food and fiber, agriculture also has relevant effects on several other functions, such as the management of renewable natural resources, landscape, conservation of biodiversity and contribution to the socioeconomic viability of rural areas (UNCED, 1992). The concept of multifunctionality of agriculture has attracted many scientific contributions from different disciplines (Renting et al., 2009), and led to the development of a wide range of modeling approaches (Rossing et al., 2007) with a special focus on trade-offs between multiple objectives (see e.g. Groot et al., 2007). Improved understanding of how local conditions (soil, weather) and cropping practices affect yield variability and cause environmental impacts is necessary to support policy-making in favor of multifunctional agriculture (Nelson et al., 2009). However, generalization is difficult as impacts may vary substantially among regions and could be altered by climate change. Moreover, it is known that adaptation strategies for improving crop yield may aggravate existing harmful impacts on the environment or lead to novel negative impacts (Schröter et al., 2005).

Ecophysiological models are widely used to examine options for adaptation by stakeholders and policy makers as they have the ability to explore large sets of agricultural practices. White et al. (2011) reported that most of previous studies focused on one crop in combination with a limited number of agricultural practices. Typically, only one cropping practice is tested, sometimes two, but rarely more than three. To the latter category belongs the study by Ruane et al. (2013) who investigated the effect of season length, planting date, fallow period, soil type, cultivar choice and fertilizer use on maize growth in Panama. They found that planting dates and soil type are important drivers of maize yield. Planting date and use of cultivar with a longer/shorter growth cycle were the most frequently varied options in the literature. For Swiss crops, Torriani et al. (2007) found that early sowing and use of crops with longer growth cycle greatly reduce negative impacts of climate change, particularly in grain maize, and Moriondo et al. (2010a) showed that expanding the growth cycle is an efficient adaptation strategy to reduce vulnerability to climate change in sunflower, soybean, spring/winter wheat. Also, use of irrigation substantially increased crop yields in areas where rainfed production is possible under current conditions. Only few studies examined nutrient fertilization, tillage practices and crop rotations as adaptation options. Van Ittersum et al. (2003) showed that some effects of climate change, for instance decreases in grain nitrogen (N) content, could be offset by extra N fertilization. Scholz et al. (2008) showed that reduced tillage could contribute to reduced erosion under climate change. Changing crop rotations has almost never been tested as adaptation option, mainly due to (i) the lack of empirical data for a proper representation of crop rotations (Schönhart et al., 2011) and (ii) the fact that models need to be calibrated specifically for every crop involved in the rotation. Nevertheless, Ko et al. (2011) simulated impacts of projected climate change on the productivity of dryland crop rotations of wheat-fallow, wheat-corn-fallow, and wheat-corn-millet and found high yield differences between crop rotations.

In general, modeling studies exploring effects of climate change and potentials for adaptation focus on impacts on economic yield (White et al., 2011), neglecting other functions. However, exceptions can be found in the literature. This is for example the case of Van Ittersum et al. (2003) who assessed impacts of climate change and agricultural practices on numerous variables connected to biomass and N allocation. Agricultural functions

(i) food and fiber production, (ii) soil conservation, and (iii) clean water provision were found to be strongly affected by climate change in previous studies (Bindi and Olesen, 2010; Nearing et al., 2004; Olesen and Bindi, 2002) and are of major importance in the context of adaptation in Switzerland (FOEN, 2012a).

In this study, we selected three indicators in order to quantify main aspects of those functions: crop yield for food and fiber production, soil erosion for soil conservation, and nutrient leaching for clean water provision. The aim of this study was to investigate the sensitivity of those indicators to a wide range of agricultural practices under current and future climate conditions based on simulation models. We address specifically three main questions:

1. How do the indicators respond to agricultural practices and to climate change?
2. Which combinations of agricultural practices provide the greatest potential for adaptation to climate change?
3. What trade-offs result from different adaptation options?

In a two-step approach, cropping practices that have largest impacts on indicators were first identified by a sensitivity analysis based on the quantification of the proportion of total variance explained by every practice. Then, combinations of practices to achieve best performance with respect to each indicator were extracted. The analysis was conducted for an agricultural area located in the western part of the Swiss Plateau where agriculture is an important sector but already suffers from water shortage (Fuhrer and Jasper, 2012). Two contrasting soil types that are representative for the study region were investigated to account for the effect of local environmental constraints, and two contrasting climate change scenarios were used in order to account for uncertainties in climate projection.

## 5.2 Methods

### 5.2.1 Crop model

*Model description*

An integrated process-based model was used, which allows for simulating a wide range of agricultural practices. CropSyst (version 4.13.04) was selected for three reasons: (i) it does not only simulate agricultural yield but also soil erosion and N-leaching; (ii) it covers most of agricultural practices currently in use in the study region; (iii) it is a generic crop model and has been successfully applied to test adaptation in similar contexts (e.g. Moriondo et al., 2010a; Torriani et al., 2007).

In CropSyst, biomass accumulation is calculated as a function of crop potential transpiration and intercepted radiation. Potential growth is corrected by factors reflecting water and N limitations to compute actual daily biomass gain. The final crop yield is the total biomass accumulation over the growing season multiplied by a harvest index.

Soil loss due to water erosion is calculated using the Revised Universal Soil Loss Equation (RUSLE) by Renard et al. (1997), which expresses average annual erosion expected on field slopes as the product of six factors. The first factor is the rainfall energy intensity, which accounts for the erosive power of rain. The second one is the soil erodibility factor, which accounts for the influence of soil properties on soil loss during storm events. Then, two factors are used to integrate the effect of slope (length and steepness). A factor for soil conservation practice is also used and, finally, the C-factor represents the effect of land management on erosion, which depends on surface residue cover, incorporated residues, crop cover and soil moisture.

The components of the simulated N balance include N transport, N transformations, ammonium sorption, and crop N uptake (Stöckle et al., 1994). N-leaching is determined on the basis of a so-called ‘bypass coefficient’ as proposed by Corwin et al. (1991). The bypass coefficient simplistically accounts for flow through cracks and macropores that bypasses small and dead-end pores, the flow of a mobile water phase independent of an immobile phase of water, and the phenomenon of dispersion-diffusion. N transformations considered in CropSyst include net mineralization, nitrification and denitrification. They are assumed to take place in the first 30-50 cm of the soil profile and are simulated by first order kinetics (Stöckle and Campbell, 1989). Ammonium in the soil is either absorbed into the soil in solid phase or dissolved in soil water. A Langmuir relationship is used to relate ammonium in solution to ammonium in the soil matrix. Crop N uptake is computed as the minimum between crop N demand and potential N uptake. Crop N demand is the amount of N the crop needs to meet its potential growth, plus the difference between the crop maximum N concentration and the actual N concentration. Potential N uptake is a function of the maximum N uptake per unit length of root, root length, N availability and soil moisture.

*Model setup and testing*

CropSyst was calibrated for seven main crops in Switzerland i.e. winter wheat, winter barley, grain/silage maize, potato, sugar beet, winter rapeseed using the calibration procedure developed by Klein et al. (2012). As grass is the primary type of livestock feed in Switzerland covering 71% of the total agricultural surface (BFS, 2010), and is frequently cultivated in rotations, CropSyst was also calibrated for grassland using data from an experimental site located on the Swiss Central Plateau near Oensingen (7°44 E, 47°17 N, 450 a.m.s.l., Ammann et al., 2009). In this experiment, the field was typically cut four times per year and was fertilized with solid ammonium nitrate or liquid cattle manure after each cut. Soil had clay content between 42 and 44%, total pore volume of 55%, and water volumetric of 32% at the permanent wilting point.
The calibration of CropSyst for grasslands was developed as follows: firstly, crop parameters were adjusted so that simulated grass biomass accumulation, leaf area index (LAI) and evapotranspiration were in line with observations. Secondly, soil parameters (e.g. saturated hydraulic conductivity) were tuned to further improve the match between observed and simulated soil moisture at various depths. Legume fraction - which is a critical parameter to compute atmospheric N fixation - was set to 0.3 representing the mean observed value. After calibration, the model was able to reproduce very well the total annual harvested biomass ($r^2$ of 0.89), the leaf area index ($r^2$ of 0.6), the actual crop transpiration ($r^2$ of 0.70), and the soil water content ($r^2$ of 0.81 for soil moisture at 30 cm).

RUSLE is the most commonly used soil erosion model worldwide and it owes its popularity to its minimal data, calibration and computation requirements as well as to its transparent and robust model structure (Prasuhn et al., 2013). Following Arnold and Williams (1989), CropSyst computes rain erosive power based on daily rainfall and a monthly factor $\alpha_m$ expressing the average fraction of daily rainfall that can occur during a 30-min period as a maximum. $\alpha_m$ was calculated from 30-min rainfall data for the period 1981-2010, and assumed to be stable under climate change. The latter assumption is supported by an analysis of the relation between peak-hourly intensity and daily total amounts, as simulated by the climate scenarios. We assumed a typical slope steepness of 10% and a slope length of 100 m. A soil conservation practice factor of 0.88 was used, which is a representative value for croplands in Switzerland (Prasuhn et al., 2007).
Validation of soil loss predictions through soil erosion models is generally difficult (Gobin et al., 2004). Prasuhn et al. (2013) attempted to validate their high-resolution soil erosion risk map of Switzerland based on RUSLE with 10-year field data for 203 plots in the Swiss Plateau and found a good congruence between modeled and observed soil loss. Simulated erosion by CropSyst after calibration compared relatively well to empirical data from Prasuhn (2012) that were collected in western Switzerland. Simulated erosion

was 6.3/1.3 t ha$^{-1}$ yr$^{-1}$ with regular tillage / no till and retention of harvest residues, while soil losses measured on experiment sites were 3.4/0.75 t ha$^{-1}$ yr$^{-1}$ on plow-tilled fields / on fields with 1% on mulch-tilled land with more than 30% surface residue cover. Despite the fact that RUSLE tends to overestimate observed soil loss values, which has been often pointed out (Bartsch et al., 2002; Evans, 2002), the ratio between erosion with regular till and erosion with no till as simulated by the model is very similar to the observations.

Empirical data on fluxes and stocks of N are scarce for Switzerland, which makes the calibration and assessment of models complicated (Dueri et al., 2007). For this reason, CropSyst could not be specifically calibrated with regard to N-leaching. Nevertheless, we tested the plausibility of N-leaching simulations by comparing them with results from a lysometer experiment by Nievergelt (2002) in NE Switzerland. After calibration, CropSyst simulated mean N-leaching values of around 30/27.5 kg N ha$^{-1}$ yr$^{-1}$, while mean values of 47.6/39.5 kg N ha$^{-1}$ yr$^{-1}$ with optimum/reduced fertilization were measured at the experimental site. The fact that simulated N-leaching values are lower than those observed in field experiments could be a consequence of different choices of rotations or different soil types (see below).

### 5.2.2 Sensitivity analysis

To quantify the relative importance of each agricultural practice for productivity, soil erosion and N-leaching, simulation outputs were subject to a factorial decomposition (ANOVA). Simulations were performed following a complete factorial design. The ANOVA-based sensitivity method is computed as follows: $SS_T = \sum_i SS_i + \sum_{i<j} SS_{ij}$, where $SS_i$ is the main effect contribution of each practice to the overall outcome variance ($SS_T$), and $SS_{ij}$ the interactions between factors. Decomposition of model response was limited to two-factor interactions since the highest sensitivities are most often associated with low-order interactions (Ginot et al., 2006). The total sensitivity index for a given factor was calculated as the sum of main and interactive effects with other factors.

## 5.3 Case study

### 5.3.1 Study region

The study region is the area located around the weather station of Payerne in the drier western part of the Swiss Central Plateau. In this region, irrigation is already applied regularly for some crops (e.g. potato or sugar beet). Soil information was derived from the Soil Suitability map of Switzerland (BFS, 2012) and adjusted with soil profile information from the Swiss Soil Monitoring Network (BUWAL, 2003). The two most common soil types in this region were considered:

- sandy loam soil characterized by a rather coarse texture with 65% sand, 25% silt and 10% clay;
- loamy soil characterized by a finer texture with 40% sand, 40% silt and 20% clay.

Observed weather data were obtained from the monitoring network of the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss). The stochastic weather generator LARS-WG (Semenov and Barrow, 1997) was used to generate 25 years of synthetic daily weather data for (i) a baseline period corresponding to 1981-2010 and (ii) two climate scenarios for the time horizon 2036-2065 that span a significant portion of the full range of changes in temperature and precipitation projected by the ensemble of regional climate model simulations carried out in the framework of the ENSEMBLES project (van der Linden and Mitchell, 2009) under the assumption of a A1B emission pathway. The first scenario refers to a run performed with *ETHZ-CLM* (ETH) and is characterized by a strong climate change signal in summer ($+3.5$ °C and $-24\%$ in seasonal precipitation amount); the second scenario refers to a run performed with *SMHIRCA-HadCM3Q3* (SMHI) and suggests more moderate changes for summer season ($+1.3$ °C and $-11\%$ in seasonal precipitation amount), but an important increase in seasonal precipitation amount during fall ($+21\%$). Both climate scenarios agree on small changes in precipitation intensity during spring, summer and fall, but a significant intensity increase ($\sim +20\%$) during winter. Seasonal changes in terms of temperature, precipitation amount and precipitation intensity for both climate scenarios can be found in the appendix (Table A.1).

### 5.3.2 Experimental plan

A complete factorial experimental plan was set up consisting of four agricultural practices: irrigation (2 levels), management intensity with regard to N fertilization and grassland clippings (3 levels), soil management (use of tillage and residue management, 2 levels), and crop rotation choice (selection of cultivars and sequence, 50 levels). Each set of practices was tested for 3 different weather datasets (baseline climate and 2 climate scenarios) and 2 soil types, resulting in a total of $2 \cdot 3 \cdot 2 \cdot 50 \cdot 3 \cdot 2 = 3600$ runs. Detailed information on crop-specific values used in the experimental design for each practice and level is listed in the appendix (Table A.2).

### *Irrigation*

Two irrigation options were included in the experimental plan: rainfed and supplemental (automatic). Automatic irrigation is triggered when soil moisture falls under a certain crop-specific threshold. Then, soil moisture is refilled until a user-defined level. Parameter values for automatic irrigation (minimum soil moisture and refill point) were determined based on economic considerations following Lehmann et al. (2013), who found that irrigation is only profitable for potato, sugar beet and grain maize under present and future climate (based on both ETH and SMHI).

### *Crop rotation*

Crop rotations affect the performance of cropping systems with respect to both productivity (e.g. effects on water/nutrient balance or pests and diseases) as well as environmental impacts (nutrient leaching or erosion). Hence, it was crucial to include crop rotation choice as a potential adaptation strategy. As a possible way to circumvent the lack of empirical data, a rotation generator can be used to create realistic crop sequences based on expert knowledge (see e.g. Bachinger and Zander, 2007; Dogliotti et al., 2003; Schönhart et al., 2011). Here, a simple crop rotation generator was developed in order to stochastically simulate 5-year rotations. These were constrained with regard to (i) the feasibility of crop sequences and (ii) maximum crop shares as recommended by Vullioud (2005). It was assumed that cropped grasslands could only be grown for two consecutive years. Following Swiss legislations for subsidies, a cover crop had to be included unless the current crop was harvested after 31 August, and/or the following crop was a winter crop.

50 different crop rotations were generated based on the eight crops for which CropSyst was calibrated (Table A.3). Rotations characterized by identical crop mixes differing only in terms of sequence were removed - new ones were generated instead - in order to maximize the variability in crop mixes. Conditional sowing dates were used for each crop within the rotation. In practice, the earliest possible sowing date was prescribed but sowing event could be postponed until a crop-specific temperature threshold was reached. Data typical for regional conditions were provided by expert judgment. Crop harvest was set to occur right after physical maturity, or five days before sowing the next crop if maturity was not reached on time.

*Management intensity*

Management intensity was related to (i) the total amount of N fertilizer and (ii) the number of grassland clippings. Three intensity levels were tested: high intensity (recommended N fertilization, 5 clippings), medium intensity (recommended N fertilization $-25\%$, 4 clippings) and low intensity (recommended N fertilization $-50\%$, 3 clippings). Recommended N fertilization was derived from Flisch et al. (2009), while application dates depended on total N applied following Janssen et al. (2009).

*Soil management*

Two types of soil management were investigated: conventional (regular tillage and removal of residues) and conservation management (no tillage and residues retained). Tillage consisted of plowing 10 days prior to sowing and harrowing one day before sowing. When residues were removed, a biomass loss coefficient of 10% was used (recommended value in CropSyst).

### 5.3.3 Model application

*Initial conditions*

Initial soil moisture was set to field capacity. A value of 12 kg N ha$^{-1}$ ($NO_3-N+NH_4-N$) was assumed for the initial soil mineral N content in the top 30 cm (Weisskopf et al., 2001). Initial values for organic N were obtained from a 300-year model spin-up. This was necessary to adjust the stable fraction of organic matter. Regular tillage was assumed for the spin-up. At equilibrium, CropSyst simulated an organic matter content of 2.9% for the first soil layer and 2% for other layers. Ranges of observations in the study area are [2.5,5%] for top layer and [0.5,2%] for deeper layers (Leifeld et al., 2003).

*Processing of model outputs*

To account for climate variability, 5-year rotations were repeated 5 times for a total of 25 years. Outputs of interest (crop yield, soil loss and N-leaching) were then averaged for every crop in the rotation, based on those 5 replicates.

Because crop types differ in potential yield level, ranging from about 2.3 t ha$^{-1}$ of dry matter for winter rapeseed to about 16.5 t ha$^{-1}$ for sugar beet, agricultural productivity of a rotation was defined as the arithmetic mean of individual crop yields scaled according to $\tilde{Y} = \frac{Y - Y_{\min}}{Y_{\max} - Y_{\min}}$, where $Y_{\min}$ and $Y_{\max}$ are the crop-specific minimum/maximum yield values obtained under current climate across all soil types.

Yearly average values of productivity, erosion and N-leaching for each set of practices were computed as the arithmetic mean of individual values reached by different crops in the rotation. These average values were then used to conduct the sensitivity analysis and to determine the most suitable adaptation strategies to achieve best performances with respect to the different indicators.

## 5.4 Results

### 5.4.1 Variability in model outputs

variability in model outputs for scaled productivity, erosion and N-leaching across the large number of cropping practices are summarized in Fig. 5.1. Variability of productivity across all agricultural practices is high, with an interquartile range of about 0.2 under current climate and slightly lower under climate change ($\sim 0.15$). Many extreme values and outliers occur in both directions (i.e. high and low productivity). Median agricultural productivity is higher on loamy soil, which is characterized by higher water retention potential. However, maximum productivity of 0.91 (i.e. 91% of maximum possible yield on average over the rotation) is reached for sandy loam soil. Median yield slightly decreases under climate change on both soil types, particularly for simulations based on the ETH climate scenario ($\sim -10\%$).

Also, variability of soil loss is high. Erosion is much higher ($\sim +50\%$) and more variable for loamy soil compared to sandy soil. Moreover, extreme values occur more frequently, but no outliers are found. For both climate scenarios, variability in simulated erosion slightly increases under climate change, and the median of soil loss increases, in particular on loamy soil ($\sim +35\%$ under climate change). The trend toward increased erosion under climate change is attributed to shorter growing cycles with more frequently uncovered soil in fall/winter, coinciding with increased precipitation intensity during this period of the year (Table A.1).

In contrast to productivity and soil erosion, variability of N-leaching across different sets of practices is very small. Indeed, simulated N-leaching is mostly driven by soil type,

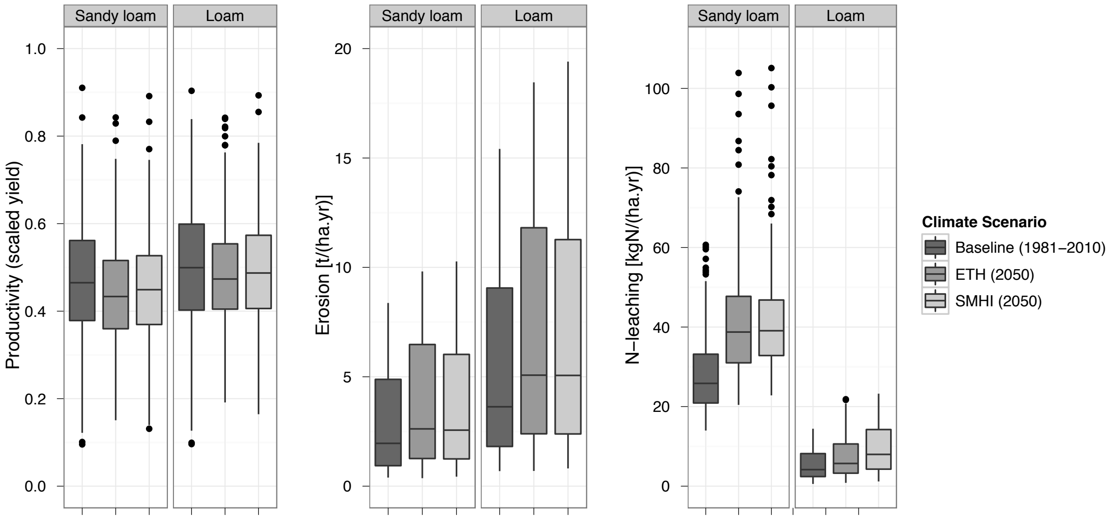

**Figure 5.1:** Variability due to agricultural practices for two soil types and for two climate scenarios for 2050 (*ETHZ-CLM* and *SMHIRCA-HadCM3Q3*), relative to the baseline (1981-2010), for the A1B emission scenario. (a) Agricultural productivity (average scaled yield over rotation); (b) Soil erosion; (c) N-leaching.

with high values on sandy loam soil and low values on loamy soil. In general, N-leaching increases under climate change due to enhanced organic matter mineralization as a consequence of higher temperatures, with sometimes values exceeding 100 kg N ha$^{-1}$ yr$^{-1}$ on sandy loam soil.

### 5.4.2 ANOVA-based sensitivity analysis

Fig. 5.2 presents the sensitivity of simulation outputs to agricultural practices split between direct and interactive effects. Main effects of rotation, intensity and soil management account for almost 100% of total variance of productivity simulations for all climate scenarios. A strong correlation between productivity of rotation and total N uptake, ranging from 0.73 to 0.79 depending on soil type and climate scenario, suggests that nutrient management is critically important to maintain productivity. An important proportion of available N for plants comes from organic matter mineralization, which is also influenced by crop management. A lower C/N ratio of dead material (i.e. straw and root residues) resulting from high N uptake enhances residue mineralization. A positive correlation between mineralization and root biomass (0.27-0.36) suggests that large root biomass allows for higher N uptake and more dead material to be mineralized. Mineralization rate is highly dependent on soil management, e.g. removal of crop residues after harvesting increases soil temperature, which consequently accelerates mineralization. Under climate change, irrigation becomes more relevant (10% of variance with ETH compared to $\sim 0\%$

under present climate). Rotation further gains in importance under climate change, while the relevance of intensity remains stable. Soil management explains a lower fraction of variance under climate change because higher temperatures lead to higher mineralization rates and increase N availability and, hence, reduce the effect of soil management on soil temperature. Very similar results are obtained with both soil types, except that irrigation is slightly more important on the coarser soil with lower water retention capacity.

Results indicate that soil management is and will be the most important driver of erosion, with nearly 70% of variance explained. Soil management has a direct effect on soil permeability and runoff, which affect in turn soil loss. Another important factor is the rotation choice (main effect $\sim$ 10% variance). No significant differences can be found between soil types.

Variability in N-leaching due to management is comparatively low and crop rotation choice explains almost 100% of the total variance. Our results exhibit high correlations ($> 0.5$) between N-leaching and the number of days of fallow (not shown), suggesting that, in order to reduce leaching, it is essential to maintain N soil content at minimum and to ensure regular N uptake even during autumn/early winter with the establishment of a winter crop or a cover crop. N fertilization has low impact on N-leaching, probably because maximum applied fertilizer amounts were set to recommended levels. In general, all factors other than crop rotation are somewhat more important on the coarser soil, but remain substantially less important than crop rotation. Moreover, relevance of irrigation slightly increases under climate change for sandy loam soil. The same trend is observed for soil management, particularly in simulations based on SMHI.

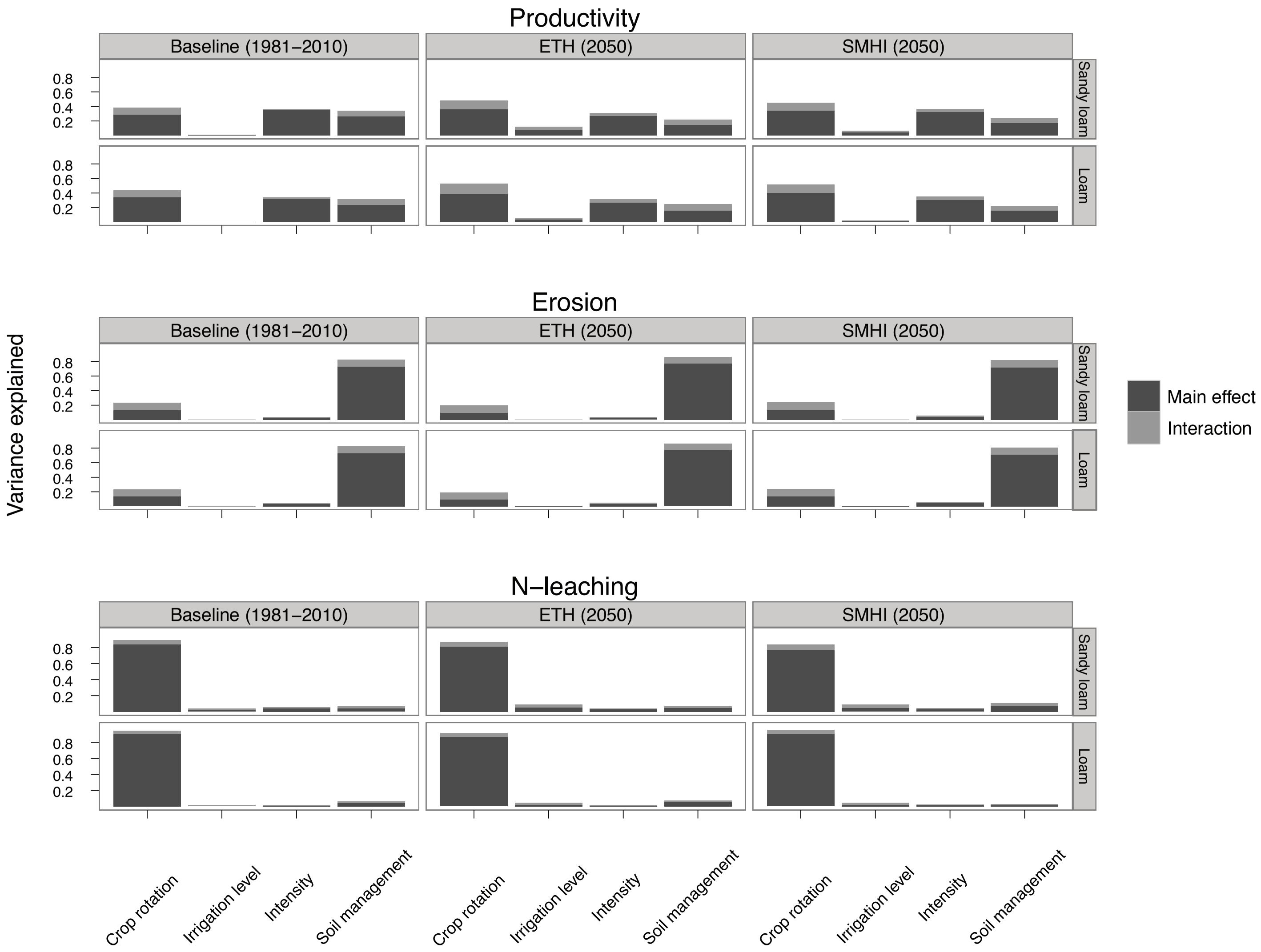

**Figure 5.2:** Results of ANOVA-based sensitivity analysis to agricultural practices of CropSyst outputs for productivity, soil erosion and N-leaching.

Interactions play an important role especially with regard to agricultural productivity and erosion, but are less important than main effects (Fig. 5.2). Most of interactions are found to be statistically significant at the $p \leq 0.001$ level and of the same magnitude on different soil types (Tables A.4 and A.5 in appendix). Highest interactions are obtained involving crop rotation with other agricultural practices, with soil management in particular. For instance, soil management type has little effect on productivity after grassland (not shown); the latter is an excellent pre-crop to increase soil organic matter and provides N through N fixation by clover. In contrast, grain maize cultivation as a pre-crop depletes soil N which results in low yield levels for following crops in the rotation. Effects of soil management and crop rotation on erosion are not additive and highly interdependent. Indeed, the crop rotation determines the time when the soil is exposed to erosion, while soil management determines the daily soil loss rates because of small aggregates (tillage) and soil protection (residues). Interactions between crop rotation and intensity have to do with the fact that some crops are more dependent on additional mineral N applications (e.g. winter rapeseed) than others that can extract more available soil N with deep rooting systems (e.g. maize). Interactions between the crop rotation and irrigation level are obvious as only a subset of crops are irrigated.

### 5.4.3 Most suitable agricultural practices

Table 5.1 lists the combinations of practices for achieving best performances in terms of: (i) agricultural productivity, (ii) erosion and (iii) N-leaching. In the following, only results for practices explaining more than 25% of variability (see Fig. 5.2) are described. Highest productivity is reached by highly fertilizing the crop rotation with sugar beet - silage maize - winter barley - maize - winter wheat and with conventional soil management. Note that highest productivity is reached with identical set of practices, irrespective of soil type and climate scenario. Even though effect of irrigation on productivity averaged for the rotation is generally low, it contributes to increase yield under climate change for this particular set of practices, especially in the case of sandy loam soil where productivity increases by 48 and 52% with irrigation for SMHI and ETH, respectively, as compared to the same set of practices without irrigation. As expected, irrigation amount increases substantially under climate change (Table 5.1).

Conservation soil management, i.e. low soil disturbance and retaining of residues after harvest, leads to lowest soil loss rates. The use of cropped grasslands within rotations is also beneficial to reduce soil loss, although the effect is small compared to that of soil management, probably because only two years of grasslands were included in the experimental plan.

Regarding N-leaching, results differ strongly between soil types. On loamy soil, the most suitable crop rotation contains high proportions of winter wheat and maize (winter rapeseed - maize - winter wheat - maize - winter wheat). On sandy loam, the most suitable crop rotation also contains two years of maize, but a lower proportion of winter wheat and a higher proportion of other crops (e.g. potato).

### 5.4.4 Trade-offs

To explore possible trade-offs between production and environmental impacts, we compare estimates of productivity, erosion and N-leaching for the most suitable agricultural practices presented above. Results in Fig. 5.3 reveal a strong trade-off between production and erosion/N-leaching. Suitable cropping practices for obtaining lowest erosion and lowest N-leaching are generally associated with medium or low productivity. Conversely, high productivity can be achieved only at the expense of high environmental impacts. While results of the ANOVA-based sensitivity analysis are similar for the two soil types the extent of these trade-offs differs between soil types. Erosion is significantly higher on loamy soil because of higher runoff, while leaching is substantially higher on sandy loam soil due to higher infiltration, but similar yield levels are reached on both soil types.

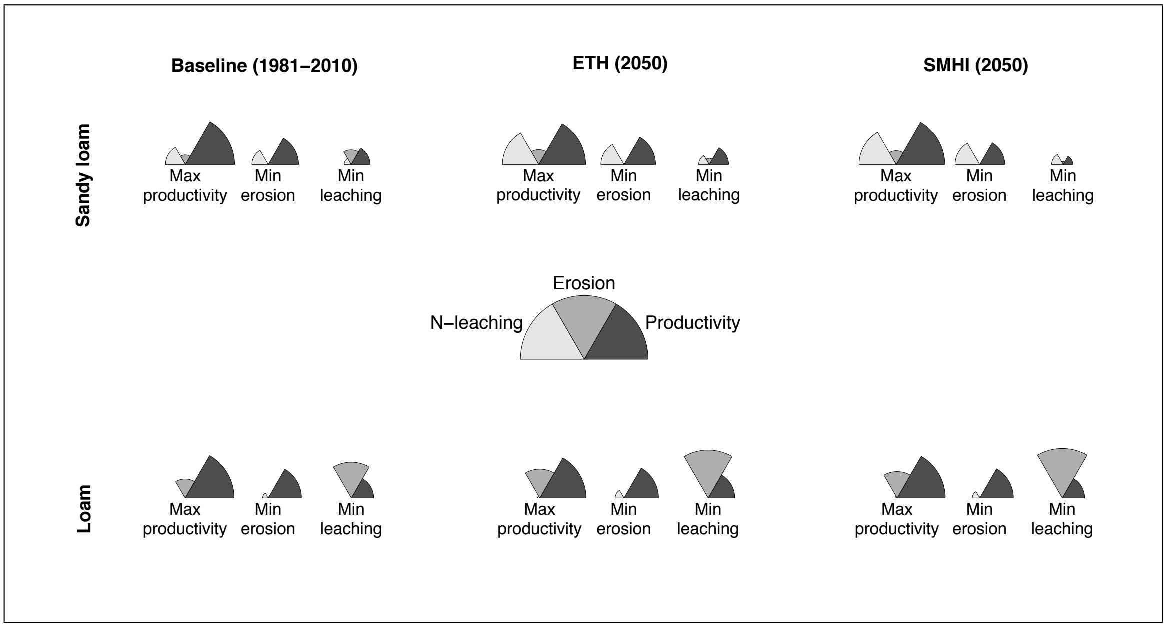

**Figure 5.3:** Trade-offs reached under the most suitable adaptation strategies (Table 5.1) to achieve best performance with respect to the different indicators.

High productivity (about 90% of maximum possible yield) can be maintained under climate change, but trade-offs with environmental impacts increase (see max productivity

**Table 5.1:** Most suitable agricultural practices for: (a) maximum productivity, (b) minimum soil erosion and (c) minimum N-leaching. WW: winter wheat, WB: winter barley, MAI: grain maize, SMAI: silage maize, POT: potato, SB: sugar beet, WR: winter rapeseed, GRASS: cropped grassland, c: winter cover crop.

**Loam soil**

| CC Scenario | Crop rotation | Irrigation m$^3$ ha$^{-1}$ yr$^{-1}$ | Intensity kg N ha$^{-1}$ yr$^{-1}$ | Soil management |
|---|---|---|---|---|
| *Maximum productivity* | | | | |
| Baseline | SB SMAI WB c MAI WW c* | 988 | 136* | Conventional* |
| ETH | SB SMAI WB c MAI WW c** | 1415 | 136* | Conventional |
| SMHI | SB SMAI WB c MAI WW c** | 1190 | 136* | Conventional |
| *Minimum soil erosion* | | | | |
| Baseline | WW GRASS GRASS WW c SMAI | 0 | 188/5 cuts | Conservation*** |
| ETH | WR GRASS GRASS SB WW | 577 | 186/5 cuts | Conservation*** |
| SMHI | WR GRASS GRASS SB WW | 360 | 186/5 cuts | Conservation*** |
| *Minimum N-leaching* | | | | |
| Baseline | WR c MAI WW c MAI WW*** | 452 | 71 | Conventional |
| ETH | WR c MAI WW c MAI WW*** | 865 | 64 | Conventional |
| SMHI | WR c MAI WW c MAI WW*** | 637 | 64 | Conventional |

**Sandy loam soil**

| CC Scenario | Crop rotation | Irrigation m$^3$ ha$^{-1}$ yr$^{-1}$ | Intensity kg N ha$^{-1}$ yr$^{-1}$ | Soil management |
|---|---|---|---|---|
| *Maximum productivity* | | | | |
| Baseline | SB SMAI WB c MAI WW c* | 986 | 136* | Conventional* |
| ETH | SB SMAI WB c MAI WW c* | 1383 | 136* | Conventional |
| SMHI | SB SMAI WB c MAI WW c* | 1213 | 136* | Conventional* |
| *Minimum soil erosion* | | | | |
| Baseline | WW GRASS GRASS WW c SMAI | 0 | 188/5 cuts | Conservation*** |
| ETH | WR GRASS GRASS SB WW | 568 | 186/5 cuts | Conservation*** |
| SMHI | WW GRASS GRASS WW c SMAI | 0 | 188/5 cuts | Conservation*** |
| *Minimum N-leaching* | | | | |
| Baseline | SB MAI POT c MAI WW c*** | 831 | 58 | Conventional |
| ETH | WR c SMAI POT c SMAI WB*** | 811 | 70 | Conservation |
| SMHI | SB MAI POT c MAI WW c*** | 901 | 58 | Conventional |

* $0.25 \geq$ variance explained $< 0.50$
** $0.50 \geq$ variance explained $< 0.75$
*** $0.75 \geq$ variance explained

scenario on Fig. 5.3). On sandy loam soil, erosion increases by 45%/38%, while N-leaching increases by 77%/85% under ETH/SMHI scenario. On loamy soil, erosion under baseline is approximately twice as high as on sandy loam soil and further increases under climate change with similar rates as on sandy loam soil, while N-leaching is low under present climate and remains low under climate change.

Low erosion rate (see min erosion scenario on Fig. 5.3) can be maintained under climate change, but N-leaching increases by +37%/+49% and is accompanied by medium productivity of 60%/55% of maximum possible yield with ETH/SMHI on all soil types

Low N-leaching values (see min N-leaching scenario on Fig. 5.3) increase under climate change, by 46%/63% (sandy loam) and 49%/110% (loam) with ETH/SMHI. Management for lowest N-leaching values leads to erosion decrease by 120%/165% for ETH/SMHI on sandy loam soil. Conversely, on loamy soil, erosion increases moderately, by 25%/30% for ETH/SMHI. The set of practices to achieve lowest N-leaching leads to very low agricultural productivity, ranging from 17% (sandy loam SMHI) to 48% (loam ETH) of maximum possible yield.

## 5.5 Discussion

### 5.5.1 Impacts of climate change, adaptation and trade-offs

Sustainable management of cropping systems aims to reach high productivity while at the same time maintaining other functions such as soil conservation and clean water provision. Simulation results in this study reveal the specific sensitivity of indicators of these functions to agricultural practices, local soil conditions and climate change, and possible trade-offs between individual indicators under current and future climatic conditions. Such information can help in designing multifunctional adaptation measures. It is well known that changes in specific farming practices may mitigate crop losses under climate change (IPCC, 2007), but by considering multiple functions and practices, the present analysis goes beyond earlier studies that addressed only individual adaptive measures.

According to our simulations, a wide range of crop yield levels can be reached, depending on the combination of crop rotation, soil management and intensity. Cropping practices identified in the sensitivity analysis all affect nutrient availability, in particular the choice of suitable crop rotations with short fallow periods between successive crops. Crop management also has implications for mineralization, but the effect is complex as mineralization is influenced by soil temperature, soil moisture and the soil C/N ratio. The present simulations suggest that practices that maintain high soil temperature and sufficient humidity, such as heavily fertilized rotations involving crops such as sugar beet in combination with conventional soil management, i.e. soil tillage and residue removal, enable high mineralization and nitrification rates and are in the short term beneficial for productivity.

With a changing climate, i.e. higher temperature and drier conditions during the growing season (CH2011, 2011), median yield level and yield variability were simulated to decline in the study area. Results suggest that a loss of productivity can be reduced by adapting rotation, soil management and fertilization. We found that the choice of suitable rotations is even more important in the future than under current climate because as crop growing season length shortens the potential for negative impacts of climate change on productivity increases. The slight decrease in variability is at first sight opposite to findings from previous studies (see e.g. Bindi and Olesen, 2010; Torriani et al., 2007). However, the latter referred only to single crops and did not account for compensating effects within a rotation cycle.

Overall, the combination of practices that can sustain high productivity in the future was found to be the same as under current climate. The main difference is given by the fact that irrigation becomes an important option to cope with higher soil moisture deficits under climate change. Note that even though the effect of irrigation on productivity averaged for the rotation is generally low - partly due to the fact that not all the crops were irrigated - effects are highly positive for some crops. Irrigation is slightly more important on the coarser soil because of its lower water retention capacity.

A trend toward increased erosion under climate change has often been modeled (Nearing et al., 2005; Yang et al., 2003) because of the intensification of the hydrological cycle, which entails increased rainfall amounts and storm intensity (Nearing et al., 2004). The increase in soil erosion under climate change disclosed by our simulations is overall more moderate than found by Michael et al. (2005) for Saxony. Apart from differences in the climate change scenarios, this likely reflects the fact that most suitable management practices identified in our analysis include a cover crop during winter (see Section 5.3.2). In our simulations soil preservation was found to be favored by soil conservation practices. Leaving crop residues in the field increases soil surface protection and reduces runoff (Scholz et al., 2008). Choice of crop rotation has a small effect on soil loss, but the results suggest benefits of an increased share of cropped grasslands and the exclusion of potato. This is in line with the finding by (Jones et al., 2003) that soil erosion is expected to be highest with root crops in Central Europe because ground and canopy cover are low during the time of seedbed preparation and in the first weeks of vegetative development, and because this period coincides with the time of the year with highest amount of erosive rainfall.

If heavy precipitation occurs during periods of high soil N availability, then the risk of N-losses in groundwater is particularly high (Weisskopf et al., 2001). Our results suggest that N-leaching is primarily dependent on soil texture and not much on management, in agreement with field observations by Askegaard et al. (2011). The inclusion of a winter crop or a cover crop in the rotation proved to be particularly beneficial to maintain N uptake during periods of high mineral N availability in autumn and early winter. The importance of cover crop to reduce N-leaching has been widely suggested in the literature, either based on modeling studies (e.g. Constantin et al., 2012; Doltra et al., 2011; Henke et al., 2008) or field experiments (e.g. Askegaard et al., 2011; Doltra et al., 2011; Weisskopf et al., 2001).

Agricultural functions are interdependent and, typically, a trade-off exists between food production and regulating functions (Power, 2010). Therefore, the choice of adaptation measures that only consider food and fiber production while ignoring concurrent effects of management on the environment does, as a rule, not conform to the objectives of a multifunctional agriculture. Our simulations reveal that maintaining high productivity is indeed associated with poor soil conservation and clean water provision, and these trade-offs appear to be more important under climate change than under present climate (Fig. 5.3). Negative impacts of practices associated with high productivity on soil and water quality were found to depend on soil type, with loamy soil being more sensitive to erosion because of lower infiltration rate and higher runoff, while sandy loam being more prone to high N-leaching and thus water pollution.

Trade-offs may exist also depending on time scale. For instance, we found positive effect of residue removal on productivity. Apparently, this is in contrast to the view that management decisions such as no-till and returning crop residue to the field increase soil organic matter content, improve infiltration and soil water retention, and thus help to maintain soil fertility in the long run and increase the resilience of cropping systems to climate change (Lal et al., 2011). However, the positive effects of conventional soil management simulated here are short-lived; by repeating simulations under climate change using 50 years of generated weather data we found a significant decrease in soil fertility that is not evident in the original results (not shown).

Apart from preventing excessive soil erosion and soil organic matter loss and thus maintaining soil fertility in the long run, we found that conservation soil management improves clean water provision. Indeed, simulated N-leaching is substantially decreased on sandy loam soil due to reduced mineralization, while the increase in permeability due to this management type has low effect on this soil type which is already permeable. As a downside, productivity was found to be lowered by $\sim 50\%$ on average under current climatic conditions under conservation soil management. However, under climate change this effect is less pronounced ($\sim -25\%$), indicating that the synergistic effects of conservation soil management could increase in the future.

Trade-offs between agricultural productivity and other ecosystem functions are not inevitable, though (Power, 2010), and in fact possible synergies between the different agricultural functions emerge from our analysis. As soil management and crop rotation are the most relevant practices to reduce soil loss and N-leaching, respectively (Fig. 5.2), and also exert a great influence on productivity, a balance between productivity and environmental impacts may be obtained from a judicious choice of crops and soil cultivation. In our analysis, best compromises are obtained with management practices that minimize soil loss (Fig. 5.3).

Our results suggest that for the study area rotations including a grass/legume crop are very important to support multifunctional agriculture. In fact, grassland serves well as a good pre-crop and a high proportion of grassland reduces erosion and helps keeping N-leaching at low levels. Soil N benefits from grass/clover mixture while grain maize cultivation as a pre-crop depletes soil N which results in low yield levels for following crops in the rotation, unless high fertilization and enhanced mineralization compensate for the N loss.

### 5.5.2 Sensitivity analysis

We applied an ANOVA-based sensitivity analysis to quantify the relative importance of different agricultural practices for productivity, soil erosion and N-leaching. Analysis of variance (ANOVA) is based on the decomposition of the response variability between contributions from each factor and from interactions between factors and is an efficient investigation tool that provides ease of interpretation comparable to that of regression methods (Ginot et al., 2006). In crop modeling, ANOVA-based sensitivity analysis is commonly used to screen a subset of model parameters to be calibrated (see e.g. Confalonieri, 2010; Monod et al., 2006).

Assumptions for the application of ANOVA include nullity of the residuals expectation, homogeneity of the residual variance and normality of residuals effects. To respect those assumptions and ensure that effects are linear, a transformation of model outputs is usually envisaged (Saltelli et al., 2007). In our study, residuals were small without transformation and nearly 100% of the variance could be explained by including only first-order interactions (see Tables A.4 and A.5), in spite of the fact that nearly all interactions were statistically significant. This suggests that effects of cropping practices are mostly additive. Similar conclusions were drawn in previous studies addressing similar contexts (Lamboni et al., 2009; Monod et al., 2006).

While N-leaching is almost only sensitive to changes in crop rotation and erosion almost only sensitive to changes in soil management and crop rotation, productivity was found to be sensitive to all driving factors (crop rotation, irrigation levels, intensity and soil management). This highlights again the fact that crop rotation and soil management are the two aspects of agricultural practice that should be examined to identify best practices for multifunctional agriculture.

### 5.5.3 Limitations and uncertainties

The effects of high temperatures, increased climate variability and limiting factors such as pests and diseases are neither fully understood nor well implemented in leading crop models (Rötter et al., 2011a; Soussana et al., 2010). There is also an ongoing debate concerning how well crop responses to elevated $CO_2$ are represented in models (Körner et al., 2007; Long et al., 2006; Parry et al., 2004). For this reason, $CO_2$ fertilization effect was not taken into account in this study.

Future adaptation options will include changes both in agricultural practices and in varieties/species. In this study, we solely focused on the first type of adaptation, mainly due to the difficulty in integrating new crop varieties within crop rotations that were generated for current climate. However, switching to cultivars that are better suited to higher temperatures is crucial (Horie, 1994) and this type of adaptation is already taking place under present climate conditions (Sacks and Kucharik, 2011). Furthermore, we expect that adoption of new cultivars could help avoiding some of the trade-offs discussed in this study, e.g. by reducing the fallow time which would decrease erosion and N-leaching. Nevertheless, skepticism toward the use of these ‘climate proof’ cultivars has been recently observed among the scientific community (Olesen et al., 2011).

From a modeling perspective, the simplest method to account for higher temperatures consists in modifying the thermal time requirements of different phenological stages, in order to mimic slower maturing cultivars that could be obtained through genetic improvement (Duvick, 2005). A few examples of modeling studies have implemented this approach (see e.g. Challinor et al., 2007; Moriondo et al., 2010a). This generally resulted in higher simulated crop yields, but without necessarily improving yield stability (Torriani et al., 2007). However, addressing thermal time requirements of different crops in crop rotation has yet to be addressed in modeling studies and future work should investigate the potentialities offered by newly developed varieties to define sets of crop sequences that are better suited under climate change.

## 5.6 Conclusions

The sensitivities of indicators of three important agricultural functions (crop yield for food and fiber production, soil erosion for soil conservation, and nutrient leaching for clean water provision) to agricultural practices were assessed for current and future climate conditions in order to explore possibilities for adaptation. The modeling approach considered a wide range of practices, including 50 crop rotations, 2 irrigation setups, 3 fertilization levels and 2 soil managements, which allowed for exploring a wider range of options than in previous studies.

The geographic focus of the study was on western Switzerland. For this study area the following conclusions can be drawn:

- Under climate change, we found a tendency for productivity to decrease, for erosion to increase due to shorter crop growth cycles and increased rainfall intensity in fall/winter, and for N-leaching to increase as a consequence of higher mineralization rate.
- Productivity and soil loss due to erosion are highly variable not only with climate scenarios, but also across cropping practices and soil types, suggesting that negative impacts of climate change can be reduced through an adequate choice of management.
- The relevance of agricultural practices as drivers of agricultural functions is not expected to change significantly with climate change. Only irrigation is likely to become more important for agricultural productivity under climate change scenarios that propose a marked decrease in water availability during summer.
- Trade-offs between agricultural productivity, soil erosion and N-leaching are likely to aggravate with climate change.
- There are possibilities to support multifunctional agricultural as some combinations of agricultural practices have beneficial effects both for productivity as well as for the environment. For the study region, the use of cropped grasslands in combination with conservation soil management appears to be the most suitable option to maintain productivity and avoid trade-offs with erosion and N-leaching.

Our work clearly shows that agricultural systems are complex and that interactions exist among agricultural practices. Therefore, trade-offs between different agricultural functions can emerge, which needs to be taken into account when planning and implementing adaptation strategies.

As trade-offs can differ substantially depending on site conditions, spatial heterogeneity and characteristics need to be considered in the process of developing adaptation strategies at the regional scale. This has been shown in the context of catchment management (Marshall et al., 2010). Our study took a local view at the multifunctionality of agriculture under climate change. In the future the modeling framework developed for the present analysis will be integrated within a spatial multi-objective optimization routine to explore the multidimensional solution space in a systematic way and define regional adaptation options that are optimal with regard to the different agricultural functions.

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## Chapter 6

# Adapting agricultural land management to climate change: A regional multi-objective optimization approach

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## Abstract

In many regions of the world, climate change is expected to have severe impacts on agricultural systems. As many previous impact studies suggest, yields could decrease, water resources may decline, and erosion risk could increase. Changes in land management are one way to adapt to future climatic conditions, including declining water resources. In previous studies, possibilities for adaptation with respect to one or multiple objectives have mostly been explored by testing alternative scenarios. Systematic explorations of land management possibilities using optimization approaches were so far mainly restricted to studies of land and resource management under constant climatic conditions. In this study, we bridge this gap and exploit the benefits of multi-objective regional optimization for identifying optimum land management adaptations to climate change. We consider two climate scenarios for 2050 in a mesoscale catchment on the Swiss Central Plateau with already limited water resources.

We designed a multi-objective optimization routine that integrates a generic crop model in combination with spatial information on soil, climate conditions and slope at a 500 m× 500 m resolution. The results demonstrate that even under the more extreme climate scenario compromise solutions maintaining productivity at the current level with minimum environmental impacts in terms of erosion and nitrogen leaching are possible. Necessary management changes include (i) adjustments of crop shares, i.e. increasing the proportion of early harvested winter cereals at the expense of irrigated spring crops, (ii) widespread use of reduced tillage, (iii) allocation of irrigated areas to soils with low water-retention capacity at lower elevations, and (iv) conversion of some pre-alpine grasslands ($>$ 700 m) to croplands. It is concluded that the potential for climate change adaptation at the regional scale is significant. The results could serve as basis for planners and decision makers to develop suitable regional land use strategies.

**Keywords** agricultural land management - adaptation to climate change - crop modeling - regional optimization - multi-objective

## 6.1 Introduction

Agriculture is an economic sector that is sensitive to climate change. In temperate regions of Europe, increased air temperature is expected to first have positive effects on agriculture through higher crop productivity and expansion of suitable areas for crop cultivation (IPCC, 2007). However, more frequent droughts and extreme weather events during the cropping season are likely to increase the frequency of unfavorable years, which may enhance yield instability and make current agricultural areas less suitable for traditional crops (Olesen and Bindi, 2002).

Changes in temperature and in precipitation pattern may lead to the emergence of new or aggravate existing water-related issues in agricultural production (Fuhrer et al., 2006; Calanca, 2007; Torriani et al., 2007) including competition for land and water resources (Lotze-Campen et al., 2008). Climate change is also expected to aggravate environmental impacts, such as higher erosion rates (Nearing et al., 2004), faster decomposition of soil organic matter and increased nitrogen (N) leaching (Bindi and Olesen, 2010). Consequently, there is a need for adaptation of agricultural land management to reduce the sensitivity of cropping systems to cope with the expected change in climatic conditions. This may include adjustments of crop rotations by shifting from high to low water demanding crops, changing fertilization intensity, use of conservation soil management such as direct seeding, or changing livestock stocking density. However, it is known that such adaptation might lead to new conflicts with other functions, or exacerbate existing ones (Schröter et al., 2005). Hence, it is crucial to consider the multifunctional role of agriculture when designing policies to support adaptation of land management (Olesen and Bindi, 2002; Betts, 2007). To maintain agricultural productivity and preserve finite natural resources, adaptation measures need to be developed at different decision levels, and scientists need to assist planers and decision makers in this process (Salinger et al., 2005).

Ecophysiological models are particularly important tools for understanding impacts of climate change (Challinor et al., 2009). Many applications of crop models to examine options for adaptation of agriculture can be found in the literature (White et al., 2011).

A literature review on adaptation and optimization of agricultural land management (Table 6.1) reveals that most previous studies focused either on adaptation or optimization, but rarely on the combination of both. In particular, the use of an optimization technique to identify adaptation strategies was only conducted in two recent studies by Lehmann et al. (2013) and Schuetze and Schmitz (2010). However, those studies solely addressed impacts of climate change and management on (economic) yield without considering the multifunctional role of agriculture. In addition, their analysis was performed at the farm level, while the regional level is particularly important as this scale is relevant for policy decision. In addition, it is a prime concern in Switzerland to develop effective site-specific measures to maintain the production level while reducing exposure to risks (FOEN, 2012a) and, therefore, it is crucial to consider spatial variability of local conditions.

**Table 6.1:** Literature review of (a) studies on adaptation of agricultural land management to climate change and (b) publications involving ecophysiological models within an optimization routine to find best possible land management with regard to (multiple) objectives.

| **Study** | **Adaptation to climate change** | **Multi-objective** | **Optimization** | **Regional (grid)** |
|---|---|---|---|---|
| White et al. (2011)[a] | 65 | 131 | | $\sim 50$ |
| Iglesias et al. (2010) | ✓ | ✓ | | ✓ |
| Rötter et al. (2011b) | ✓ | | | |
| Thaler et al. (2012) | ✓ | ✓ | | |
| Ruane et al. (2013) | ✓ | | | |
| Kuo et al. (2000) | | | ✓ | |
| Seppelt and Voinov (2003) | | ✓ | ✓ | ✓ |
| Lu et al. (2004) | | ✓ | ✓ | |
| Dogliotti et al. (2005) | | ✓ | ✓ | |
| Xevi and Khan (2005) | | ✓ | ✓ | |
| Ines et al. (2006) | | | ✓ | ✓ |
| Koo and O'Connell (2006) | | ✓ | ✓ | ✓ |
| Groot et al. (2007) | | ✓ | ✓ | ✓ |
| Latinopoulos (2007) | | ✓ | ✓ | |
| Mayer et al. (2008) | | ✓ | ✓ | |
| Sadeghi et al. (2009) | | ✓ | ✓ | ✓ |
| Gao et al. (2010) | | ✓ | ✓ | ✓ |
| Groot et al. (2012) | | ✓ | ✓ | |
| Schuetze and Schmitz (2010) | ✓ | | ✓ | |
| Lehmann et al. (2013) | ✓ | | ✓ | |

[a] Review of 221 papers (until June 2011)

The aim of this paper is to combine benefits of two approaches (optimization and adaptation) to identify optimum land management under climate change by considering multiple objectives in a case study for a Swiss mesoscale catchment. Objectives considered in this study are the main priorities set in the climate change adaptation strategy for agriculture of the Swiss Federal Council (FOEN, 2012a), namely maintaining agricultural productivity at a sufficient level, while minimizing water use for irrigation, minimizing erosion and N-leaching. Some existing optimization tools offer great potential for defining adaptation options, such as RULES (RUral Land-use Exploration System, Santeriveira et al., 2008), APPM (Assessment-, Prognosis-, Planning and Management-tool, Grundmann et al., 2011), the tradeoff analysis model (Stoorvogel et al., 2004), Sysnet (Van Ittersum et al., 2004), InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs, Nelson et al., 2009), LADSS (Land-use Planning Decision Support System, Matthews et al., 2006), MAgPIE (Model of Agricultural Production and its Impact on the Environment, Lotze-Campen et al., 2008) or MODAM (Multi-Objective Decision support tool for Agroecosystem Management, Zander and Kächele, 1999). However, those tools do not satisfy our requirements either because only a limited set of decision variables are considered, or because objective functions are different. For this reason, we have elaborated and set up a spatial optimization approach matching the specific needs of this study with the following components: (i) the generic crop model CropSyst and (ii) empirical functions to simulate grazing and excretions by livestock. The main steps involved in this study are (i) estimation of reference land management for current climate and assessment of impacts of climate change in the absence of adaptation, (ii) calculation of a large set of optimum solutions for two different climate scenarios covering the possible range of regional climate changes, (iii) clustering the solutions and identifying a subset with strongly differing combinations of objectives, (iv) extraction of compromise solutions considered as the most suitable strategies, and (v) analysis of those solutions in terms of the underlying land use and management.

## 6.2 Case study

The study region is the Broye watershed (Fig. 6.1), which is located in western Switzerland and covers an area of about 850 km$^2$. Agriculture is the most important sector in this region with 42,750 ha of agricultural area (BFS, 2010). Land use is dominated by cropland in the flat areas, while permanent grassland dominates in the SE areas at elevations above 700 a.m.s.l. Major crops are winter wheat ($\sim$ 30%), silage/grain maize ($\sim$ 15%), winter barley ($\sim$ 9%), sugar beet ($\sim$ 7%), winter rapeseed ($\sim$ 5%) and potato ($\sim$ 5%) (FOAG, 2011).

Irrigation of cropland is already a common practice in this watershed, with a yearly average of 1.13 $10^6$ m$^3$ applied to 1,377 ha (Robra and Mastrullo, 2011). Irrigation is used for

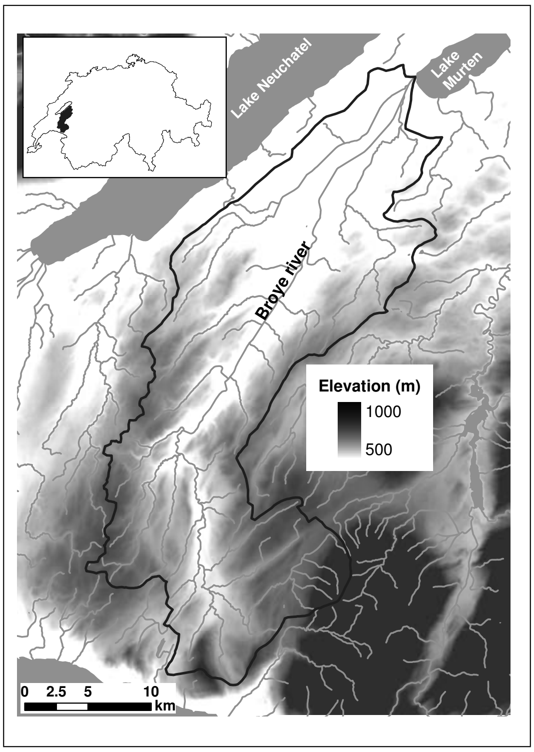


**Figure 6.1:** Map of the study area (Broye catchment in western Switzerland).

potato (50%), maize (15%), tobacco (15%), and sugar beet (8%). Most of irrigation water is pumped from the Broye river which originates from the SE part of the watershed at an elevation of about 1000 a.m.s.l. and flows into the Lake of Murten ($\sim$ 500 a.m.s.l.).

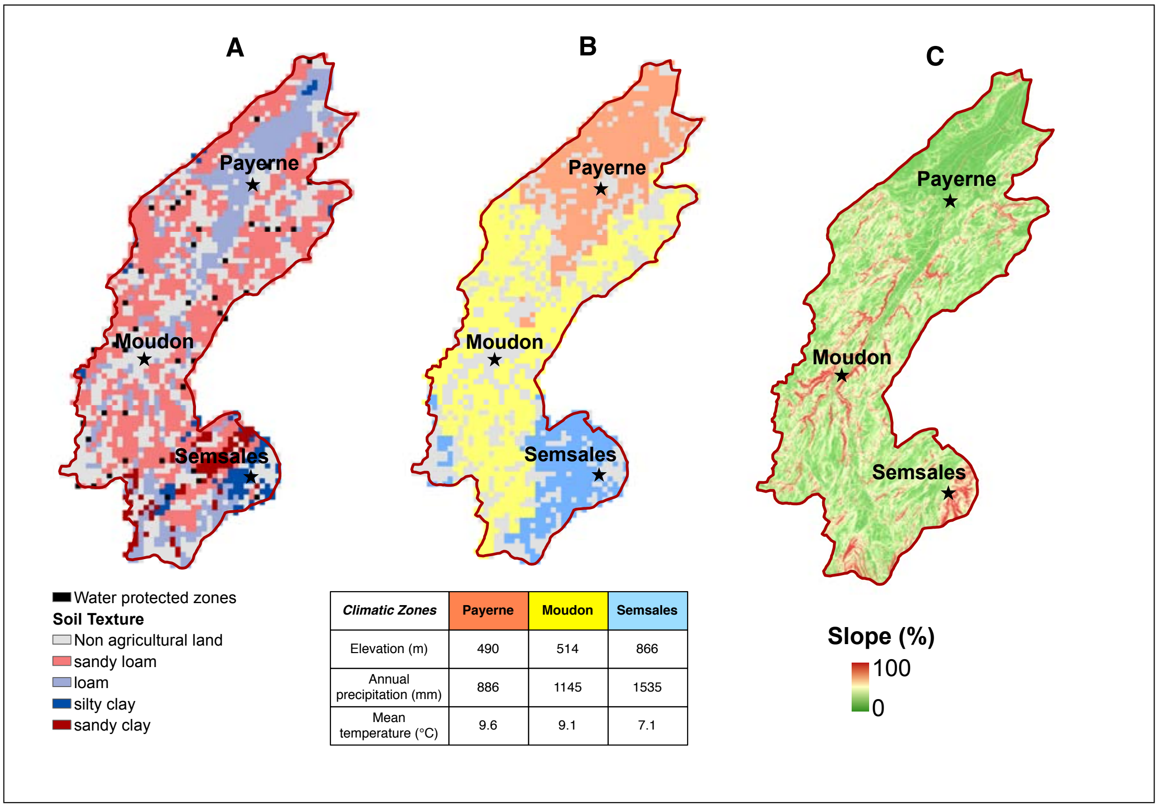
The Broye catchment is prone to erosion (Prasuhn et al., 2007) due to steep slopes (Swisstopo, 2001) and widespread use of conventional tillage ($\sim$ 98% of areas according to Ledermann and Schneider, 2008). N-leaching had been a general problem in Switzerland until around 1990 when it was substantially reduced following the introduction of financial incentives to reduce fertilizer inputs. However, N-leaching is still a concern and is expected to become a more important issue with enhanced mineralization of soil organic matter in a warmer climate (Stuart et al., 2011).

### 6.2.1 Spatial representation

The study region was divided into 500 m × 500 m pixels and agricultural areas were identified. In order to run the models, spatially explicit inputs were needed for (i) climatic variables (i.e. temperature, radiation, precipitation), (ii) soil texture and (iii) slope.

Soil information for each pixel (Fig. 6.2a) was derived from the Soil Suitability Map of Switzerland (BFS, 2012) and was adjusted with soil profile information from the Swiss

Soil Monitoring Network (BUWAL, 2003). Groundwater protection zones defined by the Swiss Federal Office of Environment (FOEN, 2012b) were also considered.



| *Climatic Zones* | Payerne | Moudon | Semsales |
|---|---|---|---|
| Elevation (m) | 490 | 514 | 866 |
| Annual precipitation (mm) | 886 | 1145 | 1535 |
| Mean temperature (°C) | 9.6 | 9.1 | 7.1 |

**Figure 6.2:** Spatial representation of the Broye catchment used to drive the simulation models: (a) soil texture and groundwater protection zones, (b) climatic zones and (c) slopes.

Climate data from three weather stations were available from the monitoring network of the Swiss Federal Office of Meteorology and Climatology (Fig. 6.2b); each pixel in the study region was allocated to one of them according to the minimum difference between annual precipitation amount observed at weather stations and interpolated annual precipitation amount obtained from Frei et al. (2006) and Frei and Schär (1998).

Information on slope steepness, necessary for computing soil loss rates, was inferred from a digital elevation model (Swisstopo (2001), Fig. 6.2c).

### 6.2.2 Climate scenarios

The stochastic weather generator LARS-WG (Semenov and Barrow, 1997) was used to generate 25 years of synthetic daily weather data for (i) a baseline period corresponding to 1981-2010 and (ii) two climate scenarios representing the time horizon 2050 under the assumption of the A1B emission scenario. The climate change signal was extracted from two different Regional Climate Model (RCM) simulations carried out in the framework of the ENSEMBLES project (van der Linden and Mitchell, 2009). The first, performed with the model *ETHZ-CLM* (referred to as ETH), is characterized by a strong climate change signal in summer (+3.5 °C and $-24\%$ in seasonal precipitation amount); the second, performed with the model *SMHIRCA-HadCM3Q3* (referred to as SMHI), projects moderate changes for the summer season (+1.3 °C and $-11\%$ in seasonal precipitation amount), but an important increase in seasonal precipitation amount during fall (+21%).

### 6.2.3 Management options

To solve the optimization problem, we considered the following management options (Table 6.2): land use type, crop rotation, intensity, irrigation, and soil management. These management options have important impacts on agricultural productivity, erosion and N-leaching and offer great room for adaptation in the study area if well adjusted. Klein et al. (2013) found that productivity highly depends on intensity level, crop rotation, soil management and irrigation. The most important factor for controlling erosion was found to be soil management, but crop sequence plays also a very important role, i.e. the fallow time during autumn/winter when highest precipitation amounts occur. N-leaching depends more on soil type than management, but the crop sequence has a significant impact on soil N availability and, thus, on N losses.

**Table 6.2:** Management options used as decision variables in the spatial optimization.

| **Management option** | | **Levels** |
|---|---|---|
| Land use | | cropland, permanent grassland, pasture |
| Crop sequence | | 50 crop rotations generated stochastically |
| Intensity | N fertilization (all)<br>clipping (grassland)<br>stocking density (pasture) | recommended: average N fertilization needs (in kgN), 5 cuts yr$^{-1}$, 3 LSU[a] ha$^{-1}$<br>reduced: N fertilization needs $-25\%$, 4 cuts yr$^{-1}$, 2 LSU ha$^{-1}$<br>low: N fertilization needs $-50\%$, 3 cuts yr$^{-1}$, 1 LSU ha$^{-1}$ |
| Irrigation | | rainfed or supplemental[b] (automatic) |
| Soil management | tillage operation<br>residue management | conventional: regular tillage & harvest residues removed<br>conservation: reduced tillage & harvest residues retained |

[a] *LSU*: Livestock Unit (1 *LSU* = 1 dairy cow)

[b] Only potato, sugar beet and grain maize can be irrigated because not profitable for other crops (Lehmann et al., 2013)

Two irrigation options were considered: rainfed and supplemental (automatic) irrigation. In CropSyst, supplemental irrigation is triggered when soil moisture falls under a crop-specific threshold and is refilled to a user-defined level. Minimum soil moisture and refill point values were determined by Lehmann et al. (2013) who found that under climate change irrigation is economically profitable only for potato, sugar beet and grain maize in the study region. Therefore, the management option irrigation was only included for these crops. An irrigation efficiency of 77% was assumed, which corresponds to the irrigation efficiency of sprinkler irrigation systems (most common irrigation technique for cropping systems in the Swiss Plateau).

50 different 5-year rotations for croplands were generated based on rules provided by Vullioud (2005) with regard to (i) feasibility of crop sequences and (ii) recommended maximum proportions of crops. Following Swiss legislations for subsidies, a cover crop was included unless the current crop was harvested after 31 August, and/or the following crop was a winter crop. In addition to those crop rotations, permanent grasslands and pastures were included in the simulations.

Management intensity was defined by (i) the total amount of N fertilizer (in kg), (ii) the number of grassland clippings, and (iii) the stocking density. Recommended N fertilization was derived from Flisch et al. (2009), while application dates depended on total N applied following Janssen et al. (2009).

Two types of soil management were investigated for croplands: conventional (regular tillage and removal of residues) and conservational (no tillage and residues retained). Tillage consisted of plowing 10 days prior to sowing and harrowing one day before sowing. When residues were removed, a loss coefficient of 10% was used.

### 6.2.4 Reference land management

Reference land management representing current conditions was necessary as a basis for evaluating impacts of climate change and to express the benefits of adaptation. The observed distribution of pastures, grasslands and croplands was defined according to data from BFS (2010). Spatial distribution of crop rotations was not available and was approximated by defining a combination of the 50 generated crop rotations that reproduce the observed crop shares from FOAG (2011).

Spatial extension of actual irrigated fields was derived from Robra and Mastrullo (2011). Management intensity was set to the recommended level in the entire region. Following Ledermann and Schneider (2008) 2.7% of conservation soil management was assumed for the study area and this management type was allocated with the priority given to pixels with steep slopes. It was assumed that the use of reduced (or no) till occurs preferentially on steep slopes to avoid high soil loss rates leading to land degradation.

## 6.3 Methods

Fig. 6.3 provides an overview of the main steps involved the identification of optimum management schemes with regard to agricultural productivity (crop yields in t ha$^{-1}$ yr$^{-1}$), minimum irrigation amounts (m$^3$ ha$^{-1}$ yr$^{-1}$), minimum erosion (t ha$^{-1}$ yr$^{-1}$) and minimum N-leaching (kg N ha$^{-1}$ yr$^{-1}$).

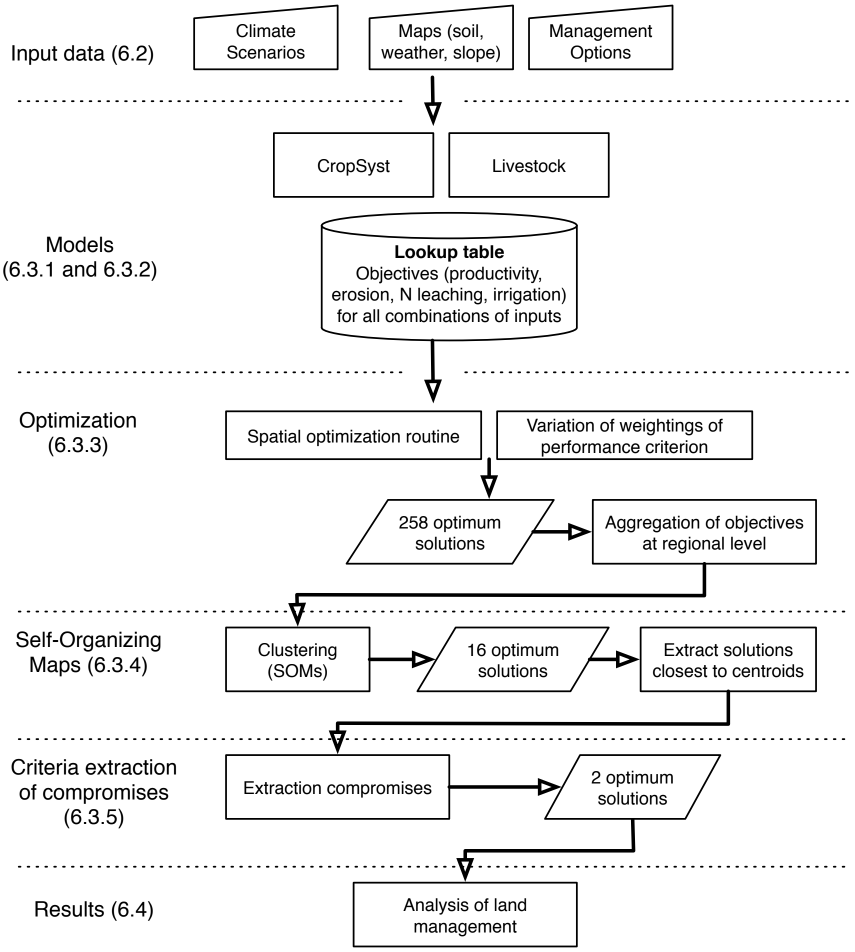


**Figure 6.3:** Overview of the steps involved for the development of land management adaptation options; the number between brackets indicates the Section number.

Simulation results for all combinations of agricultural practices and local conditions were computed prior to the optimization for the two climate scenarios and stored in a lookup table.

Then, outputs of interest (crop yield $P$, irrigation $I$, erosion $E$, N-leaching $L$) were passed to an optimization routine to identify in each pixel the best management scheme with regard to a performance criterion (see below).

The optimization routine was repeated several times by modifying the priority given to the different objectives. Results (i.e. objective values and optimized management) were aggregated at the regional level. Of all generated solutions, 16 clusters were defined based on Self-Organizing Maps (SOMs, Kohonen, 2001). For each cluster, the most representative solution was extracted. At last, a set of restrictions was applied (e.g. maximum irrigation, minimum productivity) to identify compromise solutions, which were then analyzed in detail in terms of the underlying land use and land management.

### 6.3.1 Crop model

CropSyst (version 4.13.04) process-based model was integrated for simulating a wide range of management options. In CropSyst, biomass accumulation is calculated as a function of crop potential transpiration and intercepted radiation, corrected by factors reflecting water and N limitations. Final crop yield is the total biomass accumulated over the growing season multiplied by a harvest index.

Annual soil loss due to water erosion is calculated using the Revised Universal Soil Loss Equation (RUSLE) by Renard et al. (1997) as:

$$E = R \cdot K \cdot L \cdot S \cdot P \cdot C \tag{6.1}$$

where

- $R$: rainfall energy intensity factor
- $K$: soil erodibility factor
- $L$ and $S$: slope length and steepness factors
- $P$: soil conservation practice factor (a constant value of 0.88 was assumed here, which is representative for croplands in Switzerland, Prasuhn et al., 2007)
- $C$: represents the effect of land management on erosion, which depends on surface residue cover, incorporated residues, crop cover and soil moisture

$E$ was first calculated in CropSyst with reference $L_{ref}$ and $S_{ref}$ (steepness of 10% and a slope length of 100 m) and stored in the lookup table. Then, soil loss was adjusted a posteriori in the optimization routine dividing $E$ by the reference factors and multiplying it by local $L$ and $S$ factors based on the slope map (Fig. 6.2c). This increased substantially the computation efficiency as CropSyst had to run only once with $L_{ref}$ and $S_{ref}$ for every combination of soil, weather and management.

The components of the simulated N balance include N transport, N transformations, ammonium sorption, and crop N uptake (Stöckle et al., 1994). N transport associated with infiltration is determined on the basis of a so-called bypass coefficient. N transformations developed for CropSyst include net mineralization, nitrification and denitrification. Ammonium in the soil is either absorbed into the soil in solid phase or dissolved in soil water. Crop N uptake is determined as the minimum of crop N demand and potential N uptake. Crop N demand is the amount of N the crop needs for potential growth, plus the difference between the crop maximum and actual N concentration before new growth. Potential N uptake is proportional to maximum N uptake per unit length of root, root length, N availability, and to square of a soil water availability factor.

CropSyst was calibrated following Klein et al. (2012) for the six most important crops in Switzerland, i.e. winter wheat, winter barley, grain maize, potato, sugar beet, winter rapeseed. CropSyst calibration for grassland was done based on data from a long-term trial in NW Switzerland (Ammann et al., 2009).

### 6.3.2 Livestock production

To account for the lack of animal production in CropSyst, empirical functions were used to estimate daily grazing needs and N excretion on the fields.

For the 5 livestock types considered (dairy/nurse cow, cattle fattening/breeding, calf fattening), daily grazing needs were computed as a function of fodder requirements per Livestock Unit (*LSU*) from Flisch et al. (2009), the proportion of the time on pastures (fixed animal specific values based on Agrammon, 2010) and the stocking density (optimized number of *LSU* ha$^{-1}$). Daily grazing requirements (kg dry matter) were then used in CropSyst to simulate grazing as a clipping management with the calibration for grasslands. The beginning and the end of the grazing season were specified as in Agrammon (2010). For days when the grazing needs exceeded the availability, we assumed that the entire available biomass was consumed up to a residual value of 500 kg ha$^{-1}$, as suggested by Ammann et al. (2009).

Similarly to the grazing needs, N excretions by animals on pastures were computed as a function of total N excreted in a day by one *LSU* (Flisch et al., 2009), the proportion of the time on pastures and the stocking density. In CropSyst, N excretions returning directly to the field were simulated as organic N applications.

### 6.3.3 Spatial optimization routine

Since neighborhood effects were not relevant in this study, local optimization could be applied to minimize the computational effort (Seppelt and Voinov, 2002). This means that the optimization problem was solved individually for every pixel.

Simulations were repeated with different sets of management options for each pixel. Optimal solutions determined with respect to the objective function $J$ (Eq. 6.2) were selected. Individual objectives were scaled from 0 to 1 ($P^{'}$, $E^{'}$, $L^{'}$, $I^{'}$) based on regional maximum and minimum values for current climate (for instance $E^{'} = \frac{E-E_{\text{min}}}{E_{\text{max}}-E_{\text{min}}}$). $P^{'}$ was the arithmetic mean of crop yields over the rotation, scaled with regional maximum and minimum values. For croplands, each individual yield in the rotation was scaled separately with crop-specific values. $P^{'}$ for pastures was based on total grazed biomass by animals.

In our approach, $J$ was calculated with all $N$ possible combinations of management ($\{J_k\}_{k=1}^{N}$), separately for the ETH ($J^E$) and SMHI ($J^S$) climate scenarios to account for climate projection uncertainties and identify robust optimum solutions. A robust solution was defined here as the one with best performance for the worst case scenario (Soares et al., 2009). This means in practice that, for every $k$, the minimum between $J^E$ and $J^S$ was selected to make a new series $J^*$ which was maximized for every pixel.

$$J = \max\left\{W_p P^{'} + W_i(1-I^{'}) + W_e(1-E^{'}) + W_l(1-L^{'})\right\} \text{ where} \tag{6.2}$$

$$W \in [0,1] \text{ with an increment of 0.1 and } \sum W = 1 \tag{6.3}$$

In Eq. 6.2, individual weights $W$ were varied systematically to produce a wide range of potential adaptation options with different priorities and to identify possible trade-offs between objectives. Each weight was varied from 0 to 1 with an increment of 0.1 with the constraint that the sum of all weights equals 1. This led to a total of 258 weight combinations representing the same number of adaptation options. The optimization was subject to two further constraints. First, the maximum slope for crop cultivation and use of heavy machinery was set to 33% based on expert judgment. Second, groundwater protected zones were considered to account for legal management restrictions regarding the spreading of liquid manure and the use of irrigation.

Preliminary tests of the optimization routine showed that, if economic values of livestock are not considered, pastures do not appear in the optimal solutions, unless animal production was prescribed. Hence, the number of animals was used as constraint and variables which were optimized were the spatial distribution of pastures for each livestock type and the stocking density. The total surfaces needed for pastures were determined based on current regional livestock numbers from FOAG (2011) for 2001-2010 and proportions of animals on the pastures from Agrammon (2010). In the optimization routine, pastures were first distributed across pixels where differences in the objective function values with and without pastures were the highest. Then, croplands were allocated to the remaining units.

### 6.3.4 Self-Organizing Maps

SOMs were used to identify general pattern in all 258 solutions and to reduce thus the complexity. SOMs have proved to be very powerful for feature extraction (Liu et al., 2006).

Another advantage of SOMs is that they can represent the topology of large multi-dimensional datasets. Therefore, they are very helpful to visualize trade-offs between multiple objectives (see e.g. Li et al., 2009; Norouzi and Rakhshandehroo, 2011).

SOMs were generated with the Kohonen package of the statistical language R (Wehrens, 2007) based on regionally aggregated values of the four objectives for the 258 optimum solutions. We set the number of clusters to 16 according to a criterion based on the stabilization of the so-called ‘quantization error’ (de Bodt et al., 2002).

### 6.3.5 Selection of compromise solutions

A subset of compromise solutions was selected for further analysis based on the following criteria:

- agricultural productivity is maintained or improved compared to the reference level;
- monthly irrigation needs are below the maximum amount of water that on average can be extracted from river water in the catchment. This value was computed based on discharge simulations carried out with the hydrological model WaSim (Fuhrer and Jasper, 2012) individually for ETH and SMHI, assuming a residual discharge of 515.6 l s$^{-1}$ as prescribed by local authorities to prevent river depletion. Monthly

mean maximum withdrawals in summer were $5.10^6$ $m^3$ for ETH and $12.10^6$ $m^3$ for SMHI;

- better performances with regard to soil loss and N-leaching than the reference under climate change without adaptation (Section 6.4.1).

## 6.4 Results

### 6.4.1 Impacts of climate change on reference land management without adaptation

We first assessed impacts of climate change on the status-quo scenario with unchanged land management. Results presented in Fig. 6.4 show that, without adaptation, productivity slightly decreased. These changes are less pronounced than could be expected from future precipitation deficits, partly because of higher irrigation amounts by $20-50\%$. This increase in irrigation was accompanied by largely negative impacts with regard to both N-leaching (increase by $30-45\%$) and soil erosion (increase by $25-35\%$).

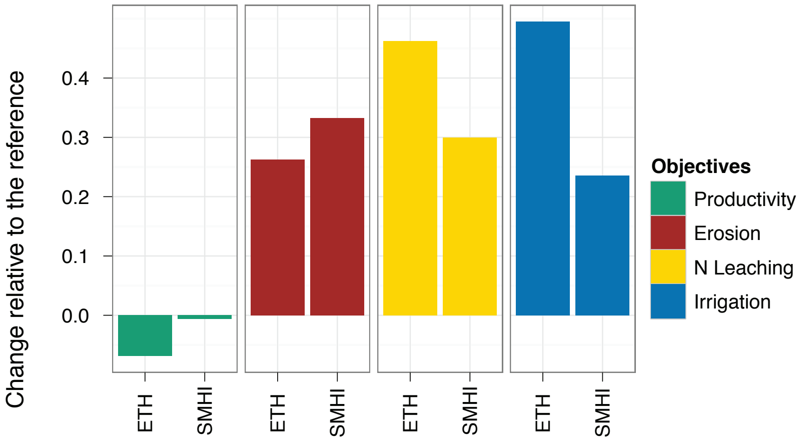


**Figure 6.4:** Impacts of climate change on the reference land management without adaptation.

Both climate scenarios agreed on negative effects of climate change on all objectives without adaptation. For SMHI, impacts on productivity were negligible and associated increased irrigation was moderate. In contrast, simulations with ETH indicated, as expected, a more pronounced productivity loss ($-10\%$) and a higher increase in irrigation needs (50%). Changes in erosion rates were similar but slightly higher with SMHI, while N-leaching was substantially higher with ETH.

### 6.4.2 Adaptation options

From regionally aggregated objective values of the 258 optimum solution, 16 clusters were generated with SOMs (Fig. 6.5). For each cluster, one representative solution was extracted based on the minimum distance to the centroids.

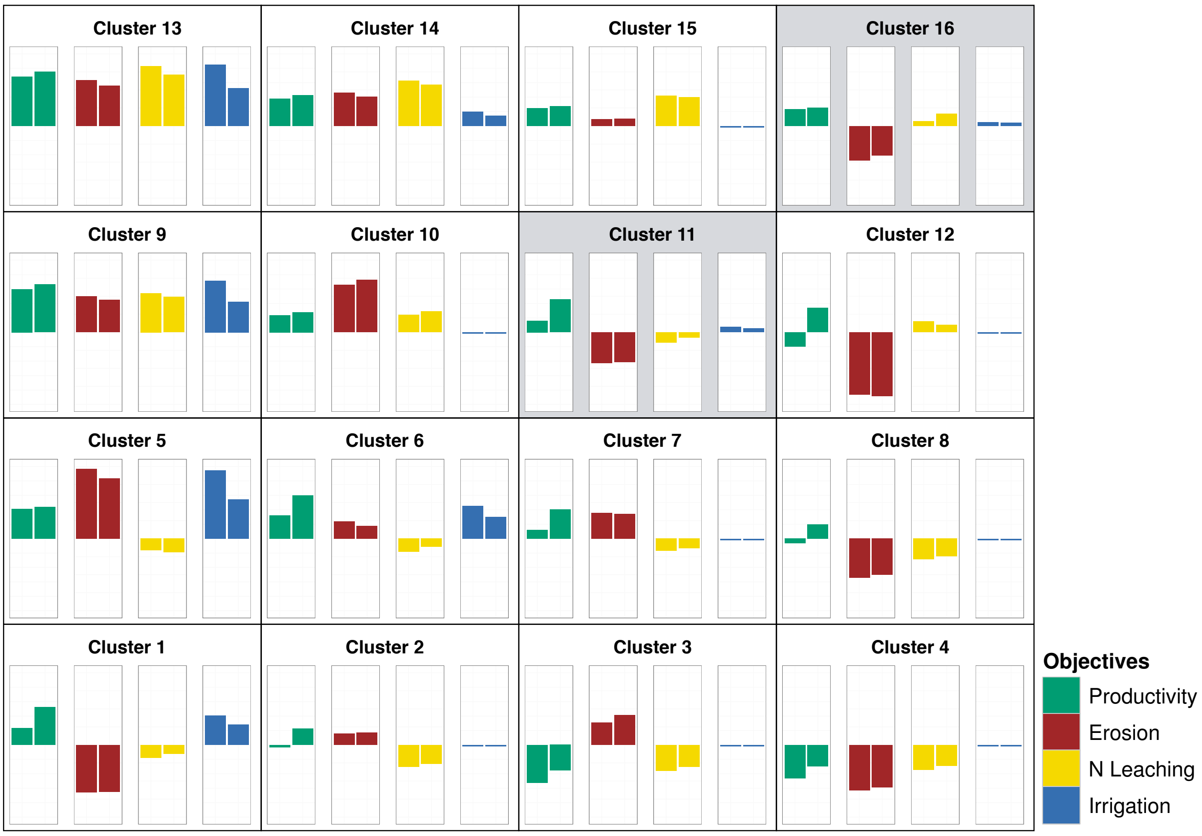


**Figure 6.5:** Impacts of climate change with adaptation (left: ETH 2050, right: SMHI 2050), expressed as change relative to the reference (1981-2010), for the 16 solutions closest to the clusters' centroids defined by Self-Organizing Maps; to facilitate the graphical interpretation, different scales are used for the objectives but they are identical across clusters to compare the latter qualitatively (a quantitative analysis can be found in the text); the two compromise solutions are highlighted with gray background.

As seen in Fig. 6.5, a wide range of different adaptation options were generated, some of them prioritizing productivity at the expense of environmental impacts and requiring high irrigation amounts (clusters 5, 9 or 13), some others more favorable for soil preservation and/or clean water provision (clusters 1 to 4). Generally, agricultural productivity conflicted with environmental objectives. Indeed, high yields were reached using large amounts of irrigation and with increased N-leaching and/or higher soil loss rates.

Of the 16 clusters, 11 allowed maintaining or even further increasing productivity compared to the reference. The maximum increase in productivity was $\sim +35\%$ (cluster 13). However, this was associated with an increase in irrigation by 4000% and 2500% for ETH and SMHI, respectively. Only 6 out of 16 solutions allowed to reduce soil loss but, in some cases, beneficial impacts were very important (up to a 85% reduction in cluster 12). More adaptation options to reduce N-leaching were found, but positive effects were moderate (up to a 30% reduction). In general, large differences were found between the two climate scenarios with regard to productivity and irrigation amounts, while very few differences were found in terms of erosion and N-leaching.

Mean proportions of area allocated to different agricultural practices are represented in Fig. 6.6 for each cluster separately. Land management differed much across the different clusters. For instance, a high proportion of permanent grassland in combination with conservation soil management was necessary to minimize erosion (cluster 12). Best performance with regard to productivity (cluster 13) was achieved with conventional soil management and a crop mix of a few crops (i.e. heavily irrigated sugar beet, silage/-grain maize, winter barley and winter wheat). To minimize leaching (clusters 3 and 4), the sequence silage maize-winter wheat with low fertilization was best in order to ensure constantly low soil N concentrations with high N uptakes due to deep rooting systems and short fallow times.

### 6.4.3 Compromise solutions for adaptation to climate change

Optimum solutions not satisfying the constraints in Section 6.3.5 were removed. Solutions in clusters 2,3,4,8 and 12 were eliminated because productivity could not be maintained under the more extreme climate scenario. Irrigation needs exceeded available surface water flow for solutions in clusters 1,5,6,9,13 and 14 and, therefore, they were excluded. Solutions in clusters 7,10 were eliminated as erosion increased compared to the status-quo scenario without adaptation (Fig. 6.4). Thus, only two solutions fulfilled all the criteria, i.e. clusters 11 and 16. These can be considered as realistic development goals for future agriculture in the Broye.

Compared to the reference, both compromise solutions indicated an increase in productivity, by 10% for cluster 16 (for both climate scenarios) and by 5% (ETH) and 20% (SMHI) for cluster 11. Both solutions had strong beneficial effects on soil protection, with a decrease in soil loss by about 50% with both climate scenarios. Impacts of adaptation on N-leaching were less extreme and varied more, ranging from an increase in leaching by 15% (cluster 16 with SMHI) to a decrease in leaching by 10% (cluster 11 with ETH).

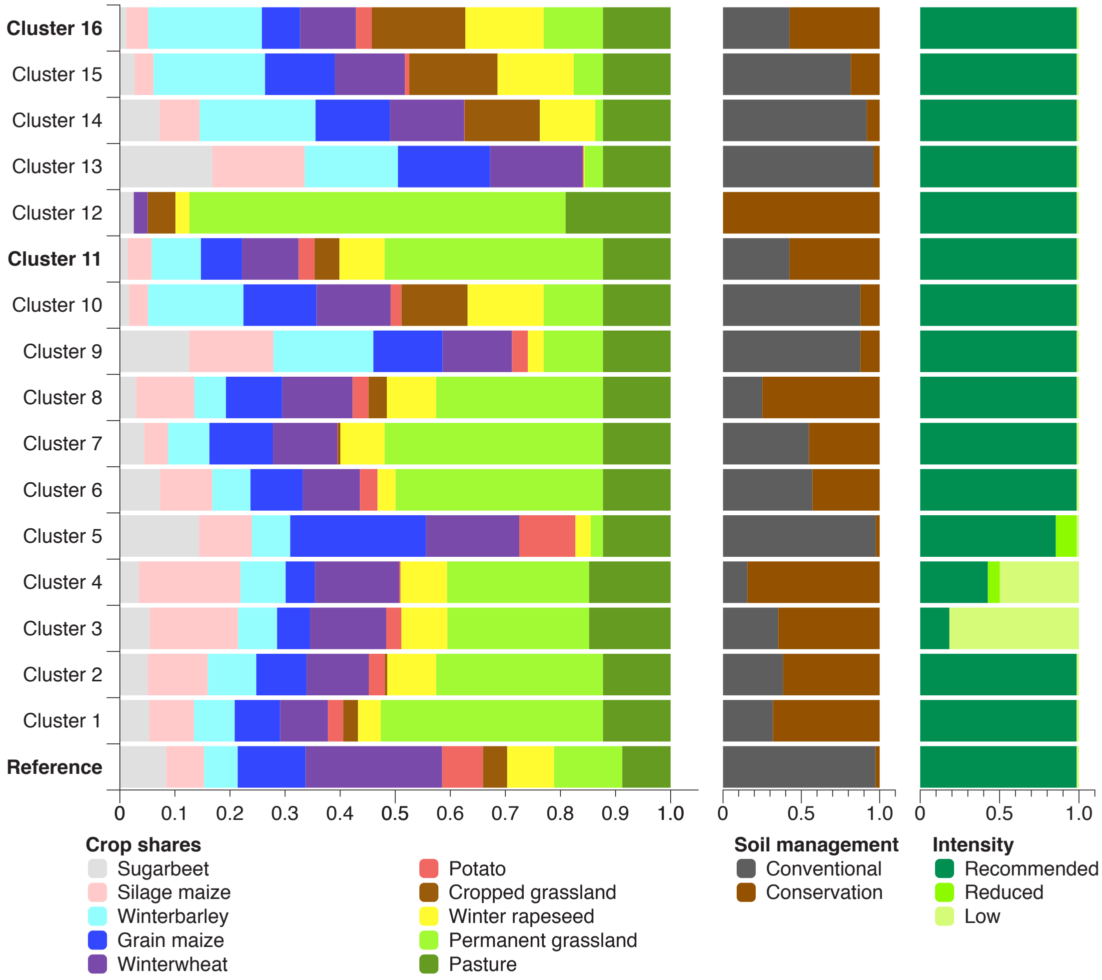
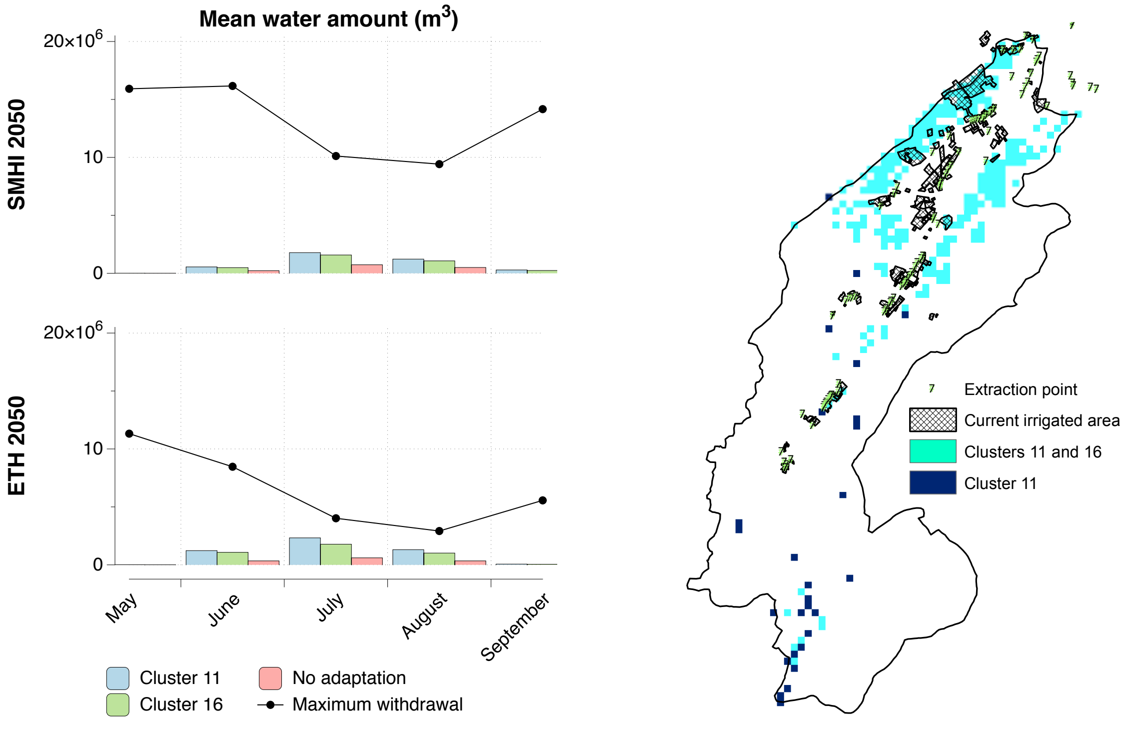


**Figure 6.6:** Optimum proportions of areas of agricultural practices and comparison with the reference (1981-2010).

On average, irrigation needs were always below the availability (Fig. 6.7a). Simulated irrigation amounts were similar in the two solutions and occurred from June to September, with a peak in July. As expected, irrigation needs were higher with ETH than SMHI, but with moderate magnitude despite the stronger signal suggested by ETH. For some months, a substantial amount of surface water was used to cover the needs in this scenario, as for instance in July when nearly 60% of the total surface water was necessary under the ETH scenario. About 10% of all agricultural areas were irrigated for both compromise solutions (Fig. 6.7b). Irrigated areas were almost exclusively located around the city of Payerne (i.e. at low elevation with higher air temperature) on sandy loam soils with low water retention capacity.

The two solutions exhibited many similarities but a few discrepancies. First, both of them agreed that conservation soil management (i.e. no till, harvest residues retained) should gain in importance and replace conventional soil management with regular till and harvest



a

b

**Figure 6.7:** (a) Mean regional monthly irrigation needs (compromise solutions and no adaptation) vs. maximum allowable water withdrawals (Fuhrer and Jasper, 2012) and (b) Spatial distribution of irrigated pixels (observed/reference, compromise solutions).

residues removed, as suggested by Fig. 6.6. However, conventional soil management was still applied in nearly 70% of the areas around Payerne, which were not subject to soil loss because of low slopes (not shown). Also, both options indicated that management intensity in terms of N fertilization, grass clippings and stocking density should remain at the recommended level. Moreover, a comparison of the two adaptation options with regard to land use as presented in Fig. 6.8, suggested that high elevation areas around the city of Semsales could become favorable for crop cultivation, which is not the case under present climate.

Both options agreed that shares of irrigated spring crops should decrease (Fig. 6.6), by 60% for potato, 75% for sugar beet, and 20% for grain maize, while production of some winter crops should increase, especially those which are harvested early in the year (i.e. barley and rapeseed). The regional share of grassland should also increase, either in rotations (cluster 16) or as permanent meadows (cluster 11). Another similarity was the allocation of pastures on the steepest slopes, which led to reduced soil loss in areas that are prone to erosion. Also in both cases, permanent grasslands covered coarse soils located at high elevations. In addition to reducing erosion in those areas, permanent grasslands would decrease soil temperature and, consequently, soil N availability and N loss from

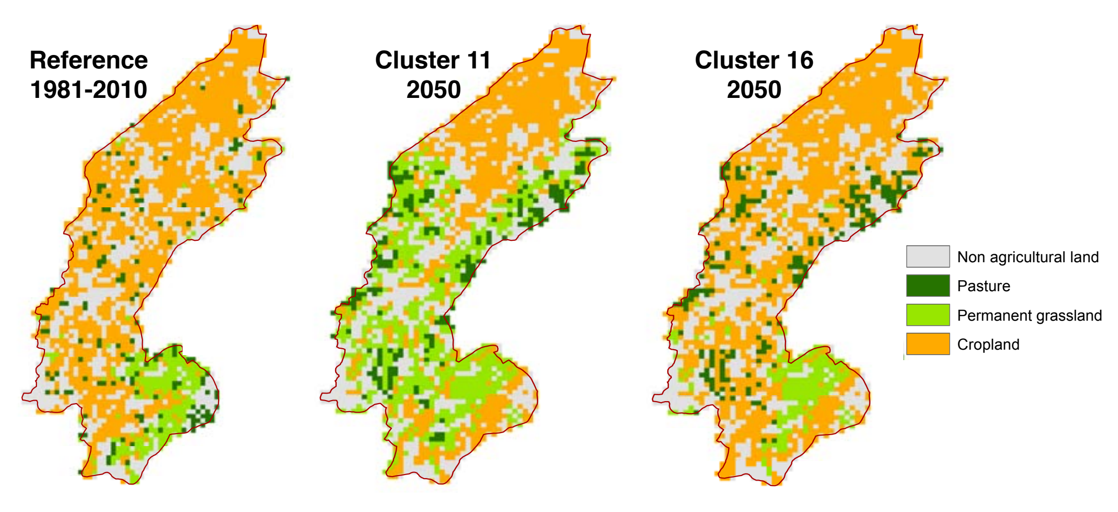


**Figure 6.8:** Land use changes to achieve compromise adaptation options.

soils which are subject to leaching. The major difference between the two compromise solutions was found in terms of the regional crop mix (Fig. 6.6). Indeed, cluster 11 was mostly dominated by permanent grassland, while cluster 16 focused more on crop production with, for instance, a large share of winter barley.

## 6.5 Discussion

The results of this multi-objective optimization reveal considerable scope for adaptation of land use and management to cope with climate change at the scale of a watershed. We selected two optimal compromise solutions for the time horizon 2050 that would allow maintaining productivity with minimum environmental impacts. One of them performs much better than the reference (1981-2010) with regard to three of the four objectives, only performing worse in terms of water saving. This information can support the learning and decision-making process necessary for developing longer-term land management adaptation strategies in the region.

### 6.5.1 Land management adaptation to climate change

Adjustments of agricultural practices can minimize negative impacts of climate change on agriculture, but might also allow exploiting some advantages of climate change. In this study, we found that areas located above 700 m - where only pastures and permanent grasslands are currently cultivated due to limiting cold temperatures - can benefit from climate change as they become suitable for crop cultivation. This situation is expected in most of cool regions of Europe for the time horizon up to 2050 (Moriondo et al., 2010a). On average, adaptation can provide around 10-15% yield benefit compared to no adaptation practice (Lotze-Campen and Schellnhuber, 2009). We found that benefits of adaptation can even be up to 35% greater if solely focusing on maximizing crop yields as suggested by Fig. 6.5. Most of the adaptation options identified here allow maintaining or even further increase productivity compared to the current level. Regarding benefits of adaptation for the environment, more than 50% of all adaptation options lead to decreased N-leaching under future climate, but with relatively low magnitude (i.e. at most 30%). In comparison, the number of options diminishing soil loss was small (about 30%) but relative positive effects were higher than for N-leaching (up to a 90% decrease under climate change compared to current climate).

From Fig. 6.6 we can draw a few general conclusions about land management adaptation under climate change. First, conventional soil management tends to disappear with climate change. The reason is that the impacts on soil temperature and N mineralization become less important as air temperature increases. Reduced tillage and retaining harvest residues is generally known to improve soil organic matter content and provide effective means to conserve soil fertility (Maltas et al., 2013). In addition, conservation soil management increases soil surface protection and reduces runoff (Scholz et al., 2008; Zhang and Nearing, 2005). Second, today's recommended intensity level is and will be best as it has a positive effect on productivity, which in turn has an influence on erosion (i.e. the more biomass, the better the soil protection) without leading to high N-leaching rates. Note that N fertilization amounts higher than recommended levels were not tested in this study, since they were not assumed to be a realistic option. Third, proportion of grassland increases in the future as it reduces the high erosion risk under climate change. On top of that, it is an excellent pre-crop and has positive effects on leaching. Note that it becomes more optimal to grow grassland as permanent meadows than as part of crop rotations. At last, potato tends to disappear with climate change due to its high sensitivity to water-stress, while the share of winter rapeseed increases. Winter rapeseed is an eco-friendly crop, and it can serve as a catch crop to reduce N-leaching during the autumn-winter period thanks to its high capacity to take up nitrate from the soil (Malagoli et al., 2005) and it has been found to limit soil loss in the study area (Prasuhn, 2012). In addition, winter rapeseed is not irrigated and performs well under climate change. Boomiraj et al. (2010) found that under rainfed conditions, rapeseed productivity is not expected to decrease significantly below a temperature rise of 2 °C .

The results confirm the typical trade-off between agricultural productivity and regulating objectives (Power, 2010). However, a few adaptation options could be identified that would allow to maintain agricultural productivity, while decreasing environmental impacts. The two selected compromise solutions presented here indicate that yields with adaptation would be on average 13% (ETH) and 16% (SMHI) higher than without adaptation, but without increasing negative impacts on other functions. The two compromise solutions exhibit many similarities with regard to soil management and irrigation. First, reduced tillage and residue removal are more widely spread in the region in the future, except in lower elevation zones with mild slopes which are not subject to erosion. Irrigation is expected to be marginal in the study catchment on the horizon 2050 and only optimal in a restricted area with highest air temperature and on sandy loam soils with low water retention capacity. This suggests that it would be preferable to apply water extracted from the Broye river more distant from the river and on coarse soils where it is really needed, as opposed to the current practice where irrigation is mostly applied on loamy soils located in proximity of the river bed. For the most extreme climate scenario, it is expected that on average 60% of water from river runoff would be necessary to cover irrigation needs in July. However, in case of extreme years with important precipitation deficits, additional water would be needed from other sources (e.g. Lake of Neuchatel or Lake of Murten, or from artificial water reservoirs). The two selected compromise solutions showed also discrepancies, especially in terms of crop mixes (Fig. 6.6) and land use (Fig. 6.8). This suggests that similar sets of objective values can be reached with different strategies. Cluster 16 is very similar to the model reference with few exceptions (e.g. slightly more winter barley and winter rapeseed), while cluster 11 would require a drastic change of crop mixes with the conversion of many croplands to grasslands.

### 6.5.2 Limitations and uncertainties

We faced different limitations in this model application, mainly related to the use of crop rotations. The first limitation was the inability of the model to capture the effect of crop rotation on pests and diseases, which in reality is a very important aspect. The lack of a routine to account for pest and disease impacts in most crop models is often pointed out as a limiting factor for climate impact studies (Soussana et al., 2010). Because we used crop rotations, sowing and harvest dates were constrained, and we did not investigate effects of different sowing dates and changing length of phenological stages on agricultural functions. Note that the lack of a routine accounting for frost damage in many crop models (see e.g. Supit et al., 2010b) might lead to an overestimation of benefits of early sowing of spring crops.

It has been shown that experiments dealing with $CO_2$ fertilization effects do not address important co-limitations due to water and nutrient availability. Hence, in modeling studies the favorable crop response to elevated $CO_2$ might be overestimated (Long et al., 2006) and the exact quantification of the $CO_2$ fertilization effect remains uncertain (Körner et al., 2007; Parry et al., 2004). For this reason, possible $CO_2$ fertilization effects were ignored in this study.

A solution is called robust here if it is insensible to uncertainties, at least within a certain range (Bohle et al., 2010). Many sources of uncertainty entering the study at different levels should be considered when estimating climate change impacts (e.g. climate scenarios or model parameterization). It has been suggested that the parametric model uncertainty can be regarded as negligible compared to RCM inter-model variability (Ceglar and Kajfež-Bogataj, 2012). To deal with uncertainties in climate scenarios, two contrasting simulated future climates were included. In a future implementation of the approach, multiple model parameterizations in addition to several RCMs should be considered.

### 6.5.3 Optimization approach

A realistic representation of the agricultural system was used, considering both crop and livestock production. In addition, 6 different agricultural practices were merged into 4 decision variables. However, the following measures were taken to reduce the complexity of the optimization task: (i) we used a simple spatial representation with 4 soil types and 3 climatic zones, (ii) we neglected neighborhood effects between pixels, and (iii) we defined a priori discrete levels for each management option. Consequently, all combinations of management options for different local conditions could be computed prior to the optimization and stored in a lookup table. Thus, we were able to identify optimal configurations at relatively low computational costs, which allowed to repeat the procedure many times with different weightings to explore a wide range of adaptation options. This procedure is significantly faster than a global optimization approach which would require the use of a mathematical optimization (e.g. linear programming or dynamic programming), without necessarily improving identified optimum solutions (Seppelt and Voinov, 2002). The downside of this approach is that the decision space can only be explored at these pre-defined intervals.

### 6.5.4 Applicability of the results

Climate change is one of the drivers that will influence the future farming landscape, but other factor such as markets (e.g. prices), policy (e.g. subsidies) and technological development are expected to be at least equally important (Mandryk et al., 2012). According to Smith (2002), agricultural adaptation options can be grouped into four main categories: (i) technological developments, (ii) government programs and insurance, (iii) farm production practices, and (iv) farm financial management. In this study we focus on the third category but categories are often interdependent. For example, government programs to develop financial incentives or new technologies might be adopted to modify farm production practices. The scale at which climate adaptations are developed and assessed is of major importance and responses at different levels of organization should be considered.

Compromise solutions selected based on politically desired criteria can be seen as guidelines towards desirable development in the region. Overall, cluster 16 could be seen as a more acceptable scenario as it would not require land use changes. Indeed, cluster 11 would target an increase in fodder production, leading to an increase in animal production and the conversion of many crop farms into livestock farms, which may not be desirable. On top of that, cluster 16 seems to be a more robust solution as impact values for all objectives are similar with both ETH and SMHI (see Fig. 6.5), thus suggesting that expected impacts are independent of the climate scenario. Nevertheless, the possibility for reaching a certain goal can be restricted by the farming structure in the region and the willingness of farmers to adopt changes. For example, it seems unrealistic that farmers would be willing to reduce the production of potato, as encouraged in our results, because of the current economic importance in this region. Therefore, policy instruments of governments, such as farm production subsidies, supports and incentives, need to be designed at the regional level to guide and encourage the necessary changes in farm-level production and management.

## 6.6 Conclusions

We identified optimum options for adaptation of agricultural land management to climate change for a small Swiss catchment where adaptation will be necessary on the horizon 2050, mostly to limit increasing environmental impacts. To this end, we applied a modeling approach, relying on a crop and a livestock model which were integrated within a spatial multi-objective optimization routine. The multifunctional role of agriculture was examined by including four of the most important aspects of Swiss agriculture for future adaptation, namely agricultural productivity, water saving, soil preservation and clean water provision. A large number of decision variables was considered to cover a wide range of potential farm production adaptation practices.

Conflicts exist between productivity and regulating functions, but compromises are possible. Indeed, the method presented here allowed identifying several acceptable solutions, one of them performing much better than the reference (1981-2010) with regard to three of the four objectives for both climate scenarios. The only objective that could not be improved was water saving but on the average estimated irrigation needs did not exceed surface water availability.

Different management schemes are possible to achieve compromises between objectives, ranging from a conversion of most croplands into grasslands to the conservation of the same crop mix with only small adjustments of some agricultural practices such as soil management. Nevertheless, we could identify the following general recommendations to be taken to cope with climate change around 2050 in the Broye catchment:

- recommended intensity level should be maintained;
- conservation soil management should be more widely used at the expense of conventional soil management, except in flat areas;
- high elevation grasslands should be converted to croplands under climate change, as those areas become favorable for crop cultivation in a warmer climate; however, grasslands should remain at high elevations on coarse soils;
- shares of irrigated spring crops should decrease, while shares of early harvested winter crops (i.e. rapeseed and barley) should increase;
- pastures should be located on steeper slopes in the region around Moudon (medium elevation) to avoid severe soil losses.

Our results are encouraging and could provide a useful basis for discussion with regional planners about the strategies to be implemented for achieving the most desirable solution(s).

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# Chapter 7

# Adapting crop management practices to climate change: Modeling optimal solutions at the field scale

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# Adapting crop management practices to climate change: Modeling optimal solutions at the field scale

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ABSTRACT

Climate change will alter the environmental conditions for crop growth and require adjustments in management practices at the field scale. In this paper, we analyzed the impacts of two different climate change scenarios on optimal field management practices in winterwheat and grain maize production with case studies from Switzerland. Management options included nitrogen fertilization (amount, timing and allocation) as well as irrigation. Optimal solutions that maximize the farmer's utility were sought with the help of a bioeconomic modeling system that integrated the process-based crop growth model CropSyst into an economic decision model. The latter accounted not only for the crop specific average profit margins, but also for production risks, reflecting the utility (expressed as the certainty equivalent) of a risk-averse farmer's management decisions at field scale. In view of the non-linearity and complexity of the problem, we used a genetic algorithm as optimization technique. For grain maize, our results showed that climate change will foster the use of irrigation, not only at sites prone to water limitation already under current climatic conditions, but more in general for climate change scenarios projecting a substantial decrease in summer precipitation. For winterwheat, irrigation was never identified as an optimal management option. For both crops and sites, climate change reduced the optimum nitrogen fertilization amount and decreased for winterwheat the number of fertilization applications. In all cases, the farmer's certainty equivalent decreased between 7% and 25% under climate change, implying negative impacts on winterwheat and grain maize production even under the assumption of an adjustment of the optimum management practices.

## 1. 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). Even taking beneficial direct effects of $CO_2$ fertilization and adaptation measures into account, projected changes in global climate conditions over the coming decades are expected to further decrease world crop yields at the global scale (Parry et al., 2004). At a regional scale, however, climate change (CC) impacts are likely to lead to more heterogeneous results. For instance, while in Northern Europe moderate changes in climatic conditions are projected to have positive effects on agricultural systems, in Southern Europe, agriculture is very likely to suffer from global warming (Olesen and Bindi, 2002).

To abate the negative impacts of CC, the adaptation of agricultural practices will play a decisive role (Lobell et al., 2008). Agricultural production can benefit already from small changes at the tactical level, e.g. adjustments in sowing dates and fertilization intensity, as shown by Torriani et al. (2007b) and Lehmann et al. (2011). More effective results, however, are likely to require measures that either are costly, as in the case of irrigation (Rosenzweig and Parry, 1994), or can be implemented only slowly, as in the case of breeding of drought-tolerant cultivars (Araus et al., 2008; Campos et al., 2004). Furthermore, it is clear that the consideration of economic constraints is necessary for assessing the potential for adaptation and inform stakeholders and policy makers (Kaufmann and Snell, 1997).

In this context, the use of bioeconomic models linking crop growth models with economic decision models has been suggested in various studies as a way forward toward integrated assessments (Challinor et al., 2009; Finger et al., 2011; Olesen et al., 2011; Reidsma et al., 2010). Process-based crop growth models as stand-alone tools have been extensively used in CC impact studies in agriculture (Eitzinger et al., 2003; Finger et al., 2011; Guerena et al., 2001; Haskett et al., 1997; Jones and Thornton, 2003; Torriani et al., 2007a, 2007b). The benefits are obvious. Crop models

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are able to simulate crop growth under climate scenarios that exceed the range of current conditions (Finger and Schmid, 2008) and can thus be used to explore a whole range of alternatives climate or management scenarios (Bellocchi et al., 2006). The drawback, however, is that crop models are not designed to simulate adjustments in farm management in response to economic and political constraints (Risbey et al., 1999). Furthermore, earlier studies assessing the potential benefits of adjustments in agricultural management practices often focused on a narrow subset of management decision options (e.g. Finger et al., 2011; Gonzalez-Camacho et al., 2008; Torriani et al., 2007b). However, most crop growth models allow to investigate various aspects of crop management simultaneously. Thus, the full potential of such 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).

In this study, we developed a bioeconomic modeling system for applications in integrated CC impact and adaptation assessments at field scale. The developed modeling system integrates the crop growth model CropSyst (Stöckle et al., 2003) with an economic decision model that represents the farmer's decision making process. The system operates at the daily scale and is thus suitable to examine tactical adaptation. The model was applied to examine CC impacts on winterwheat (*Triticum* spp. L.) and grain maize (*Zea mays* L.) production at two different study sites in Switzerland. Nitrogen fertilization and irrigation were considered as management options. The analysis of these two factors was motivated by the fact that nitrogen and water inputs control not only average yield levels but also yield variability. Previous assessments (e.g. Finger et al., 2011) have shown that irrigation is expected to gain in importance in crop production in Switzerland under CC even in regions that do not face water scarcity under present climate conditions. Furthermore, the costs of both, nitrogen fertilization and irrigation, make up a large part of the total production costs in winterwheat and grain maize production and are thus highly relevant from an economic perspective. In order to optimize on-farm management decisions related to both production factors, we integrated the crop growth simulation model CropSyst into a complex economic decision model. For our analysis, we relied on an economic decision model that represents a risk-averse decision maker, i.e. a decision maker that cares not only about the long-term average revenue but also bases his decisions on considerations of the income variability. This interest for production risks was motivated by the observation that CC may have particularly large effects on production variability (Torriani et al., 2007b).

## 2. Methodology

### 2.1. Optimization problem

The study's objective was to optimize management decisions in winterwheat and grain maize production under different climate scenarios at two study sites in Switzerland from a risk-averse farmer's perspective (Fig. 1). Optimal solutions were sought that maximize the farmer's utility in crop production relatively to the certainty equivalent (CE). The CE accounts for both average profit levels and production risks, i.e. profit variability, and can be interpreted as the guaranteed payoff which a risk-averse decision maker views as equally desirable as higher but more uncertain levels of payoffs. For both crops, twelve management decision variables related to the nitrogen fertilization and irrigation strategy were optimized. The modeling approach is sketched in Fig. 1.

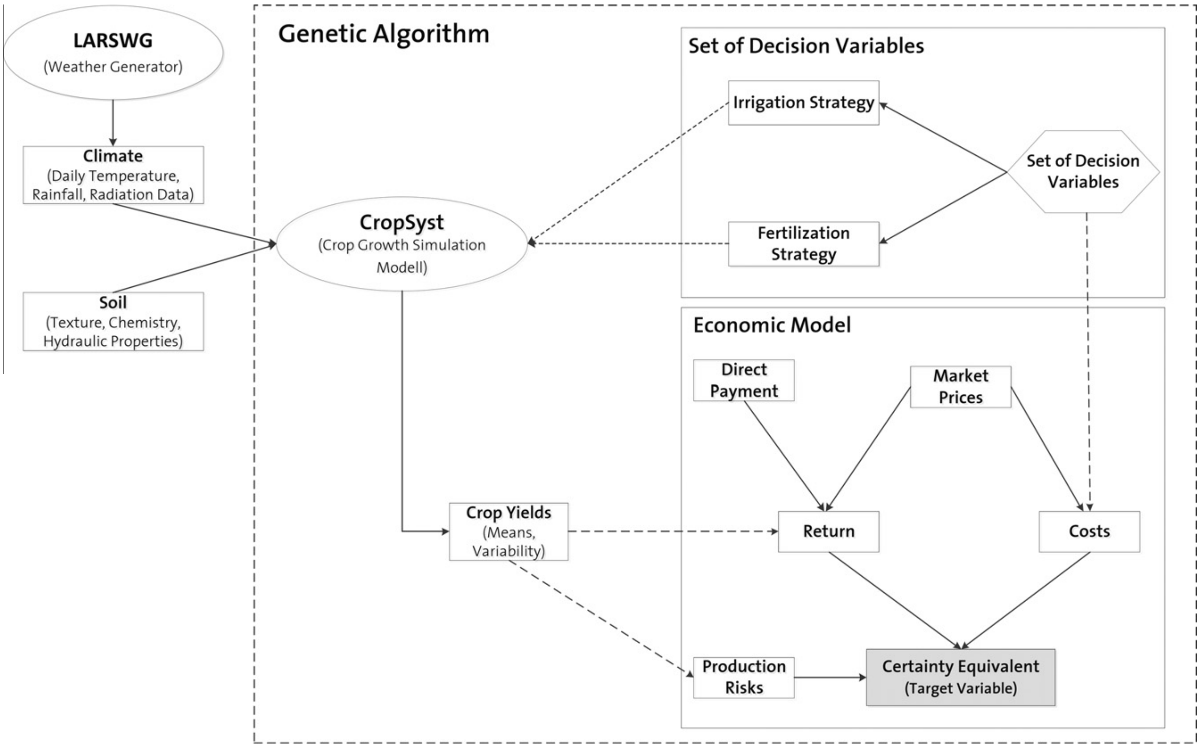

**Fig. 1.** Structure of the modeling system used in our study. At each iteration of the genetic algorithm (GA), a set of decision variables is generated for each individual. These decision variables are passed to CropSyst and used to simulate crop yields. Daily weather data needed as input data in CropSyst is generated by the LARS-WG weather generator. The simulated crop yields are further passed to the economic decision model where the farmer's certainty equivalent (CE) (i.e. target variable) is computed. The latter information is fed back into the GA. This procedure is repeated until the CE converges to a maximum value.

The core of the bioeconomic model consists of the crop growth model CropSyst and the economic decision model operating at field scale. Both are embedded in a genetic algorithm (GA) that generates different sets of management decision variables (see upper right part in Fig. 1). These decision variables are passed to CropSyst where they are used, along with daily weather data and soil information, as input factors for simulating mean and standard deviation of crop yields (see upper center part in Fig. 1). The simulated crop yields are fed into the economic model in order to compute the return of a specific set of management decisions (see lower right part in Fig. 1). Under consideration of production risks, the economic returns are finally used along with production costs to evaluate the CE, which is the target variable in the optimization routine. Besides CropSyst and the economic decision model, the modeling suite includes LARS-WG, a stochastic weather generator used for the generation of daily weather data as needed as input for CropSyst.

### *2.2. Study sites and simulation of weather data*

Two sites in Switzerland (Fig. 2) were selected to conduct the case studies. The first site, Payerne, is located in Western Switzerland (cantons of Vaud and Fribourg) within the Broye-Watershed. Water scarcity is frequent at this site already under current climate conditions and irrigation is thus a common management practice (Robra and Mastrullo, 2011). The second site, Uster, lies in the Greifensee-Watershed, which is located in the Northeastern part of Switzerland (canton of Zurich). Compared to Western Switzerland, this region is characterized by more humid weather conditions. Consequently, current crop production in this region is essentially rainfed.

For both sites, synthetic weather data (daily minimum and maximum temperature, rainfall occurrence and amount and daily total solar radiation) was generated for present and future climatic conditions using the stochastic weather generator LARS-WG (Semenov et al., 1998; Semenov and Barrow, 1997). Local weather observations of two climate stations located at Payerne and Uster, respectively, of the Swiss Meteorological Network spanning the period 1981–2010 were used to calibrate LARS-WG. After calibration, 25 years of synthetic weather data were generated for both, the Baseline period as well as for two CC scenarios. The latter are valid for the year 2050 and refer to the A1B emission scenario, a path-way envisaging a future world of very rapid economic growth, a global population that peaks in mid-century and declines thereafter, the rapid introduction of new and more efficient technologies and a balanced use of fossil and non-fossil energy sources (Nakicenovic et al., 2000).

Following Semenov (2007), data for the CC scenarios was simulated by specifying changes in monthly mean climate (see Appendix A). The latter were derived from the outputs of two climate model runs performed in the context of the ENSEMBLES project (van der Linden and Mitchell, 2009). The first was conducted with regional climate models maintained by the Swiss Federal Institute of Technology (ETHZ-CLM scenario), while the second was completed with the regional climate model of the Swedish Meteorological and Hydrological Institute (SMHI-Had scenario). For both runs, boundary conditions were obtained from global simulations with the Hadley Centre global climate model HadCM3. Both scenarios indicate for 2050 a significant temperature increase (see Appendix A). The ETHZ-CLM scenario is furthermore characterized by a substantial decrease in precipitation during spring and summer. With the SMHI-Had scenario, precipitation is projected to increase in all months except in June at Uster, and to decrease at Payerne in spring and summer months, although less markedly than with the ETHZ-CLM scenario.

### *2.3. CropSyst*

Crop growth was simulated with CropSyst (Version 4.13.09), a process-based, multi-crop, multi-year cropping simulation model that addresses biological and environmental above- and below-ground processes of a single land block fragment at the daily scale (Stöckle et al., 2003). CropSyst allows the simulation of a wide range of management options including crop rotation, cultivar selection, irrigation, nitrogen fertilization, tillage operations and residue management.

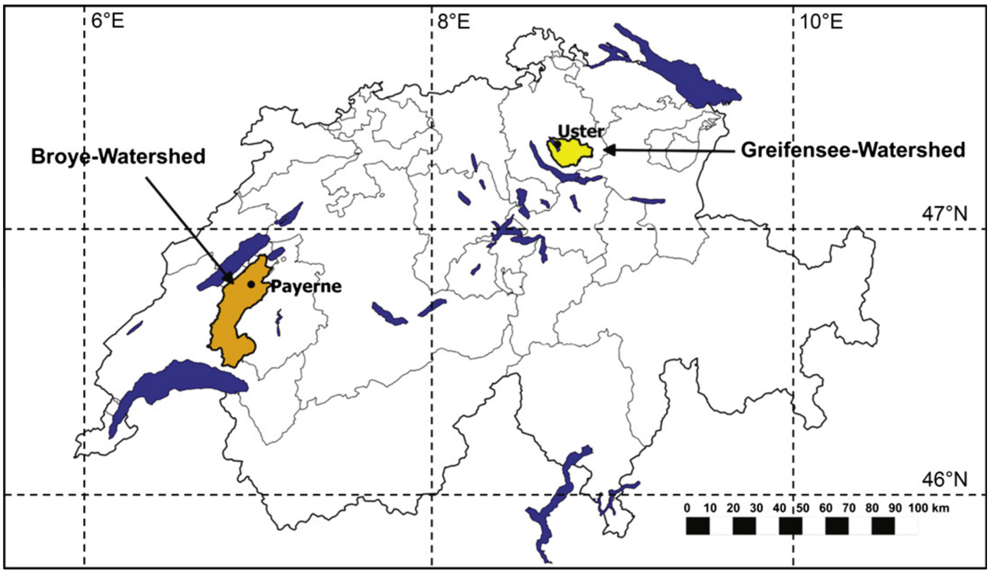

**Fig. 2.** Geographic location of the two study sites: Payerne (6°57′E, 46°49′N, 490 m a.s.l.) and Uster (8°42′E, 47°21′N, 440 m a.s.l.). Since the meteorological station at Uster measures only precipitation-related variables, representative temperature and solar radiation measurements for the Greifensee were obtained from the record at a nearby climate station (Zurich-Fluntern, 8°34′E, 47°23′N, 555 m a.s.l.).

In recent years, the model has been applied to simulate crop responses to climate for a wide range of environmental conditions (Donatelli et al., 1997; Pannuk et al., 1998; Sadras and Roget, 2004; Stöckle et al., 1997; Todorovic et al., 2009). Several examples of applications to crop production in Switzerland are also available from literature (Finger and Schmid, 2008; Finger et al., 2011; Lehmann et al., 2011; Torriani et al., 2007a, 2007b). Moreover, the model has been applied to examine management options in cropping systems. For instance, Garofalo et al. (2009) employed CropSyst to evaluate the effect of faba bean cultivation as a break crop in the continuous durum wheat cropping system in southern Italy. The model was further used by Bellocchi et al. (2006) to gauge the benefits and drawbacks of different nitrogen fertilization regimes in winterwheat production. In another study, Benli et al. (2007) evaluated CropSyst for its ability to simulate growth, biomass, grain yield and evapotranspiration of wheat applying different sowing dates and irrigation strategies. Furthermore, Jalota et al. (2010) assessed the effects of tillage, date of sowing, and irrigation practices on a maize–wheat cropping system using CropSyst as crop growth model. All of these studies conclude that CropSyst is an appropriate model for the evaluation of different management options in cereal cropping systems.

For our analysis crop specific parameters were specified according to calibration runs performed by Klein et al. (2012). Soil textural characteristics, which are an important input factor in CropSyst, were defined based on information from soil profiles recorded in close proximity to the two climate stations at Payerne and Uster. The soil profile at Payerne indicates a soil texture with 60% of sand, 11% of clay and 29% of silt. Corresponding percentages at Uster are 66% for sand, 12% for clay and 22% for silt. An initial soil organic carbon concentration of 2.8% for the top soil layer and 2% for the other layers was obtained from the results of a 300 years spin-up run performed by Klein et al. (2012). These values are typical for the Swiss Plateau and within the range of observations presented by Dubois et al. (1999) and Leifeld et al. (2003). More details on soil profiles and initial soil organic carbon conditions are given in the Appendix B.

### 2.4. Economic model

The economic model adopted for our study maximizes the farmer's certainty equivalent (CE) on his management decisions in the specific cropping system. The CE is defined as shown in Eq. (1) which formulates the target function of the optimization problem:

$$\max(CE|DV_1, DV_2, \ldots, DV_{12}|) = E(\pi) - RP \tag{1}$$

where $DV_i$ stands for decision variable $i$ (e.g. irrigation strategy, fertilization amount), $E(\pi)$ is the expected profit margin and $RP$ is the risk premium (both expressed in CHF $ha^{-1}$).

The risk premium is the 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 risk premium can be approximated by:

$$RP \approx 0.5 \cdot \gamma / E(\pi) \cdot \sigma_{\pi}^2 \tag{2}$$

where $\gamma$ is the coefficient of relative risk aversion and $\sigma_{\pi}^2$ is the variance of the profit margins. Values for $\gamma$ between 1 and 4 represent typical forms of risk behavior (Gollier, 2001). For this study, we assumed $\gamma = 2$, representing a moderate risk-aversion and implying a decreasing absolute risk aversion (Di Falco and Chava, 2006).

The profit margin $\pi$ can be obtained from:

$$\pi = \rho + DP - c_{fix} - c_{\mathrm{var}} \tag{3}$$

where $\rho$ is the revenue, DP are the governmental direct payments, $c_{fix}$ the fixed costs and $c_{\mathrm{var}}$ the variable costs (all expressed in CHF $ha^{-1}$).

Variable production costs are comprised of charges for fertilizer, water, insurance and capital as well as yield dependent cleaning and drying costs at harvest (Table 1). Since in CropSyst only nitrogen fertilization is considered, we coupled the costs of $P_2O_5$, $K_2O$ and Mg fertilizer to the applied nitrogen amount. Insurance costs were assumed to be proportional to the expected revenue (i.e. premiums are higher for higher production levels). The interest claim was defined as product of the interest rate and the invested capital (fixed costs and variable costs) for an average commitment of 6 months.

The considered fixed costs comprise costs for seeds, plant protection and growth regulation as well as contract work and machinery. Contract work and machinery costs, were specified following AGRIDEA and FIBL (2010). Regarding the price of winterwheat and maize, we followed the recommendation of AGRIDEA and FIBL (2010) published for the year 2010. In view of the specificities of agricultural markets in Switzerland (i.e. the agricultural markets in Switzerland are characterized by high entry barriers), these prices are higher than found in other European countries.

### 2.5. Decision variables

For both crops, we considered twelve different management decision variables, all of them related to nitrogen fertilization and irrigation (Table 2). In order to enable feasible computation times to solve the model, we integrated all management variables as discrete values.

Regarding fertilization, we considered for both crops up to four applications per year. In the context of standard fertilization procedures, three nitrogen fertilization applications are currently rec-

**Table 1**
Revenue and costs in winterwheat and grain maize production.

| | Winterwheat | Grain maize |
|---|---|---|
| *Revenue* | | |
| Crop price (CHF $t^{-1}$)[a] | 0.51 | 0.37 |
| *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 |
| Irrigation system costs (CHF $ha^{-1}$)[b,c] | 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,d] | 39.5 | 71.3 |
| Other costs (CHF $t^{-1}$)[a] | 6.7 | 0 |
| Variable irrigation costs (CHF $mm^{-1}$ $ha^{-1}$)[a] | 1.00 | 1.00 |
| Interest rate (%)[a,e] | 3.0 | 3.0 |

[a] *Source*: AGRIDEA and FIBL (2010).

[b] *Source*: Spörri (2011).

[c] Note that the irrigation system costs disappear if irrigation is not chosen as management option.

[d] Note that the cleaning and drying costs depend on the yield at harvest which have a higher water content than the final yield. The dry matter contents of the winterwheat and grain maize harvest are assumed to be 85.5% and 86%, respectively (AGRIDEA and FIBL, 2010).

[e] Interest claims have been calculated on the invested capital (fixed costs, fixed irrigation costs and variable costs) for an average commitment of 6 months.

**Table 2**
Considered management variables.

| Decision variable | Management variable | Unit | Range (min–max) | | Variable increment | | Number of alternatives | |
|---|---|---|---|---|---|---|---|---|
| | | | Grain maize | Winterwheat | Grain maize | Winterwheat | Grain maize | Winterwheat |
| 1 | Total nitrogen amount | kg 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 | 10 | 10 | 11 | 11 |
| 4 | Timing of 1st N application | Days after sowing | 0–150 | 120–220 | 10 | 5 | 31 | 21 |
| 5 | Amount of 2nd N application | % | 0–100 | 0–100 | 10 | 10 | 11 | 11 |
| 6 | Timing of 2nd N application | Days after sowing | 10–150 | 140–220 | 10 | 10 | 29 | 17 |
| 7 | Amount of 3rd N application | % | 0–100 | 0–100 | 10 | 10 | 11 | 11 |
| 8 | Timing of 3rd N application | Days after sowing | 20–150 | 160–220 | 10 | 10 | 27 | 13 |
| 9 | Amount of 4th N application | % | 0–100 | 0–100 | 10 | 10 | 11 | 11 |
| 10 | Timing of 4th N application | Days after sowing | 30–150 | 180–220 | 10 | 10 | 25 | 9 |
| 11 | Maximum allowable depletion | – | 0–1 | 0–1 | 0.1 | 0.1 | 11 | 11 |
| 12 | Irrigation refill point | – | 0–1 | 0–1 | 0.1 | 0.1 | 11 | 11 |

ommended in Switzerland both for winterwheat as well as for grain maize (Flisch et al., 2009). A minimum interval of 20 and 10 days was specified between two consecutive fertilization applications for winterwheat and grain maize, respectively. More frequent applications are not considered, because in this case marginal labor and machinery costs exceed the benefits. Apart from timing, we also considered a variable fraction of the total nitrogen amount applied with each fertilization event as decision variable (Table 2).

Irrigation was simulated using the automatic irrigation option available from CropSyst. Two decision variables were considered in this case. The first was the maximum allowable depletion. This value triggers irrigation as soon as the soil water depletion at 1 m soil depth is larger than this user-defined threshold (Stöckle and Nelson, 2000). The maximum allowable depletion is expressed as percentage of the maximum field water content (e.g. a maximum allowable depletion of 0.6 means that irrigation starts if the soil's water content is 60% smaller than the soil's field capacity). The second decision variable was the refill point, i.e. the relative soil water level up to which water is added during irrigation (Stöckle and Nelson, 2000). In relative units, the refill point also ranges from 0 (permanent wilting point) to 1 (field capacity). Since the two are complementary, the refill point must be specified so as to exceed one minus the maximum allowable depletion.

As a rule, the lower the maximum allowable depletion, the more frequent will be irrigation. In contrast, the refill point determines the intensity (i.e. applied water amount) of each irrigation event. The joint consideration of both variables allowed to mimic deficit irrigation, i.e. the application of water below the optimum evapotranspiration requirements of crops (English, 1990). The purpose of deficit irrigation is to maximize the economic returns rather than physical crop yield levels.

We assumed an irrigation efficiency of 77% corresponding to the irrigation efficiency of sprinkler irrigation systems (Irmak et al., 2011), the most common technique employed in Switzerland (Weber and Schild, 2007). In order to account for hydraulic limitations of the irrigation equipment, a minimum irrigation quantity of 15 mm per irrigation event was specified. Thus, irrigation was delayed if the difference between the refill point and one minus the maximum allowable depletion value was less than this threshold of 15 mm.

In agreement with the current practice, the sowing date of winterwheat was fixed for all climate settings (Baseline and CC scenarios) to October, 10. For maize, the sowing date was specified depending on temperature. Currently, in Switzerland sowing is recommended when the soil temperature at a depth of 0.05 m exceeds 10 °C (AGRIDEA, 2011). An analysis of observed daily mean air and soil temperature at Payerne suggested that this condition is fulfilled when the 5-day average mean air temperature also exceeds 10 °C Thus, we used the conditional sowing model in CropSyst for maize, whereas maize was sown if the 5-day average air temperature exceeded 10 °C.

### 2.6. Genetic algorithm

Due to the discrete nature of the decision variables, the presented optimization problem could be interpreted as a combinatorial problem. 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. Moreover, the relations between the decision variables and the target variable (CE) could not be represented with analytic functions. Therefore, the optimization problem was solved with the help of a genetic algorithm (GA).

GAs are based on the biological concepts of genetic reproduction and survival of the fittest (Aytug et al., 2003; Mayer et al., 1999). A population of individuals, each representing a possible solution for a given problem, evolves over time by selecting the best individuals in each generation and reproduction. 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 reproduction of offspring (Beasley 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 (Beasley 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). A GA involves at least the following three types of operators: selection, crossover and mutation (Mitchell, 1998). 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).

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, this non-parametric optimization technique avoids the often required intermediate step of statistical coefficient estimation of crop yield – input factor relations (e.g. Finger et al., 2011).

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, whereby at each step the overlap defines the percentage of the current population that is replaced (Wall, 1996). In line with Mayer et al. (2001), we applied the following control parameters to the GA: genome size = 8 bits; population size = 40; proportion of replacement = 0.2; selection routine = roulette wheel; mutation probability = 0.15; crossover probability = 0.5; fitness function = a sigma truncation scaling (Wall, 1996). Furthermore, the convergence criterion stopped the optimization when no improvement of the target variable was observed over 1000 generations. Nevertheless, since even this strict convergence criterion does not guarantee attaining a global optimum, each optimization run was repeated three times using different, randomly generated initial populations. In our case, this led for all scenarios to the same optimal solution. Results from the optimization presented in this paper are thus interpreted as global optima.

Although GA are computationally efficient, the overall setup of our optimization problem was computational intensive, requiring 1 week on a PC with Intel Pentium Core™ i5 at 3.33 GHz.

## 3. Results

The optimal management schemes for all climate scenarios are presented for both sites and crops in the Table 3 and 4.

In spite of contrasting precipitation scenarios, neither in the ETHZ-CLM nor in the SMHI-Had scenario irrigation was identified as an optimum management strategy for winterwheat production. For winterwheat, however, differences in the specification of the CC scenario had a strong impact on fertilization. As a rule, the stronger the increase in temperature and decrease in precipitation, the smaller was the optimal total nitrogen fertilization amount. The results also suggest a single application at mid-May as optimum fertilization strategy under both CC scenarios and for both study sites. This can mainly be explained by the fact that CC shortens the vegetation period of winterwheat at both locations. At Payerne, for instance, maturity is reached in the ETHZ-CLM scenario 1 month earlier than in the Baseline scenario.

Regarding grain maize production at Payerne, irrigation was identified as optimum management option for all climate conditions, including the Baseline scenario. A value for the maximum allowable depletion between 0.5–0.6 and a refill point between 0.6–0.7 was found to be optimal for three climate scenarios at Payerne. Nevertheless, since the irrigation demand depended on the season's prevailing climate conditions, the applied average water amount increased under the ETHZ-CLM and the SMHI-Had scenario by 84% and 41%, respectively, relatively to the Baseline scenario (Table 4).

At Uster, irrigation of grain maize was found to be profitable only under the ETHZ-CLM scenario, whereas irrigation was not required to achieve the maximum CE under the Baseline and the SMHI-Had climate conditions. Under the ETHZ-CLM scenario, a rather extensive irrigation strategy was found to be optimal, with both, a maximum allowable depletion and a refill point at 0.6. As seen in Table 3, this strategy results in an annual irrigation amount of 101 mm.

Regarding fertilization, the optimal nitrogen amounts in grain maize production decreased under the applied CC scenarios, similarly to what has been found in winterwheat production. However, in the case of grain maize CC did not imply changes in the number of fertilizer applications. Nevertheless, CC led to a slightly shorter time span between the first and last nitrogen fertilization event.

The annual profit margins and crop yields for the identified optimal management patterns are shown in Fig. 3. Under CC, the average profit margin and the average crop yield decreased at both locations and for both crops. Furthermore, CC led to a reduction of the variability of the winterwheat profit margins and yields at Uster. At Payerne, the crop yield variability in winterwheat production increased under the ETHZ-CLM scenario, while the SMHI-Had scenario led to a decrease of the crop yield and profit margin variability.

For grain maize production, the variability in profit margins and crop yields increased at Payerne under both, the ETHZ-CLM and the SMHI-Had scenario. At Uster, irrigation reduced the variability of crop yields and profit margins in grain maize production under the ETHZ-CLM scenario. In contrast, a significant increase in the variability of profit margins and yields was found at this location under the rainfed production conditions identified as optimal under the SMHI-Had scenario.

For both CC scenarios, adjustments in the management practices were not sufficient to maintain farmers' utility (expressed as the CE) at current levels. CC reduced the CE for both crops and at both sites up to 25% relatively to the Baseline scenario (Fig. 4).

**Table 3**
Optimal management parameters for winterwheat.

| Management variable | Unit | Winterwheat at Payerne Baseline | Winterwheat at Payerne ETHZ-CLM | Winterwheat at Payerne SMHI-Had | Winterwheat at Uster Baseline | Winterwheat at Uster ETHZ-CLM | Winterwheat at Uster SMHI-Had |
|---|---|---|---|---|---|---|---|
| Total N amount | kg ha$^{-1}$ | 150 | 110 | 120 | 140 | 80 | 110 |
| Number of fertilization events | – | 2 | 1 | 1 | 3 | 1 | 1 |
| Percentage of 1st N application | % | 60 | 100 | 100 | 30 | 100 | 100 |
| Timing of 1st N application | Days after sowing | 120 | 140 | 140 | 120 | 140 | 140 |
| Percentage of 2nd N application | % | 40 | 0 | 0 | 30 | 0 | 0 |
| Timing of 2nd N application | Days after sowing | 140 | – | – | 140 | – | – |
| Percentage of 3rd N application | % | 0 | 0 | 0 | 40 | 0 | 0 |
| Timing of 3rd N application | Days after sowing | – | – | – | 160 | – | – |
| Percentage of 4th N application | % | 0 | 0 | 0 | 0 | 0 | 0 |
| Timing of 4th N application | Days after sowing | – | – | – | – | – | – |
| Mean irrigation amount (standard deviation of irrigation amount) | mm ha$^{-1}$ | 0 | 0 | 0 | 0 | 0 | 0 |
| Maximum allowable depletion | – | 1 | 1 | 1 | 1 | 1 | 1 |
| Irrigation refill point | – | 1 | 1 | 1 | 1 | 1 | 1 |

**Table 4**
Optimal management parameters for grain maize.

| Management variable | Unit | Grain maize at Payerne Baseline | Grain maize at Payerne ETHZ-CLM | Grain maize at Payerne SMHI-Had | Grain maize at Uster Baseline | Grain maize at Uster ETHZ-CLM | Grain maize at Uster SMHI-Had |
|---|---|---|---|---|---|---|---|
| Total N amount | kg/ha | 200 | 160 | 180 | 140 | 120 | 110 |
| Number of fertilization events | – | 4 | 4 | 4 | 4 | 4 | 4 |
| Percentage of 1st N application | % | 40 | 40 | 30 | 70 | 50 | 70 |
| Timing of 1st N application | Days after sowing | 10 | 10 | 10 | 10 | 10 | 10 |
| Percentage of 2nd N application | % | 30 | 30 | 40 | 10 | 10 | 10 |
| Timing of 2nd N application | Days after sowing | 50 | 50 | 60 | 50 | 20 | 50 |
| Percentage of 3rd N application | % | 10 | 10 | 20 | 10 | 30 | 10 |
| Timing of 3rd N application | Days after sowing | 80 | 70 | 80 | 70 | 50 | 60 |
| Percentage of 4th N application | % | 20 | 20 | 10 | 10 | 10 | 10 |
| Timing of 4th N application | Days after sowing | 90 | 90 | 90 | 90 | 80 | 70 |
| Mean irrigation amount (standard deviation of irrigation amount) | mm/ha | 126 (59) | 231 (61) | 177 (66) | 0 (0) | 101 (58) | 0 (0) |
| Maximum allowable depletion | – | 0.6 | 0.5 | 0.6 | 1 | 0.6 | 1 |
| Irrigation refill point | – | 0.6 | 0.6 | 0.7 | 1 | 0.6 | 1 |

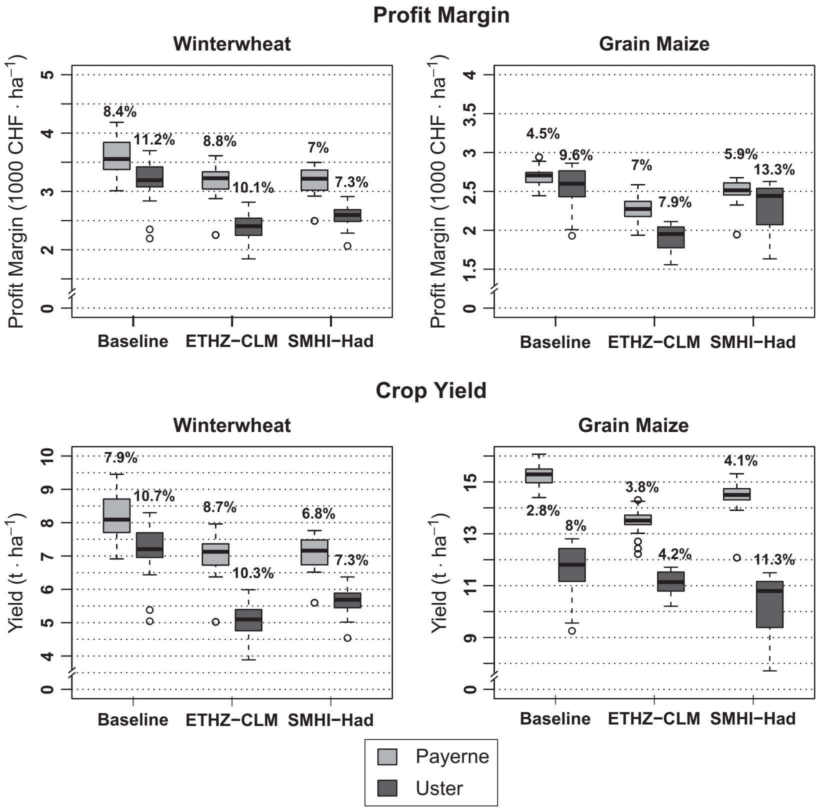

**Fig. 3.** Profit margins (upper plots) and crop yields (bottom plots) as obtained for each scenario with optimal management decision. The horizontal line denotes the median. The whiskers extend to a maximum of 1.5 times of the inter-quartile range. The white circles are outliers, which are not included in the range of the whiskers. The numbers above or below the boxplots indicate the coefficient of variation of the profit margins and crop yields. According to an Ansari–Bradley test (Ansari and Bradley, 1960), only the change in crop yield variability of grain maize cultivated at Uster between the Baseline and ETHZ-CLM scenario was significant.

The more extreme CC scenario ETHZ-CLM led for both crops and at both locations to a larger reduction in the CE. Furthermore, under both CC scenarios, the relative reductions in the CEs were found to be higher at Uster than at Payerne.

## 4. Discussion

The results of our bioeconomic modeling approach indicate that in Switzerland adaptation measures that take economic con-

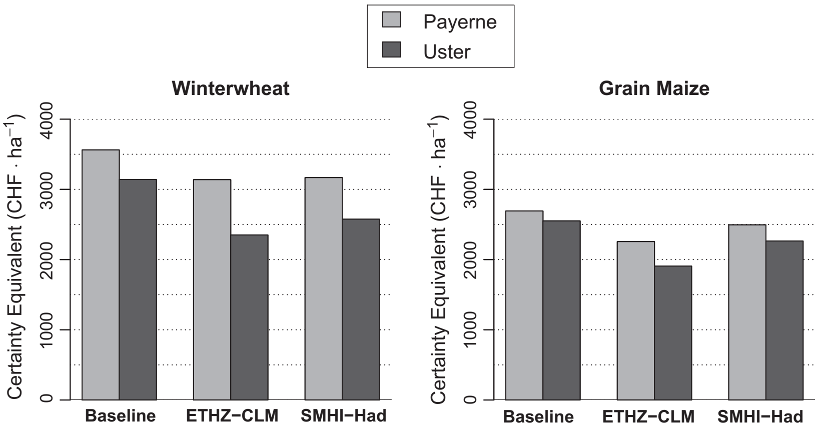

**Fig. 4.** Certainty equivalents (CE) in winterwheat and grain maize production in each scenario applying the optimal management schemes (see Tables 3 and 4).

straints into account may not be sufficient to counteract the negative impacts of CC on winterwheat and grain maize productivity. Thus, strategies to close the income gap are necessary to support producers under future climatic conditions.

Our analysis clearly showed that impacts and adaptation options depend to large extent on specific site conditions and climate scenarios. For instance, at Payerne reduction in farmers' utility (expressed in CE) in grain maize production amounted only to about 7% under the SMHI-Had scenario as compared to current climatic conditions. In contrast, at Uster a decrease in the CE in winterwheat production of 25% was found under the ETHZ-CLM.

Irrigation was found to be necessary to support maize production in Switzerland. However, for moderate shifts in climate conditions, as suggested in the SMHI-Had scenario, irrigation of grain maize may not be equally profitable in all regions. In fact, at Uster irrigation was identified as optimum strategy only under the ETHZ-CLM scenario.

Flexible irrigation strategies (i.e. with local adjustments of both, the irrigation refill point and maximum allowable depletion) can help to increase the benefits of irrigation under CC. This is because excessive irrigation in sufficiently wet years can be avoided considerably reducing variable irrigation costs. The increased water demand in maize production under CC indicated by our results, however, 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.

An increasing importance of irrigation in grain maize production under CC for Northeastern Switzerland was also outlined by Torriani et al. (2007b). Nevertheless, our study showed that for this area, irrigation of grain maize becomes a profitable adaptation measure only under a rather strong CC scenario. This stresses the importance of the consideration of the economic profitability in CC impact assessments.

In contrast to the results for grain maize, irrigation was not found to be necessary for sustaining winterwheat production, regardless of the applied climate scenarios. There are two reasons for this. On the one hand, higher winterwheat yield levels caused by supplemental irrigation cannot completely offset the associated fix costs of sprinkler irrigation systems. On the other hand, the expected decreases of monthly precipitation under CC are highest in summer months, whereas water availability is crucial for wheat growth mainly in spring (Lehmann, 2010). Additionally, winterwheat grown in the Swiss Plateau is more sensitive to high temperatures than to low precipitation levels in summer months (Lehmann, 2010).

For both crops and locations, a decrease in fertilization intensity was proposed by the simulations as adaptation strategy to CC. For winterwheat, the simulation results further suggest consideration of a single application to account for the shorter vegetation period under CC. However, since a single nitrogen application strategy may cause environmental problems compared to split applications (Hyytiäinen et al., 2011), the implementation of such a strategy will require changes in the current agri-environmental policies.

## 5. Conclusions

The developed modeling approach consisting of the biophysical crop growth model CropSyst coupled with an economic decision model proved to be suitable for CC impact assessments at the field scale. Due to the application of CropSyst, crop growth and its response to weather and crop management could be simulated under different management and climate regimes for specific locations. Furthermore, the economic evaluation of management strategies led to a more comprehensive analysis of potential adaptation measures in Swiss agriculture. In addition, the application of the GA 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.

Nonetheless, the computational load was considerable. As reported in Section 2.6, 1 week was necessary to solve our optimization problem on a PC with Intel Pentium Core™ i5 at 3.33 GHz. Clearly, ways to overcome the computational demands are therefore needed before this approach can be applied in an operational context. Within our GA approach, there are two basic ways to do so. The first is to modify the GA parameter settings specified in Section 2.6 in order to accelerate the evolution process. This, however, requires specific investigations that were beyond the scope of this paper. The second, is to reduce the computational time by relaxing the convergence criterion. In the present application, the algorithm stopped when the best fitness value did not change for 1000 generations. However, in all scenarios optimal solution with less than 1% deviation from the global optimum could be obtained already after the first 200 generations. Note also that we repeated each optimization run three times to ensure global convergence. While this is desirable for scientific analyses, in most practical situation a slight loss in accuracy is probably acceptable.

A key element of our modeling system was the crop model CropSyst. Crop models have become indispensable for CC impact studies and will continue to deliver essential information also for years to come. Nevertheless, when used for integrated assessments they present limitations that need to be considered. For instance, a major deficiency of most of the currently available crop growth models is the lack of modules for simulating other biotic components of cropping systems. We think in particular of pests, plant diseases, weeds, beneficial organisms (Bergez et al., 2010). There is little doubt that shifts in the occurrence and distribution of pests, plant diseases and weeds could become one of the major challenges for agriculture during the coming decades (Hirschi et al., 2012; Trnka et al., 2007).

Two other important aspects were also disregarded in our study. On the one hand, we did not consider the $CO_2$ fertilization effect, because its quantification is still highly uncertain (Körner et al., 2007) and the application of experimental results to crop models opens to debate (see e.g. Tubiello et al., 2007). On the other hand, we neglected the possibility that market constraints and input- and output-prices could change in the future. This could have strong effects on both mean and variability of prices in Switzerland (Finger, 2012).

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## Appendix A. Tabulated are the absolute changes in monthly mean minimum and maximum temperature ($\Delta T_{min}$ and $\Delta T_{max}$) and relative changes in the monthly mean radiation (ΔRad) and monthly mean precipitation totals (ΔPrecip) as projected for 2050 by simulations with the ETHZ-CLM and SMHI-Had regional climate models

| Month | ETHZ-CLM | | | | | | | | SMHI-Had | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\Delta T_{min}$ (°C) | | $\Delta T_{max}$ (°C) | | ΔRad (%) | | ΔPrecip (%) | | $\Delta T_{min}$ (°C) | | $\Delta T_{max}$ (°C) | | ΔRad (%) | | ΔPrecip (%) | |
| | PAY | UST | PAY | UST | PAY | UST | PAY | UST | PAY | UST | PAY | UST | PAY | UST | PAY | UST |
| January | +2.51 | +2.58 | +2.51 | +2.6 | −3 | −3 | −4 | −4 | +2.33 | +2.21 | +1.74 | +1.67 | −6 | −5 | +14 | +8 |
| February | +1.82 | +1.84 | +2.00 | +2.07 | −4 | −5 | −2 | −2 | +1.90 | +1.87 | +1.34 | +1.37 | −4 | −4 | +6 | +6 |
| March | +1.91 | +1.89 | +2.14 | +2.28 | −4 | −5 | −2 | −1 | +1.31 | +1.31 | +1.11 | +1.05 | −3 | −4 | +2 | +8 |
| April | +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 |
| June | +2.18 | +2.11 | +3.08 | +2.64 | +7 | +5 | −18 | −7 | +2.00 | +2.10 | +2.13 | +2.02 | +1 | −1 | −8 | −1 |
| July | +2.82 | +2.67 | +4.23 | +3.9 | +9 | +9 | −30 | −24 | +2.08 | +2.21 | +2.15 | +2.16 | +0 | −1 | −3 | +3 |
| August | +3.11 | +2.96 | +4.39 | +4.19 | +8 | +9 | −28 | −23 | +2.00 | +2.12 | +1.98 | +2.04 | −2 | −2 | −1 | +6 |
| September | +2.78 | +2.7 | +3.41 | +3.29 | +3 | +5 | −11 | −5 | +1.67 | +1.72 | +1.61 | +1.53 | −2 | −3 | +4 | +1 |
| October | +2.29 | +2.36 | +2.36 | +2.39 | +0 | +1 | −1 | +1 | +1.46 | +1.43 | +1.32 | +1.17 | −5 | −6 | +16 | +19 |
| November | +2.28 | +2.44 | +2.23 | +2.42 | +0 | +1 | −4 | −6 | +1.86 | +1.77 | +1.56 | +1.45 | −8 | −8 | +24 | +22 |
| December | +2.69 | +2.8 | +2.6 | +2.81 | −2 | −1 | −4 | −6 | +2.34 | +2.21 | +1.92 | +1.79 | −8 | −7 | +22 | +17 |

## Appendix B. Soil profile and initial soil conditions at Payerne and Uster

| | | | | | |
|---|---|---|---|---|---|
| *Soil parameters at Payerne* | | | | | |
| Depth (m) | 0–0.2 | 0.2–0.3 | 0.3–0.7 | 0.7–0.9 | 0.9–1.2 |
| 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 |
| $NO_3$ (kgN $ha^{-1}$) | 5 | 5 | 5 | 5 | 5 |
| $NH_4$ (kgN $ha^{-1}$) | 5 | 5 | 5 | 5 | 5 |
| Volumetric permanent wilting point ($m^3$ $m^{-3}$) | 0.105 | 0.094 | 0.09 | 0.09 | 0.097 |
| Volumetric field capacity ($m^3$ $m^{-3}$) | 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 (m) | 0–0.15 | 0.15–0.35 | 0.35–0.76 | 0.76–1.0 | 1.0–1.2 |
| 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 |
| $NO_3$ (kgN $ha^{-1}$) | 5 | 5 | 5 | 5 | 5 |
| $NH_4$ (kgN $ha^{-1}$) | 5 | 5 | 5 | 5 | 5 |
| Volumetric permanent wilting point ($m^3$ $m^{-3}$) | 0.118 | 0.106 | 0.111 | 0.082 | 0.054. |
| Volumetric field capacity ($m^3$ $m^{-3}$) | 0.236 | 0..217 | 0.222 | 0.176 | 0.134 |
| pH | 6.2 | 5.9 | 6.7 | 7.5 | 7.5 |

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# Chapter 8: Synthesis

## 8.1 Answers to the research questions

### 8.1.1 How can a crop model be calibrated in data-limited situation for climate impact studies?

Default crop parameter values usually result in poor predictive power of crop models (Guillaume et al., 2011) and, for this reason, calibration is indispensable to improve the quality and reliability of simulations in climate impact studies (Jagtap and Jones, 2002). Arguably the best references for crop model calibration are experimental data (e.g. Wallach et al., 2011), but the availability of such data is limited as field experiments are time-consuming and expensive (Wallach et al., 2006). In this thesis, a calibration procedure that can be applied to any location covered by the widely available FADN database is presented. The present method consists of three successive steps: (i) the extraction of reference data from the FADN dataset, (ii) a parameter screening to identify sensitive parameters based on the Morris method (Morris, 1991) and (iii) an automatic parameter estimation relying on a genetic algorithm (Wall, 1996). To circumvent the lack of data on cropping practices in the FADN, the concept of 'Meteorologically Possible Yield' (MPY; Karing et al., 1999) is used. MPY represents maximum rainfed yields under non-limiting nutrient availability and optimal pest/disease management, hence, only driven by climatic variations. Estimates of the MPY are computed based on a statistic of the upper tail of yield distribution, defining the latter with respect to a threshold that needs to be adjusted to provide results that are both plausible and robust.

Besides being widely applicable, the calibration procedure has proved to be feasible at low-computation costs thanks to the combination of the Morris method with a genetic algorithm. Repeating the procedure multiple times allows obtaining several reliable parameter sets, which is crucial to estimate effects of parametrization uncertainties in climate impact studies (discussed below). Parameter sets that perform equally well under present conditions can produce large deviations under future climate, an effect that is even more pronounced when applying the model to other site conditions, even for locations that are in geographic terms relatively close to each other. This suggests that the predictive power of crop models declines substantially when used with conditions that differ significantly from those that are representative for the calibration. This is opposed to the belief that the validity of dynamic crop models is beyond the conditions for which they have been calibrated (Wallach et al., 2006). This is particularly problematic for climate impact assessments as current climate is not representative for future conditions, which further emphasizes the need to consider parameter uncertainties.

### 8.1.2 Which agricultural practices have the greatest potential for adaptation of multifunctional agriculture?

In the simulations presented here, a tendency for productivity to decrease by $2-3\%$ is found, for erosion to increase by $25-30\%$ due to shorter crop growth cycles and increased rainfall intensity in fall/winter, and for N-leaching to increase by $43-52\%$ as a consequence of higher mineralization rates in a warmer and sufficiently wet climate. Crop yields and erosion are highly variable not only with climate scenarios, but also across cropping practices and soil types, suggesting that negative impacts of climate change can be reduced through an adequate choice of management. In contrast, leaching is primarily driven by soil texture and does not depend much on the management scheme, which is in line with a long-term experiment by Askegaard et al. (2011).

The variability of crop yields induced by the choice of cropping practices depends exclusively on the crop rotation choice, the intensity level (fertilization and frequency of grass clipping) and the soil management type (tillage operations and residue management), each option explaining about one third of the total variance. A strong correlation between productivity and total N uptake suggests that nutrient management is critically important to maintain productivity, which is in line with the finding by Mueller et al. (2012) that the yield gap can be closed with appropriate nutrient management. Simulations indicate that a management scheme that maintains high soil temperature and sufficient humidity enabling high mineralization and nitrification rates would be most beneficial for productivity. This can best be obtained with heavily fertilized rotations involving crops such as sugar beet in combination with conventional soil management, i.e. soil tillage and residue removal. High fertilization has two beneficial effects, a direct one by increasing soluble N in the soil, and an indirect effect by decreasing the C/N ratio of dead materials, which enhances residue nitrogen net mineralization and reduces N immobilization. Conventional soil management increases soil temperature leading to higher mineralization and nitrification rates in turn. However, in the longer run, this option decreases soil organic matter and hence soil fertility.

The combination of practices that can sustain high productivity in the future is expected to be the same as under current climatic conditions. The relative importance of different cropping practices is also expected to remain unchanged under future climatic conditions, with few exceptions. Soil management explains a lower fraction of variance under climate change because higher temperatures lead to higher mineralization rates, increasing N availability and, hence, reducing the effect of soil management on soil temperature. Conversely, the importance of crop rotation slightly increases, and irrigation becomes a relevant option in particular on coarser soils because of their lower water retention capacity.

Erosion is also very sensitive to agricultural practices. Soil losses are mainly controlled by soil management (70% of variance explained) and to some extent by the crop rotation choice ($\sim$ 10% of variance explained). Conservation soil management is the most effective practice to reduce erosion. Rotations with short fallow periods thanks to the use of catch crop or cropped grassland and the exclusion of root crops (e.g. potato) have also proved to offer good protection against erosive winter rainfall. Unlike productivity, erosion rates depend on local conditions; erosion is on average 50% higher on loamy soils than on sandy loam soils because of lower infiltration rates and higher runoff.

Although leaching is not very sensitive to management, the rotation choice can contribute to some extent to reduced leaching, with the establishment of a catch crop or the use of cropped grassland to ensure N uptake in autumn/early winter when temperatures are still sufficient to enable organic matter mineralization. The importance of catch crops to reduce leaching has been widely suggested in the literature, either based on modeling studies (e.g. Constantin et al., 2012; Doltra et al., 2011; Henke et al., 2008) or field experiments (e.g. Askegaard et al., 2011; Doltra et al., 2011; Weisskopf et al., 2001). Results show also that leaching is the lowest when a winter crop follows maize (e.g. winter wheat) to deplete soil N and keep fallow periods to a minimum.

### 8.1.3 What are the trade-offs resulting from adaptation?

In agreement with most previous studies (see e.g. Power, 2010), a trade-off exists between agricultural productivity and environmental impacts. From the results presented here, it can be anticipated that the trade-offs between agricultural productivity, soil erosion and N-leaching are likely to aggravate with climate change. However, results show that there are possibilities for synergies between the different agricultural functions. Soil management and crop rotation have been found to be the most relevant practices to reduce soil loss and N-leaching, respectively, while productivity also depends greatly on the two latter practices (see Section 8.1.2). Note that it may be simpler to identify synergies on loamy soil as N-leaching is not an issue; moreover, it is not advisable to focus on minimizing the latter on this particular soil type because it results in low productivity and high erosion.

For the study region, the use of cropped grasslands in combination with conservation soil management appears to be the most judicious choice to maintain productivity and avoid trade-offs with erosion and N-leaching. Rotations including a grass/legume crop can be beneficial for productivity as grassland serves well as a good pre-crop and a high proportion of grassland also reduces erosion and helps to reduce N-leaching. Conservation soil management is very efficient to prevent excessive soil erosion and soil organic matter loss maintaining soil fertility in the long run. Moreover, conservation soil management improves clean water provision. Indeed, N-leaching is substantially reduced on sandy loam soil due to reduced mineralization, while the decrease in runoff and thus increase in permeability due to this management type has low effects on a soil that is already very permeable and prone to leaching. As a downside of conservation soil management, productivity is decreased by $\sim 50\%$ on average under current climatic conditions due to reduced mineralization. However, under climate change this effect is reduced ($\sim -25\%$), which indicates that the synergistic effects of conservation soil management could increase in the future.

Trade-offs can also be envisaged from the time scale perspective. A positive impact of residues removal on productivity has been suggested here, which is in contrast to the view that management decisions such as no-till and returning crop residue to the field increase soil organic matter content, improve infiltration and soil water retention, and thus help to maintain soil fertility in the long run and increase the resilience of cropping systems to climate change (Lal et al., 2011). However, the positive effect of conventional soil management is short-lived as CropSyst simulates a decline in soil fertility in the longer term.

### 8.1.4 What are the benefits of regional adaptation compared to the status-quo scenario?

Without changes in agricultural land management, mean regional productivity of crops in the Broye catchment will decrease by $0-10\%$ on the time horizon 2050, in parallel with an increase in water needs by $20-50\%$. In contrast to those moderate changes in productivity, impacts of climate change on erosion and leaching are expected to be largely negative (increase by $30-45\%$ for leaching and $25-35\%$ for erosion). These results emphasize that, in order to cope with increasing environmental pressure, adaptation is needed, either through adjustment of agricultural practices (e.g. crop rotations, tillage operations), or redistribution of agricultural land uses.

Results show that a wide range of different adaptation options is possible depending on the goals to achieve. If productivity is the only objective, then nearly all grasslands of the region should be converted to croplands with high shares of irrigated maize and sugar beet. In those conditions, crop yields would increase by 35% compared to the current level, which is more than the 10-15% yield adaptation benefits suggested by Lotze-Campen and Schellnhuber (2009). However, consequences on the environment would be disastrous, leading to an increase of erosion by $50-57\%$ and leaching by $73-84\%$ compared to the current situation. Furthermore, irrigation would have to be $26-41$ times higher, exceeding systematically average surface water availability during summer months. In contrast, if the main objective is to reduce environmental impacts, then crop yields would decrease by up to 28%.

In spite of these conflicts between agricultural functions, the possibilities for compromises have been highlighted. Two different acceptable solutions have been presented, one of them performing much better than the reference (1981-2010) with regard to three of the four objectives for both climate scenarios. The only objective that cannot be improved is water saving with an increase in water needs by $500-600\%$, which, nevertheless, remains below available surface water on average. The two selected compromise solutions presented here indicate that yields with adaptation would be on average $13-16\%$ higher than without adaptation, but without increasing negative impacts on other functions.

### 8.1.5 Which guidelines can be provided based on this work for adapting agricultural land management in the Broye catchment around 2050?

Adaptation of agricultural land management to climate change in the Broye catchment will be necessary for the time horizon 2050, mostly to limit increasing environmental impacts. In order to cope with changing climate conditions and maintain productivity while minimizing environmental impacts, general recommendations to be undertaken have been identified:

- **maintaining recommended intensity level.** Today's recommended intensity level is and will be best as it has a positive effect on productivity, which in turn has an influence on erosion (i.e. the more biomass the better the soil protection) without leading to high N-leaching rates;
- **increased use of conservation soil management.** Reduced tillage and retaining harvest residues are known to improve soil organic matter and conserve soil fertility (Maltas et al., 2013), while increasing soil surface protection and reducing runoff (Scholz et al., 2008; Zhang and Nearing, 2005). In addition, it has been shown that impacts on soil temperature and N mineralization become less important as air temperature increases (see Section 8.1.2). However, conventional soil management can still be applied on flat areas that are not subject to erosion;
- **conversion of grassland to cropland in the South.** Crop cultivation is currently not possible in those areas due to limiting temperatures, but becomes possible in a warmer climate. However, grasslands should remain at high elevations on coarse soils to decrease soil temperature and consequently N-leaching;
- **decrease in share of irrigated spring crops.** Water-stress sensitive crops (e.g. potato) should be partly replaced by winter rapeseed. Winter rapeseed is an eco-friendly crop that can serve as a catch crop to reduce N-leaching during the autumn-winter period thanks to its high capacity to take up nitrate from the soil (Malagoli et al., 2005). In addition, winter rapeseed has been found to limit soil loss in the study area (Prasuhn, 2012) and to perform well under climate change (Boomiraj et al., 2010);

- **relocation of pastures around Moudon (medium elevation).** Very steep slopes are found in the region around Moudon and locating pastures in those areas allows to drastically reducing erosion;
- **irrigation applied in priority on coarse soils around Payerne.** Optimal irrigation patterns do not differ significantly from current irrigated areas as irrigation is and will be worthwhile only in the lowlands of the Broye. However, it would be preferable to apply water extracted from the Broye river on coarse soils that are more distant from the river as opposed to the current practice where irrigation is mostly applied on soils located close to the river bed with high water retention capacity.

## 8.2 Modeling uncertainties

Climate impact and adaptation studies supply valuable information to support decision-making and can provide guidelines on suitable adaptation strategies. Hence, it is crucial to consider sources of uncertainty that enter the study at different levels and implications on simulations. For complex planning problems, it is strongly advised to develop optimization approaches to generate alternative solutions that integrate the concept of robustness to identify strategies that perform well across many uncertain factors (so-called ‘many objective robust decision-making’, Kasprzyk et al., 2013).

In crop modeling, sources of uncertainty are related to: (i) input data (i.e. climate scenario, soil, weather), (ii) model parametrization and (iii) model structure. Uncertainty analysis consists of quantitatively evaluating the sources of uncertainty; it is often completed by a sensitivity analysis to determine impacts of the latter on model outputs. The role of those three major sources of uncertainties and the way they were treated in this thesis are discussed in the next paragraphs.

**Input data** Because of the lack of alternative datasets, uncertainties related to soil and weather data resulting from measurement errors have only been assessed in a few studies (e.g. Aggarwal, 1995). The Swiss soil suitability map (BFS, 2012) is the only spatially-explicit source of information on soil textures available in Switzerland. The quality of this dataset was controlled by comparing it with available observed soil profiles in the study region (BUWAL, 2003). National offices of meteorology usually control the quality and reliability of weather data; hence, weather data uncertainties were not considered in this thesis. Uncertainties of climate projections with respect to the selection of Regional Climate Model (RCM) can have large impacts on outputs of crop models (see e.g. Ceglar and Kajfež-Bogataj, 2012). For this reason, two contrasting climate scenarios that span a significant portion of the full range of changes in temperature and precipitation projected by the ENSEMBLES model runs (van der Linden and Mitchell, 2009) were selected. Conversely, it has been recognized that emission scenario uncertainties are less relevant until the middle of the 21st century (van der Linden and Mitchell, 2009) as illustrated by climate projections in Switzerland for 2050 from CH2011 (2011); thus, all simulations were conducted based on a single emission scenario (A1B).

**Model parametrization** Parameter values result from various estimation procedures or sometimes from literature reviews or expert knowledge, and their precision is necessarily limited by the variability and possible lack of adequacy of the available data (Monod et al., 2006). Also, it is recognized that different parameter sets can be acceptable in reproducing the observed data, a phenomenon known as 'equifinality' (Beven and Freer, 2001). Implications of equifinality when applying a crop model for climate impact studies have been covered in Chapter 4. Although it has been suggested that parametrization uncertainties have negligible effects on yield simulations (Ceglar et al., 2011), the importance of using several calibrations and of treating subsequent uncertainties carefully for climate impact studies have been emphasized in this thesis. Therefore, methodologies to estimate posterior distribution of model parameters like Bayesian calibration (e.g. Lehuger et al., 2009) or the GLUE methodology (generalized likelihood uncertainty estimation, Beven and Freer, 2001) are particularly promising. Furthermore, efforts on developing modeling environments including uncertainty/sensitivity and automating calibration of complex models - such as the one coded in R by Wu and Liu (2012) or the one presented here - should be encouraged to help researchers to deal with similar issues.

**Model structure** Model equations are all subject to variability or uncertainty, and functional relationships between input/state variables and outputs may sometimes be quite subjective, which is leading to not always clear consequences (Monod et al., 2006). Also, processes included in simulation models are not always fully understood or well implemented. This is for instance the case for the fertilization effect of increased atmospheric $CO_2$. Free Air Carbon Enrichment (FACE) experiments indicate productivity increases but do not address important co-limitations due to water and nutrient availability. Thus, the magnitude of crop's response to elevated $CO_2$ is uncertain and subject to ongoing debates (Körner et al., 2007; Long et al., 2006; Parry et al., 2004). $CO_2$ fertilization effect was not considered here for two reasons: first, many crop models have shown the inability to capture important underlying processes connected with $CO_2$ fertilization and are, therefore, not able to reproduce experimental results (Biernath et al., 2011), and then it has been shown that uncertainty associated with $CO_2$ fertilization can have significant effects on crop yield simulations ($10-20\%$ according to Ruane et al., 2013, based on CERES-Maize). Uncertainties in model structure are more complicated to assess, therefore, they are beyond the scope of this thesis. They require the use of different modeling approaches (Adam et al., 2011) or different crop models (Palosuo et al., 2011; Rötter et al., 2012). In this context, the AgMIP Project (Agricultural Model Intercomparison and Improvement, Rosenzweig et al., 2012) has emerged with the goal to coordinate internal research activities that address uncertainty sources, aggregation and scaling issues, and the development of representative agricultural pathways to enable testing of climate change adaptations.

## 8.3 Limitations

The modeling approach used in this thesis faced a number of limitations, mainly emerging from (i) the use of a crop model, (ii) the use of a Weather Generator (WG) to downscale climate model outputs, (iii) the simplified spatial representation, (iv) the lack of knowledge on future technologies, and (v) other external factors not taken into account.

The vast majority of generic crop models were developed two decades ago and urgently need to be updated to reflect new research in crop physiology, agronomy and soil science (Rötter et al., 2011a). The main limitations of crop models come from the lack of routines to account for (i) impacts of pests/diseases (e.g. Soussana et al., 2010), (ii) impacts of extreme events such as extremely hot temperatures (e.g. Moriondo et al., 2010b), and (iii) important aspects of implemented agricultural practices (e.g. Sommer et al., 2007).

Impact assessments have been performed using an empirical downscaling of RCM simulations based on LARS-WG (Semenov and Barrow, 1997). In this approach, the outputs of RCMs are used to compute the so-called 'delta changes', which are applied to the observed meteorological data in order to reproduce future climate. However, changes in climatic variability are not included, and, therefore, possible changes in climate extreme events are not simulated (Moriondo et al., 2010a). Alternative downscaling methods exist, such as dynamic downscaling but, given the existence of substantial biases in current RCMs, results based on future scenario integrations from these models should be treated with care (Moberg and Jones, 2004).

The level of spatial complexity was substantially reduced in order to ensure a fast implementation of the optimization routine to explore a wide range of alternative adaptation options with different priorities. In particular, the fact that only a few combinations of soil types and climate zones were used is expected to alter the quality of impact assessment. It has been mentioned in Chapter 4 that local recalibration is crucial in climate impact studies; nevertheless it was not feasible to calibrate CropSyst for all combinations of local conditions of the Broye due to the lack of observed farm yield records in the FADN. In line with the findings of this thesis, Rivington et al. (2006) found that using a neighboring meteorological station that is not representative for the site conditions drastically decreases the quality of predictions. This stresses the need to quantify performances of models with regard to reference data based on various metrics (see reviews by Bennett et al., 2012; Bellocchi et al., 2009) but also considering the variability of explored conditions (Confalonieri et al., 2010).

Technological improvements will contribute to increase adaptive capacity and could even overweight impacts of climate change (Ewert et al., 2005), but the current rate of yield technology might be insufficient to maintain current productivity level (Hawkins et al., 2012). However, this thesis focused on adaptation options with present technology ('dumb farmer' scenario). Integrating technology in models remains a challenge since adaptive processes and technologies are more than simple technical responses to biophysical conditions; farmer's innovative, creative and sociocultural aspects will be decisive for climate change adaptation (Crane et al., 2011).

The capacity to adapt to climate change will also depend on other external factors that were not considered. First, off-site effects can play an important role (Seppelt et al., 2011), for instance crops that cannot be produced in the Broye catchment could be grown elsewhere since impacts of climate change will have distinct regional patterns. Another aspect that was not included is related to the costs of adaptation, in particular the high costs of transformational adaptation (Rickards and Howden, 2012), which could seriously hamper the feasibility of those measures. Then, if climate change is one of the possible drivers that will change the farming landscape, other factors such as markets and policies may be at least equally important (Mandryk et al., 2012).

## 8.4 Perspectives for future work

Until now, the modeling approach developed in this thesis has been applied to the Broye catchment (presented here) and the Greifensee catchment (not shown). These two study areas differ significantly in their current climatic conditions and are considered to cover most of the Swiss conditions. Nevertheless, since models' responses can be highly nonlinear (see Morris $\sigma$ of parameters in Chapter 4), the method should be applied to more catchments in Switzerland.

The robustness of the calibration procedure presented here could be further improved. The risk of over-parameterization emerging from site-specific factors in parameter values that should describe only plant processes could be reduced by estimating parameter values from pooled data from locations with different local conditions (soil and weather). In addition, several detrending methods should be applied to the reference data and the subsequent impacts on model calibration should be evaluated. This is suggested by the fact that detrending or not reference data to remove effects of technological improvements has a significant effect on calibration results (not shown in this thesis).

Future work should address the effects of different sources of uncertainties highlighted in the previous section to improve the understanding of the propagation of errors through the spatial optimization. For example, parametrization uncertainty should be included in the further development of the framework. Also, improvement of predictive power of the models due to more detailed spatial representation should be investigated (e.g. benefits of it against increased computation time).

In addition to incremental and transformational adaptation options, systems adaptation such as breeding technology improvements could be included. The development of slower maturing crops taking advantage of a longer growing season already occurs (Sacks and Kucharik, 2011), and it is anticipated that it would reduce the trade-offs between productivity and environmental impacts due to shorter fallow times and hence reduced erosion and leaching. However, benefits of such cultivars are highly uncertain (Olesen et al., 2011) and implementation in models is complicated when considering crop rotations.

Finally, spatial optimization results were mainly presented in an aggregated way to visualize trade-offs among objectives. However, recommendations to support decision-making should focus on subregional characteristics. Hence, the spatial distribution of agricultural practices (e.g. crop choice, irrigation) would be a very valuable source of information for future regional planning of agriculture.

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# List of appendices

# A 1 Climate scenarios

**Table A.1:** Changes in seasonal precipitation (%), daily precipitation intensity index (%) and temperature (°C) for two climate scenarios for 2050 (*ETHZ-CLM* and *SMHIRCA-HadCM3Q3*), relative to the baseline (1980-2009), for the A1B emission scenario (CH2011, 2011); the daily precipitation intensity index is defined as the sum of daily precipitation amounts for wet days ($> 1$ mm) divided by the number of wet days.

| | **Precipitation amount (%)** | | **Precipitation intensity (%)** | | **Temperature (°C)** | |
|---|---|---|---|---|---|---|
| Months | ETH | SMHI | ETH | SMHI | ETH | SMHI |
| M-A-M | −14.18 | −1.35 | 3.27 | −3.2 | 2.22 | 0.98 |
| J-J-A | −23.75 | −11.49 | 10.43 | −8.11 | 3.45 | 1.32 |
| S-O-N | −1.76 | 20.73 | 8.83 | 3.61 | 2.44 | 1.24 |
| D-J-F | −3.01 | 5.83 | 23.08 | 16.31 | 2.11 | 1.03 |

## A 2 Experimental design

**Table A.2:** Overview of the experimental design; DOY: day of the year, $\alpha$: min allowable plant available water, $\beta$: refill point.

| **Management Option** | **Level** | **Crop** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Winter wheat | Winter barley | Grain maize | Potato | Sugar beet | Winter rapeseed | Silage maize | Grassland |
| **Crop rotations** | | 50 rotations Generated stochastically based on specific rules (max crop charges, feasibility of crop sequences.) | | | | | | | |
| **N-fertilization** | | 70 kg | 55 kg | 55 kg | 60 kg | 50 kg | 70 kg | 55 kg | 32 kg |
| - Total N (kg) | Low intensity | mineral | mineral | mineral | mineral | mineral | mineral | organic | organic |
| - Form | | 112 (100%) | 112 (100%) | 90 (100%) | 130 (100%) | 130 (100%) | 189 (100%) | 90 (100%) | clipping+5 |
| - Application dates | | 105 kg | 82 kg | 82 kg | 90 kg | 75 kg | 105 kg | 82 kg | 95 kg |
| (DOY) | Medium intensity | mineral | mineral | mineral | mineral | mineral | mineral | organic | organic |
| | | 32 (40%), 112 (60%) | 112 (100%) | 90 (100%) | 130 (100%) | 130 (100%) | 120 (30%), 189 (70%) | 90 (100%) | clipping+5 |
| | | 140 kg | 110 kg | 110 kg | 120 kg | 100 kg | 140 kg | 110 kg | 165 kg |
| | High intensity | mineral | mineral | mineral | mineral | mineral | mineral | organic | organic |
| | | 32 (40%), 112 (60%) | 32 (40%), 112 (60%) | 90 (100%) | 130 (100%) | 130 (100%) | 120 (30%), 189 (70%) | 90 (100%) | clipping+5 |
| **Grass clipping** | Low intensity | - | | | | | | | 3 (150,200,250) |
| (N and | Medium intensity | - | | | | | | | 4 (130,170,210,250) |
| dates in DOY) | High intensity | - | | | | | | | 5 (130,170,210,250,300) |
| **Irrigation** | No irrigation | - | | | | | | | |
| | Automatic ($\alpha$, $\beta$) | - | - | $\alpha = 0.2$ | $\alpha = 0.4$ | $\alpha = 0.4$ | - | - | - |
| | | - | - | $\beta = 0.5$ | $\beta = 0.5$ | $\beta = 0.5$ | - | - | - |
| **Soil management** | Conventional: regular tillage (plowing 10 days and harrowing 1 day prior to sowing) / residues removed from the field after harvest | | | | | | | | |
| | Conservation: no tillage / residues retained on the field after harvest | | | | | | | | |

# A 3 Generated crop rotations

Table A.3: List of the 50 crop rotations generated.

| Year 1 | Year 2 | Year 3 | Year 4 | Year 5 |
|---|---|---|---|---|
| Sugar beet | Silage maize | Winter barley | Grain maize | Winter wheat |
| Winter barley | Potato | Grain maize | Winter wheat | Silage maize |
| Sugar beet | Grassland | Grassland | Winter rapeseed | Winter barley |
| Grain maize | Grassland | Grassland | Grain maize | Winter wheat |
| Grassland | Grassland | Winter barley | Grain maize | Potato |
| Winter wheat | Winter barley | Silage maize | Grassland | Grassland |
| Potato | Grain maize | Winter wheat | Silage maize | Winter wheat |
| Grain maize | Potato | Grassland | Grassland | Winter wheat |
| Sugar beet | Grain maize | Winter wheat | Silage maize | Winter wheat |
| Winter rapeseed | Grassland | Grassland | Winter wheat | Winter barley |
| Winter wheat | Grassland | Grassland | Winter wheat | Silage maize |
| Sugar beet | Grain maize | Grassland | Grassland | Winter wheat |
| Silage maize | Grassland | Grassland | Grain maize | Potato |
| Sugar beet | Winter wheat | Winter rapeseed | Potato | Winter wheat |
| Winter wheat | Winter barley | Grassland | Grassland | Potato |
| Winter rapeseed | Silage maize | Grassland | Grassland | Winter barley |
| Sugar beet | Silage maize | Grassland | Grassland | Potato |
| Sugar beet | Grain maize | Winter wheat | Winter barley | Potato |
| Winter rapeseed | Grain maize | Winter wheat | Grain maize | Winter wheat |
| Winter rapeseed | Potato | Silage maize | Winter wheat | Winter barley |
| Sugar beet | Potato | Winter barley | Grassland | Grassland |
| Winter barley | Grassland | Grassland | Winter barley | Potato |
| Sugar beet | Grain maize | Winter wheat | Winter rapeseed | Winter wheat |
| Winter rapeseed | Winter barley | Grassland | Grassland | Winter barley |
| Silage maize | Winter barley | Silage maize | Grassland | Grassland |
| Sugar beet | Grain maize | Potato | Grain maize | Winter wheat |
| Winter rapeseed | Grain maize | Grassland | Grassland | Winter wheat |
| Sugar beet | Winter wheat | Silage maize | Winter wheat | Potato |
| Sugar beet | Winter wheat | Winter rapeseed | Winter barley | Potato |
| Winter rapeseed | Winter wheat | Potato | Grain maize | Winter wheat |
| Sugar beet | Winter wheat | Grassland | Grassland | Winter wheat |
| Sugar beet | Grain maize | Grassland | Grassland | Winter barley |
| Winter rapeseed | Grassland | Grassland | Sugar beet | Winter wheat |
| Silage maize | Winter barley | Potato | Silage maize | Winter barley |
| Grassland | Grassland | Winter barley | Silage maize | Winter barley |
| Winter rapeseed | Silage maize | Potato | Silage maize | Winter barley |
| Winter rapeseed | Grain maize | Potato | Sugar beet | Winter wheat |
| Winter wheat | Grassland | Grassland | Winter wheat | Potato |
| Winter rapeseed | Potato | Winter wheat | Grassland | Grassland |
| Sugar beet | Grassland | Grassland | Potato | Winter wheat |
| Winter rapeseed | Silage maize | Winter barley | Potato | Winter barley |
| Sugar beet | Silage maize | Winter barley | Winter rapeseed | Winter barley |
| Winter rapeseed | Potato | Grassland | Grassland | Winter barley |
| Sugar beet | Silage maize | Winter barley | Silage maize | Winter barley |
| Winter rapeseed | Winter wheat | Grassland | Grassland | Winter wheat |
| Winter rapeseed | Silage maize | Potato | Grain maize | Winter wheat |
| Winter rapeseed | Silage maize | Winter wheat | Silage maize | Winter barley |
| Sugar beet | Grassland | Grassland | Winter wheat | Winter barley |
| Winter rapeseed | Potato | Grain maize | Grassland | Grassland |
| Winter rapeseed | Potato | Sugar beet | Grassland | Grassland |

## A 4 Sensitivity analysis (ANOVA) of CropSyst to simulated agricultural practices

**Table A.4:** Proportion of variance explained (main effects and interactions) by different agricultural practices on sandy loam soil.

| | Productivity | | | Erosion | | | N-leaching | | |
|---|---|---|---|---|---|---|---|---|---|
| | Baseline | ETH | SMHI | Baseline | ETH | SMHI | Baseline | ETH | SMHI |
| Crop rotation | $0.288^{a}$ | $0.364^{a}$ | $0.347^{a}$ | $0.135^{a}$ | $0.098^{a}$ | $0.132^{a}$ | $0.839^{a}$ | $0.810^{a}$ | $0.766^{a}$ |
| Irrigation level | $0.005^{a}$ | $0.08^{a}$ | $0.041^{a}$ | $< 0.001^{b}$ | 0 | 0 | $0.021^{a}$ | $0.052^{a}$ | $0.049^{a}$ |
| Intensity | $0.346^{a}$ | $0.273^{a}$ | $0.325^{a}$ | $0.029^{a}$ | $0.03^{a}$ | $0.041^{a}$ | $0.041^{a}$ | $0.029^{a}$ | $0.031^{a}$ |
| Soil management | $0.261^{a}$ | $0.152^{a}$ | $0.172^{a}$ | $0.731^{a}$ | $0.771^{a}$ | $0.716^{a}$ | $0.043^{a}$ | $0.046^{a}$ | $0.078^{a}$ |
| Crop rotation:Irrigation level | $0.003^{a}$ | $0.028^{a}$ | $0.015^{a}$ | $0.001^{b}$ | $0.001^{a}$ | $0.001^{b}$ | $0.019^{a}$ | $0.034^{a}$ | $0.036^{a}$ |
| Crop rotation:Intensity | $0.017^{a}$ | $0.031^{a}$ | $0.036^{a}$ | $0.006^{a}$ | $0.008^{a}$ | $0.009^{a}$ | $0.012^{a}$ | $0.007^{a}$ | $0.010^{a}$ |
| Crop rotation:Soil management | $0.076^{a}$ | $0.058^{a}$ | $0.055^{a}$ | $0.094^{a}$ | $0.088^{a}$ | $0.096^{a}$ | $0.022^{a}$ | $0.017^{a}$ | $0.025^{a}$ |
| Irrigation level:Intensity | $0.001^{a}$ | $0.003^{a}$ | $0.002^{a}$ | 0 | $< 0.001^{c}$ | 0 | $< 0.001^{a}$ | $0.001^{a}$ | $0.001^{a}$ |
| Irrigation level:Soil management | $0.002^{a}$ | $0.006^{a}$ | $0.006^{a}$ | 0 | $0.001^{a}$ | $< 0.001^{a}$ | $0.001^{a}$ | $0.002^{a}$ | $0.002^{a}$ |
| Intensity:Soil management | $0.001^{a}$ | $0.004^{a}$ | $0.001^{a}$ | $0.004^{a}$ | $0.002^{a}$ | $0.004^{a}$ | $< 0.001^{a}$ | $0.001^{a}$ | $0.001^{a}$ |

Significancy codes: 0 ‘$^{a}$’ 0.001 ‘$^{b}$’ 0.01 ‘$^{c}$’ 0.05

**Table A.5:** Proportion of variance explained (main effects and interactions) by different agricultural practices on loamy soil.

| | Productivity | | | Erosion | | | N-leaching | | |
|---|---|---|---|---|---|---|---|---|---|
| | Baseline | ETH | SMHI | Baseline | ETH | SMHI | Baseline | ETH | SMHI |
| Crop rotation | $0.343^{a}$ | $0.387^{a}$ | $0.405^{a}$ | $0.133^{a}$ | $0.092^{a}$ | $0.135^{a}$ | $0.904^{a}$ | $0.870^{a}$ | $0.908^{a}$ |
| Irrigation level | $0.001^{a}$ | $0.038^{a}$ | $0.014^{a}$ | 0 | $0.001^{a}$ | $0.001^{a}$ | $0.005^{a}$ | $0.02^{a}$ | $0.02^{a}$ |
| Intensity | $0.322^{a}$ | $0.266^{a}$ | $0.306^{a}$ | $0.033^{a}$ | $0.034^{a}$ | $0.045^{a}$ | $0.008^{a}$ | $0.009^{a}$ | $0.012^{a}$ |
| Soil management | $0.239^{a}$ | $0.157^{a}$ | $0.158^{a}$ | $0.733^{a}$ | $0.773^{a}$ | $0.711^{a}$ | $0.042^{a}$ | $0.053^{a}$ | $0.013^{a}$ |
| Crop rotation:Irrigation level | $0.001^{a}$ | $0.016^{a}$ | $0.007^{a}$ | 0.001 | $0.002^{a}$ | $0.002^{b}$ | $0.015^{a}$ | $0.023^{a}$ | $0.026^{a}$ |
| Crop rotation:Intensity | $0.018^{a}$ | $0.041^{a}$ | $0.041^{a}$ | $0.006^{a}$ | $0.009^{a}$ | $0.010^{a}$ | $0.006^{a}$ | $0.006^{a}$ | $0.010^{a}$ |
| Crop rotation:Soil management | $0.073^{a}$ | $0.083^{a}$ | $0.062^{a}$ | $0.090^{a}$ | $0.084^{a}$ | $0.091^{a}$ | $0.019^{a}$ | $0.018^{a}$ | $0.011^{a}$ |
| Irrigation level:Intensity | $< 0.001^{a}$ | $0.002^{a}$ | $0.002^{a}$ | 0 | $< 0.001^{a}$ | $< 0.001^{b}$ | 0 | $< 0.001^{a}$ | $< 0.001^{a}$ |
| Irrigation level:Soil management | $0.001^{a}$ | $0.003^{a}$ | $0.003^{a}$ | 0 | $0.002^{a}$ | $0.001^{a}$ | $< 0.001^{a}$ | 0 | $< 0.001^{c}$ |
| Intensity:Soil management | $0.001^{a}$ | $0.005^{a}$ | $0.002^{a}$ | $0.004^{a}$ | $0.003^{a}$ | $0.004^{a}$ | $0.001^{a}$ | 0 | $< 0.001^{b}$ |

Significancy codes: 0 ‘$^{a}$’ 0.001 ‘$^{b}$’ 0.01 ‘$^{c}$’ 0.05

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> *"Tommy, stop playing with the models and do some real work!"*
> (Jürg Fuhrer)

# Declaration

under Art. 28 Para. 2 RSL 05

Last, first name: Klein, Tommy

Matriculation number: tk09z931

Programme: Climate Sciences (Oeschger Center)

Bachelor ☐ Master ☐ Dissertation ☒

Thesis title: Adapting agricultural land management to climate change:
A regional multi-objective optimization study

Thesis supervisor: Prof. Dr. Jürg Fuhrer

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due acknowledgement has been made in the text. In accordance with academic rules and ethical conduct, I have fully cited and referenced all material and results that are not original to this work. I am well aware of the fact that, on the basis of Article 36 Paragraph 1 Letter o of the University Law of 5 September 1996, the Senate is entitled to deny the title awarded on the basis of this work if proven otherwise.

Zurich, May 20, 2013

Unterschrift

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## Personal Data

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