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An approach for Identifying Optimal Solutions for Adapting Agricultural Land Management to Climate Change#

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Abstract: In many regions of the world, climate change is expected to have severe impacts on agricultural systems. As many previous impact studies suggest, yields could decrease, water resources may decline, and erosion risk could increase. Climate change is likely to alter agro-climatic conditions with distinct regional patterns, which necessitates adaptation measures that are adjusted to local characteristics. The objective of this study was to identify agricultural land management adaptation measures with regard to indicators reflecting major aspects of four important agricultural functions: crop yield, soil erosion by water, nutrient leaching, and water use. Changes in land management are one way to adapt to future climatic conditions, including declining water resources. Systematic explorations of land management possibilities using optimization approaches were so far mainly restricted to studies of land and resource management under constant climatic conditions. In this study, we bridge this gap and exploit the benefits of multi-objective regional optimization for identifying optimum land management adaptations to climate change. We consider two climate scenarios for 2050 in the Lakes Prespa watershed. We designed a multi-objective optimization routine that integrates a generic crop model in combination with spatial information on soil, climate conditions and slope at a 500 m x 500 m resolution. The results demonstrate that even under the more extreme climate scenario compromise solutions maintaining productivity at the current level with minimum environmental impacts in terms of erosion and nitrogen leaching are possible. Necessary management changes include (i) adjustments of crop shares, i.e. increasing the proportion of early harvested winter cereals at the expense of irrigated spring crops, (ii) widespread use of reduced tillage, and (iii) allocation of irrigated areas to soils with low water-retention capacity at lower elevations. It is concluded that the potential for climate change adaptation at the regional scale is significant. Overall, this study shows that negative climate change impacts on agro-ecosystems can be limited to a large extent by adaptation. However, such adaptation measures are expected to cause a sharp increase in the region's agricultural water demand. The results could serve as basis for planners and decision makers to develop suitable regional land use strategies.

Keywords*: agricultural land management, climate change adaptation, CropSys model, multi-objective regional optimization*

Introduction

Agriculture is an economic sector that is sensitive to climate change. In temperate regions of Europe, increased air temperature is expected to first have positive effects on agriculture through higher crop productivity and expansion of suitable areas for crop cultivation (IPCC 2007). 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; Torriani *et al*., 2007) including competition for land and water resources (Lotze-Campen *et al*. 2008). Climate change is also expected to aggravate environmental impacts, such as higher erosion rates (Nearing *et al*., 2004), faster decomposition of soil organic matter and increased nitrogen (N) leaching (Bindi & Olesen 2010). Consequently, there is a need for adaptation of agricultural land management to reduce the sensitivity of cropping systems to cope with the expected change in climatic conditions. This may include adjustments of crop rotations by shifting from high to low water demanding crops, changing

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fertilization intensity, use of conservation soil management such as direct seeding, or changing livestock stocking density. To maintain agricultural productivity and preserve finite natural resources, adaptation measures need to be developed at different decision levels, and scientists need to assist planers and decision makers in this process (Salinger *et al*., 2005).

Ecophysiological models are particularly important tools for understanding impacts of climate change (Challinor *et al*., 2009). Many applications of crop models to examine options for adaptation of agriculture can be found in the literature (White *et al*. 2011). A literature review on adaptation and optimization of agricultural land management reveals that most previous studies focused either on adaptation or optimization, but rarely on the combination of both. The aim of this study is to combine benefits of two approaches (optimization and adaptation) to identify optimum land management under climate change by considering multiple objectives in a case study for Lakes Prespa watershed. For this reason, we have elaborated and set up a spatial optimization approach matching the specific needs of this study with the following components: (i) the generic crop model CropSyst and (ii) empirical functions to simulate grazing and excretions by livestock. The main steps involved in this study are (i) estimation of reference land management for current climate and assessment of impacts of climate change in the absence of adaptation, (ii) calculation of a large set of optimum solutions for two different climate scenarios covering the possible range of regional climate changes, (iii) clustering the solutions and identifying a subset with strongly differing combinations of objectives, (iv) extraction of compromise solutions considered as the most suitable strategies, and (v) analysis of those solutions in terms of the underlying land use and management.

Materials and Methods

Case study

The study region is the Lakes Prespa watershed, which is located on the borders between eastern Albania, Greece and Macedonia, in south-eastern Europe and covers an area of about 1,218.1 km^2. It is a high-altitude basin, which includes two inter-linked lakes, the Macro Prespa (259.4 km^2) and the Micro Prespa (47.4 km^2) at approximately 850 meters above sea level. Agriculture is by far the most important sector for employment in Park Prespa. Of the total employed labour pool in the Prespa Basin, approximately seventy-five percent are engaged in agriculture. Land use is dominated by cropland in the flat areas, while permanent grassland dominates areas at elevations above 700 a.m.s.l. Major crops are winter wheat, silage/grain maize, dry beans, and potato.

Lakes Prespa area is prone to erosion due to steep slopes and widespread use of conventional tillage. N-leaching had been and is still a concern and is expected to become a more important issue with enhanced mineralization of soil organic matter in a warmer climate.

Spatial representation

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

Climate data from three weather stations were available from the monitoring network; 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 & Schär (1998).

Information on slope steepness, necessary for computing soil loss rates, was inferred from a digital elevation model

Climate scenarios

The stochastic weather generator LARS-WG (Semenov & Barrow, 1997) was used to generate 25 years of synthetic daily weather data for (i) a baseline period corresponding to 1991-2015 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 & Mitchell 2009). The first, performed with the model ETHZ-CLM (referred to as ETH), is characterized by a strong climate change signal in summer (+3:5 ºC and -24% in seasonal precipitation amount); the second, performed with the model SMHIRCA-HadCM3Q3 (referred to as SMHI), projects moderate changes for the summer season (+1:3 ºC and -11% in seasonal precipitation amount), but an important increase in seasonal precipitation amount during fall (+21%).

Management options

To solve the optimization problem, we considered the following management options (Table 1): land use type, crop rotation, intensity, irrigation, and soil management. These management options have important impacts on agricultural productivity, erosion and N leaching and offer great room for adaptation in the study area if well adjusted (Klein *et al*., 2013). found that productivity highly depends on intensity level, crop rotation, soil management and irrigation. The most important factor for controlling erosion was found to be soil management, but crop sequence plays also a very important role, i.e. the fallow time during autumn/winter when highest precipitation amounts occur. N-leaching depends more on soil type than management, but the crop sequence has a significant impact on soil N availability and, thus, on N losses.

Table 1. Management options used as decision variables in the spatial optimization

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

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

Two irrigation options were considered: rainfed and supplemental (automatic) irrigation. In CropSyst, supplemental irrigation is triggered when soil moisture falls under a crop specific threshold and is refilled to a user-defined level.

50 different 5-year rotations for croplands were generated based on rules provided by Vullioud (2005) with regard to (i) feasibility of crop sequences and (ii) recommended maximum proportions of crops. 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.

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.

Methods

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

Simulation results for all combinations of agricultural practices and local conditions were computed prior to the optimization for the two climate scenarios and stored in a lookup table. Then, outputs of interest (crop yield P, irrigation I, erosion E, N-leaching L) were passed to an optimization routine to identify in each pixel the best management scheme with regard to a performance criterion (see below).

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

Crop model

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

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

$$E = RxKxLxSxPxC \quad (1)$$

where: *R*: rainfall energy intensity factor; *K*: soil erodibility factor; *L* and *S*: slope length and steepness factors; *P*: soil conservation practice factor; *C*: represents the effect of land management on erosion, which depends on surface residue cover, incorporated residues, crop cover and soil moisture.

*E*was first calculated in CropSyst with reference *Lref* and *Sre*f. Then, soil loss was adjusted a posteriori in the optimization routine dividing *E* by the reference factors and multiplying it by local *L* and *S* factors based on the slope map. This increased substantially the computation efficiency as CropSyst had to run only once with *Lref* and *Sref* 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. N transport associated with infiltration is determined on the basis of a so-called bypass coefficient. N transformations developed for CropSyst include net mineralization, nitrification and denitrification. Ammonium in the soil is either absorbed into the soil in solid phase or dissolved in soil water. Crop N uptake is determined as the minimum of crop N demand and potential N uptake. Crop N demand is the amount of N the crop needs for potential growth, plus the difference between the crop maximum and actual N concentration before new growth. Potential N uptake is proportional to maximum N uptake per unit length of root, root length, N availability, and to square of a soil water availability factor.

CropSyst was calibrated following Klein *et al*. (2012) for the most important crops in Lakes Prespa, i.e. winter wheat, maize, potato, and dry beans. CropSyst calibration for grassland was also done.

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 3 livestock types considered (dairy/nurse cow, cattle fattening/breeding, calf fattening), daily grazing needs were computed as a function of fodder requirements per Livestock Unit (LSU), the proportion of the time on pastures and the stocking density (optimized number of LSU ha^{-1}). Daily grazing requirements (kg dry matter) were then used in CropSyst to simulate grazing as a clipping management with the calibration for grasslands.

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, the proportion of the time on pastures and the stocking density. In CropSyst, N excretions returning directly to the field were simulated as organic N applications.

Spatial optimization routine

Since neighbourhood effects were not relevant in this study, local optimization could be applied to minimize the computational effort (Seppelt & 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. Individual objectives were scaled from 0 to 1 (P', E', L', I') based on regional maximum and minimum values for current climate.

(for instance $E' = \frac{E - Emin}{Emax - Emin}$).

P' was the arithmetic mean of crop yields over the rotation, scaled with regional maximum and minimum values. For croplands, each individual yield in the rotation was scaled separately with crop-specific values. *P'* for pastures was based on total grazed biomass by animals.

In our approach, *J* was calculated with all N possible combinations of management ($\{f_k\}_{K=1}^{N}$), separately for the ETH (J^E) and SMHI (J^S) climate scenarios to account for climate projection uncertainties and identify robust optimum solutions. 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.

$$J = \max\{W_p P' + W_i(1-I') + W_e(1-E') + W_l(1-L')\} \text{ where} \quad (2)$$

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

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 objectives. Each weight was varied from 0 to 1 with an increment of 0.1 with the constraint that the sum of all weights equals 1. This led to a total of 258 weight combinations representing the same number of adaptation options. The optimization was subject to two further constraints. First, the maximum slope for crop cultivation and use of heavy machinery was set to 33% based on expert judgment. Second, groundwater protected zones were considered to account for legal management restrictions regarding the spreading of liquid manure and the use of irrigation. Preliminary tests of the optimization routine showed that, if economic values of livestock are not considered, pastures do not appear in the optimal solutions, unless animal production was prescribed. Hence, the number of animals was used as constraint and variables which were optimized were the spatial distribution of pastures for each livestock type and the stocking density. In the optimization routine, pastures were first distributed across pixels where differences in the objective function values with and without pastures were the highest. Then, croplands were allocated to the remaining units.

Selection of compromise solutions

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

- agricultural productivity is maintained or improved compared to the reference level;
- monthly irrigation needs are below the maximum amount of water that on average can be extracted from lakes water in the watershed;
- better performances with regard to soil loss and N-leaching than the reference under climate change without adaptation.

Results

Impacts of climate change on reference land management without adaptation

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

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

Adaptation options

From regionally aggregated objective values of the 258 optimum solutions, 16 clusters were generated with. For each cluster, one representative solution was extracted based on the minimum distance to the centroids. A wide range of different adaptation options were generated, some of them prioritizing productivity at the expense of environmental impacts and requiring high irrigation amounts (clusters 5, 9 or 13), some others more favourable for soil preservation and/or clean water provision (clusters 1 to 4). Generally, agricultural productivity conflicted with environmental objectives. Indeed, high yields were reached using large amounts of irrigation and with increased N-leaching and/or higher soil loss rates.

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

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

Compromise solutions for adaptation to climate change

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

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

On average, irrigation needs were always below the availability. Simulated irrigation amounts were similar in the two solutions and occurred from June to September, with a peak in July. As expected, irrigation needs were higher with ETH than SMHI, but with moderate magnitude despite the stronger signal suggested by ETH. For some months, a substantial amount of surface water was used to cover the needs in this scenario, as for instance in July when nearly 60% of the total surface water was necessary under the ETH scenario. About 10% of all agricultural areas were irrigated for both compromise solutions.

The two solutions exhibited many similarities but a few discrepancies. First, both of them agreed that conservation soil management (i.e. no till, harvest residues retained) should gain in importance and replace conventional soil management with regular till and harvest residues removed. Also, both options indicated that management intensity in terms of N fertilization, grass clippings and stocking density should remain at the recommended level.

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

In addition to reducing erosion in those areas, permanent grasslands would decrease soil temperature and, consequently, soil N availability and N loss from soils which are subject to leaching. The major difference between the two compromise solutions was found in terms of the regional crop mix. Indeed, cluster 11 was mostly dominated by permanent grassland, while cluster 16 focused more on crop production with, for instance, a large share of winter barley.

Conclusions

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

Conflicts exist between productivity and regulating functions, but compromises are possible. Indeed, the method presented here allowed identifying several acceptable solutions, one of them performing much better than the reference (1991-2015) with regard to thereof the four objectives for both climate scenarios. The only objective that could not be improved was water saving but on the average estimated irrigation needs did not exceed surface water availability.

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

- 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 favourable 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 (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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