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Agent-based modeling of agricultural adaptation to climate change in a mountainous area of Southwest Germany

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Abstract: We present an agent-based model of climate change adaptation for the agricultural sector of the Central Swabian Alps, a mountainous area in South Western Germany. Apart from climate effects on crop yields, the model also captures effects on crop rotation options, available time for fieldwork and exogenous price effects as potential pathways of climate change impact. First results underline the capacity of the model to simulate short-term adaptation and point to the importance of capturing future price developments to predict land-use effects of adaptation. For full dynamic simulations of the process of adaptation, the model will be extended with realistic learning algorithms and a land market module.

Keywords: agent-based modeling; climate change; adaptation; agro-environmental policy

1 INTRODUCTION

Understanding adaptation of agricultural production to changes in the natural and economic environment is a key requirement for assessing the effect of climate change on agricultural ecosystems, food and nutrition systems, and the economic development of the agricultural sector. Moreover, improving quality and precision of climatic predictions themselves, especially rainfall and water availability, requires integrating feedback loops with land use and land cover.

As Rosenzweig and Tubiello [2007, p. 860] note: “Adaptation in agriculture is the norm rather than the exception”. Farmers are used to react to constant changes in market prices, technological progress and changes in consumer preferences, and they are used to deal with weather variability. Adaptation of farming systems is therefore expected to occur autonomously to a large extent. Important questions for policy analysis are whether autonomous adaptation can keep up with the speed and extent of climate change in order to ensure food security and farm incomes, and whether it may trigger detrimental environmental or social effects. Governments may try to improve the outcomes of adaptation by implementing targeted policies of adaptation, which can, however, only be successful if incentives are effective in influencing farmer behavior. While climate change effects on crop yields are usually the primary focus of current studies, climate change may also affect agriculture via several other pathways including new options in crop rotation due to changed growing periods, changes in the available time for weather sensitive field work and changes in world market prices due to changing production potentials elsewhere.

Even though agent-based models are especially suited to form the socioeconomic component of an integrated model system of climate change adaptation in agriculture at a regional scale, their use for the simulation of agricultural adaptation to climate change has still been limited [Troost et al., 2010]. Here we present an empirical application of the agent-based software package MP-MAS [Schreinemachers and Berger, 2011] to assess climate change adaptation in South Western Germany. For this purpose, MP-MAS has been coupled with Expert-N, a software package for plant growth and nutrient matter cycling at plot level.

2 The MP-MAS/Expert-N model system for the Central Swabian Alps

2.1 Study area

The Central Swabian Alps are a low mountainous area (650-850 m.a.s.l.) in South West Germany, where agricultural production is constrained by shallow soils and a comparatively harsh climate (mean annual temperatures around 7 ℃, mean annual precipitation 800-1000 mm). Agriculture in the study area, which is located between Stuttgart and Ulm, is characterized by a relatively balanced mix of crop and animal production. Currently, a sequence of winter barley, winter rapeseed, winter wheat and summer barley is the dominant crop rotation, with some silage maize, clover and field grass production intermixed for dairy and cattle farmers. Silage maize production is considered risky due to a comparatively short growing season and the possibility of crop failure in early winters. Late wheat harvest dates that overlap with rapeseed sowing dates make rapeseed-wheat-wheat rotations infeasible for most farms.

A warmer climate with longer growing season is expected to increase flexibility in the choice of crop rotations and reduce the risk of silage maize production. Subsidies under the German renewable energy law (EEG) encourage investments into biogas plants and cultivation of silage maize and other ‘energy crops’. At the same time, environmental policy schemes (MEKA III), which form part of the second pillar of the European common agricultural policy (CAP), reward ecosystem services related to agriculture by subsidizing a diverse set of measures such as the diversification of crop rotations and grassland extensification.

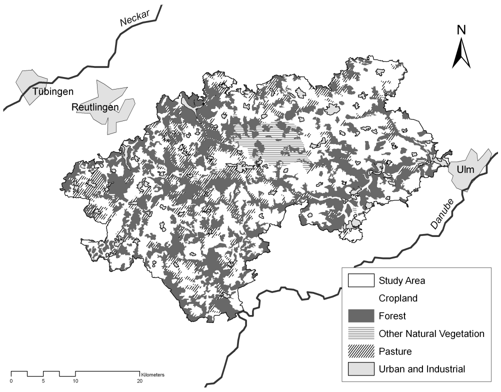

Figure 1: Study area (land use adapted from CLC2006)

2.2 The research project

The study area has been chosen as one of two model regions of a joint project[1] of the University of Hohenheim and Helmholtz Center Munich, which combines the development of an integrated land model system – consisting of climate, land surface, plant growth and socioeconomic model components – with field measurements, laboratory experiments and farm surveys to enhance process understanding and system knowledge. The land model system is build step-by-step, with software components and various set-ups of model linking being available for immediate testing and analysis. Here we present the

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[1] `http://www.uni-hohenheim.de/klimawandel`

coupling of the agent-based socioeconomic component implemented in MP-MAS with the plant growth and soil component implemented in Expert-N.

2.3 The multi-agent component MP-MAS

The socioeconomic component of the integrated model system is formed by an empirical application of MP-MAS [Schreinemachers and Berger, 2011]. MP-MAS provides a framework for recursive-dynamic modeling of farm holdings, using mathematical programming for the representation of agent investment, production and consumption decisions. The software supplies the accounting functions needed for temporal carry-over of financial and physical assets of each farm agent and the agent-specific rules for updating of price and yield expectations. In addition, it offers a spatial interface for soil type and land tenure maps, and a dynamic spatial interface that allows the export of land-use maps to and the import of yield maps from external crop growth models at run time. Optionally, different types of agent-agent interactions can be added including land markets, innovation diffusion, endogenous price formation, producer organizations or water reuse in irrigation systems.

The crucial element in applying MP-MAS to an empirical case study is the specification of the agent decision module that captures the relevant relationships between farmer objectives, production activities, available technology, resources and environmental and economic conditions. In our case, the implementation needs to be able to represent the adaptation of farm production (i.e. crop areas, animal numbers, intensity of grassland use, biogas production) to climate-induced changes in crop yields, changes in available time for field work, changes in crop rotation options as well as farmer response to changes in policy and market prices.

Agents in MP-MAS maximize expected farm income by choosing the optimal combination of land use, animal husbandry and biogas production subject to resource availabilities. Expected farm income is calculated as the sum of expected revenue from crop production R_c, animal husbandry R_h, biogas production R_b and received premiums from the MEKA policy schemes R_p minus variable costs V and fix costs F as shown in Equation 1, where $\mathbf{p}_e$ denotes expected prices, $\mathbf{y}_e$ expected yields, $\mathbf{a}$ crop and grassland activities, $\mathbf{f}$ the part of the crop that is used as animal feed, $\mathbf{h}$ animal husbandry activities, $\mathbf{k}$ biogas production, z the first year of biogas production, $\mathbf{M}$ the machinery owned and employed , $\mathbf{B}$ buildings and infrastructure owned and l hired labor. While the general structure of the goal function is the same for all agents, differences between agents arise due to different resource endowments and the development of different price and yield expectations based on the agents' experiences over the time of the simulation.

$$\begin{aligned} \max! \quad \pi_e = {} & R_c(\mathbf{p}_e, \mathbf{y}_e, \mathbf{a}, \mathbf{f}) + R_h(\mathbf{p}_e, \mathbf{h}) + R_b(\mathbf{k}, z) + R_p(\mathbf{a}, \mathbf{h}) \\ & - V(\mathbf{p}_e, \mathbf{a}, \mathbf{h}, \mathbf{f}, \mathbf{M}, l) - F(\mathbf{p}_e, \mathbf{B}, \mathbf{M}) \end{aligned} \tag{1}$$

Data on constraints and management practices for crop, animal and biogas production as well as machinery costs and capacities were taken from KTBL [2010] and cross-checked and, if necessary, adapted to local conditions with information from expert interviews and a farm survey. When selecting among various production options the following technical and legal constraints have to be considered : (1) Manure produced by animals and in the biogas plant has to be applied to the field during crop and grassland production; (2) crop yields depend on climate, soil and crop management; (3) harvested products can either be sold or used to cover the feedstock demand of animals and biogas plants; (4) production inputs, additional feedstock and investment goods can be bought from the market; (5) cropping activities are constrained by agronomic upper limits for the overall share of cereals (80%), maize (60%) and rapeseed (25%) in the rotation; and (6) by requiring a suitable preceding crop on each plot.

Further, all land-use activities are constrained by the time budget, which depends on available labor, machinery capacity and suitable weather for field work. For field work, agents have the choice between different equipment bundles with different capacities. The capacity of the available equipment for field work in each time slot is calculated using farm engineering data. KTBL [2010] provides a division of Germany into climatic regions and an estimate of expected days for field work of different weather sensitivity levels for each region and half-month of the growing season. Following this approach, we distinguish five levels of weather sensitivity: (i) cereal harvest; (ii) hay harvest; (iii) harvest of hay silage; (iv) medium sensitive activities such as harvest of silage maize, mineral fertilization, and sowing; and finally (v) less sensitive activities such as organic fertilization and incorporation of crop residues into the soil. We defined nine work seasons comprising between one and seven half-months (with fine resolution in summer and coarse resolution in winter), and calculated expected field working days for each sensitivity level and season based on the KTBL data.

To assess policy response of farmers, we included three measures from the current MEKA III scheme. Measure N-A2 rewards farms that produce at least four crops with a minimum share of 15% of their total arable area and less than 40% of maize with currently 20€ per ha. Measure N-B1 rewards farms that restrict livestock density to under 2 LSU/ha, abstain from grassland conversion and maw 5% of their committed grassland area after the 15th of June with 50€ per ha of grassland committed. Measure N-B2 rewards extensive livestock densities under 1.4 LSU/ha with 50€ per ha of grassland committed, additionally requiring between 0.3 and 1.4 grazing LSU/ha fodder area, no grassland conversion and no use of chemical plant protection on grassland. Participation in this environmental services scheme is voluntary, but agents have to commit to a measure for at least five years. We further considered the complete prohibition of grassland conversion enacted in 2011 and do not allow conversion of grassland to arable land in the model.

2.4 The biophysical model Expert-N

The Expert-N [Stenger et al., 1999] software package is used as the biophysical component of the model system. Expert-N integrates various modules for soil water flow, soil heat transfer, soil carbon and nitrogen turnover and crop processes in the soil-plant-atmosphere system on a daily basis. Expert-N provides a common interface to exogenous data such as meteorology, crop management and soil parameters. For each soil-plant sub-process, different module specifications can be chosen, which either have been developed for Expert-N or have been based on published model specifications. In our setup, we use DAISY [Müller et al., 2003] to simulate nitrogen and carbon dynamics in the soil, CERES [Ritchie et al., 1998; Ritchie, 1991] for plant growth of winter wheat, silage maize and barley, and GECROS [Yin and van Laar, 2005] for winter rapeseed. Currently, hay, hay silage and pasture yields for grassland and grass cultivation are not simulated explicitly. The mixed growth of different grassland species and growth interrupted by several harvests requires more sophisticated models, which still have to be incorporated into Expert-N.

Parameters for the DAISY, CERES and GECROS modules of Expert-N were estimated using weather and soil data as well as observations of field management, phenological growth stages, leaf area indexes (LAI) and biomass production that were collected in field measurements in the study area.

2.5 Integration: Cascading and coupling

Consistent integration of the two software packages is ensured by a shared MySQL database, which contains a complete description of crop production activities including the associated input quantities, costs, labor and machinery needs. Expert-N uses the data on sowing dates, fertilizer application, soil preparation and harvesting to calculate crop yields for specific soil and weather conditions, while MP-MAS uses the data on costs as well as labor and machinery requirements in the agent decision module.

The two software packages can either be used as a model cascade or as a run-time coupled model system. In the model cascade, Expert-N is run first in order to estimate yields for every predefined crop production activity under all soil and weather conditions. Results are written back into the database and can be used in subsequent MP-MAS runs to obtain crop yields under given weather scenarios. In the coupled model setup, MP-MAS and Expert-N exchange land use and yield maps at run-time through TCP/IP. This coupled setup allows recording soil state variables for each pixel and using them as start values for the subsequent year in order to simulate the feedback of production decisions on soil dynamics.

3 SIMULATION EXPERIMENTS

3.1 Prediction of crop yields

Spatial information of soil properties in the study area has been obtained using the LUBW [2007] digital soil map. The nine relevant soil mapping units were linked to reference soil profiles from the experimental sites and the profile database of the Institute of Soil Science and Land Evaluation of University of Hohenheim. Pedo-transfer functions were used to estimate soil properties. A meteorological time-series from the weather station in Stötten provides weather data for the years 1951-2010.

The calibrated Expert-N package was used to simulate yields for every possible combination of crop production activity and soil type and every year of the weather time series. Visual comparison with a “de-trended” time series of average regional yields (available for the years 1983-2009) showed satisfactory coincidence of yearly deviations from the long-term mean.

Table 1 provides results from yield simulation for various crops grown on two typical soil types in the study area. The table shows the average yields and standard deviation over all years and for the 20% warmest years only. Average yearly temperature in the 20% warmest years is 8.2℃, i.e. about 1.1℃higher than in the whole period, which gives a first, coarse indication for yield effects to be expected by an increase in average temperature.

3.2 Simulation of short-term adaptation

Cumulative distribution functions for farm endowments with land and livestock in 2007 were estimated from FDZ [2010] data and complemented by expert opinion, farm survey findings and spatial information on grassland, forest and arable land areas provided by CLC2006. We used an extended and improved version of the Monte-Carlo approach of Berger and Schreinemachers [2006] to create 533 agents representing the full-time farms of the area.[2] These agents differ greatly in their endowments with soil, buildings

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[2] at least 16 EGE (1 EGE = 1200€of standard gross margin) and at least one full time worker)

Table 1: Cereal yields predicted by Expert-N

		Average yield [dt/ha]		
Crop	Soil	1951-2010 (sd)	20% warmest	Change [%]
Winter wheat	Leptosol	6.1 (1.0)	6.5	+5.2
	Antrosol	6.7 (1.2)	7.2	+7.3
Winter barley	Leptosol	4.9 (0.5)	5.1	+4.1
	Antrosol	6.4 (0.9)	6.8	+6.4
Summer barley	Leptosol	4.1 (0.7)	4.0	-2.3
	Antrosol	5.0 (0.6)	4.9	-0.8
Winter rapeseed	Leptosol	3.3 (0.5)	3.6	+9.9
	Antrosol	3.6 (0.5)	4.0	+11.8
Silage maize	Leptosol	35.2 (8.2)	42.7	+21.3
	Antrosol	45.2 (8.1)	53.2	+17.5

and machinery (56 types of assets). Table 2 provides an overview of the distribution of a few key assets in the model population.

Table 2: Overview of the distribution of key assets in the sampled agent population

		Percentiles				
Resource	Avg	P10	P25	P50	P75	P90
Land [ha]	69.8	21	37	61	93	133
Grassland [%]	35.9	1.4	17.6	38.5	51.7	61.6
Dairy cow places	26.6	0	0	20	45	65
Sow places	25.7	0	0	0	0	100
83 kW tractors	.62	0	0	1	1	1
102 kW tractors	.30	0	0	0	1	1

Starting with this initial agent population, we use the model system to demonstrate the simulation of short-term adaptation of agricultural land use to biophysical effects that are likely associated with climate change. We first run a baseline scenario, then several scenarios considering each climate-related effect individually and finally scenarios with combinations of several effects. In all cases, agents fully anticipate the assumed changes and immediately adapt their production decision as far as possible within one year, i.e. taking into account their individual resource availabilities and farm management constraints.

The climate effect on crop yields is emulated by comparing land-use activities with average yield for the 1951-2010 period in the baseline, and the average yields of the 20% warmest years in the climate effect scenarios, each as predicted by Expert-N. The climate effect on available time for field work is emulated by using the days expected in neighboring less mountainous areas (KTBL zone 7, e.g. Kraichgau) instead of the original time spans in the study area (KTBL zone 4). With respect to crop rotations, we assume that growing winter rapeseed after winter wheat might become possible in the study area under climate change. Additionally to these biophysical effects, we also consider potential changes in world market prices. We obtained a time series of producer prices for agricultural products from 1998 to 2008 from vTI [2010], and took the average prices in this period for the baseline scenario, and the prices of the cereal price boom in 2007 as a representative of potential future price developments that might be caused by climate change, but also by increasing food demands due to a growing world population.

Simulation results shown in Table 3 point to a general increase of wheat and rapeseed area at the expense of barley and temporary grassland under a warmer climate. Yield effects are most pronounced, rotational effects point into the same direction, but are less strong, while climate effects on increased field work time only lead to an intensification of grassland production. Combined, these three biophysical effects lead to an increase of winter wheat (12%) and rapeseed (3%) production at the expense of all other crops. Price effects – at least if as extreme as in 2007 – are much stronger than the predicted climate effects, and most importantly lead to a near-complete reduction of fallow area compared to a 3-5% reduction in the climate scenarios.

Table 3: Predicted effect of short-term adaptation on crop areas in the study area

	Individual effects				Combined effects	
Crop	Yield	Work time	Rotation	Prices	Without prices	All
Winter wheat	10%	0%	1%	34%	12%	38%
Winter barley	-4%	0%	-2%	-3%	-7%	-7%
Summer barley	-5%	0%	-1%	-5%	-7%	-9%
Winter rapeseed	1%	0%	1%	27%	3%	28%
Silage maize	1%	1%	-3%	2%	-1%	4%
Temporary grassland	-3%	0%	-4%	-45%	-6%	-48%
Fallow	-5%	-3%	-3%	-97%	-6%	-94%
Intensive grassland	0%	3%	0%	3%	-2%	1%
Extensive grassland	0%	-1%	0%	-2%	-1%	-3%

All scenarios presented so far assumed the continuation of the MEKA III environmental service payments. Table 4 shows the effect of abolishing the measures in the baseline and the two combined effect scenarios. According to our simulations, this would lead to a reduction of wheat and rapeseed production and an increase in fallow – except in the scenario that includes the high price scenario. Apparently, for many farm agents wheat and rapeseed production is rather unprofitable under average ‘normal’ prices.

In any case, all of the results should be interpreted with care and mainly as a demonstration of the model’s predictive capacity, as the baseline still shows an overestimation of summer barley and an underestimation of silage maize areas compared to the situation observed in 2007. We attribute this to the fact that we have not yet implemented selling of silage maize to other farms that has become common after the expansion of biogas production.

4 CONCLUSIONS AND OUTLOOK

In this paper, we demonstrate the use of an agent-based coupled model system to simulate the adaptation of agricultural land use to climatic changes, representing the interaction between biophysical processes and farm management choice in a balanced way. Our model system captures different pathways of climate change relevant for the local

Table 4: Predicted effect of abolishing MEKA III policies on crop areas in the study area

		With climate effects	
Crop	Baseline	Without prices	All
Winter wheat	-16%	-7%	2%
Winter rapeseed	-18%	-8%	2%
Winter barley	7%	6%	2%
Summer barley	5%	5%	2%
Silage maize	0%	3%	1%
Temporary grassland	8%	9%	-1%
Fallow	56%	37%	0%
Intensive grassland	3%	4%	3%
Extensive grassland	0%	2%	2%

study area: yield effects, rotational effects and effects on available time slots for field work. We showed preliminary results of simulating short-term farm adaptation and the effect of environmental policy measures. At the same time, we showed that socioeconomic changes, like changes in product prices exogenous to the area, may have stronger effects than changes of climate.

In the presented short-term simulations, the agent-based setup allows to reflect the heterogeneity of farms in production decisions. Especially, the participation in subsidy schemes, which impose constraints on crop rotations and livestock density, can only be simulated at the individual farm level. The analysis of farm incomes and adaptive capacity of different farm types has been omitted for space considerations, but is facilitated by the disaggregated setup. Moreover, the agent-based setup will allow for fully dynamic simulations of the process and speed of adaptation and the analysis of long-term, structural effects in the next steps. To achieve this, our modeling framework is currently being extended to incorporate adaptive learning and regional markets for land and intermediate farm products. Using farm panel data from FDZ [2010] available for the years 1999, 2003 and 2007, our dynamic model system can then be validated against past development of the agricultural sector.

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