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Coupling the 4M crop model with national geo-databases for assessing the effects of climate change on agro-ecological characteristics of Hungary

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The 4M crop model was used to investigate the prospective effects of climate change on the agro-ecological characteristics of Hungary. The model was coupled with a detailed meteorological database and spatial soil information systems covering the whole territory of Hungary. Plant-specific model parameters were determined by inverse modeling. Future meteorological data were produced from the present meteorological data by combining a climate change scenario and a stochastic weather generator. Using the available and the generated data, the present and the prospective agro-ecological characteristics of Hungary were determined. According to the simulation results, average yields will decrease considerably (~30%) due to climate change. The rate of nitrate leaching will prospectively decrease as well. The fluctuations of both the yields and the annual nitrate leaching rates will most likely increase approaching the end of the twenty-first century. On the basis of the simulation results, the role of autumn crops is likely to become more significant in Hungary. The achieved results can be generalized for more extended regions based on the concept of spatial (geographical) analogy.

Keywords: agro-ecological features; crop modeling; climate change effects; spatial soil information systems

Introduction

The Carpathian basin is an important area of crop production in Europe. Around 10^7 tonnes of yields of different crops are produced here for eight countries, not counting the exports. The majority of the agricultural land in the basin is located in Hungary (Figure 1). Regarding its plant production, Hungary ranks among the best in the world concerning the average yields of her main crops. One of the most important questions that Hungarian agriculture faces is whether this performance can be maintained in the future. Will the present agricultural practice be sustainable in the future or do we need new, profitable alternatives for sustainable agriculture in Hungary?

More and more observations prove that the Middle-European climate is changing faster than in any other period since the end of the Pleistocene epoch. A recent report of the European Environment Agency (EEA 2007) predicts that this

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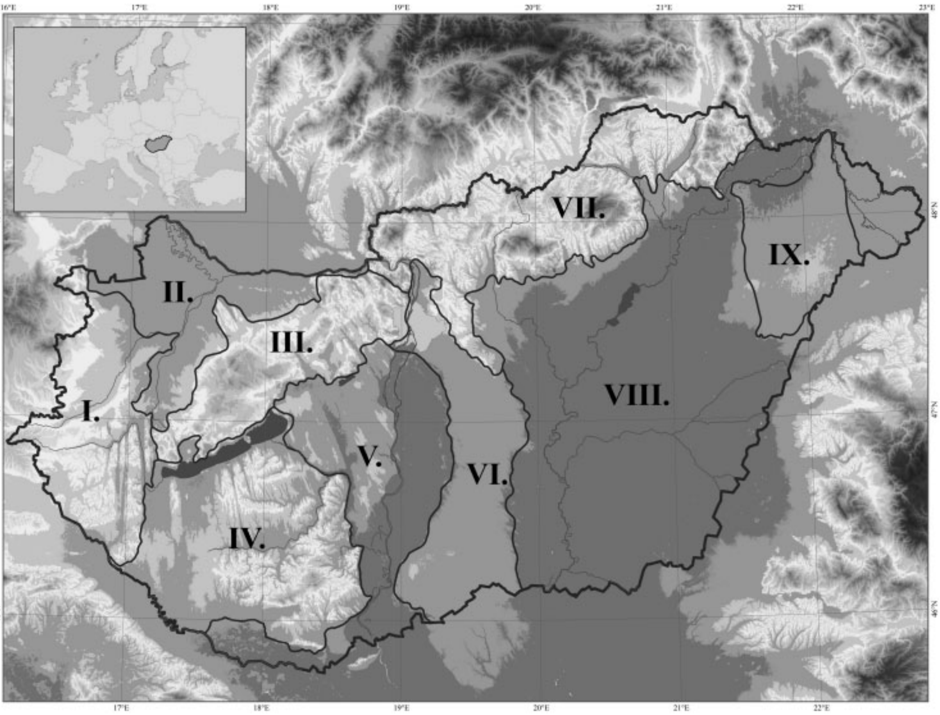

Figure 1. Location of Hungary within Europe and its main regions: Feet of the Alps (I.), Little Hungarian Plain (II.), Transdanubian Mountains (III.), Transdanubian Hills (IV.), Great Hungarian Plain (V., VI, VIII., IX), North Hungarian Mountains (VII.). The Great Hungarian Plain can be divided into four well-distinguishable regions, two of which (VI., IX.) are covered by coarse texture sandy soils while the other two regions (V., VIII.) are covered with fine texture loamy and clayey soils.

area will lose more plant species than it gains in the next 100 years mainly due to climate change. The human provision (plant breeding, developments in agro-technology, etc.) will help agricultural plants to adjust to the changing (climatic) conditions, but the question is to what extent?

Due to the complexity of the atmosphere–soil–plant system, it is very difficult to quantify the agriculture-related effects of the climate change. In the Carpathian basin, on one hectare of agricultural land around 4 TJ solar energy and 5–7000 tonnes of precipitation reach the soil surface in a year. From the several 100 kg of seeds, 10–50 tonnes of biomass develop within a couple of months. In the meanwhile, innumerable slower and faster, significant and less important processes take place that are more or less interdependent on each other. Crop simulation models were developed to give an approximate description of this complex system.

Models have been playing a very important role in scientific research from the beginning. In fact, any model is only a simplified representation of the components and their relationships of the examined system. The primary purpose of crop simulation models is to describe the processes of the very complex atmosphere–soil–plant system using mathematical tools and to simulate them with the help of computers. The ultimate aim of using these models, however, is to answer such production and environment-related questions that otherwise could only be answered by carrying out expensive and time-consuming experiments. The main advantage of simulation models is that they are capable of exactly describing the processes within, and interactions between complex systems. Theoretically, system models are the only scientific tools with which we can look into the future and assess the prospective effects of climate change (Rosenzweig and Parry 1994, Dhakhwa and Campbell 1998, Tubiello *et al.* 2000, Rosenzweig *et al.* 2002, Fodor 2006).

Practically, every model includes some kind of approximation, assumption, or simplification introducing some extent of error in the model calculations. Obviously, the main goal of model developers is to decrease this type of error. However, there is another error source. The main hindrance of improving and using crops simulation models is the lack of good quality measured input data that is required for operating and testing these models. Missing data could be provided by estimation procedures (Vereecken *et al.* 2010, Fodor and Mika 2011) or from databases (Gijsman *et al.* 2007, Horváth *et al.* 2007).

Despite the fact that many aspects of the potential effects of climate change in Hungary have already been investigated by researchers (Ladányi and Hufnagel 2006, Sipkay *et al.* 2008, Ladányi and Horváth 2010), very few studies have been carried out investigating the possible effects from an agro-ecological point of view (Harnos 2000, Boksai and Erdélyi 2009, Diós *et al.* 2009). These studies either focused on the changes in phenology and biomass production of some selected crops/species only, or used simplified soil databases and/or obsolete climate change scenarios. The main objective of the present study is to enlarge the scope of the previous studies by exploring and estimating the prospective effects of climate change on the agro-ecological characteristics of Hungary in more detail, more accurately by coupling the 4M crop simulation model with national geodatabases.

Materials and methods

Hungary is situated in the deepest part of the hydrogeologically closed Carpathian basin, where the majority of the parent material is of relatively young geological formation. The climate includes Atlantic, Continental, and Mediterranean elements. The water balance of the Great Hungarian Plain is negative (the deficit being mitigated by surface runoff, seepage, or groundwater flow from the more humid mountainous regions). Horizontal and vertical drainage conditions are poor; consequently the accumulation processes prevail in soil formation. Human activities (such as deforestation, grazing, water regulation, intensive farming, and urbanization) have had both significant effects on the soil formation and soil-degradation processes. Hungarian soil cover is highly heterogeneous.

Land, including soil, water, and near-surface atmosphere continuum, with its geology, relief, and biota, represents the most important part of Hungary's natural resources. The natural conditions (climate, water, soil, and biological resources) of the Carpathian basin (particularly in the lowlands and plains) are generally favorable for rain-fed biomass production. However, these conditions show high spatial and temporal variability; they are often extreme and sensitive to various natural or human-induced stresses.

Water resources are limited in Hungary. Spatio-temporal distribution of precipitation is highly irregular and more and more frequently produce extremities.

Most surface waters rise from beyond the national borders, whilst a considerable part of the limited amount of sub-surface waters is of poor quality (exhibiting high salinity and/or sodicity).

The arable lands (5.77 million hectares) in the country cover 62.5% of the total area. The average area of the farms is very low (8.6 ha). More than 90% of the private farms are smaller than 10 ha. Only 1% of the farms are over 100 ha. Fifty percent of the arable land is used for growing cereals (maize, winter wheat, and spring barley). Another 20% is used for growing industrial crops (sunflower and rape). Fertilizer consumption in Hungary is under the European average. The annual N balance of the country is around 20 kg ha^{-1} compared to the >100 kg ha^{-1} average of the Western European countries. The role of irrigation is insignificant in Hungary.

Meteorological data

A database of the Hungarian Meteorological Service for the 2002–2006 period was used in the study: including daily maximum temperature, daily minimum temperature, and daily precipitation, covering the area of Hungary with an one-sixth degree resolution grid. The Meteorological Interpolation based on Surface Homogenized Data Basis (MISH) interpolation technique (Szentimrey *et al.* 2011) was used for producing the grid of meteorological data from the local observations. The country is covered by 466 rectangles considered meteorologically homogenous. Despite of its shortness, the 2002–2006 period is representative for Hungary regarding the average annual precipitation sum and the mean temperature. Within this five-year period there is an average year, two years that are slightly under and above the average and two years that are considerably under and above the average regarding both the above-mentioned meteorological parameters. The average precipitation sum in the vegetation period is the one climatic factor that affects the final yield in Hungary the most. The spatial distribution of this parameter is presented in Figure 2.

Using the MV-WG stochastic weather generator (Fodor *et al.* 2010), a 31-year-long (1985–2015) artificial weather data series were produced for every meteorological grid cell based on their measured data series (2002–2006). The data generation procedure of MV-WG guarantees that there are no significant differences ($<5\%$) between the synthetic and the observed data with regard to the most relevant climatic characteristics (annual precipitation amount, average temperature, etc.).

A climate scenario was constructed based on the outputs of the ARPEGE-CLIMATE global circulation model (Déqué *et al.* 1998), which was then dynamically downscaled for Hungary with the ALADIN-Climate V4.5 regional climate model (RCM) (Bubnova *et al.* 1995, Wang *et al.* 2011). The IPCC SRES A1B scenario (Nakicenovic and Swart 2000) was used in the ALADIN simulations. The 10 km horizontal resolution outputs of the RCM (daily maximum/minimum temperature and precipitation data for the 1951–2100 period) were validated using the interpolated gridded data-set (0.1 deg regular grid) of observed data over Hungary for the 1961–1990 reference period (CECILIA 2009). The average prospective changes of the monthly climatic variables were estimated by comparing the 1961–1990 and 2071–2100 periods of the climate model outputs (Table 3). The parameterization of the MV-WG weather generator was altered according to these changes for every meteorological grid cell and two different 31-year-long (2085–2115) data series were generated for the future. The first parameterization was based

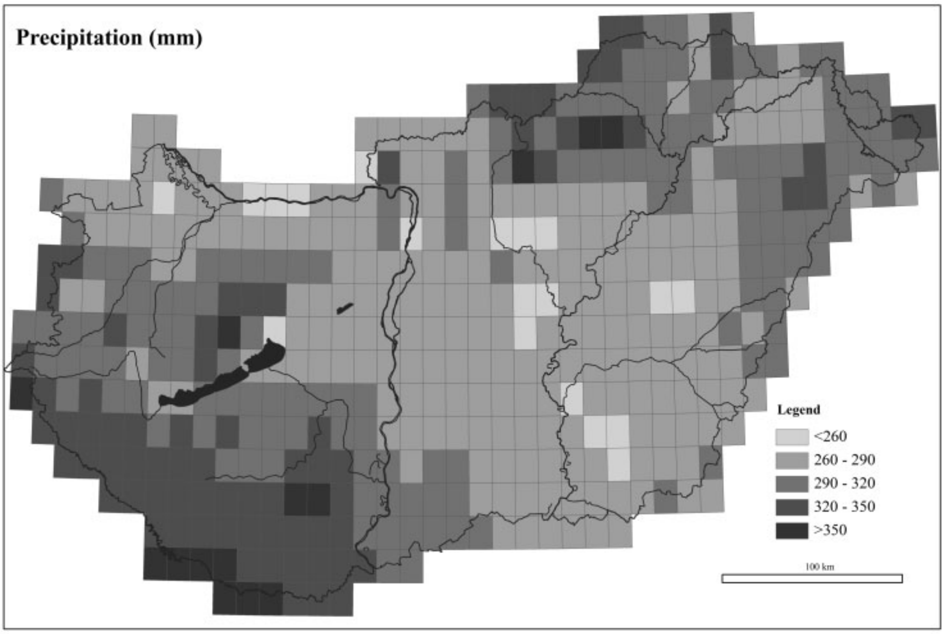

Figure 2. Spatial distribution of the cumulative precipitation in the vegetative period in Hungary, 2002–2006.

solely on the climate model outputs, while in the second one the predicted increase of the possibility of extreme weather events (Mika and Lakatos 2008) was also taken into account.

Based on the available generated temperature and precipitation data, the daily global solar radiation values were estimated using the S-shape method (Fodor and Mika 2011).The atmospheric CO_2 concentration raised from 350 to 400 and from 660 to 760 ppm in the 1985–2015 and the 2085–2115 series, respectively. Figure 3 summarizes the most important climatic characteristics of the weather data used in the study. The presented graphs provide an overview of the prospective changes of climatic conditions (elevated temperature and considerably less precipitation during the summer) as well as the increased possibility of extreme weather events (lower/higher minimum/maximum temperatures, higher one day precipitation rates and longer dry periods).

Soil- and land-use data

The majority of the soil properties are much less variable in time than the climatic characteristics. This is especially valid for the set of the soil parameters used in crop simulation models. Consequently, these can be represented by static data in modeling and there is no need for new data collection, input requirements can be fulfilled by available datasets.

An impressive amount of soil information is available in Hungary as a result of long-term observations, various soil surveys, analyses, and mapping activities (Várallyay 2002). The collected data are accessible in different scales: national,

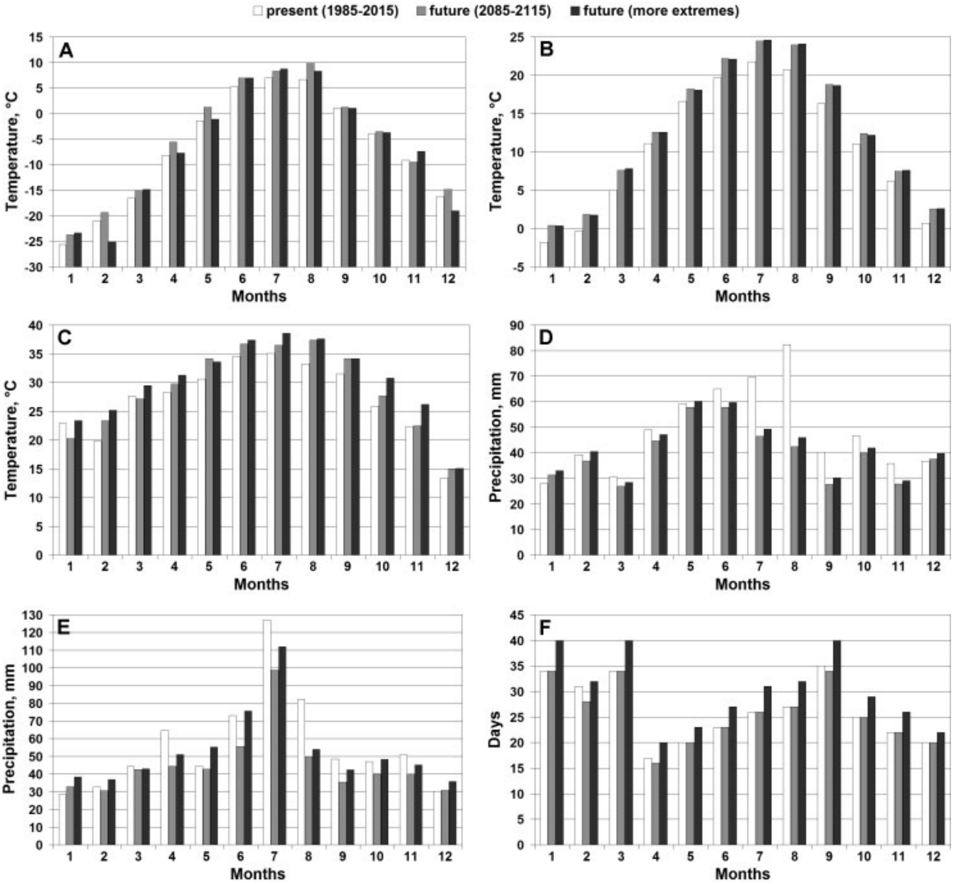

Figure 3. Climatic characteristics of weather data used in the study: (A) Minima of the daily minimum temperatures, (B) monthly mean temperatures, (C) maxima of the daily maximum temperature, (D) average monthly precipitation sums, (E) maxima of the daily precipitations, (F) longest dry spells.

regional, micro-regional, farm, and field level. Generally, these are related to maps and serve different needs for spatial and/or thematic aspects. Since spatial and semantic resolution can (and usually does) significantly differ, better results could be achieved by the integrated usage of various datasets (Szabó 2002).

Since the late 1980s, a gradually increasing part of these soil-related data has been digitally processed and organized into various spatial soil information systems (SSIS). The first national SSIS was the so-called AGROTOPO, which is practically the GIS adaptation of the ‘Assessment of the agro-ecological potential of Hungary’ program output in the form of 1:100,000 scale maps (Várallyay *et al*. 1979). AGROTOPO provides a suitable data source on the national–regional level for various applications. The Hungarian Soil Information and Monitoring System (SIMS) thematically covers a very wide range of soil characteristics providing a unique opportunity for detailed monitoring of the state of Hungarian soils and follow up of major trends in their conditions. Unfortunately, the 1200 SIMS observation locations were not selected to be spatially representative. The sampling was not designed for spatial inference of spatial information collected at SIMS points. As a consequence, SIMS provides vast and suitable information on actual soil conditions while the spatial features of this information are rather unsatisfactory. In order to provide reliable spatial inventories on the state of national soil resources, SIMS-based information need to be regionalized by adequate spatial inference of the collected data. This can be supported by spatially more detailed auxiliary soil information. This process requires the existence of an adequate national spatial soil information system with appropriate data structure and spatial resolution, as well as a proper methodology for the integration of the different type of datasets. The Digital Kreybig Soil Information System (DKSIS; Pásztor *et al.* 2010) represents a suitable candidate being the most detailed spatial data-set covering the whole country.

In order to combine the advantages of the two datasets, they were integrated in a specific way, elaborated by Pásztor *et al.* (2011). As a result, the quantitative parameters of SIMS could be regionalized for the area of the whole country with increased spatial resolution and accuracy, providing a more complex and realistic distribution of selected soil properties. For the present purpose, clay and sand content determined in SIMS plots were mapped this way, which facilitated the elaboration of Hungary's first detailed, digital soil map, displaying texture classes (Table 1) according to USDA classification (Soil Survey Staff 1951). The spatial resolution of the resulted map is approximately 1:50,000–1:100,000. The mapping units of this map defined the ultimate modeling units. The areal percentage of these basic physical soil types within each meteorological cell was then calculated. For the modeling units, average organic matter content and average soil depth were also determined. Based on the available clay, sand, and organic matter content data the rest of the required soil input data were estimated by the following pedotransfer functions: bulk density (Rawls 1983); field capacity, wilting point (Rajkai *et al.* 2004),

Table 1. Medians of the most important soil parameters for the 12 USDA soil categories for the 466 cells covering Hungary.

Soil texture category	BD (g cm^{-3})	SOM (%)	FC (cm^3 cm^{-3})	WP (cm^3 cm^{-3})	K_s (cm d^{-1})
Clay	1.26	1.90	0.380	0.180	5.9
Clay loam	1.24	1.68	0.374	0.174	13.5
Loam	1.34	1.36	0.355	0.175	14.9
Loamy sand	1.48	1.14	0.235	0.095	87.4
Sand	1.45	1.02	0.149	0.029	154.0
Sandy clay	1.43	2.02	0.310	0.160	6.6
Sandy clay loam	1.43	1.44	0.331	0.171	12.0
Sandy loam	1.43	1.27	0.309	0.149	28.1
Silt	1.31	1.59	0.385	0.205	7.0
Silty clay	1.26	2.00	0.384	0.194	5.2
Silty clay loam	1.23	1.78	0.382	0.192	10.4
Silty loam	1.20	1.46	0.376	0.196	22.3

BD, bulk density; SOM, soil organic matter content; FC, field capacity; WP, wilting point; K_s, saturated hydraulic conductivity.

and saturated hydraulic conductivity (Campbell 1985). Land-use information has also been available in various scales and details for Hungary. In the recent study the National Land Cover Database (CLC50; Büttner *et al.* 2004) was used for the calculation of agricultural areas within the meteorological cells used for the simulation. The standard CORINE Land Cover (CLC) database (scale 1:100,000) covers most of the EU Member States and is used to support policy-making at the pan-European level while national applications represent more detailed databases on land cover. In CLC50, the standard (level 3) CLC nomenclature was enhanced to include nearly 80 (levels 4 and 5) sub-classes. The 4 ha area minimum mapping unit provides enhanced geometric details. We exploited this latter feature. In each cell, only those areas were included in the model simulations that lie within the borders of Hungary and are involved in agricultural production.

Plant data

The approximate values of the plant-specific parameters (phenological characteristics and stages, maximum root depth, light use efficiency, specific N content, etc.) were determined based on the relevant scientific literature (Hodges 1990; Stockle and Nelson 1996). Then, the parameters were fine-tuned in four steps by inverse modeling (Soetaert and Petzoldt 2010), so that the averages and the variances of the simulated yields were similar to those observed in the 1961–1990 reference period. First, the phenological parameters (base temperature and length of phenological stages) were set so that the simulated occurrence of the main phenological stages would be in conformity with the real dates well known from the literature. In the second step, the model calculated the potential yields of the crops. This was achieved by adjusting the radiation-use efficiency and the specific leaf area parameters. Then, in the third step, the effect of the water stress was ‘switched on’ in the model, and the parameters of the relationship defining the effect of water stress were set so that the model results would be realistic among rain-fed conditions. Finally, the parameters defining the effect of nitrogen stress were determined. The obtained values of the most important plant parameters are summarized in Table 2.

The development and growth of the plants indicated in Table 2 were simulated. Although, it is obvious that some of the plant-specific parameters did change and will change in the investigated periods, all these parameters were considered to be constant during the simulations.

Agrotechnical data

The plant production model input data (planting date, plant density, fertilization doses, etc.) were provided according to the usual agro-technology of each plant (Table 3). The potential and the circumstances of plant production depend on many factors. Varieties are developing continuously thanks to the work of plant breeders. More and more Information and Communication Technology (ICT) applications (Global Positioning System [GPS], environmental monitoring sensors, advisory systems, etc.) are used for supporting plant production. Precision agriculture gains more and more ground. The volume of used fertilizers, irrigation water, growth regulators, and fungicides depends on the market status (relation of demand to supply), on business interests or even on political deliberations. For example, in

Table 2. The most important plant parameters obtained during the calibration of the model.

Parameter	Maize	Winter wheat	Sunflower	Spring barley	Rape
	Crop				
Base temperature (°C)	8	0	8	2	4
GDD from emergence to flowering (°Cd)	720	950	600	800	1050
Radiation use efficiency (g MJ^{-1})	3.85	2.60	3.60	2.35	2.25
Mass partition among root/stem/leaf in the early growth stage (%)	20/10/70	15/20/65	20/25/55	20/10/70	20/40/40
Mass partition among root/stem/leaf after the early growth stage till flowering (%)	15/45/40	15/70/15	20/45/35	15/65/20	15/70/15
Specific leaf area (m^2 kg^{-1})	22	16	14	16	18
Life span of leaves (°Cd)	850	800	650	700	650
Maximum root depth (m)	1.7	1.3	1.8	1.3	1.5

Hungary, owing to the socialist ideal of production there were state farms where 900 and 600 kg ha^{-1} of active ingredient N–P_2O_5–K_2O fertilizer was applied annually in the 1970s and 1980s for maize and winter wheat, respectively. Due to the withdrawal of subsidies, after the change of regime in the early 1990s, N fertilizer consumption dropped by 80% while PK fertilizer consumption decreased by more than 95% in a few years compared to the earlier intensive period. Despite these facts, the agrotechnics was postulated to be invariant throughout the investigated periods.

Table 3. Relevant agrotechnical data used as model input data in the study.

Crop rotation		Planting date (mm/dd)	Plant density (plant m^{-2})	Date of N fertilization (mm/dd)	Amount of N fertilization (extensive/ intensive) (kg ha^{-1})	Depth on N fertilizer incorporation (cm)
I.	Maize	04/20	7	04/01	85/170	25
	Sunflower	04/20	5	04/01	40/80	25
				10/05	15/30	25
	Winter wheat	10/15	500	02/28	45/90	0
				04/25	15/30	0
II.	Maize	04/20	7	04/01	85/170	25
				02/15	20/40	25
	Spring barley	03/05	500	04/25	20/40	0
				08/15	15/30	25
	Rape	09/10	100	02/01	35/70	0
				04/20	35/70	0
				10/05	15/30	25
	Winter wheat	10/10	500	02/28	45/90	0
				04/25	15/30	0

Note: Two scenarios with different N fertilization loads (extensive/intensive) were defined for both rotations.

Crop simulation model

The 4M crop simulation model (Fodor *et al.* 2002, Máthéné *et al.* 2005, Fodor 2006) was used in the study. 4M is a daily-step, deterministic model whose computations are determined by the numerical characteristics (defined by input parameters) of the atmosphere–soil–plant system. Besides the data that describe the physical, chemical, and biological profile of the system, it is also necessary to set its initial, boundary, and constraint conditions in the input file of the model. The parameters regulate the functions and equations of the model: the development and growth of plants and the heat, water, and nutrient balance of the soil. The initial conditions are the measured system variables at the beginning of the simulation run such as the water or nutrient content of the soil. The boundary conditions are primarily the daily meteorological data, such as global radiation, temperature, and precipitation. The constraint conditions cover the numerical expressions of human activities such as data about planting, harvest, fertilization or irrigation. Besides the plant development and growth, the model calculates the water, heat, and nitrogen flow as well as the nitrogen transformation processes of the soil: for example the amount of nitrate that percolates down under the root zone and the amount of the NO_x gases released from the soil due to denitrification (Figure 4).

The plant phenological development is dependent on temperature and is related to thermal time (TT). Thermal time is a summation of the differences between the daily mean temperature and a plant-specific base temperature, and has a unit of degree-days (°Cd). Under the base temperature the plant ceases to develop. The

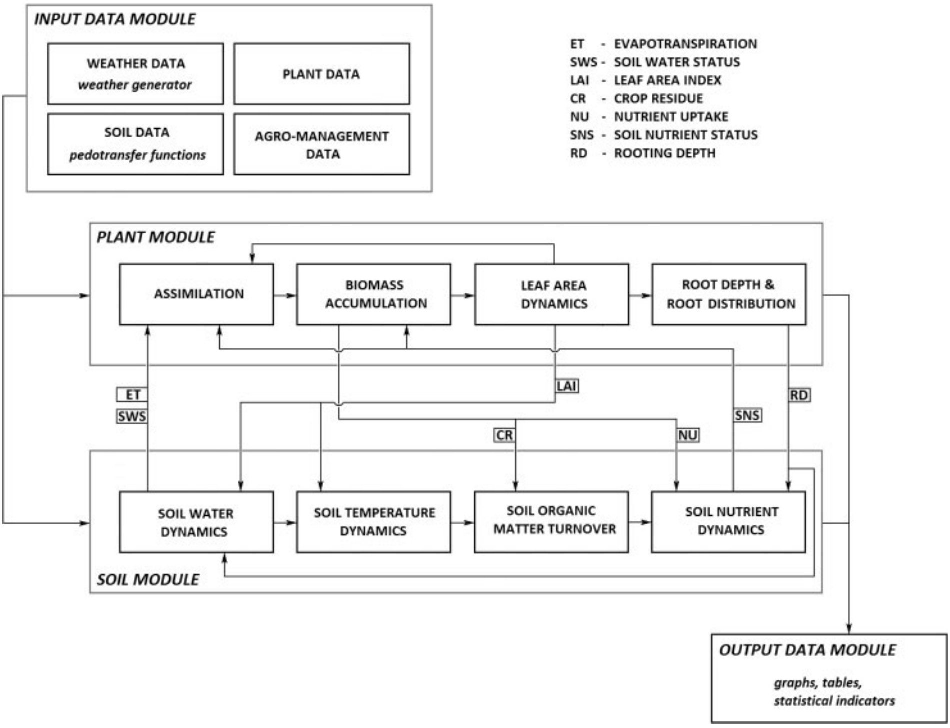

Figure 4. Flow chart of the 4M crop simulation model.

length of the phenological stages (in degree day) should be provided by the user. Daily assimilation is calculated by a light-to-biomass conversion equation (Equation 1). Its key parameter is the radiation use efficiency (RUE). The daily assimilation rate (M) depends on the global radiation (R), the leaf area index (LAI), the plant density (D), the minima of the heat (S_T), water (S_W), and nitrogen (S_N) stress-factors and a function of CO_2 concentration in the air.

$$\mathrm{M} = \mathrm{RUE} \cdot \frac{\mathrm{R} \cdot (1 - \mathrm{e}^{-0.55 \cdot \mathrm{LAI}})}{D} \cdot \min(\mathrm{S_T}, \mathrm{S_W}, \mathrm{S_N}) \cdot \mathrm{f}(\mathrm{CO_2}) \tag{1}$$

After calculating its mass, the generated matter is divided into the major parts (root, stem, leaf, yield) of the plant. The ratios of the partitioning (Table 2) change with the phenological stages. In the early development period, the majority of the matter is allocated to the leaves. For the simulated plants, in the last stage almost 100% of the matter is moved to the grains (The exception is the sunflower as its head stores lots of matter.). The matter allocated to the leaves is converted to area by multiplying the mass with the specific leaf area. The age of every leaf area portion that is added to the total area in a day is kept on record. If the age of a portion exceeds the value of the 'life span of leaves' parameter it 'dies' ceasing to take part in the photosynthesis. Root expansion (RE) is dependent on the daily thermal time (TT_d) and the minima of the water (S_W) and nitrogen (S_N) stress factors (Equation 2). The value of a parameter may change during plant development.

$$\mathrm{RE} = \mathrm{a} \cdot \mathrm{TT_d} \cdot \min(\mathrm{S_W}, \mathrm{S_N}) \tag{2}$$

The shape of the root distribution function is defined by the user.

The water balance module calculates the following elements: runoff, evaporation, transpiration, and the volume of water percolating both downward and upward. It models the soil layers as a series of water reservoirs characterized by four parameters: maximum water-storing capacity (Θ_{max}), field capacity or drained upper limit (Θ_{fc}), water content at wilting point or lower limit (Θ_{wp}), and saturated hydraulic conductivity (K_S). If the incoming water fills up the layer ($\Theta > \Theta_{max}$) the excess water is redistributed in the layers above. If the water content is above the field capacity ($\Theta_{max} \geq \Theta > \Theta_{fc}$) a definite portion of water flows (Q) to the layer below (Equation 3).

$$Q = \mathrm{DC} \cdot (\Theta - \Theta_{\mathrm{fc}}) \cdot \Delta z \tag{3}$$

DC is the drain constant, which is derived from K_S, and Δz is the thickness of the soil layer. If the water content is less than the field capacity ($\Theta_{fc} \geq \Theta > \Theta_{wp}$) no downward flow occurs, however the water content of the layer can decrease due to plant uptake. If the water content is below Θ_{wp} the plant water uptake ceases.

When calculating the actual soil temperature (T_{soil}) at a given depth (x), this model takes into account that the upper soil layers absorb energy and the heat needs time to reach the lower layers. The effect of the energy reaching the soil surface appears delayed and decreased in the lower soil layers. The extent of the delay and the decrease is a function of the actual average moisture content (Θ_{avg}) and the average bulk density of the topsoil (BD_{avg}). The model assumes a sinusoidal annual course of the soil surface temperature that is modified by an additive term of a 5-day moving average of a factor (F_{D5}), which is a function of the albedo of the surface, the daily mean, and maximum temperature as well as the daily global radiation (Equation 4).

$$T_{\mathrm{soil}}^{i}(x) = T_{\mathrm{avg}} + \left(\frac{T_{\mathrm{amp}} \cdot \cos\left(0.0174 \cdot (i - I) + x \cdot f\left(\Theta_{\mathrm{avg}}, BD_{\mathrm{avg}}\right)\right)}{2} + F_{D5} \right) \cdot e^{x \cdot f\left(\Theta_{\mathrm{avg}}, BD_{\mathrm{avg}}\right)} \qquad (4)$$

where T_{avg} and T_{amp} denote the average temperature and the average temperature difference of the site, i denotes the day of the year, I equals 200 on the Northern hemisphere, while it is 20 on the Southern hemisphere.

The soil organic matter (SOM) sub-model is based on the work of Parton *et al.* (1987). The sub-model includes three SOM pools (active, slow, and passive) with different potential decomposition rates, above and belowground crop residue pools and a surface microbial pool, which is associated with decomposing surface residue. The decomposition of both plant residues and SOM is assumed to be microbially mediated with an associated loss of CO_2 due to microbial respiration. Each pool is characterized by different maximum decomposition rates, which are reduced by multiplicative functions of soil moisture and soil temperature. The decomposition rate of the active SOM pool (turnover time: months to a few years) is influenced by the soil texture (lower rates for clayey soils), as well.

The nutrient sub-model uses simple equations to represent N inputs and outputs attributed to atmospheric deposition, fertilization, mineralization, nitrification, immobilization, denitrification, plant uptake, and nitrate leaching. Atmospheric N input is a linear function of precipitation. The model includes N inputs through inorganic and organic fertilizer additions. The rate of mineralization is function of the soil humus content as well as of the water content and temperature. The soil water content and temperature also influence the nitrification and the denitrification rates, which are functions of the soil NH_4 and NO_3 contents, respectively. The potential rate of plant N uptake depends on the volume of roots present in the soil and is reduced by a multiplicative function of soil moisture. The actual uptake depends on the plant N demand, which is a function of the daily matter production and the specific N content of the plant. The latter changes during the phenological development of the plant. The amount of nitrate leaching is proportional to the soil NO_3 concentration and the volume of drainage water.

Verification of the model

The actual fertilization levels as well as the observed yield levels for maize, wheat, sunflower, barley, and rape were collected from the yearbooks of the Hungarian Central Statistical Office for the 2002–2006 period for the 19 counties of Hungary (Figure 5). The available (weather, soil, plant, etc.) data were given to the model as inputs. For each cell, five-year-long monocultures were simulated with the investigated crops. The calculated yields were standardized as these were converted into cereal units (CU) by multiplying the actual yields with 1 for maize, wheat, and barley, with 1.3 for sunflower and with 1.8 for rape. County averages were calculated by averaging the CU yields of the five crops for the five years over the modeling units pertaining to the counties.

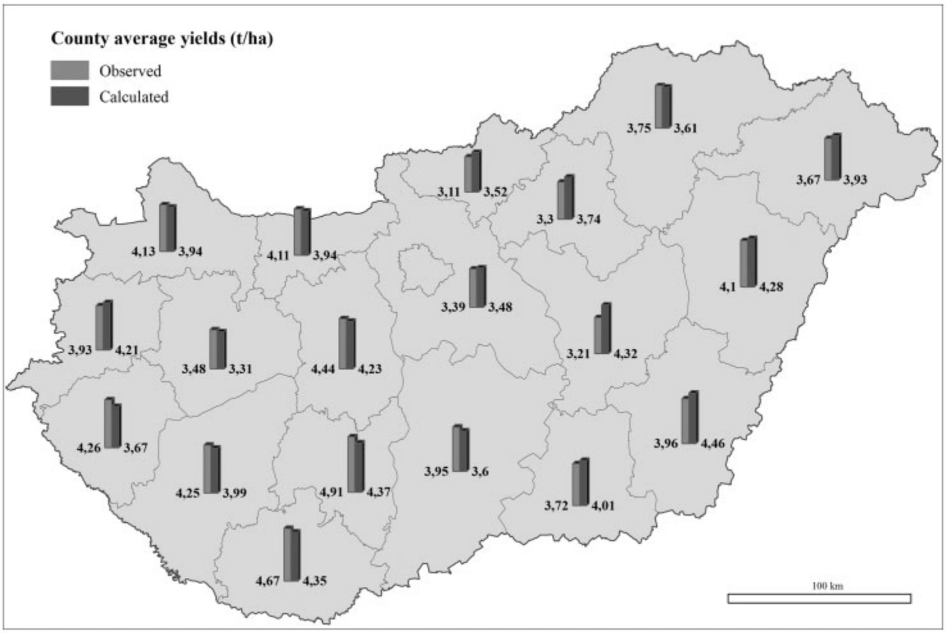

Figure 5. Observed and calculated county average yields in cereal unit for the 2002–2006 period in Hungary.

Numerical experiments

The weather, soil, and plant data described previously were provided as inputs for the 4M model. The model was run for every meteorological cell for every existing USDA soil texture category within the cell for both crop rotations and fertilization levels. This resulted in $1652 \times 2 \times 2 = 6608$ runs as there are 1652 existing combinations of the 466 meteorological cells and 12 soil categories. Normally, only three or four categories are represented in a meteorological cell. These simulations were carried out with the present (1985–2015) and the two types of future (2085–2115) weather data series. Simulation results were then summarized for each cell using territorial occurrence percentage of the soil categories present in the given cell as weights. The following model outputs were investigated:

- Average cumulative precipitation in the growing season, mm.
- Average denitrification rate, kg ha^{-1} y^{-1}.
- Average nitrate leaching rate, kg ha^{-1} y^{-1}.
- Average cumulative evapotranspiration in the growing season, mm.
- Average biomass, tha^{-1} and t per cell.
- Average yield, t ha^{-1} and t per cell (in cereal unit: yields of the sunflower and the rape were multiplied with 1.3 and 1.8, respectively).
- Cumulative water stress.
- Cumulative nitrogen stress.
- Cumulative heat stress.

Water stress factor (WSF): As the soil dries out the plant water uptake and the transpiration become limited. WSF is the ratio of the actual and the potential daily transpiration. Its value is between 0 and 1. It is used as a multiplicative factor when calculating mass production. Since the WSF works with a logic opposite to the common sense (it is small/great when the stress is great/small) in the output file the 1-WSF value is cumulated and defined as cumulative water stress.

Nitrogen stress factor (NSF): The ratio of the actual plant N uptake and the plant N demand. It works similarly to WSF.

Heat stress factor (HSF): There is a range for every plant (depending on the species) when the temperature does not limit the development and growth. As the temperature decreases/increases below/above the lower/upper limit of this range, the plant senses more and more heat stress as the HSF tends to zero. HSF works similarly to the other two stress factors.

Every day, only one of the stress factors (with the lowest value) affects mass production. If the WSF/NSF/HSF are 0.25/0.35/0.55 on a given day the actual mass production is only one quarter of the potential and only the 'cumulative water stress' variable is increased with 0.75.

Results and discussion

The county-level averages of the observed and simulated yields are represented in Figure 5. The relative error of the calculated yield levels was not larger than 15% (average: 10.9%, range: 6.1%–37.8%) for all of the counties, except for one. In Jász-Nagykun-Szolnok county, the model considerably overestimated the observed yield (in average: 4.32 vs. 3.21 t ha^{-1}) in all of the investigated years (2002–2006). In this county, large areas are covered by salt-effected soil and/or high clay content soils with shrinking–swelling characteristics. High salt content in the soil may cause increased water-stress. The shrinking–swelling soil feature is disadvantageous both in dry and in moist periods. In dry periods, the presence of cracks increases soil evaporation. In moist periods, the soil surface with extremely low conductivity may cause inland waters. Neither one of these phenomena are accounted for in 4M, which may explain the poor performance of the model in this county.

The outputs of the maize–sunflower–wheat and the maize–barley–rape–wheat rotations did not differ significantly though the latter resulted in smaller average nitrate leaching rates: 14.6 kg ha^{-1} y^{-1} compared to 13.1 kg ha^{-1} y^{-1}. This difference might be attributed to the higher ratio of crops sown in autumn in the latter rotation: 50% compared to 33%. Due to the small differences only the results of the maize–sunflower–wheat rotation, which is more frequently used in Hungary, are presented. The summarized model outputs are presented in Figures 6 and 7.

The yields of the regions with sandy soils (VI., IX) are low (Figure 6), though the latter region (in the North-Eastern part of the country) is more fertile owing to the greater volume of precipitation (Figure 2). The better soils of the Great Plain (region VIII.) can produce higher yields than the sandy soils (region IX.) even though the latter receives considerably more (~30 mm) precipitation in the vegetation period (Figure 2). The loamy and clayey soils are able to store 60–80 mm more precipitation in their root zone than the sandy soils. By saving more winter precipitation than the rain surplus of the North-eastern sandy territory, the region (VIII.) with finer soil texture can produce higher yields. The sandy area in the middle of the country

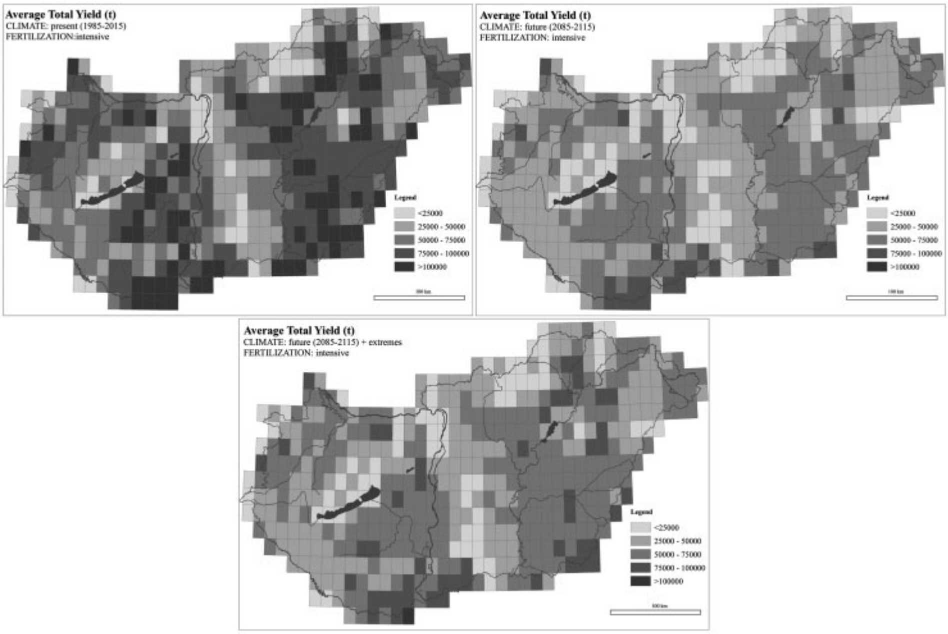

Figure 6. Prospective changes of the spatial distribution of yields due to climate change.

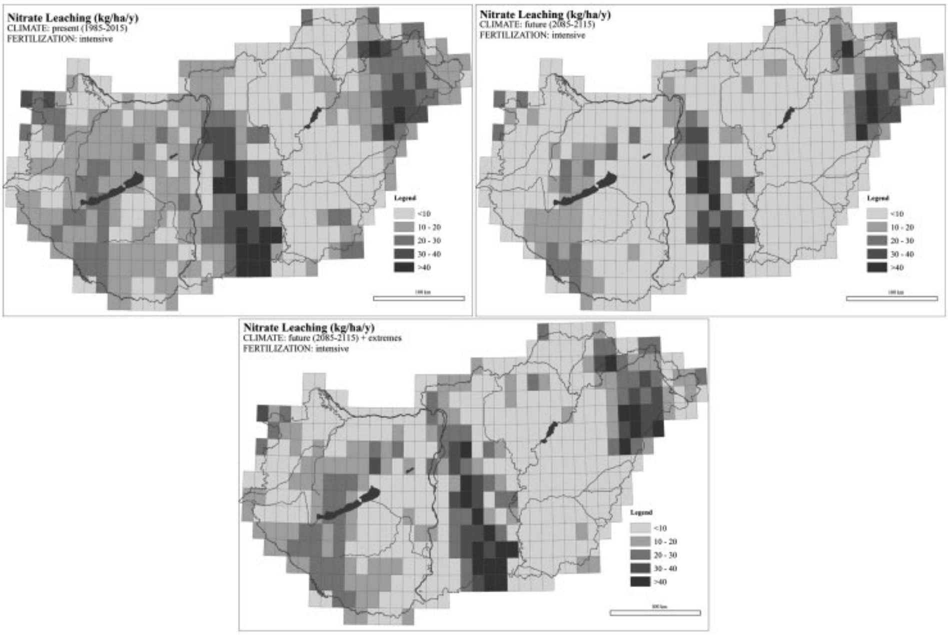

Figure 7. Prospective changes of the spatial distribution of nitrate leaching rates due to climate change.

(region VI.) is the most disadvantageous part of Hungary regarding plant production as it receives a relatively small amount of precipitation in the vegetation period and has poor hydrological characteristics.

Among the plant stress reactions water stress is the most significant. Water stress was clearly dominating on the soils with poor hydrological characteristics combined with extensive fertilization as well as on every soil type with intensive fertilization. There were exceptions, of course. Sunflower has low N demand, thus with the exception of the 'low humus content sandy soil – extensive fertilization' combination, N stress is negligible compared to the water stress in case of this plant. The nitrogen and the HSFs were found to be invariant for the two investigated periods. It is not surprising in case of the NSF, since the N demand of plants were constant during the simulations. The invariance of the HSF can be explained by the fact that hot days coincide with the days with high potential transpiration when water deficit usually occurs. The water stress typically exceeds heat stress since plants are more sensitive to water shortage. The difference between the calculated WSFs of the present and future scenarios was significant. The increase of water shortage has a clear effect on the biomass production.

Prospective yields will considerably decrease due to the climate change (Figure 6). One hundred years from now average yields will be some 34% lower than the present yields according to the simulation results. Owing to the decreased precipitation sum in the summer the typical cumulative WSFs in the vegetation period will be significantly higher in the future. Though higher CO_2 concentration in the atmosphere results in an increased plant stomatal resistance and a better water-use efficiency (Garcia *et al.* 1998, Anda and Kocsis 2008), this effect cannot counterbalance the summer water shortage. According to the simulation results, average future yields for the country will be 3475 or 3800 kg ha^{-1} cereal unit depending on whether the predicted increase of extreme weather events will or will not take place. At present, this figure is 5200 kg ha^{-1}. The higher yields of the future scenario with more extremes could be attributed to the soil, which can store the increased amount of precipitation coming with the more intense rainfall events (Figure 3E). It has to be noted that the applied crop simulation model is a daily step model that postulates evenly distributed precipitation throughout the day during the water balance calculations. This may result in underestimating the runoff (especially for clayey soils) as it is obviously not indifferent whether the daily precipitation reaches the soil surface within 30 minutes or 24 hours. Consequently, it cannot be stated explicitly that the increased extreme weather events would result in increased yields. The 'effect' of hail storms was not (and cannot be) simulated. Nonetheless, it seems that the increased temperature (longer heat waves) will not cause serious yield loss as it will not affect the simulated plants considerably. As a result of the shortened vegetation period, wheat will be harvested in the second half of June, thus it is less likely to be affected by the extremely hot periods usually occurring in July and August. Maize and sunflower originate from the subtropical climate, thus they tolerate high temperatures well. Due to its earlier harvest time, winter wheat yields will change to a considerably smaller extent than that of the maize and sunflower. According to the simulation results, the average yields will decrease with 500, 2000, and 800 kg ha^{-1} for wheat, maize, and sunflower, respectively. The coefficient of variation of the simulated yields (31 years for each cell) was higher for the future climate scenarios (53%) than for the present (46%). This difference corresponds with a 15% increase predicting a considerable decrease of yield safety. These findings are in line with the results of the earlier (lower spatial resolution or local) studies that also predict the decrease of yields (Bacsi *et al.* 1991, Harnos *et al.* 2002, Erdélyi *et al.* 2007) owing to the increase of water limitation in crop production (EEA 2011). The negative effects of water stress would only be partially compensated by elevated CO_2 concentration (Chloupek *et al.* 2004). The above results seem to contradict with the findings of Iglesias *et al.* (2012) who prognosticate a significant (>20%) increase of yields for this region of Europe. It is very important to note that their simulations considered no restrictions on water use for irrigation nor in the application of nitrogen fertilizers, which is quite an unrealistic scenario for Hungary though their results emphasize the importance and the potential of irrigation. According to Olesen *et al.* (2011), the increased risk of hail, pest, and weed damages will further decrease the agricultural productivity in the Carpathian basin.

The nitrate leaching rates will prospectively decrease as a result of the climate change (Figure 7). According to the simulations, the present annual leaching rate (14.6 kg ha^{-1}) will decrease (to 8.1 kg ha^{-1}). Though, if the predicted rise of the frequency and severity of the weather extremes is taken into account the rate decrease is not so pronounced (the simulations provided a 11.6 kg ha^{-1} average). This favorable change is most likely due to the decreased amount of precipitation since the transpiration rate will not change significantly according to the model results. It is distinctly visible in Figure 7 that nitrate leaching is characteristic of only the course textured sandy (regions VI and IX) and sandy loam (Western part of region IV) soils. The average nitrate leaching rate for the rest of the country is below 5 kg ha^{-1} y^{-1} at present and will prospectively decrease practically to zero in the future.

Conclusion

National geo-databases provide a great possibility for supplying the input data requirements of crop simulation models. The 4M crop model was coupled with detailed meteorological and soil databases and was used for investigating the prospective effects of climate change on the agro-ecological characteristics of Hungary.

The regions traditionally used for agricultural production corresponded well with the territories for which the model calculated the highest total yields. The location of arable lands is determined by the soil characteristics rather than the climatic conditions. The model was successfully verified by using observed county-level yields of the simulated crops.

According to the results, the average yields will most likely decrease considerably in the whole country due to the climate change. Depending on the crops 0.5–2 t ha^{-1} yield decrease is predicted mainly as a result of the significantly less (–30%) summer precipitation coupled with increased evapotranspiration as a consequence of raised (+3°C) temperature. Fluctuations of the yield levels will increase causing even more difficulty for profitable production.

Hungarian farmers and agricultural enterprises should consider investing in irrigation to mitigate the harmful effects of severe summer hot and dry periods. The possible increase in food demand as well as the need for increasing yield safety definitely substantiate investments in irrigation in Hungary similarly to the Mediterranean countries whose present climate is similar to the future climate of the Carpathian basin (Horváth 2008). One possible way of accommodating the climatic changes is to increase the ratio of crops sown in the autumn in the crop rotation since these crops are less affected by the summer droughts. Moreover, the amount of nitrate leaching could also be decreased by using these kinds of crop rotations. Another alternative for Hungarian agriculture is to start experimenting with alternative crops, such as energy crops (robinia (*Robinia pseudoacacia*), poplar (*Populus*), etc.) or crops native to or successfully produced in Mediterranean areas (fenugreek (*Trigonella foenum-graecum* L.), lady's thistle (*Silybum marianum* (L.) *Gaernt.*) or cotton (*Gossypium*), etc.). Well-calibrated crop simulation models could support these testing efforts by carrying out virtual experiments.

Probably the only positive effect of climate change is the decreased risk of polluting sub-surface water reservoirs thanks to the reduced nitrate leaching rates. In the regions traditionally used for agricultural production, the annual nitrate leaching rates will most likely decrease to zero approaching 2100.

Since soil- and land-use information is available with considerably higher spatial resolution, better results could be achieved with a spatially more detailed meteorological database.

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