Identifying Optimum Strategies for Land Management Adaptation to Climate Change - A Multiobjective Approach

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Abstract: Climate change is likely to alter the conditions for agricultural production with distinct regional patterns, which necessitates adaptation measures that are adjusted to local conditions, but adaptation to maximize production may increase environmental impacts. The objective of this research is to identify sustainable regional land management adaptation strategies to maximize agricultural productivity, while minimizing environmental impacts such as nutrient leaching, soil erosion and an excessive use of water resources. The study area is the Broye catchment in Western Switzerland, where water shortage is common and irrigation is already applied regularly. For this region, the generic crop model CropSyst was calibrated for the most common field crops and for grassland. To account also for livestock production, a simplified livestock model based on empirical functions was developed to estimate water consumption, nutrient loads and forage requirements. The crop model in connection with the livestock model can be applied to test a multitude of management scenarios under different conditions including soil type, slope, or current and future climate. By integrating these models into a multi-objective spatial optimization routine, we can produce a series of optimum trade-off scenarios for regional adaptation strategies with varying weights for development goals (i.e. agricultural productivity, water saving, soil protection). A selected series of such trade-off scenarios can be presented to regional planners as possible goal scenarios, showing which adaptation strategies should be promoted in order to achieve most important regional planning goals (e.g. maintain productivity while minimizing water use and environmental impact).

Keywords: Multi-objective spatial optimization; agricultural management; crop modeling; adaptation to climate change

1 Introduction

Agriculture is an economic sector which is likely to be strongly affected by Climate Change (CC). In cool temperate regions of Europe, CC during the next decades is expected to produce positive effects on agriculture through higher crop productivity and expansion of suitable areas for crop cultivation [IPCC, 2007]. However, increasing water shortage and extreme weather events during the cropping season may cause more frequent crop loss, yield instability, and make areas less suitable for traditional crops [Olesen and Bindi, 2002]. Changes in temperature and in precipitation pattern may thus lead to water-related risks in agricultural production and competition for land and water resources [Lotze-Campen et al., 2008]. Hence, adaptive strategies for agricultural water resource management are needed to cope with the expected change in climatic conditions. These may include adjustments of crop rotations (e.g. shifting from high to low water demanding crops) and of production intensities, use of reduced (or no) tillage, in-
integration of cover crops, or changes in stocking rates and livestock types. However, such adaptation might lead to new conflicts or aggravate existing conflicts with other ecosystem services [Schröter et al., 2005]. For example, increased water use for irrigation could conflict with water demands for domestic or industrial uses, and lead to negative ecological implications. To prevent continued degradation of natural resources, policy will need to support farmers’ adaptation while considering the multifunctional role of agriculture [Olesen and Bindi, 2002; Betts, 2007]. Hence, effective measures to minimize productivity losses and preserve finite natural resources need to be developed at all decision levels, and scientists need to assist planers and decision makers in this process [Salinger et al., 2005].

Multi-objective optimization methods in connection with biophysical models have shown great potential. Bryan and Crossman [2008] developed an optimization-based regional planning approach to identify geographic priorities for on-ground natural resource management actions that most cost-effectively meet multiple natural resource management objectives. Higgins et al. [2008] applied a multi-objective programming model, with objective functions representing biodiversity, water run-off and carbon sequestration. Sadeghi et al. [2009] applied an optimization approach to maximize profits from land use, while minimizing erosion risk. Meyer et al. [2009] coupled SWAT (Soil and Water Assessment Tool) with an optimization routine to determine optimum farming system patterns to reduce nitrogen (N) leaching while maintaining income. Similarly, Whittaker et al. [2009] applied SWAT in connection with a Pareto-optimization approach for analysis of trade-offs between profits from land use and chemical pollution from farm production. Latinopoulos [2007] applied optimization to solve a problem of water and land resource allocation in irrigated agriculture formulated in terms of a series of socioeconomic and environmental objectives. Such approaches can be very useful to support the development of regional land use adaptation strategies. However, they have not been used yet in combination with scenarios of CC.

In this paper we present a multi-criteria optimization approach which relies on the use of component models, in order to identify spatially explicit optimum land use management with respect to multiple goals. These include agricultural productivity, water regulation, soil protection and N leaching. We describe the modeling framework, which consists of a generic crop model and an empirical livestock model. We present an approach for multi-objective spatial optimization based on a local optimization and apply it to a small catchment in the Swiss Pre-Alps. We show the potential trade-offs between sub-goals both under current and future climate conditions predicted by an extreme climate scenario. In addition, we illustrate how the proposed procedure can be used to investigate agricultural land use adaptation strategies in the context of CC.

2 Method

Figure 1 presents an overview of the approach. Component models (left-hand side of the chart) are driven by climate and soil data, topographic data to estimate soil loss and a series of crop and livestock management options to be optimized (e.g. crop sequence, irrigation, livestock density). Model outputs of interest (i.e food production, water use, soil loss, N leaching) are passed to a multi-criteria spatial optimization routine where each sub-goal is attributed a specific weight. In order to identify potential trade-offs, the procedure has to be repeated several times with different weightings. The optimization is subject to constraints related to the minimum regional productivity, the maximum slope for crop cultivation and the maximum monthly irrigation amounts under current and future climate conditions which were computed by Fuhrer [2012]. In our approach, livestock numbers and types, together with the timing of grazing are derived from regional observations.
Figure 1: Overview of the method

**Crop and Livestock Management: Options**
- Crop sequence: 50 rotations generated stochastically
- N fertilization: 3 levels (recommended, medium, low)
- Irrigation: recommended, no irrigation
- Tillage/residues: conservation/conventional
- Number of grass clippings: 3, 4 or 5
- Livestock density: 1 UGB/ha to 3.5 UGB/ha

**Component Models**
- **Generic Crop Model (CropSyst)**
  - Manure
  - Winter wheat
  - Grain maize
  - Potato
  - Pastures
  - Cropped grassland
  - Perennial grassland
  - Winter barley
  - Potato
  - Silage maize
  - Sugarbeet
  - Dry matter fodder

**Constraints**
- Animal numbers of each livestock type: regional observations 1999-2008
- Timing grazing: number of days and day length from Agrammon (2010)
- Minimum regional yield: 70% of the maximum possible yield
- Maximum regional irrigation amount: monthly discharge of main river
- Slope steepness for crop cultivation: if slope > 33% only permanent grasslands or pastures

**Optimization Routine**
1. Normalization of model outputs based on regional max and min values: $F = \frac{F - F_{min}}{F_{max} - F_{min}}$
2. Calculate goal function $J$ for every pixel of agricultural land:
   $$J = \max \left[ W_p F_p + W_r (1 - J) + W_h (1 - L) + W_e (1 - N) \right]$$
   with $W_p + W_r + W_h + W_e = 1$
3. Allocate optimum land management:
   - First pastures at locations least favorable for crops and grasslands
   - Then crops and grasslands when all animals are allocated

Repeat the procedure with multiple combinations of weights


2.1 Crop model

CropSyst 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, residue management.

CropSyst was calibrated for six main crops in Switzerland i.e. winter wheat, winter barley, grain maize, potato, sugar beet, winter rapeseed. The calibration procedure relied on farm accountancy yield records as reference and included the Morris method for parameter screening, together with an automatic parameter estimation method using a genetic algorithm (Klein et al., accepted for publication). The model was validated against data from a long-term trial lead in Eastern Switzerland (Chaiblen). As seen in Figure 2, simulated and observed yield were perfectly in line, both regarding the mean yield level and yield variability, with RMSE of 8.33 dt ha⁻¹.

![Figure 2: Yields simulated by CropSyst compared with observed crop yields in Chaiblen (Dubois et al. [1998]); MAI: silage maize, WW: winter wheat, WB: winter barley and WR: winter rapeseed](image)

CropSyst calibration for grassland was done based on data from a long-term trial in NW Switzerland (Oensingen) [Ammann et al., 2009]. Results showed that CropSyst can not only satisfactorily reproduce observed yields, but also the dynamics of the soil water content, leaf area index and actual crop transpiration (Figure 3).

2.2 Livestock model

The developed livestock model is based on empirical functions to estimate water consumption, N loads and forage requirements. These functions were largely derived from literature and, in most cases, were specific for Switzerland. Key figures of nutrient excretion and fodder requirements for livestock farming came from the Swiss guidelines for fertilization in agriculture [Flisch et al., 2009], whereas requirements for drinking water
were obtained from McDonald et al. [2002]. Regarding the coupling of the two models, CropSyst simulates the productivity of croplands and grasslands, while the livestock model simulates the food consumption either taken directly from the field (grazing) or as fodder. Moreover, N fluxes between models are represented in a consistent way. Manure is produced directly during grazing or applied as organic fertilizer after collection in the stable.

2.3 Optimization routine

The spatial optimization routine developed for this study integrates CropSyst and the livestock model with the goal of identifying optimum land management by maximizing a user-defined goal function $J$ (linear combination of sub-goal functions). In practice, the optimization problem is reduced to the optimization of land management for every grid cell, neighborhood effects being neglected as described in Seppelt [2002]. Simulations are repeated with different sets of management options (e.g. irrigation amount, tillage, N fertilization, . . . ) and the ones achieving the desired environmental goals defined by $J$ are selected. Sub-goal function values are scaled from 0 to 1 based on regional maximum and minimum values for current climate.

2.4 Case study

To illustrate the implementation of the presented framework and its possible outcomes, we conducted preliminary model tests for the Broye catchment, which covers an area of 635 km$^2$ (≈ 422 km$^2$ of agricultural areas) and is located in Western Switzerland. Water shortage is common in this Swiss catchment and irrigation is already applied regularly for some crops (e.g. potato or sugar beet). The study area was divided into 500 m X 500 m pixels called decision units. Soil information for each decision unit was derived from the Swiss Soil Suitability Map. Data from three weather stations were used; each pixel was allocated to one of them, minimizing the difference between annual precipitation amount observed at weather stations and interpolated annual precipitation amount 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 20 years of synthetic daily weather data form (a) a baseline period corresponding to 1981-2010 and (b) a climate scenario representing the period 2036-2065 and referring to the A1B emission scenario. The climate change signal used to modify the generation parameters of LARS-WG was extracted from a regional climate model simulation carried out in the framework of ENSEMBLES [der Linden, 2009] with ETHZ-CLM regional climate model. The climate change signal suggests precipitation decrease during the summer months (∼−25% in July and August), and a very marked temperature increase up to +3.75°C in August. Note that CO₂ fertilization effect was not included in this study, because the exact quantification of the CO₂ fertilization effect is still highly uncertain [Körner et al., 2007].

3 RESULTS AND DISCUSSION

Trade-off scenarios between productivity, irrigation, N leaching and erosion were developed by modifying the specific weights attributed to the different sub-goals. In total, 35 trade-offs scenarios were constructed based on 35 sequences of weights, where each specific weight varied from 0 to 1 with an increment of 0.25 while the sum of all weights was 1. Figure 4 presents the regionally aggregated trade-offs for the baseline and the climate scenario. Results showed that the maximum rain-fed yield under present climate in the Broye was ∼80% of the current maximum yield, but decreased to ∼70% under CC. Maximum rain-fed yields were obtained with high fertilization, which led to high leaching values (red, yellow and orange dots on Figure 4). When irrigation occurred, then productivity reached ∼85% under present climate and ∼83% under CC. In general, leaching tended to increase with increasing productivity, while erosion tended to decline due to higher biomass accumulation and thus better soil protection. In our application, erosion was stable with CC, but leaching substantially increased as a result of higher nitrification rate due to higher temperature.

Spatial pattern of land management (e.g. crop rotation, N fertilization level, livestock density) are computed for each trade-off scenario. In this paragraph we present the spatial land use pattern of one optimum solution. We selected the blue dot on Figure 4 (highlighted with its bigger size) for further analysis. This solution was assumed to be an interesting goal scenario as productivity was relatively high, while erosion and leaching values were rather low. However, irrigation needs were high, reaching 4.10^7 m³ yr⁻¹ for the baseline, which is considerably higher than actual irrigation needs estimated in a recent project [Robra and Mastrullo, 2011], due to a higher proportion of irrigated crops (i.e. potato and sugar beet) in the optimum crop mix (not shown). With the application of the climate scenario, irrigation needs increased further more by ∼50%.

Figure 5 shows a comparison between the current land use [BFS, 2001] and optimum patterns for this solution, both under current and future climate conditions. Results showed that the current land use and the optimum baseline land use are in line. Indeed, pastures and grasslands were allocated in Southern regions with higher elevation where temperature is a limiting factor, whereas crops were distributed on all other locations with few exceptions. The optimum land use under CC exhibited many discrepancies with the current state. In this scenario, Southern regions became favorable for crop cultivation, pastures were located at lower elevations and permanent grasslands disappeared completely. Conversely, the spatial distribution of productivity showed that Northern regions became very unproductive under CC due to lower precipitation and higher temperatures, which enhanced crop transpiration (not shown).

As a plausibility test, spatially explicit erosion results for the current climatic conditions
Figure 4: Trade-offs between sub-goals identified with the proposed framework (a) under present climate and (b) under climate change. Each dot represents an optimum solution in terms of land management. Values of the different sub-goals are aggregated at the regional level, by summing spatially explicit outputs (i.e. erosion, N leaching and irrigation amount) or by computing the regional mean (i.e. productivity defined as the scaled yield). Out of the 35 optimum solutions, only 12 of them are displayed following a set of restrictions (productivity > 0.7 and monthly irrigation amount < discharge of main river).
Figure 5: Comparison between current observed land use, optimum land use under present climate conditions and optimum land use under CC for one selected trade-off scenario were compared with values from the Swiss erosion risk map developed by Prasuhn et al. [2007] and were found to be in the same range. Unfortunately, a similar comparison for other sub-goals (e.g. leaching) was not possible as such data are missing.

4 CONCLUSIONS

In this paper we presented an approach for identifying optimum adaptation strategies for agricultural land management. The method is based on the integration of the process-based simulation model CropSyst and an empirical livestock model within a spatial optimization routine to allow for the consideration of complex interactions between agricultural land management and site conditions. Preliminary results showed the types of trade-offs which can be identified with this framework. We found out that, in general, erosion tended to decline with productivity but leaching tended to increase. With the application of one climate scenario we showed that productivity decreased under CC, erosion remained stable, while irrigation and leaching drastically increased. We illustrated the changes in terms of land use for one trade-off scenario in the context of CC. If the simulated optimum land use was very similar to the current situation, it was not the case under CC. Southern regions (higher elevation) - which are currently unproductive for crop cultivation due to limiting temperatures - became favorable under CC, while Northern regions became unfavorable resulting from more frequent water stress. Simulated irrigation needs were relatively high, both under and future climate conditions, exceeding estimated actual needs to a great extend. A more detailed comparison of estimated irrigation demands with water availability will be subject of further research. In the further implementation of the presented approach, several climate change signals simulated by different regional climate models will be considered, in order to take the uncertainties of the climate scenarios into account. In our future work, the framework will be applied to other catchments in Switzerland which experience different current climate conditions.
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