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RESEARCH ARTICLE

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

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Abstract In several regions of the world, climate change is expected to have severe impacts on agricultural systems. Changes in land management are one way to adapt to future climatic conditions, including land-use changes and local adjustments of agricultural practices. In previous studies, options for adaptation 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 design a multi-objective optimization routine that integrates a generic crop model and considers two climate scenarios for 2050 in a mesoscale catchment on the Swiss Central Plateau with already limited water resources. The results indicate that adaptation will be necessary in the study area to cope with a decrease in productivity by 0–10 %, an increase in soil loss by 25–35 %, and an increase in N-leaching by 30–45 %. Adaptation options identified here exhibit conflicts between productivity and environmental goals, but compromises 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 to croplands.

Keywords Agricultural land management · Adaptation to climate change · Crop modeling · Regional optimization · Multi-objective

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

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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), or 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 cope with the expected change in climatic conditions. In this paper adaptation refers to 'adjustments in ecological–social–economic systems in response to actual or expected climatic stimuli, their effects or impacts' (Smit et al. 2000). It includes a large variety of activities directly related to reducing vulnerability to climate change such as technological developments or changes in farm production practices (Smit et al. 2002). 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, changing livestock stocking density, or changes in land use. 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). Most appropriate management practices can be identified either based on a number of pre-established scenarios or using algorithms of optimization. Optimization consists of automatically and systematically searching through the space of management options to find a combination of them that controls the system in the desired way as defined by an objective function (Seppelt et al. 2013). Despite the fact that optimization is more efficient than scenarios technique to deal with numerous parameters, they have been rarely used for climate adaptation studies (see Table 1 for a literature review). Indeed, 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 potentials of production while reducing exposure to risks (FOEN 2012a) and, therefore, it is crucial to consider spatial variability of local conditions.

Our aim in this paper was 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 meso-scale catchment. Objectives considered in this study were four major agricultural functions in the context of adaptation in Switzerland (FOEN 2012a): agricultural productivity, soil conservation, clean water provision, and water saving. Some existing optimization tools offer great potential for defining adaptation options, such as RUral Land-use Exploration System (RULES, Santeriveira et al. 2008), Assessment-, Prognosis-, Planning and Management-tool (APPM, Grundmann et al. 2011) or Multi-Objective Decision support tool for Agroecosystem Management (MODAM, Zander and Kächele 1999). However, those tools did not satisfy our requirements, either because a limited set of decision variables are considered, or because objective functions are not compatible. For this reason, we have elaborated and set up a spatial optimization approach matching the specific needs of this study with the

Table 1 Literature review of (a) studies on adaptation of agricultural land management to climate change and (b) publications involving biophysical models within an optimization routine to find best possible land management with regard to different objectives

Study	Adaptation to climate change	Multi-objective	Optimization	Regional (gridded)
White et al. (2011)[a]	65	131		~ 50
Rötter et al. (2011)	✓			
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)

following components: (a) the generic crop model CropSyst and (b) 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 (status-quo scenario), (ii) calculation of a large set of optimum solutions for two different climate scenarios covering the solution space for regional climate change adaptation, (iii) clustering the solutions and identifying a subset with strongly differing combinations of objectives, (iv) extraction of compromise solutions considered as the most desirable strategies, and (v) analysis of those solutions in terms of the underlying land use and management.

Case study

Indicators

To analyze agricultural functions of interest, diverse indicators reflecting their main aspects were defined:

- scaled crop yield for agricultural productivity function;
- soil erosion by water (t ha^{-1} $year^{-1}$) for soil conservation function;
- N-leaching (kg N ha^{-1} $year^{-1}$) for clean water provision function;
- irrigation amount (m^3 ha^{-1} $year^{-1}$) for water saving function.

Study region

The study region is the Broye catchment (Fig. 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 2004), and about 2,500 farms with an average size of ~20 ha (FOAG 2011). 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 m a.s.l. Major crops are winter wheat (~30 %), silage/grain maize (~15 %), winter barley (~9 %), sugar beet (~7 %), winter

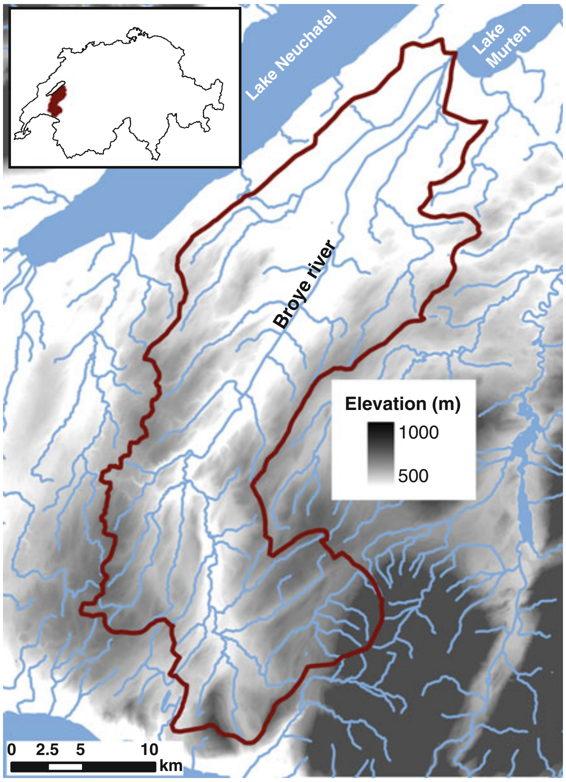


Fig. 1 The study area is the Broye catchment located in western Switzerland, which covers an area of about 850 km^2

rapeseed (~5 %), and potato (~5 %) (FOAG 2011). Main livestock types are dairy cows and cattle breeding with about 30,000 *LSU*s (Livestock Units, 1 *LSU* = 1 dairy cow) and accounting for more than 80 % of the total animal production.

Irrigation of cropland is already a common practice in this catchment, 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 % of the total regional water use for irrigation), maize (15 %), tobacco (15 %), and sugar beet (8 %). Most of irrigation water is pumped from the Broye river which originates from the southwestern part of the catchment at an elevation of about 1000 m a.s.l. and flows into the Lake of Murten at ~500 m a.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 that represents ~98 % of total areas according to Ledermann and Schneider (2008). N-leaching had been a general problem in Switzerland until the early 1990s 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).

Spatial representation

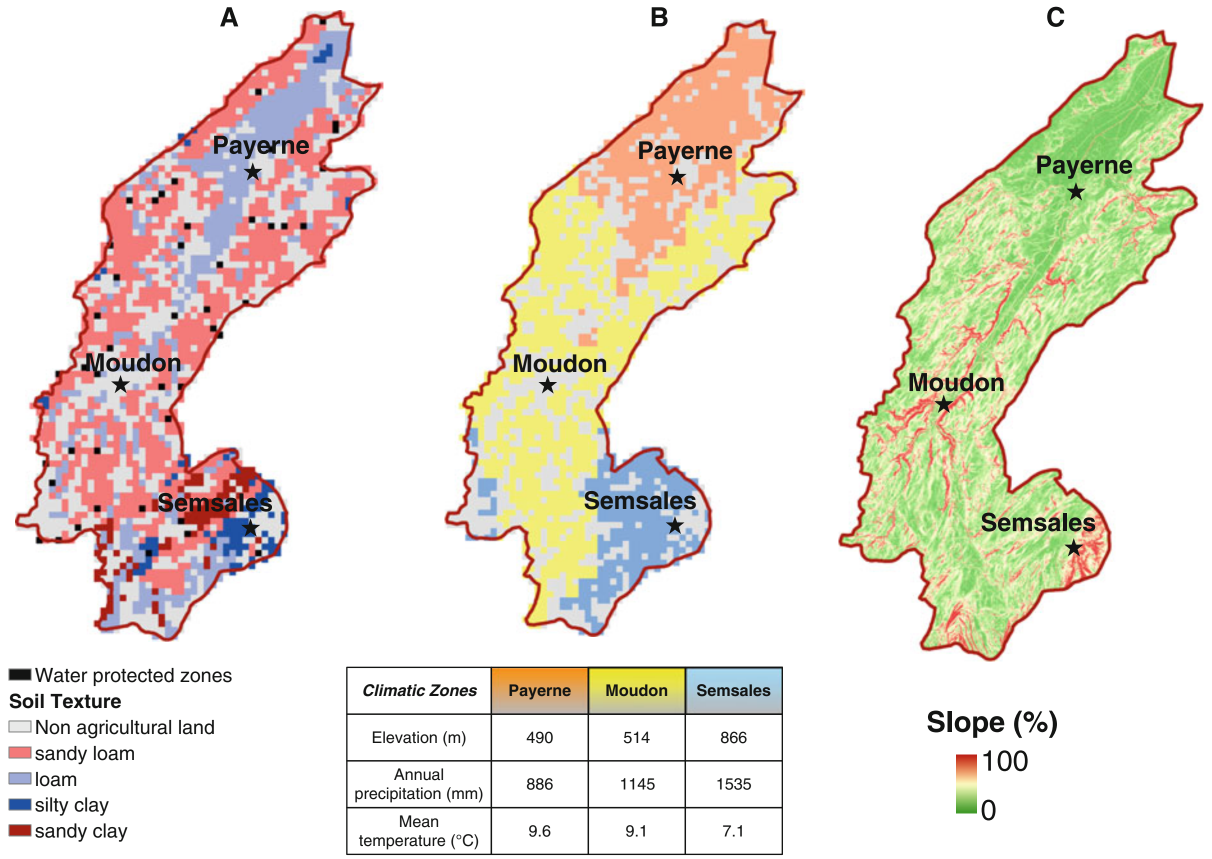
The study region was divided into 500 m × 500 m pixels and agricultural areas were identified. In order to run the models, spatially explicit inputs were needed for (i) climatic variables, (ii) soil texture and (iii) slope. Soil information for each pixel (Fig. 2a) was derived from the Soil Suitability Map of Switzerland at 1:200,000 (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 with respect to legal restrictions on irrigation and fertilizer use.

Climate data from three weather stations were available from the monitoring network of the Swiss Federal Office of Meteorology and Climatology (Fig. 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 the Swiss digital elevation model (Swisstopo 2001, Fig. 2C).

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 with +3.5 °C and −24 % in



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

Fig. 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; the three weather stations that are available in the study area are indicated with *star symbols*

seasonal precipitation amount (Table 2); the second, performed with the model SMHIRCA-HadCM3Q3 (referred to as SMHIRCA), projects moderate changes for the summer season with +1.3 °C and −11 % in seasonal precipitation amount, but an important increase by +21 % in seasonal precipitation amount during fall.

Management options

To solve the optimization problem, we considered the following management options (Table 2): land-use type, crop rotation, intensity, irrigation, and soil management. These management options have important impacts on crop yields, erosion and N-leaching and offer scope for adaptation in the study area. 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.

Two irrigation options were considered: rain-fed and supplemental irrigation. In CropSyst, supplemental irrigation is triggered automatically when soil moisture falls below 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

Table 2 Management options used as decision variables in the spatial optimization

Management options	Levels
Land use	Cropland, permanent grassland, pasture
Crop sequence	50 crop rotations generated stochastically
Intensity	
N fertilization (all)	Recommended: average N fertilization needs (in kg N), 5 cuts year^{-1}, 3 LSU ha^{-1}
Clipping (grassland)	Reduced: N fertilization needs −25 %, 4 cuts year^{-1}, 2 LSU ha^{-1}
Stocking density (pasture)	Low: N fertilization needs −50 %, 3 cuts year^{-1}, 1 LSU ha^{-1}
Irrigation	Rain-fed or supplemental[a] (automatic)
Soil management	
Tillage operation	Conventional: regular tillage & harvest residues removed
Residue management	Conservation: reduced tillage & harvest residues retained

LSU: Livestock Unit (1 *LSU* = 1 dairy cow)

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

of sprinkler irrigation systems (Irmak et al. 2011), the most common irrigation technique for cropping systems in the Swiss Plateau.

Fifty 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 amounts were 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.

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 (2004). 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 at the municipality level 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 till occurs preferentially on steep slopes to avoid high soil loss rates leading to land degradation.

Methods

This section provides an overview of the main steps involved in the identification of optimal management with regard to the different indicators (Fig. 3). Crop model simulations 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, i.e. crop yield, irrigation, erosion, N-leaching, were passed to an optimization routine to identify in each pixel the best agricultural management with regard to a performance criterion. The optimization routine was repeated several times by modifying the weights given to the different indicators in a systematic way. In total, 258 weightings were tested leading to a similar number of spatially-explicit solutions, each solution being characterized by the same weighting at all pixels. Spatially-explicit indicators were then aggregated at the regional level for each solution separately. Then 16 clusters were defined based on the 258 aggregated solutions by means of SOMs (Self-Organizing Maps,

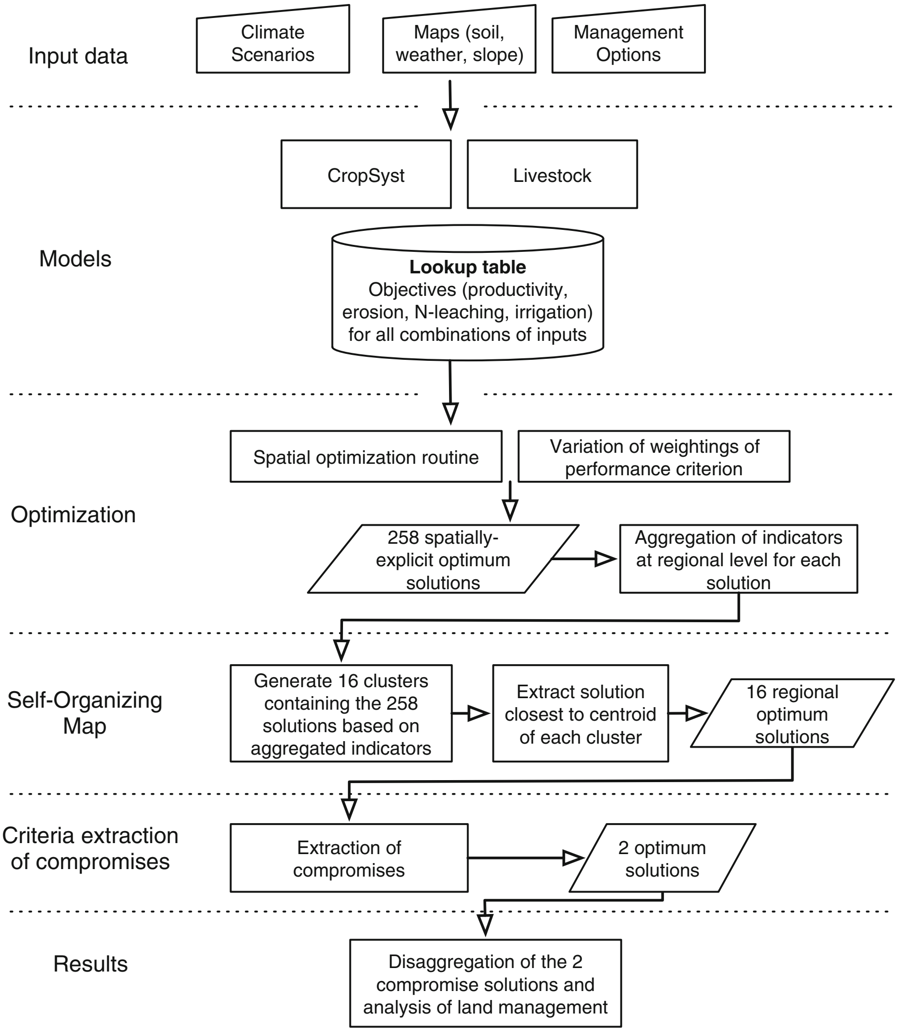


Fig. 3 *Flowchart* of the steps involved for the development of land management adaptation options. Steps are grouped into main categories separated by *dashed lines*, which correspond to different sections in the paper

Kohonen 2001). For each cluster, the most representative solution was extracted based on the minimum distance to the centroids. At last, a set of restrictions was applied to identify compromise solutions, which were then disaggregated and analyzed in detail in terms of the underlying land use and land management.

Crop model

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, soil, 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.

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, Renard et al. 1997) as:

$$E = R \cdot K \cdot L \cdot S \cdot P \cdot C \qquad (1)$$

where R is the rainfall energy intensity factor, K the soil erodibility factor, L and S the slope length and steepness factors, P the 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 L_{ref} and S_{ref} based on slope steepness of 10 % and 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 L_{ref} and S_{ref}, and multiplying it by local L and S factors based on the slope map (Fig. 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 simulated by 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).

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 five livestock types considered, i.e. dairy/nurse cow, cattle fattening/breeding, calf fattening, daily grazing needs were computed as a function of fodder requirements per LSU from Flisch et al. (2009), the proportion of the time on pastures based on Agrammon (2010), and the stocking density i.e. LSU ha^{-1}. Daily grazing requirements were then used in CropSyst to simulate grazing as a clipping management with the calibration for grassland. 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 application.

Spatial optimization routine

Since neighborhood effects were not relevant in this study, a local optimization approach 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. 2) were selected. Therefore, all indicators (crop yield Y, erosion E, N-leaching N, and irrigation I) were scaled separately (Y', E', N', and I' in Eq. 2) following a min-max normalization (value - minimum, divided by the range of values) based on regional maximum and minimum values for current climate. Y' was computed as the arithmetic mean of crop yields over the rotation, each individual crop yield being scaled separately with crop-specific values (Y' is referred to as ‘productivity’ later in the text). For pastures, the total grazed biomass by animals was used as yield value.

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 SMHIRCA (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.

$$J = \max\left\{W_y Y' + W_e(1 - E') + W_n(1 - N') + W_i(1 - I')\right\} \quad \text{where} \tag{2}$$

$$W \in [0, 1] \quad \text{with an increment of 0.1 and} \quad \sum W = 1 \tag{3}$$

In Eq. 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 the agricultural functions. The sensitivity of optimization results to weighting was tested by varying systematically each weight between 0 and 1 with an increment of 0.1, with the constraint that the sum of all weights equals 1 (Eq. 3). 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, ground water protected zones were included 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 surface needed for pastures was determined based on current regional livestock numbers from FOAG (2011) averaged on 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 pixels.

Self-organizing maps

SOMs were used to identify general pattern in all 258 solutions and cluster the solutions. 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 multidimensional datasets. Therefore, they are very helpful to visualize trade-offs between multiple objectives (see e.g. Li et al. 2009 or Norouzi and Rakhshandehroo 2011).

SOMs were generated with the Kohonen package of the statistical language R (Wehrens and Buydens 2007) based on regionally aggregated values of the four indicators 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).

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 current level computed with reference land management under present climate;
- 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 SMHIRCA, 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 SMHIRCA;
- better performances with regard to soil loss and N-leaching than without adaptation.

Results

Impacts of climate change for the status-quo scenario

In this section, impacts of climate change on the reference land management without adaptation corresponding to a status-quo scenario are assessed. Results show that without adaptation productivity slightly decreases (Fig. 4). These changes are less pronounced than what could be expected from future precipitation

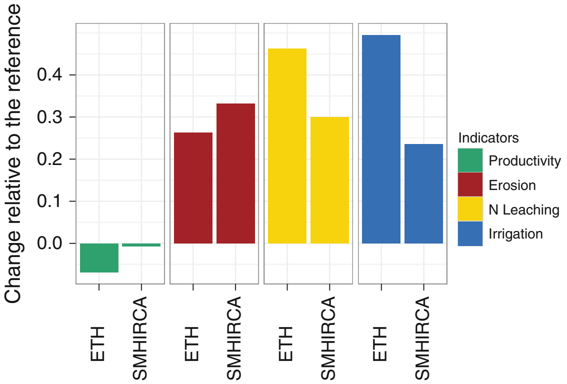


Fig. 4 Regionally-aggregated impacts of the two climate change scenarios (*left* ETH 2050, *right* SMHIRCA 2050) for the status-quo scenario with respect to the four indicators; the status-quo scenario corresponds to the reference (1981–2010) land management without adaptation

deficits, partly because of higher irrigation amounts by 20–50 %. This increase in irrigation is accompanied by largely negative impacts with regard to both N-leaching (increase by 30–45 %) and soil erosion (increase by 25–35 %).

Both climate scenarios agree on negative effects of climate change on all indicators without adaptation. For SMHIRCA, impacts on productivity are negligible and associated increased irrigation is moderate. In contrast, simulations with ETH indicate, as expected, a more pronounced productivity loss (−10 %) and a higher increase in irrigation needs (−50 %). Changes in erosion rates are similar but slightly higher with SMHIRCA, while N-leaching is substantially higher with ETH.

Adaptation options

Based on regionally aggregated indicators of the 258 solutions, 16 clusters were generated with SOMs (Fig. 5). As seen in this figure, a wide range of different adaptation options are possible, 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 1–4). Results show that agricultural productivity generally conflicts with environmental objectives. Indeed, high yields are reached using large amounts of irrigation and with increased N-leaching and/or higher soil loss rates.

Of the 16 clusters, 11 allow maintaining or even further increasing productivity compared to the reference. The maximum increase in productivity is ∼ + 35 % (cluster 13). However, this is associated with an increase in irrigation by 4,000 and 2,500 % for ETH and SMHIRCA, respectively. Only six out of the 16 solutions allow reducing soil loss but, in some cases, beneficial impacts are very strong, e.g. reduction of erosion up to 85 % in cluster 12. More adaptation options to reduce N-leaching can be found, but positive effects are moderate, i.e. reduction up to 30 % in cluster 2. In general, large differences are found between the two climate scenarios with regard to productivity and irrigation amounts, while very few differences are found in terms of erosion and N-leaching.

Mean regional proportions of areas allocated to different agricultural practices were computed for each cluster separately (Fig. 6). Land management differs much across the different clusters. For instance, a high proportion of permanent grassland in combination with conservation soil management is necessary to minimize erosion (cluster 12). Best performance with regard to productivity (cluster 13) is 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 is best in order to ensure constantly low soil N concentrations with high N uptakes due to deep rooting systems and short fallow times.

Compromise solutions for adaptation to climate change

Optimum solutions not satisfying the selection criteria for compromise solutions as stated in the methods section are not included for further analysis. This is the case for clusters 2, 3, 4, 8 and 12 because productivity cannot be maintained under the more extreme climate scenario. Irrigation needs exceed available water in rivers for clusters 1, 5, 6, 9, 13 and 14 and, therefore, they are also excluded. Solutions in clusters 7 and 10 are omitted as well since erosion increases compared to the status-quo scenario (Fig. 4). Thus, only two solutions fulfill all the criteria, i.e. clusters 11 and 16, which can be considered as realistic development goals for future agriculture in the Broye. Clusters 11 and 16 contain 28 and 13 solutions, accounting for about 16 % of all 258 generated solutions.

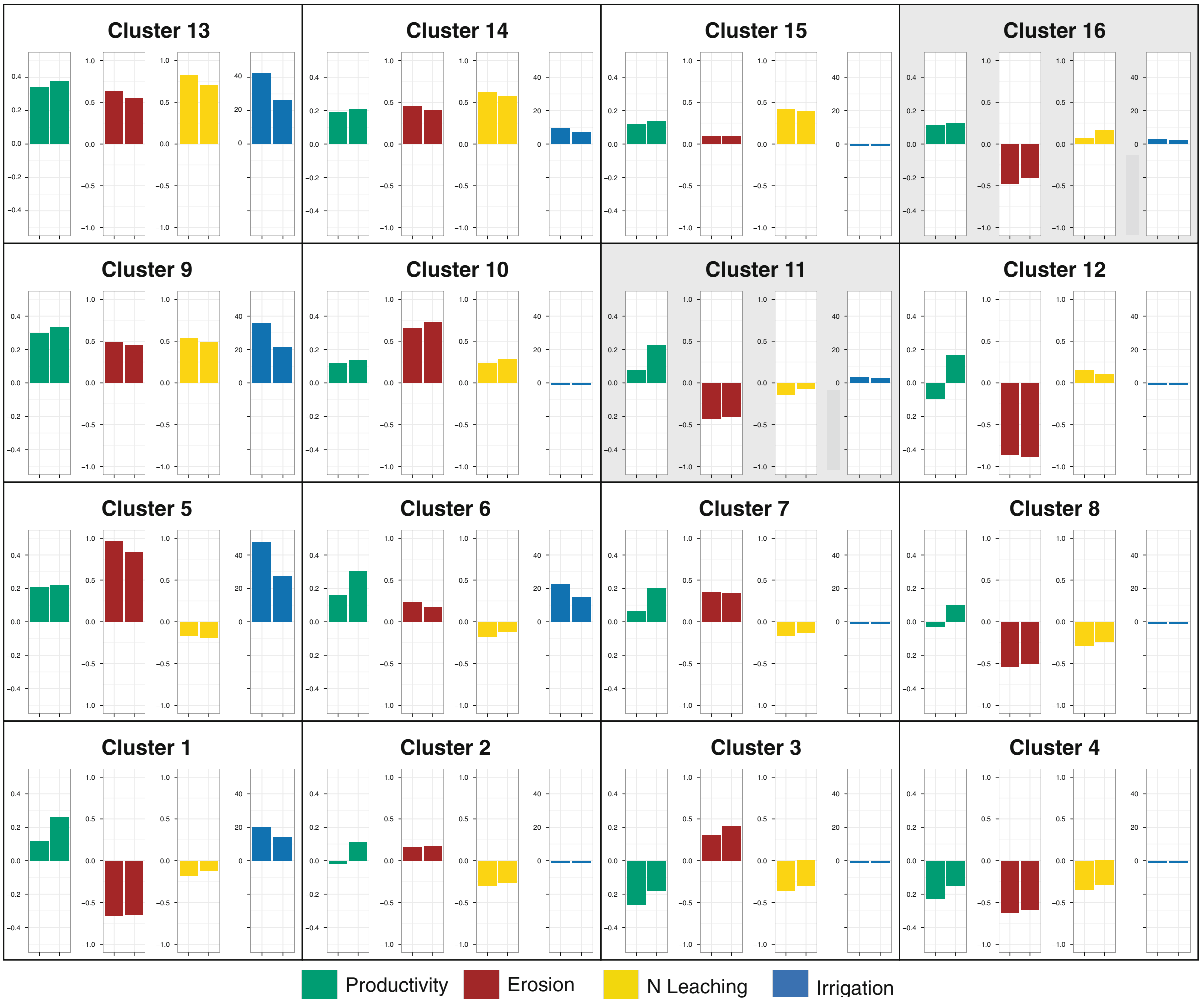


Fig. 5 Regionally-aggregated impacts of the two climate change scenarios (*left* ETH 2050, *right* SMHIRCA 2050) with adaptation, expressed as change relative to the reference (1981–2010), for the 16 solutions closest to the clusters' centroids defined by SOMs; the two compromise solutions are highlighted with *gray background*

Compared to the reference, both compromise solutions indicate an increase in productivity, by 10 % for cluster 16 (for both climate scenarios) and by 5 % (ETH) and 20 % (SMHIRCA) for cluster 11. Both solutions have strong beneficial effects on soil preservation, with a decrease in soil loss by about 50 % with both climate scenarios. Impacts of adaptation on N-leaching are less marked and vary more, ranging from an increase in leaching by 15 % (cluster 16 with SMHIRCA) to a decrease in leaching by 10 % (cluster 11 with ETH).

On average, monthly irrigation needs are expected to be below available water in rivers (Fig. A1a in the Appendix—Supplementary material). Simulated irrigation amounts are similar in the two solutions, occurring from June to September with a peak in July. As expected, irrigation needs are higher with ETH than SMHIRCA, but with moderate magnitude despite the stronger signal suggested by ETH. For some months, a substantial amount of water in rivers would be required to cover the needs in this particular scenario, e.g. 60 % of the total available water in rivers in July. About 10 % of all agricultural areas should be irrigated according to both compromise solutions (Fig. A1b in the Appendix—Supplementary material). Irrigated areas are 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.

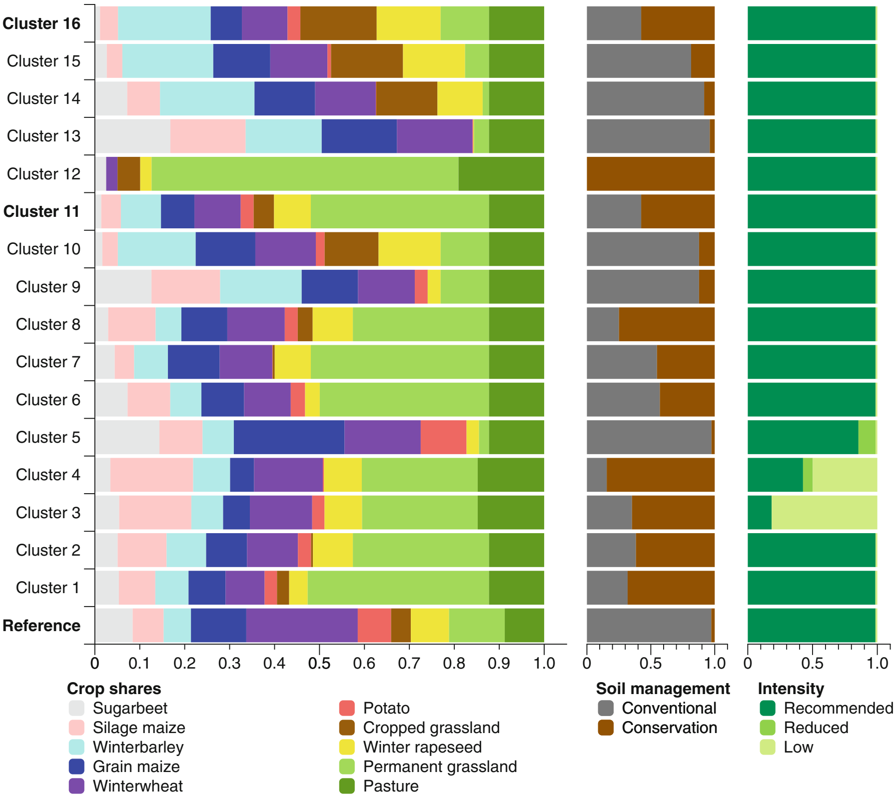


Fig. 6 Regional proportions of areas of optimized agricultural practices and comparison with the reference (1981–2010); the two compromise solutions and the reference are highlighted with *bold font*

The two solutions exhibit many similarities but a few discrepancies. First, both of them agree 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 residues removed (suggested by Fig. 6). However, conventional soil management should still be applied in nearly 70 % of the areas around Payerne, which are not subject to soil loss because of low slopes (not shown). Also, both options indicate 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 (Fig. 7) suggests 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 agree that shares of irrigated spring crops should decrease (Fig. 6), by 60 % for potato, 75 % for sugarbeet, and 20 % for grain maize, while production of some winter crops should increase, especially those that are harvested early in the year (i.e. winter barley and winter rapeseed). The regional share of grassland should also increase, either in rotations (cluster 16) or as permanent meadows (cluster 11). Another similarity is the allocation of pastures on the steepest slopes, which leads to reduced soil loss in areas that are prone to erosion. Also in both cases, permanent grasslands cover 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 soils that are subject to leaching. The major difference between the two compromise solutions is found in terms of the regional crop mix (Fig. 6). Indeed, cluster 11 is mostly dominated by permanent grassland, while cluster 16 focuses more on crop production with, for instance, a large share of winter barley.

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 catchment. We selected two optimal compromise

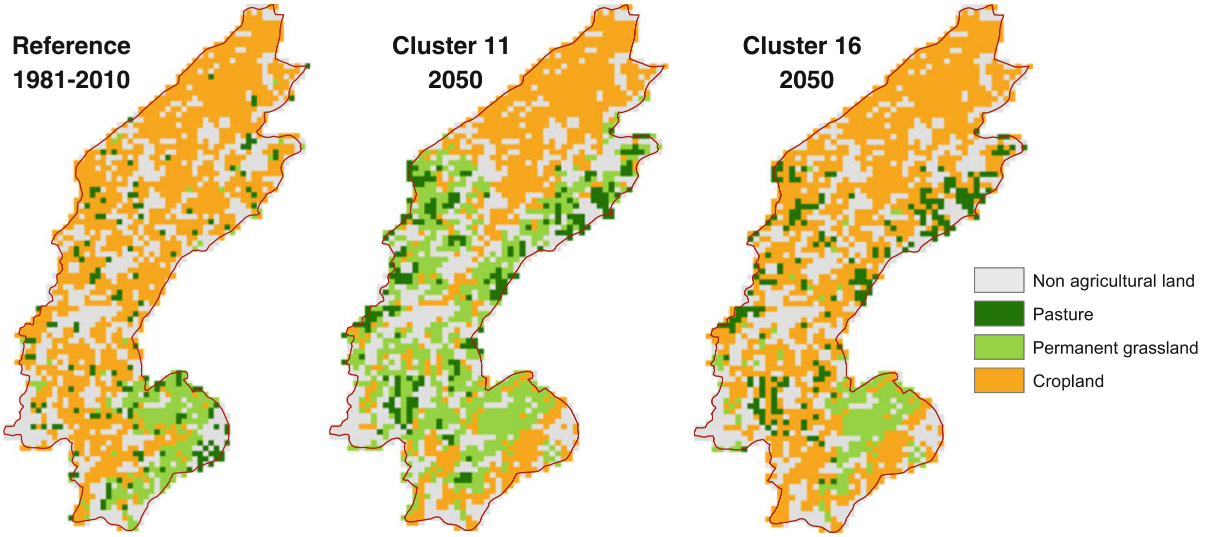


Fig. 7 Land-use changes to achieve compromise adaptation options

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 indicators, 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.

Land management adaptation to climate change

Changes in land-use types and/or their location can minimize negative impacts of climate change on agriculture, but might also allow exploiting some advantages of climate change, a phenomenon known as 'transformational adaptation' (Rickards and Howden 2012). 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. 2010). 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 (Fig. 5). However, such an extreme productivity increase could only be achieved at the expense of strongly increasing environmental impacts. Most of the adaptation options identified here allow to maintain or even further increase productivity compared to the current level. Regarding benefits of adaptation for the environment, 11 out of the 16 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 is small, i.e. six out of 16, but relative positive effects are higher than for N-leaching, i.e. reduction up to 90 % under climate change compared to current climate.

From the regional proportions of areas of optimized agricultural practices (Fig. 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 (Zhang and Nearing 2005; Scholz et al. 2008). 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 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, 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 rain-fed 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 services (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 % (SMHIRCA) higher than without adaptation, but without increasing negative impacts on other functions except water saving. 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 it 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 close 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 also showed discrepancies, especially in terms of crop mixes (Fig. 6) and land use (Fig. 7). This suggests that similar sets of indicator 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.

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. 2010) 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 (Parry et al. 2004; Körner et al. 2007). 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.

Optimization approach

A realistic representation of the agricultural system was used, considering both crop and livestock production. In addition, six different agricultural practices were merged into four decision variables. However, the following measures were taken to reduce the complexity of the optimization task: (i) we used a simple spatial representation with four soil types and three 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.

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 Smit et al. (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 focused 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.

The 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. In contrast, 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 all indicators are similar with both ETH and SMHIRCA (see Fig. 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.

Conclusions

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).

To assess benefits of adaptation of agricultural land management, we developed and 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 functions of Swiss agriculture for future adaptation, namely agricultural productivity, soil preservation, clean water provision, and water saving. A large number of decision variables was considered to cover a wide range of potential farm production adaptation practices.

Most adaptation options identified here exhibit conflicts between productivity and regulating functions. Nevertheless, about 16 % of all generated solutions fulfill a set of restrictive and politically desirable criteria. Those solutions perform well with respect to all agricultural functions and can be considered as enviable compromises. They outperform the status-quo scenario in terms of agricultural productivity, soil preservation and clean water provision. In contrast, water saving cannot be improved, and water needs are expected to be four to five times higher than today, but without exceeding future available water in rivers on average.

Different sets of management options to achieve compromises between agricultural functions have been highlighted, 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 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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