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Identifying optimum strategies for agricultural management considering multiple ecosystem services and climate change

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Abstract: In many European regions, the likely increase in water shortage and extreme weather events during the coming decades may cause more frequent crop loss, yield instability, and make cultivated areas less suitable for traditional crops. Possible adaptation measures are for example changes in crop choice, rotation and a more widespread adoption of irrigation. However, increased water use for irrigation may lead to conflicts with other ecosystem functions. Hence, measures to minimize productivity losses and preserve other ecosystem services such as water regulation, erosion control and nutrient cycling need to be developed. In this paper, we present an approach for identifying optimum adaptation strategies for agricultural management considering multiple ecosystem services and climate change. The method is based on a multi-objective spatial optimization routine which integrates the crop model CropSyst for evaluating the effects of climate and management changes on yields, water consumption, soil erosion and nutrient leaching. The method is illustrated with results from a preliminary model test, where we maximize crop production, while meeting a constraint on agricultural water use for two climate scenarios. Trade-offs between maximum crop production and minimum water use are investigated.

***Keywords**: Agricultural management; ecosystem services; multi-objective spatial optimization; climate change adaptation*

1. INTRODUCTION

Agriculture is an important economic sector which is going to be strongly affected by climate change. In cool temperate regions of Europe, climate change during the next decades is expected to have positive effects on agriculture through higher crop productivity and expansion of suitable areas for crop cultivation, and introduction of adapted crop species and new varieties [IPCC 2007a]. However, increasing water shortage and extreme weather events such as summer droughts during the cropping season may also cause more frequent yield loss and instabilities, and make areas less suitable for traditional crops [Olesen and Bindi 2002]. The drought risk on the Swiss Central Plateau may increase from about 15% to over 50% with future climate change [Calanca 2007]. In Swiss agriculture, this trend is expected to have negative impacts on productivity and to increase production risks by the end of the century [Fuhrer et al. 2006, Torriani et al. 2007, Finger and Schmid 2008]. Hence, adaptation strategies for agricultural water resource management are needed to cope with the expected change in climatic conditions, taking into account possible increases in costs for supplemental water. 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, integration of cover crops, adoption of irrigation with efficient technologies and choice of water sources (surface water or groundwater), retention of water in reservoirs (e.g. rainwater harvesting with cisterns), introduction of suitable landscape elements to reduce runoff, or changes in stocking rates and livestock types.

Farmers who have sufficient access to capital and technologies should be able to continuously adapt their farming system by changing the mix of crops, adopting irrigation and adjusting fertilization and plant protection [Easterling and Apps 2002]. However, in connection with climate change this might intensify existing impacts on the environment and lead to new conflicts between ecosystem services [MA 2005, Schröter et al. 2005, IPCC 2007b]. For example, increased water use for irrigation could conflict with water demands for domestic or industrial uses, and lead to negative ecological implications [Bates et al. 2008]. Also, soil loss through erosion may increase due to climate change, an effect which could be aggravated through changes in land management [Lee et al. 1999, O'Neal et al. 2003]. 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 2006]. 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 decision makers in this process [Salinger et al. 1999, Salinger et al. 2002].

Multi-objective optimization methods in connection with biophysical models have shown great potential for addressing such issues of opposing management goals [Ines et al. 2006, Bryan and Crossman 2008, Higgins et al. 2008, Sadeghi et al. 2009, Meyer et al. 2009, Whittaker et al. 2009 and Latinopoulos 2009]. 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 integer 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 leaching while maintaining income. Similarly, Whittaker et al. [2009] applied SWAT in connection with a Pareto-optimization approach considering profits from land use and chemical pollution from farm production. Latinopoulos [2009] applied optimization to a problem of water and land resource allocation in irrigated agriculture with respect to a series of socio-economic 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 climate change.

In this paper we present an approach for identifying optimum adaptation strategies for agricultural land management with respect to multiple ecosystem services. These include not only food production but also water regulation, soil protection and nutrient cycling. We present an approach for multi-objective spatial optimization based on a genetic algorithm and discuss ways to account for uncertainties in climate projections. The methodology will be applied to identify optimum land management patterns in a small catchment in the Swiss Pre-Alps. Preliminary results are presented to illustrate the optimization method and possible outcomes.

2. METHOD

To investigate optimum agricultural management adaptations to climate change, a variety of management options have to be considered, including crop/rotation choice, irrigation levels, fertilization levels, soil and residue management. The diversification of crops may decrease the risk of crop failure through extreme weather events and pests. Rotations may be adapted by shifts in sowing dates. Earlier sowing dates can be advantageous for summer crops under increased temperature conditions, as plants can utilize the higher soil moisture during spring, thus decreasing the risk of water stress in the growth cycle. On the other hand this may increase the risk of crop failure through late frosts. For winter crops later sowing dates could be beneficial to avoid damages that can occur during the cold period if crops are too far developed. As CO_2 concentration and temperatures increase, fertilization and irrigation requirements may also increase. Soil and residue management can have impacts on evaporation and thus on the soil water balance.

2.1 Optimization

For identifying optimum patterns of agricultural management considering multiple ecosystems and climate change, we apply a multi-objective spatial optimization routine based on the tool developed by Holzkämper and Seppelt [2007]. The approach is based on a genetic algorithm library by Wall [1996]. The genetic algorithm had proven to be highly suitable for addressing complex combinatorial problems in many previous applications [Kuo et al. 2000, Ines et al. 2006, Whittaker et al. 2009, Liu 2009]. It is an iterative search algorithm that is based on the principles of evolution [Goldberg 1989]. A solution is represented as a "genome". The optimization starts with an initial "population" of "genomes". With each iterative step the "genomes" of the "population" are evaluated with a defined objective function and the "fittest genomes" are chosen to be recombined. The newly generated solutions or "offspring genomes" also are evaluated and the least "fittest genomes" are excluded from the population to maintain the original population size.

Genome definition

In order to represent the land management pattern within the optimization, we first divide the study area into a number of decision units. Decision units are defined as parcels of agricultural land within which soil conditions are assumed to be homogenous and which are thought to be managed as entire units. The decision units can be derived by clipping a raster layer of soil types with a layer of cropland (Figure 1). The resulting raster of soil types under cropland can be used as the basis for the derivation of an ID-map where unique identifiers are assigned to all cropland clusters with homogenous soil type and a certain minimum size. The unique identifiers in the map are related to places in a one-dimensional array that defines the genome in the genetic algorithm. Each place in the array defines the management in one decision unit of the study area.

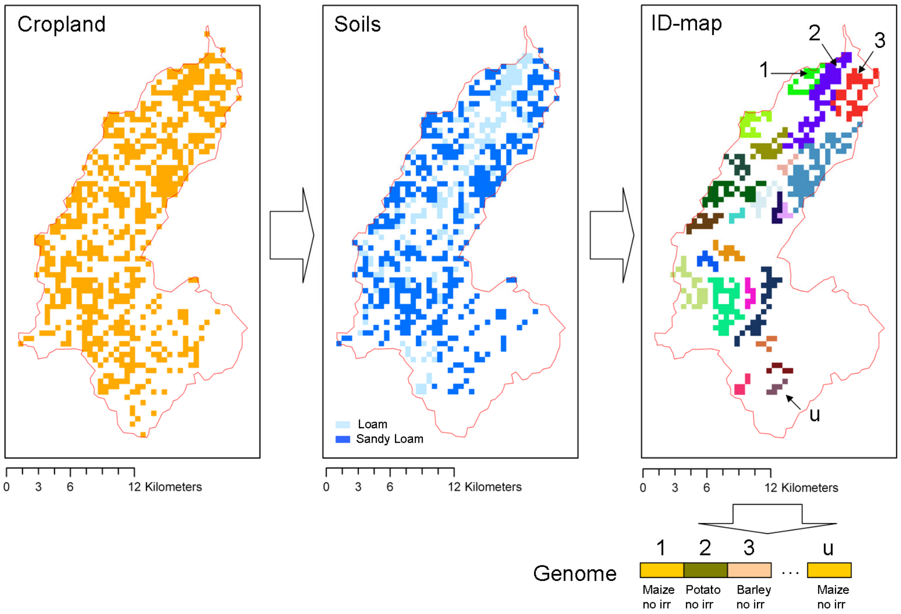

Figure 1. Data processing for derivation of decision units in a test study area: The procedure is based on a layer that defines all cropland (first map); the map of soil types is clipped with the cropland layer to result in the second map; unique identifiers are assigned to all cropland clusters with a homogenous soil type and a minimum size of 25 ha (third map); a one-dimensional array genome is derived from the ID map and initialized with different management types (e.g. consisting of combined crop and irrigation options).

Objective function

Management options intended to increase agricultural productivity can have various positive or negative impacts on other ecosystem services such as water regulation, erosion control/sediment retention and nutrient cycling. Thus, in order to identify management patterns that maximize food production, while minimizing environmental management impacts, we need to define an objective function that combines all these ecosystem services (1) Food production P is maximized; water consumption for irrigation I is minimized to support the water regulation function and avoid conflicts with other water users; erosion control is considered through the minimization of soil loss E; and nutrient leaching N is minimized to represent the ecosystem service of nutrient cycling. As the objective function combines four variables with different ranges and units, the variable values need to be normalized and weighted.

$$J = \max\left\{w_P P' + w_I\left(1 - I'\right) + w_E\left(1 - E'\right) + w_N\left(1 - N'\right)\right\} \tag{1}$$

In (1) P', I', E' and N' denote normalized values of total food production, water consumption for irrigation, soil loss through erosion and nutrient leaching within the study region. By substracting the values of I', E' and N' from 1, we allow for all ecosystem service goals to be maximized. The weights are defined so that $w_P + w_I + w_E + w_N = 1$.Thus, the optimization criterion J ranges from 0 to 1. One possibility to obtain dimensionless variables with values between 0 and 1 is to define:

$$V' = \frac{\sum_{i=1}^{u} V_i - \sum_{i=1}^{u} V_{\min,i}}{\sum_{i=1}^{u} V_{\max,i} - \sum_{i=1}^{u} V_{\min,i}} \tag{2}$$

where V represents any of P, I, E *or* N; u is the number of decision units within a study area; and for each decision unit i $V_{max,i}$ and $V_{min,i}$ denote the maximum and minimum of V, respectively, over the set of climatic conditions and management options envisaged for the study. These values have to be determined prior to the optimization for all possible combinations of management, climate and soil type, and could be stored for convenience in a look-up table.

The objective function is subject to constraints regarding P, I, E and N to take account of landscape planning goals for the region (e.g. minimum amounts of specific crops, maximum irrigation, maximum soil loss, maximum nutrient leaching). These constraints will have to be defined in consultation with regional stakeholders. The optimization will be performed multiple times using different weighting combinations to derive a series of optimum trade-off solutions. The trade-off solutions can be presented to regional stakeholders as a basis for discussing the perspectives of adaptation strategies for agricultural land management.

2.2 Simulation model

Solution of the optimization problem requires evaluation of each of the terms in (1) as a function of climate and management. To accomplish that, we use the generic crop model CropSyst [Stöckle et al. 2003]. CropSyst simulates the soil water budget, soil-plant nitrogen budget, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and salinity on a daily basis. It is driven by daily weather data and requires specification of crop and soil characteristics, as well as management options including crop rotation, cultivar selection, irrigation, nitrogen fertilization, tillage operations, and residue management.

2.3 Climate change scenarios

Daily weather data at the local scale cannot directly be extracted from the output of Global Climate Model (GCMs) or even Regional Climate Model (RCMs) simulations. One reason for that is the coarse spatial resolution of current GCMs and RCMs. This is for example the case with the models used to create the IPCC AR4 scenarios (http://www.ipcc-data.org/). Therefore, downscaling techniques need to be applied. Stochastic weather generators are among the most convenient downscaling tools for applications at the scale of small catchments.

3. PRELIMINARY MODEL TESTS

To illustrate the implementation of the presented approach and its possible outcomes, we conducted preliminary model tests in the agricultural areas of the Broye catchment, which covers an area of 392 km^2 (57% agricultural land use; [BFS 2001]) and is located in Western Switzerland.

3.1 Genome definition

For this simplified test study, we considered only a limited number of management options, i.e. crop choice and irrigation level. Crop choice included winter wheat, winter barley, maize, potato and canola. Irrigation options included five different levels of maximum allowable depletion to trigger irrigation, i.e. fractions of 0.7, 0.8, 0.9, 0.95, 1 of the minimum plant available water required for optimum production. Thus, 25 combinations of crop choice and irrigation level are possible and each place in the genome is filled with one out of these 25 combinations. The genome represents the pattern of decision units shown in Figure 1.

3.2 Objective function

The optimization goal was to maximize food production *P* in terms of yields from all decision units *i* in tons, subject to a constraint *c* on water consumption for irrigation water *I* from all decision units *i* in m^3.

$$J = \max\left(\sum_{i=1}^{u} P_i\right) \tag{3}$$

subject to

$$\sum_{i=1}^{u} I_i \leq c$$

By shifting the constraint value, the trade-off between food production and water regulation can be investigated.

The optimization was performed with a steady state genetic algorithm of the following specifications: number of generations = 1000; genome size = 24, population size = 50; proportion of replacement = 0.25; selection routine = roulette wheel; mutation probability = 0.01. As the genetic algorithm is a stochastic search technique, it produces slightly diverging results with each optimization run. To take this stochasticity into account, each optimization run was repeated 100-times.

3.3 Climate scenarios

The stochastic weather generator LARS-WG [Racsko et al. 1991; Semenov and Barrow 1997] was used to generate 50 years of daily weather data for 2046-2065 assuming a climate change signal consistent with the IPCC-AR4 scenarios HADCM3-SRA2 (scenario *A*) and IPCM4-SRA2 (scenario *B*). The weather generator was calibrated with data from the climate station of Payerne, which was assumed to be representative for the study region (data courtesy of the Swiss Federal Office of Meteorology and Climatology, MeteoSwiss. See also www.meteoswiss.ch).

3.4 Optimization results

Preliminary optimization results for the two climate scenarios are shown in Figure 2. If no water is available for irrigation, the optimum management pattern would be only barley under scenario *A*. Under scenario *B* the optimum management pattern would contain 8000 ha of barley, but also 2000 ha of maize. As the irrigation constraint is released, the maize areas increase under both climate scenarios, while area with barley decreases. Area with potato increases slightly with increasing availability of irrigation water, but seems to decrease as water availability increases further. In contrast to these results, the optimum management identified under current climatic conditions would be only maize irrespective of the irrigation constraint.

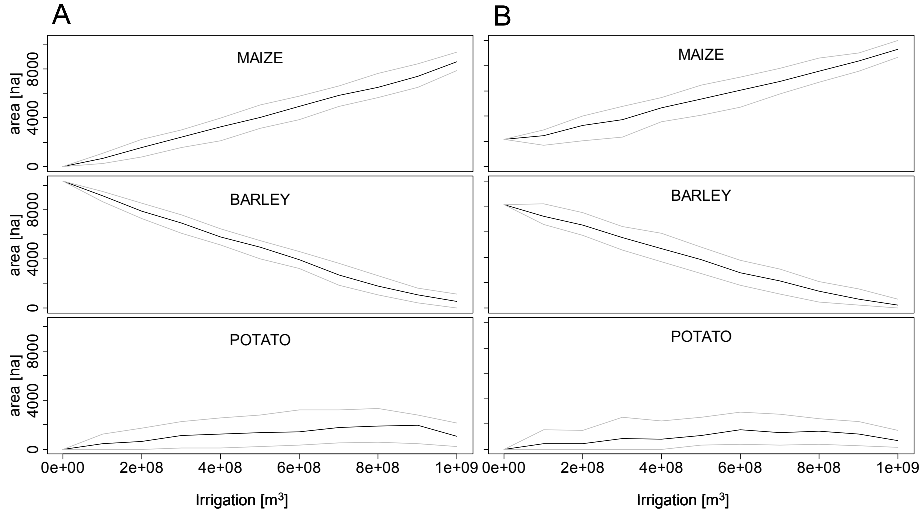

Figure 2. Crop area in optimization results with varying constraints to irrigation and scenario A and scenario B, respectively (black line indicating median, grey lines indicating 10th and 90th percentiles of outputs from the 100 optimization runs).

Comparing the water consumption for irrigation on the two most dominant soil types for these optimization runs (Figure 3), we can see a trend towards higher irrigation on loam than on sandy loam in both climate scenarios A and B.

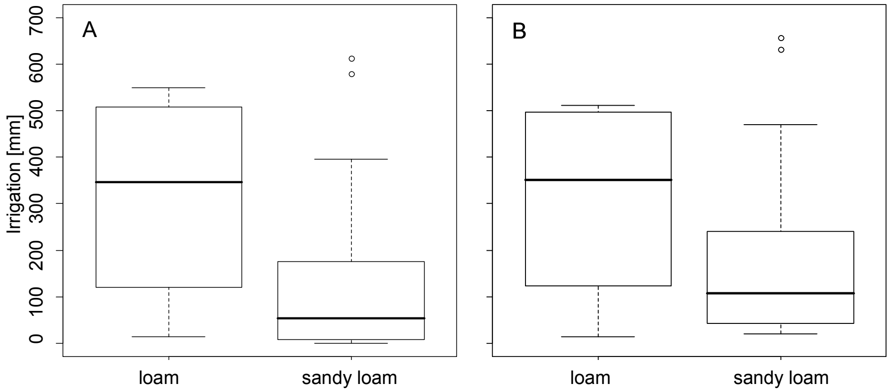

Figure 3. Boxplots of distributions of water consumption for irrigation on loam and sandy loam derived from optimization results considering climate scenarios A and B with an irrigation constraint of 10000000 m^3 (A = scenario HADCM3_SRA2, B = scenario IPCM4_SRA2; boxes extend from 25th to 75th percentiles with horizontal line indicating the median, whiskers extend to most extreme values or a maximum of 1.5 of the interquantile range, points beyond whiskers are suspected outliers).

4. CONCLUSIONS AND OUTLOOK

In this paper we presented an approach for identifying optimum adaptation strategies for agricultural management. The method is based on a genetic algorithm, which allows for an efficient optimization of highly complex spatial allocation problems. Thereby, the integration of the process-based simulation model CropSyst allows for the consideration of complex interactions between crop management and site conditions. Through the consideration of different climate scenarios, the uncertainties of the climate scenarios can be taken into account. Preliminary test results showed how optimum solutions can vary in terms of composition and configuration depending on a constraint for irrigation and depending on the climate projection.

In the further implementation of the presented approach, the spatial heterogeneity of the study area will be considered in more detail and a greater variety of management options and objectives will be taken into account (as outlined above). For erosion and nutrient leaching barrier effects can be taken into account, relating the objective function to spatial interactions between decision units. For quantifying food production it might be more adequate to use calories rather than dry matter yields, as yields do not necessarily refer to food energy. Furthermore, a measure of interannual yield variability needs to be integrated into the objective function to allow for the minimization of production risks. For a more comprehensive consideration of uncertainties in climate projections, the objective function could be defined as a weighted linear combination of objective values as calculated in (1) based on different climate scenarios, where the weights represent the probabilities of the climate scenarios.

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