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Modelling climate effects on Hungarian winter wheat and maize yields

Hungarian cereal production is situated in the zone of Europe which is most vulnerable to the effects of changes in climatic conditions. The objectives of this paper are to present the calibration and validation of the 4M crop simulation model using farm-level observed representative values, and to estimate the potential yields of winter wheat and maize production for the next three decades. Analysing the differences between the estimated and observed yields, we identified as key influencing factors the heterogeneity of technologies and of land quality. A trend of slightly decreasing yields is projected for the next three decades for both cereals. The precise impact of environmental change on crop yields will depend on which climate scenario occurs.

Keywords: crop simulation, climate change, yields

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Introduction

Agriculture is sensitive to changing temperature and precipitation patterns as well as to frequencies of extreme weather events. A growing number of studies have dealt with the impact of climate change on agricultural production and the farming sector (e.g. Mendelsohn *et al.*, 1994; Chang, 2002; Seo and Mendelsohn, 2008; van der Werf, 2008; Wang *et al.*, 2009; Di Falco *et al.*, 2011; Chang *et al.*, 2012; Kaminiski *et al.*, 2013; Nelson *et al.*, 2014; Mitter *et al.*, 2015). The effects of climate change on agricultural production would highly depend upon the geographical location of the crop and animal production, with farms in some regions benefiting (Ghaffari *et al.*, 2002) and farms in other regions suffering adverse effects under new climatic conditions (Jones and Thornton, 2003; Key and Sneeringer, 2014).

Modelling supply and market price adjustments of the European Union (EU) agricultural sector as well as technical adaptation to climate change, Shrestha *et al.* (2013) estimated an increase in yields and production volume. In general, there are relatively small effects at the EU aggregate level and stronger impacts at regional level with some stronger effects prevailing in the Central and Northern EU and higher impacts in Southern Europe. The most negative effects of climate change in Europe were found to occur in the continental climate in the Pannonian environmental zone, which includes Bulgaria, Hungary, Romania and Serbia (Olsen *et al.*, 2011).

A growing number of recent studies provide evidence of climate change in Hungary (Spinoni *et al.*, 2013) and on the likely effects of climate change on Hungarian agriculture (Fodor and Pásztor, 2010; Fodor *et al.*, 2014; Gaál *et al.*, 2014; Kemeny *et al.*, 2014). These studies focus on biophysical and environmental consequences of climate change, and there are no empirical investigations on economic impacts of climate change on Hungarian agricultural production.

The objectives of this paper are, firstly, to estimate the impacts of climate change on yields in the Hungarian cereal

sector using the 4M crop simulation model and, secondly, to assess the possibilities for technological adaptation with regression analysis. The 4M model has been applied in previous studies focusing on soil and weather influence (Máthé-Gáspár *et al.*, 2005), and on the effects of climate change on crop yields in Hungary (Fodor and Pásztor, 2010; Fodor *et al.*, 2014). However, these studies are based mainly on experimental and non-representative farm-level data, whereas in this study we apply the model to representative Hungarian Farm Accountancy Data Network (FADN) data.

Methodology

Here we present the crop simulation and regression analysis models with the implementation settings and describe the data of the case study application.

Crop simulation model and implementation

The simulation of the effects of climate change on cereals yields is performed by using the 4M deterministic crop model. This mathematical programming crop model is adjusted to the Hungarian agro-technical and environmental conditions from the CERES model (Fodor *et al.*, 2002; Fodor, 2006). 4M is a daily-step deterministic model using input parameters of the atmosphere, soil and plant system. These input parameters are processed by the functions and equations of the model simulating the development and growth of plants and the heat, water and nutrient balance of the soil. The boundary conditions are primarily the daily meteorological data such as radiation, temperature and precipitation. The constraint conditions are the numerical expressions of human activities such as planting, harvesting, fertilisation and irrigation. In addition to plant development and growth, the model calculates the water, heat and nitrogen flows as well as the nitrogen transformation process of the soil.

The meteorological data include daily maximum and minimum temperatures and daily precipitation covering the area of Hungary with a one-sixth degree resolution grid, and were provided by the Hungarian Meteorological Service. The

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Meteorological Interpolation based on Surface Homogenised Data Basis (MISH) interpolation technique (Szentimrey *et al.*, 2005) was used for producing the grid of meteorological data from the local observations (Szépszó and Horányi, 2008; Szépszó *et al.*, 2011; Szépszó *et al.*, 2013). The soil use data are from the Hungarian Soil Information and Monitoring System (SIMS) covering clay, sand and organic matter soil types. The land use information was collected from the National Land Cover Database and was used to calculate agricultural areas within the meteorological cells used for simulation. The plant data, such as the phenological characteristics and stages, maximum root depth, light use efficiency and specific nitrogen content were determined from the relevant scientific literature (Fodor *et al.*, 2014). Agro-technical data such as planting date, plant density and fertiliser applications were provided according to the usual Hungarian agro-technology of each plant (Fodor *et al.*, 2014).

The calibration and validation of the crop simulation model

The calibration and validation of the 4M model was performed using actual crop fertilisation data as well as the observed yields for winter wheat and maize from the Hungarian FADN database for the period 2001-2012. The survey comprises detailed farm-level information on cost accounting, farming system and structural aspects.

The differences between the yields obtained from simulation and observed inputs were tested using equation (1):

$$Y_i = c + \beta_1 Y_{e,i} + \beta_2 dY_{e,i} + \beta_3 TC_i + \beta_4 LQ_i + e_i \quad (1)$$

where Y_i denotes the observed yield of every i farms, c is the constant term, $Y_{e,i}$ represents the simulated yields of the different farms by the 4M model, $dY_{e,i}$ is the difference of estimated yields of every farms from the average, TC_i and LQ_i denote deflated total costs and land quality of every farms obtained from Hungarian FADN survey data, e_i is the error term, and β are the parameters of the regression. The data used for the regression analysis are given in Table 1.

The effects of climate change on cereal yields

After validation of the model using observed Hungarian FADN data, the projections of the yields until 2050 were calculated based on the data of the farms selected for calibration and validation. The simulated yield values were adjusted using the parameters of the regression analysis.

The forecast of climate change is performed by the Hun-

garian Meteorological Service (*Országos Meteorológiai Szolgálat*, OMSZ) employing three regional climatic models from the ENSEMBLES project (van der Linden and Mitchell, 2009). The ALADIN, RACMO and REGCM models simulate different climate scenarios for the Carpathian Basin and Central and Eastern European regions respectively. These models are based on 50 km, 25 km and 10 km grids for the period 1951-2100, applying the newest emission scenarios. The model results are validated with observed data from the periods 1961-1990 and 1971-2000 and the projections are made for the periods 2021-2050 and 2050-2100 (Szépszó *et al.*, 2013). The interpretation of climate simulation models results should be made taking into account the uncertainty due to the estimation of physical processes and human activities. The application of these three regional climatic models offers the opportunity of addressing these uncertainties, but for a more complete estimation the regional simulation results of the ENSEMBLES project with 25 km grid density were applied (van der Linden and Mitchell, 2009).

Results

The differences between observed yields and the yields estimated with the 4M model indicated the need for calibration and validation. After adaptation to the changed environmental conditions, the model was used for the projection of winter wheat and maize yields.

Calibration and validation

In comparison to the observed yields, the winter wheat and maize yields calculated by the 4M model were lower in the years with favourable climatic conditions for cereal production, and higher in the years with unfavourable climatic conditions. To improve the comparability of the simulated yields with the observed yields, only those farms with the smallest differences between observed and estimated yields were retained in the sample. Based on five-year farm-level data sets during the period 2001-2012, 1,002 winter wheat and 1,075 maize producing farms were chosen. The 4M model was validated for these selected sample farms, the causes of differences between observed and estimated yields were investigated using regression analysis, and this validated crop simulation model was used to estimate the potential yields in the selected farms.

The regression analysis was based on estimated yield per hectare, difference of estimated yield per hectare, deflated total production costs per hectare and land quality parameters, and we found that main error source of the 4M model (the difference between observed and estimated yields) can be attributed primarily to heterogeneity of production technologies and the quality of land (Table 2).

In the calibration process, water stress and dry matter values were modified (Table 3). The calibration resulted in slightly higher coefficients of determination (R^2), but a more efficient indicator of calibration is the coefficient of variation of root mean square error – CV(RMSE). As a result of calibration we obtain values for CV(RMSE) that are closer to the critical value 40, when the estimated yields with the

Table 1: Description of the data used for the regression analysis.

| Parameter | Winter wheat | Maize |
|---|--------------|---------|
| Number of farms | 1,002 | 1,075 |
| Number of observations | 7,811 | 7,675 |
| Average observed yield, t/ha ⁻¹ (Y) | 4.16 | 6.48 |
| Average estimated yield, t/ha ⁻¹ ($Y_{e,i}$) | 4.21 | 6.50 |
| Average total production costs, HUF/ha ⁻¹ (TC_i) | 78,677 | 103,700 |
| Average utilised agricultural area, ha | 21.70 | 21.60 |

Source: own calculations based primarily on Hungarian FADN data

Table 2: Regression analysis results of the selected sample of farms.

| Parameter | Winter wheat | Maize |
|---|--------------|----------|
| Estimated yield per hectare ($Y_{e,i}$) | 0.284*** | 0.215*** |
| Difference of estimated yields per hectare ($dY_{e,i}$) | 0.045*** | 0.284*** |
| Total production costs per hectare (TC_i) | 0.305*** | 0.332*** |
| Land quality (LQ_i) | 0.183*** | 0.127*** |
| Constant (c) | 1.678*** | 1.534*** |
| Adjusted R square | 0.279 | 0.448 |

***/**/*: statistically significant, respectively at the 1%, 5%, and 10% levels
 Source: own calculations based primarily on Hungarian FADN data

calibrated simulation model can be accepted. Validation of our calibrated 4M model indicated that we improved the estimation characteristics of the model, which can therefore be used for yield forecasts.

Climate effects on expected crop yields

The forecasted yields of winter wheat and maize as a consequence of changes in the climatic conditions without more efficient risk mitigation follow a slightly decreasing

Table 3: Calibration and validation results of 4M crop simulation model.

| Calibration | | Calibration values | | Calibration/validation equation | | | Error indicators | | |
|--------------|------------|--------------------|------------|---------------------------------|----------|----------|------------------|--------|-----------|
| | | Water stress | Dry matter | Slope | Constant | R square | Mean difference | RMSE | CV (RMSE) |
| Winter wheat | Initial | 1.0 | 0.0022 | 0.5132 | 1.9952 | 0.1268 | -0.0243 | 1.8322 | 44.1677 |
| | Calibrated | 1.6 | 0.0021 | 0.4660 | 2.3001 | 0.1465 | 0.0848 | 1.5953 | 38.4551 |
| | Validated | 1.6 | 0.0021 | 0.4767 | 2.1753 | 0.1486 | -0.0173 | 1.5936 | 38.0350 |
| Maize | Initial | 1.0 | 0.0027 | 0.7456 | 0.6342 | 0.3112 | -1.0030 | 2.9280 | 45.4956 |
| | Calibrated | 1.7 | 0.0029 | 0.7638 | 1.4661 | 0.3203 | -0.0543 | 2.7494 | 42.7185 |
| | Validated | 1.7 | 0.0029 | 0.7401 | 1.4895 | 0.2969 | -0.1776 | 2.8418 | 44.3074 |

Source: own calculations (4M model)

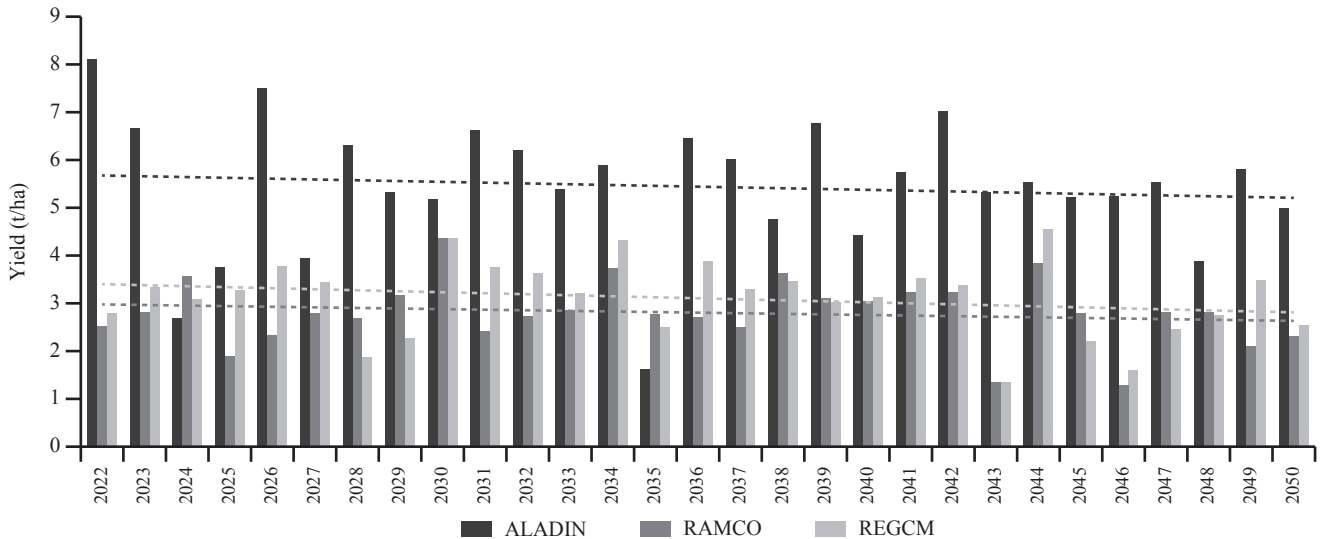


Figure 1: Winter wheat yield estimations according to three climate scenarios, 2022-2050.

Source: own calculations (4M model)

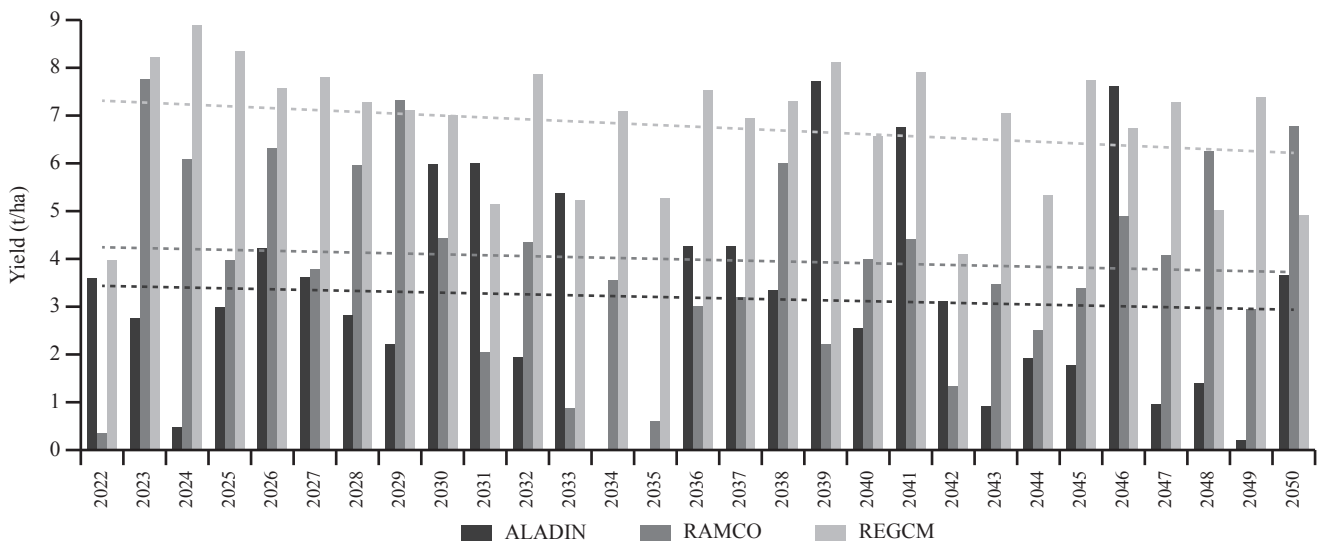


Figure 2: Maize yield estimations according to three climate scenarios, 2022-2050.

Source: own calculations (4M model)

trend in the coming decades (Figures 1 and 2). The average forecasted yields vary according to the climate scenario: for winter wheat and maize the estimated yields are close to current yields when the ALADIN and REGCM climate scenarios are considered, respectively. The predicted yields of winter wheat are sharply lower under the RACMO and REGCM climate scenarios while for maize production this trend is predicted under the ALADIN and RACMO climate scenarios. No climate scenario is favourable for both crops.

Considering farmers’ resilience and adaptation to the changing climate conditions, we adjusted the yield projections obtained with the 4M model with the parameters of the regression analysis (Figures 3 and 4). After adjusting the technology, the favourable climate scenarios for winter wheat and maize result in lower yields and the unfavourable climate scenarios result in higher yields. In both cases the ‘volatility’ of yearly average yields is reduced as a result of farmers’ risk mitigation arrangements.

Discussion

This paper investigates the impact of changes in climatic conditions on Hungarian winter wheat and maize yields using the linear programming 4M model and regression analysis to highlight the necessity of adaptation in private and public decisions (Antle and Capalbo, 2010). Previous studies (e.g. Fodor *et al.*, 2014) indicated that the 4M model provides realistic estimations for Hungarian crop yields. Other crop production optimisation models display similar performance at larger spatial scales (Moriondo *et al.*, 2011; Liu *et al.*, 2013).

Before calibration and validation, the simulated yields were systematically underestimated, but with the calibration and validation of the 4M model based on a Hungarian FADN representative sample of farms resulted in improved performance indicators (Table 2), the model is able to reproduce better the trend of observed yields variations. The regression parameters of the calibrated and validated 4M simulation

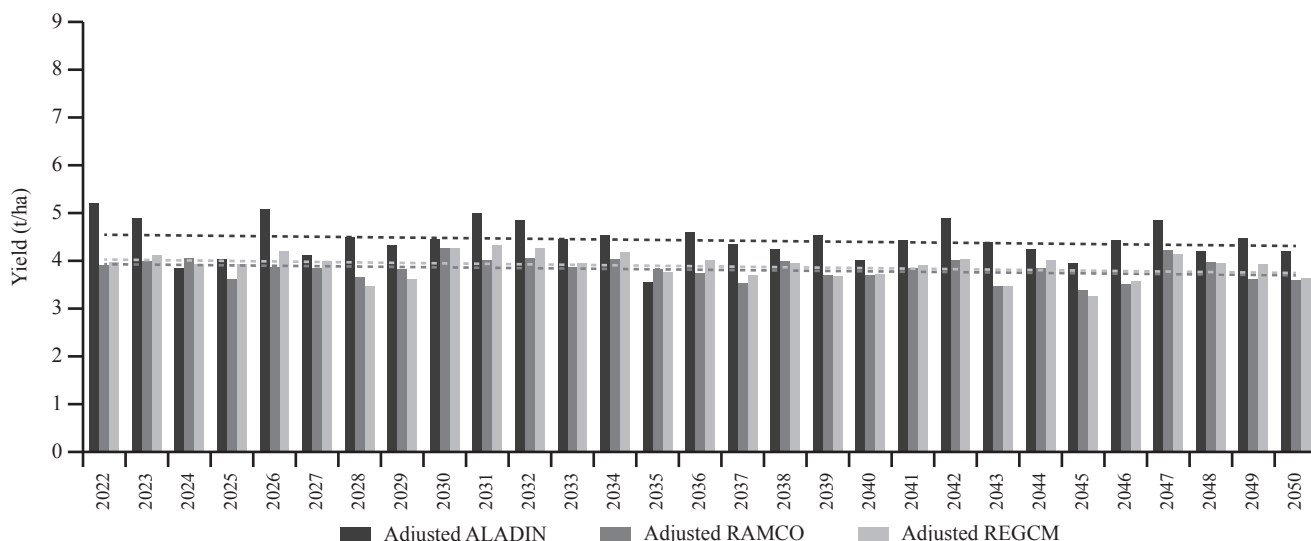


Figure 3: Adjusted winter wheat yields estimation according to three climate scenarios, 2022-2050.

Source: own calculations (4M model)

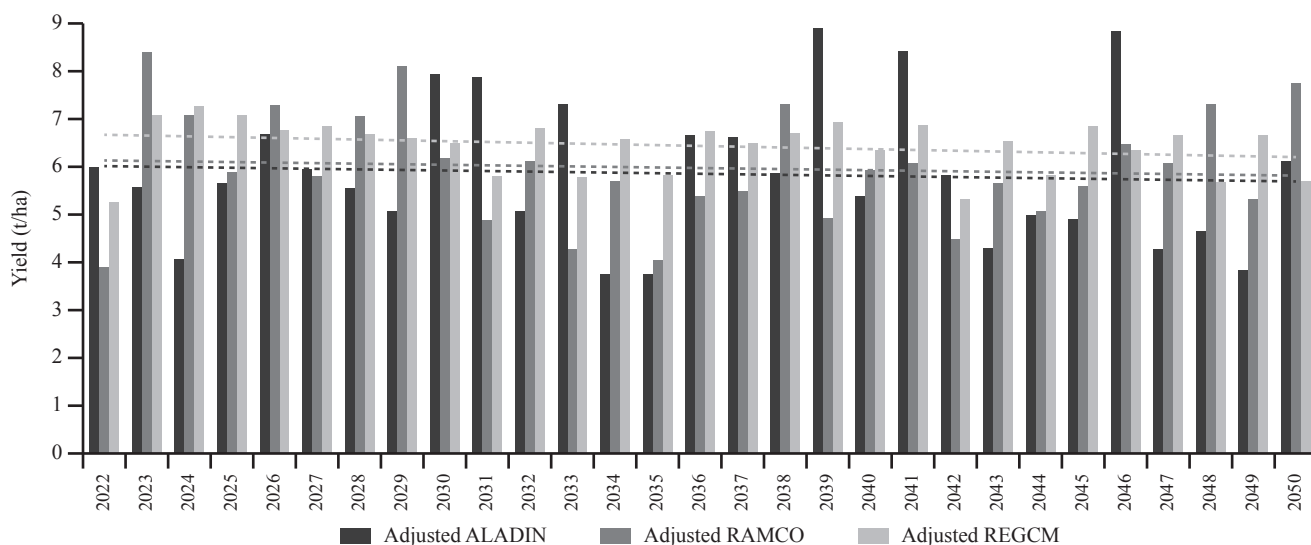


Figure 4: Adjusted maize yields estimations according to three climate scenarios, 2022-2050.

Source: own calculations (4M model)

results and the observed values indicate that the main factors causing the differences in the simulated and observed yields are the heterogeneity of production technology and land quality.

A slightly decreasing trend in the yields of both analysed crops is estimated for the next three decades due to the changes in climatic conditions. This trend for Hungarian crop production was also reported by Neményi (2015); his research shows that a sharp decrease in yields is expected in the second half of this century. This suggests that further investigations are needed to assess the capacity of Hungarian crop producers to adapt to the variations of climatic conditions that consider longer projections than those presented in this paper, changing sowing dates (Dobor *et al.*, 2016), and evaluation of different private and public adaptation measures.

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