Original paper

WATER USE EFFICIENCY IN AGRICULTURAL AREAS OF SLOVAKIA IN THE PERIOD 1961–2020 AND ACCORDING TO CLIMATE CHANGE SCENARIOS

Jozef Takáč, Jaroslava Sobocká, Pavol Bezák

National Agricultural and Food Centre – Soil Science and Conservation Research Institute, Trenčianska 55, 821 09 Bratislava, Slovak Republic

Corresponding author: *RNDr. Jozef Takáč, PhD., National Agricultural and Food Centre, Soil Science and Conservation Research Institute, Trenčianska 55, 821 09 Bratislava, Slovakia, e-mail: jozef.takac@nppc.sk, ORCID 0000-0003-4923-4601*

Citation: Takáč, J., Sobocká, J., Bezák, P.. (2024). Water use efficiency in agricultural areas of Slovakia in the period 1961–2020 and according to climate change scenarios. *Pedosphere Research,* vol. **4,** 2024, no. 1, pp. 55–75. NPPC – VÚPOP Bratislava. ISSN 2729-8728.

Abstract

An assessment of the trend in water use efficiency (WUE) in agricultural regions of Slovakia was carried out for the period 1961–2020 and climate change scenarios. For the assessment, simulations with agroecological model DAISY were applied. Simulations were carried out for representative soil profiles of selected regions. Crop rotations including grain maize, spring barley, winter wheat, sugar beet and potatoes were taken for modelling. According to the results the average WUE of crops decreased by approximately 1 kg/mm in the period 1991–2020 compared to the period 1961–1990. The largest decrease in WUE was found in the northeast of the Danube Lowland in the Nitra area, in the case of potatoes on the upper Žitný ostrov (Bratislava area). Simulations have confirmed that soil properties and nutrient reserves in the soil play an important role in WUE in addition to climatic conditions. With lower fertilization doses, WUE achieves lower values. Simulations according to emission scenarios for the Rišňovce and Milhostov sites showed an increase in WUE at higher CO_2 concentrations (RCP 8.5) for spring barley at both sites and for winter wheat at the Rišňovce site. In the case of maize, there was a slight increase in both locations under the RCP 2.6 emission scenario, and in the RCP 4.5 and 8.5 scenarios, there was a decrease in the WUE of maize. Statistical analysis of the results according to the scenarios revealed a higher variability of WUE values for all crops compared to the period 1961–1990.

Keywords: agroecological model DAISY, field crops, water stress, soil groups, fertilisation, emission scenarios

INTRODUCTION

Climate, with its regional and temporal variability, is the main determinant of agricultural production. Crop yields vary from year to year depending on hydroclimatic conditions and are influenced by many other factors. The most important climatic factors determining yields are solar radiation, air temperature, and precipitation. Extreme temperatures and precipitation variability can negatively affect crop yields. From the point of view of impacts on crop formation, both the amount of usable water in the soil and the water use efficiency are important, i.e., the amount of biomass created or economic yield per unit of transpired water. The amount of usable water in the soil depends on the amount of atmospheric precipitation, or on the inflow from groundwater, and on the hydro-physical properties of the soil. Spatial variability of soil properties significantly affects the variability of water use efficiency and yields since the dynamics of water reserves in the soil is significantly influenced by the hydro-physical properties of the soil.

Water in the soil-vegetation-atmosphere system is one of the basic and limiting factors. Soil water content is one of the most dynamic parameters influencing soil processes, plant growth and development. The soil water regime responds sensitively to changes in the regime of climatic factors. The results of simulations using the DAISY model confirmed the trend of a decrease in the average soil water supply and a gradual extension of the duration of the period with soil moisture between the semi-arid and arid

Original paper

intervals on Žitný ostrov (Takáč 1999). According to climate change scenarios applied to the territory of Slovakia, the lack of soil water during the growing season will worsen in the Danube Lowland (Takáč 2001). In the warm and dry Danube Lowland, production potential will be increasingly limited by the decreasing availability of water for crops and heat waves (Eitzinger *et al.* 2013). The increase in extreme weather events (heat waves, drought) will lead to increased crop variability. The risk of extremely adverse years is likely to increase in many European regions (Trnka *et al.* 2011).

Despite the fact that no area in Slovakia meets the conditions for being classified as dry region and the coverage of crop moisture requirements is insufficient in the southern regions. In dry years, the coverage of crop moisture requirements in summer is below 40 % and the number of days with water stress can exceed 90 (Takáč & Ilavská 2021).

According to meteorological observations, local or area-wide droughts have occurred much more frequently in our territory in recent decades. The distribution of atmospheric precipitation and its intensity have changed. According to the 7th National Communication of the Slovak Republic on Climate Change (2017), severe droughts occurred in the years 1990–1994, 2000, 2002, 2003, 2007, 2009, 2011, 2012, 2015 and 2017. The reason for the observed increased incidence of drought is, in addition to the amount and distribution of precipitation, also in increasing temperatures and thus increasing demands for evapotranspiration.

In recent years, the requirements for the efficiency of crop production have increased. The issue of production efficiency of water use is increasingly being discussed. Production efficiency of water use is also among the basic characteristics evaluated in connection with the consequences of climate change on agriculture and the preparation of adaptation and mitigation measures (Pohanková *et al.* 2018).

The factors that influence the water use efficiency are diverse and depend on the crop, the natural environment, and the management method. The influence of environmental factors and the influence of structural and functional characteristics of plants on the relationship between dry matter production and water consumption is expressed using the concept of water use efficiency (WUE). Water use efficiency for dry matter production is defined as the ratio of dry matter production to water consumption, with the value of water consumption corresponding to the total evapotranspiration of the stand (Larcher 1988). WUE is the amount of water consumed by the crop without water loss through surface runoff, interception, or seepage into groundwater.

Simulation models play an important role in understanding and quantifying the relationships between temporally and spatially variable natural conditions, management, and crop production. Several studies have been devoted to the issue of crop water security and water production efficiency using the agroecological simulation model DAISY in the past (Takáč 2008, Takáč *et al.* 2009, Takáč *et al.* 2017, Takáč & Ilavská 2021).

Water stress can be partially compensated under climate change by increased water use efficiency (WUE) due to increased atmospheric CO_2 concentration (IPCC 2007). Increased atmospheric CO_2 concentration stimulates photosynthesis, as it reduces the rate of transpiration through reduced stomatal conductance at higher temperatures, which leads to increased water use efficiency, known as the CO_2 fertilization effect (Kostrej *et al.* 1998). Based on the interaction of increased atmospheric CO_2 concentration and higher precipitation totals, it is possible to assume an increase in the water use efficiency of spring barley and winter wheat. The results obtained for maize indicate the opposite trend. The moisture security of crops with a growing season in the spring months will improve according to the calculated average values, but the variability will increase. Conversely, the moisture security of crops with a growing season in the summer months will deteriorate (Takáč *et al.* 2009). On the other hand, high temperatures during the growing season (higher than optimal) affect photosynthesis, accelerate phenological development, and due to increased evaporation, reduce water reserves in the soil and thus may reduce the production efficiency of water use and cause a decrease in economic yields.

The effects of increased atmospheric CO_2 and climate change are expected to lead to a modest increase in crop yields in Europe by 2050 (Alcamo *et al.* 2007). A temperature increases of more than 2 °C is expected to lead to a decrease in yields for many crops (Easterling *et al.* 2007). Increased CO_2 may partially compensate for the decrease in yields by increasing CO_2 absorption and water use efficiency (Leakey *et al.* 2009).

A set of seven growth models was used to assess the impacts of climate change on crop yields and water production efficiency of field crops in crop rotations in the Czech Republic. The set of crop models assumed an increase in average production due to climate change. The general increase in yields expected in future conditions is mainly due to the direct effect of higher atmospheric CO_2. If only the climate effect (without CO_2 increase) is taken into account, average yields in the lowlands will be lower (Pohanková *et al.* 2022).

Simulations by agroecological model DAISY confirmed the acceleration of spring barley and winter wheat development due to temperature increase. Soil water content was the main limiting factor of spring barley and winter wheat yields. Simulated yields were influenced by CO_2 concentration defined by emissions and climate change scenarios (Takáč & Šiška 2009).

The aim of the paper is to estimate the water use efficiency depending on local and regional weather and soil conditions. For this purpose, the results of field experiments and simulations in agricultural regions of Slovakia using the agroecological model DAISY were used.

MATERIALS AND METHODS

In a field stationary experiment based on the field experimental station in Most near Bratislava in 1973, there were seven fertilization variants in blocks under irrigation and without irrigation with different doses of N, P and K with annual fertilization combinations O, NP, PK, NK, NPK, N1PK, N1P1K1. Index 1 corresponds to 1.5 times the dose of the respective nutrient, variant O was without fertilization (Bízik 1999). During the period 1973–2006, the crops winter wheat, spring barley and corn for grain were evaluated 7 times. Meteorological data were measured at the meteorological station located in Most near Bratislava. Missing data from years when measurements were interrupted were supplemented according to data from the Bratislava – Airport meteorological station. Evapotranspiration characteristics were calculated according to the FAO methodology (Allen *et al.* 1998).

Determining WUE from field experiments is generally more accurate than modelling, but its application is local and does not allow for the determination of spatial heterogeneity on a regional scale. The results of yield simulations of selected crops carried out as part of several projects using the agroecological model DAISY were also used to calculate the WUE. DAISY is a one-dimensional agroecosystem model that, based on information on the management method and weather data, simulates crop growth, water regime, thermal regime, organic matter balance, and nitrogen dynamics in agricultural soils. The model includes key interactions between crops, their environment and management method. The model allows the construction of complex management scenarios (Hansen *et al.* 1990, Abrahamsen & Hansen 2000). The crop parameters of the DAISY model were optimized and verified for our conditions (Takáč & Šiška 2011, Takáč *et al.* 2018). The reliability of the model has been demonstrated in several comparative studies (Palusao *et al.* 2011, Rötter *et al.* 2012).

To assess the impact of climate conditions on WUE, simulations were conducted in agriculturally used regions of Slovakia for the period 1961–2020. The simulations were performed on representative soil profiles (Table 2) using climate data from local meteorological stations (Table 1). The evaluated crops (grain maize, spring barley, winter wheat, sugar beet, potatoes) were arranged in crop rotations. In simulations with irrigation, irrigation doses were applied in an automatic irrigation mode when the soil water supply in the root zone of the crop fell below 50 % of the available water capacity (AWC).

Soil properties are a significant natural factor affecting crop yields at the local and regional level, as they directly affect the amount of water in the soil and its interactions with other natural factors. In field conditions, we observe significant variability in the hydro-physical characteristics of soils, mainly caused by the heterogeneity of the soil cover (Cambel & Takáč 2000). The choice of spatial resolution of soil data can have a decisive impact on the accuracy of reproducing the variability of water production efficiency and yields.

To assess the impact of soil on WUE, simulations were performed using the DAISY model in the Danube Lowland. According to climatic criteria, the Danube Lowland belongs to a warm region with an average number of summer days of 50 or more. The predominant soil types in the Danube Lowland are Chernozems (47%) and Luvisols (23%) (IUSS Working Group WRB 2015).

The territory of the Danube Lowland was divided into four climatic regions. In each of the regions, five dominant soil types were identified covering 99 % of the agricultural land – Chernozem, Luvisol, Fluvisol, Fluvic Chernozem and Phaeozem as shown in the Tab. 3. The soil horizons of the soil profiles were defined by grain size composition, bulk density, retention curve parameters, saturated hydraulic conductivity, humus content and C:N ratio. In the case of Luvisols, Phaeozems and Fluvic Chernozems, a fixed groundwater level at a depth of 170 to 250 cm was considered, depending on the soil type. Numerical simulations were performed for the period 1961–2020 with a series of daily values of global radiation, air temperature, relative air humidity, wind speed, and atmospheric precipitation. The evaluated crops, grain corn, spring barley and winter wheat, were arranged in crop rotations.

Table 1

Geographical coordinates and altitude of the evaluated locations

Locality	**Latitude**	**Longitude**	**Altitude [m]**
Kuchyňa	48°24′	17°09′	206
Stupava	48°17′	17°01′	179
Malacky	48°27′	17°02′	165
Holíč	48°49′	17°10′	178
Myjava	48°46′	17°35′	375
Bratislava	48°10′	17°12′	131
Hurbanovo	47°52′	18°12′	115
Kráľová pri Senci	48°12′	17°28′	123
Gabčíkovo	47°54′	17°36′	114
Žihárec	48°04′	17°52′	111
Jaslovské Bohunice	48°29′	17°40′	176
Piešťany	48°37′	17°50′	165
Podhájska	48°06′	18°20′	140
Nitra	48°19′	18°07′	173
Mochovce	48°16′	18°27′	212
Želiezovce	48°02′	18°38′	135
Turčianske Teplice	48°52′	18°51′	502
Trenčín	48°52′	18°01′	205
Beluša	49°04′	18°19′	254
Topoľčany	48°34′	18°09′	174
Dudince	48°10′	18°52′	140
Dolné Plachtince	48°12′	19°19′	200
Bzovík	48°19′	19°06′	355
Žiar nad Hronom	48°35′	18°52′	250
Sliač	48°39′	19°08′	313

Locality	Latitude	Longitude	Altitude [m]
Lučenec	48°20′	19°44′	214
Rimavská Sobota	48°22′	20°01′	214
Rožňava	48°39′	20°32′	289
Moldava nad Bodvou	48°37′	21°00′	210
Košice	48°40′	21°13′	230
Prešov	49°02′	21°19′	307
Somotor	48°24′	21°49′	100
Michalovce	48°45′	21°57′	112
Trebišov	48°40′	21°44′	104
Vysoká nad Uhom	48°37′	22°05′	105
Orechová	48°42′	22°14′	122
Kamenica nad Cirochou	48°56′	22°00′	178
Medzilaborce	49°15′	21°55′	308
Stropkov	49°13′	21°39′	219
Spišské Vlachy	48°57′	20°48′	396
Liptovský Hrádok	49°02′	19°44′	640
Poprad	49°04′	20°15′	695

Table 2
Basic characteristics of soil profiles of selected locations

Locality	Soil type (WRB 2015)	Soil texture	*FC* [mm]	*WP* [mm]	*AWC* [mm]
Kuchyňa	Regosol	Sandy loam	230	51	179
Stupava	Phaeozem	Sandy loam	244	67	177
Malacky	Phaeozem	Sandy loam	264	78	186
Holíč	Phaeozem	Loamy	355	158	197
Myjava	Cambisol	Clayey loam	377	168	209
Bratislava	Chernozem	Loamy	359	122	237
Hurbanovo	Chernozem	Loamy	348	124	224
Kráľová pri Senci	Chernozem	Loamy	324	108	216
Gabčíkovo	Phaeozem	Loamy	342	125	217
Žihárec	Chernozem	Loamy	349	133	216
Jaslovské Bohunice	Chernozem	Loamy	369	147	221
Piešťany	Phaeozem	Clayey loam	377	192	185
Podhájska	Chernozem	Loamy	307	91	216
Nitra	Luvisol	Clayey loam	369	160	208
Mochovce	Planosol	Clayey loam	403	198	205
Želiezovce	Chernozem	Clayey loam	393	165	228
Turčianske Teplice	Luvisol	Clayey loam	358	187	171
Trenčín	Luvisol	Loamy	319	122	197
Beluša	Luvisol	Loamy	346	128	218

Original paper

Locality	**Soil type (WRB 2015)**	**Soil texture**	***FC*** **[mm]**	***WP*** **[mm]**	***AWC*** **[mm]**
Topoľčany	Luvisol	Clayey loam	376	165	211
Dudince	Cambisol	Clayey loam	395	212	183
Dolné Plachtince	Luvisol	Clayey loam	390	193	197
Bzovík	Cambisol	Loamy	363	176	187
Žiar nad Hronom	Fluvisol	Sandy loam	281	92	189
Sliač	Luvisol	Loamy	346	135	211
Lučenec	Luvisol	Clayey loam	387	196	191
Rimavská Sobota	Luvisol	Clayey loam	379	164	215
Rožňava	Cambisol	Loamy	353	139	214
Moldava nad Bodvou	Fluvisol	Loamy	324	121	213
Košice	Luvisol	Loamy	362	141	220
Prešov	Luvisol	Loamy	331	118	213
Somotor	Fluvisol	Sandy-loam	322	113	209
Michalovce	Fluvisol	Clayey loam	383	163	220
Trebišov	Fluvisol	Clayey	423	194	229
Vysoká nad Uhom	Fluvisol	Clayey loam	394	173	221
Orechová	Luvisol	Loamy	362	147	215
Kamenica nad Cirochou	Fluvisol	Loamy	350	139	211
Medzilaborce	Cambisol	Loamy	405	188	217
Stropkov	Luvisol	Loamy	335	109	218
Spišské Vlachy	Cambisol	Loamy	340	133	207
Liptovský Hrádok	Cambisol	Loamy	331	98	233
Poprad	Cambisol	Sandy loam	297	65	232

Explanations: *FC* – field capacity in the soil horizon 0–100 cm, *WP* – wilting point in the soil horizon 0–100 cm, *AWC* – available water capacity in the soil horizon 0–100 cm

Table 3
Characteristics of Danube Lowland regions; *FC* – field capacity, *WP* – wilting point, *AWC* – available water capacity (Takáč & Ilavská 2021)

Region / meteorological station	**Soil group**	***FC* [mm]**	**WP [mm]**	**AWC [mm]**
Northwest *Jaslovské Bohunice*	Haplic Phaeozems	420	216	204
	Haplic Chernozems	408	171	237
	Fluvic Chernozems	387	147	240
	Haplic Fluvisols	384	144	240
	Cutanic Albic Luvisols	408	177	231
Northeast *Nitra*	Haplic Phaeozems	432	228	204
	Haplic Chernozems	420	171	249
	Fluvic Chernozem	372	159	213
	Haplic Fluvisols	408	159	249
	Cutanic Albic Luvisols	423	195	228
Southwest *Bratislava*	Haplic Phaeozems	423	207	216
	Haplic Chernozems	396	147	249
	Fluvic Chernozems	384	132	252
	Haplic Phaeozems	384	117	267
	Cutanic Albic Luvisols	408	213	195
Southeast *Hurbanovo*	Haplic Phaeozems	423	219	204
	Haplic Chernozems	408	168	240
	Fluvic Chernozems	384	147	237
	Haplic Fluvisols	387	147	240
	Cutanic Albic Luvisols	429	210	219

The effect of fertilization on WUE was carried out based on simulations of different fertilization variants on 5 different soils in the Rišňovce location (Danubian Lowland, Nitra region). A total of 13 fertilization variants were simulated. To assess the effect of fertilization on WUE, 5 fertilization variants were used, namely N0 – unfertilized N, plowing of post-harvest residues, NA – automatic fertilization of 30 kg N/ha when the N stock in the 0–100 cm horizon drops below 60 kg N/ha, plowing of post-harvest residues, NN – low dose N, plowing of post-harvest residues, NS – medium dose N, plowing of post-harvest residues and NV – high dose N, plowing of post-harvest residues.

To assess the impacts of climate change on WUE, numerical simulations for the period 2020–2100 were performed for the emission scenarios RCP 2.6, RCP 4.5, and RCP 8.5 according to the outputs of the NORESM climate scenarios of the general circulation model NCC-NorESM1-M. The emission scenario RCP 2.6 is considered strict, it is based on the hard application of mitigation measures. The RCP 4.5 scenario is a medium, so-called first stabilization scenario. The RCP 8.5 scenario is a pessimistic scenario without the implementation of mitigation measures. The simulations were performed for the locations Rišňovce (Nitra region, Danube Lowland) and Milhostov (Trebišov region, Eastern Slovakian Lowland). At the Rišňovce location, the crops spring barley, winter wheat, oilseed rape, maize and alfalfa were simulated. At the Milhostov site, the simulated crops were spring barley, winter wheat, oilseed rape and corn.

Crops were arranged in crop rotations with different fertilization rates. In the irrigation simulations, irrigation rates were applied in an automatic irrigation mode when the soil water supply in the root zone of the crop fell below 50% of the available water capacity (AWC). The beginning and end of the irrigation season were defined by the development phase of the crop. The aim was not to cover the crop's moisture needs during its entire growing season, but only in important phases of economic yield formation. The simulations also took into account the increasing concentration of CO_2 in the atmosphere.

According to the expected concentration of CO_2 in the atmosphere, the coefficients of radiation utilization, respectively, responses of photosynthesis to increased concentration of CO_2 in the atmosphere, were calculated. DAISY model calculates photosynthesis rate using a light saturation response curve. The effect of CO_2 concentration was included to the DAISY parameterization according to light-saturated photosynthesis rate *Fm* (g CO_2 m^{-2} h^{-1}) and initial light use efficiency [(g CO_2 m^{-2} h^{-1})/(Wm^{-2})].

The water use efficiency (WUE) [$kg.mm^{-1}$] was calculated from the simulation results according to the relationship:

$$WUE = \frac{Y}{ET}$$

where Y is the economic yield of the crop [$kg.ha^{-1}$] and ET is the actual evapotranspiration of the crop from sowing to harvest [mm].

RESULTS AND DISCUSSION

According to the obtained results, the water use efficiency (WUE) in rainfed variants of winter wheat in the field stationary experiment ranged from 5.6 $kg.mm^{-1}$ to 17.8 $kg.mm^{-1}$, the WUE of spring barley in rainfed variants reached 6.9 $kg.mm^{-1}$ to 16.6 $kg.mm^{-1}$ and the WUE of rainfed maize fluctuated in a wide range from 3.1 $kg.mm^{-1}$ to 30.6 $kg.mm^{-1}$. In the irrigated variants in the field stationary experiment, the WUE of winter wheat ranged from 6.0 $kg.mm^{-1}$ to 17.0 $kg.mm^{-1}$, the WUE of spring barley in the irrigated variants reached 6.0 $kg.mm^{-1}$ to 16.4 $kg.mm^{-1}$ and the WUE of rainfed maize fluctuated from 10.7 $kg.mm^{-1}$ to 20.8 $kg.mm^{-1}$. Higher WUE values were calculated for rainfed variants than for irrigated variants (Tab. 4).

Table 4

Average WUE [$kg.mm^{-1}$] of spring barley, winter wheat and grain maize on irrigated and rainfed variants of the field stationary experiment in Most near Bratislava in the period 1973–2007

Variant	Spring barley	Winter wheat	Grain maize
Rainfed	11,8	12,1	16,7
Irrigated	11,0	10,6	15,9

In general, it can be stated that in the field stationary experiment, higher water use efficiency was also calculated for higher yields. On the other hand, precipitation totals, or the amount of water supplied to the system, is not the only decisive factor determining the water use efficiency by crops, so therefore, it was not possible to establish a clear dependence between precipitation totals and WUE from the obtained results. As will be shown below, the production efficiency of water use depends, in addition to climatic conditions, also on soil conditions, nutrition, crop rotations and specialization of plant production. The dependence between precipitation totals and WUE was covered in the stationary field experiment by other environmental and management factors, especially fertilization variants.

From the comparison of the results obtained from the field stationary experiment in Most near Bratislava and the simulations, it was concluded that the statistical characteristics of the production WUE calculated from the simulation results were close to the statistical characteristics calculated from the field stationary experiment. Thus, based on the comparison of the calculated values of the production WUE from the field stationary experiment and from the simulations, the results obtained by the DAISY model can be considered satisfactory and suitable for assessing the impacts of the management method on agricultural production using various scenarios of climatic, hydrological and soil conditions (Takáč 2008).

The critical parameter of the water balance is evapotranspiration, which is the main loss component of the water balance. According to the results of simulations with the DAISY model for the Bratislava region, the yield increases with increasing relative evapotranspiration and with increasing precipitation totals during the growing season and decreases with increasing evapotranspiration deficit. On the other hand, even based on the simulation results, no dependence was demonstrated between precipitation totals and WUE, when the value of the correlation coefficient was less than 0.025.

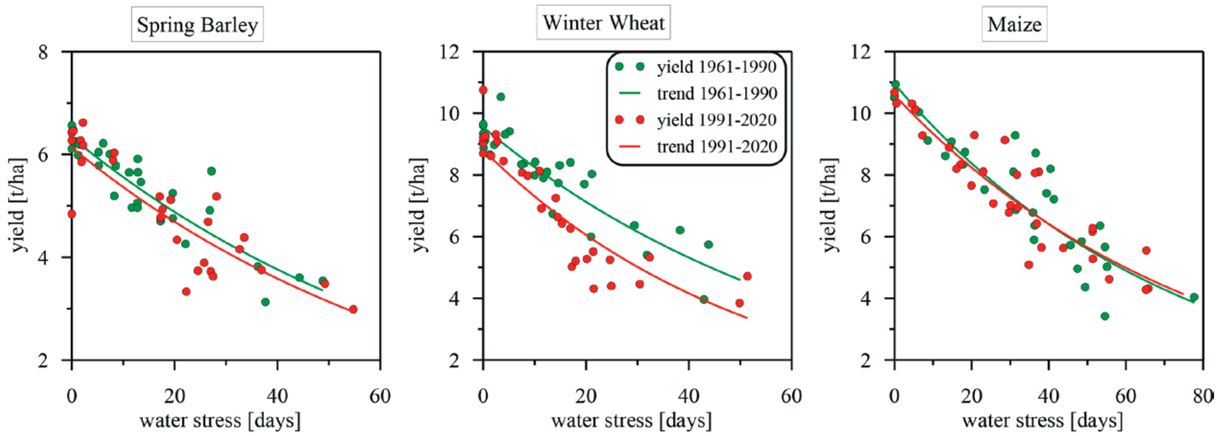

Figure 1 Relationship between the number of days with water stress and grain yield of selected crops of Danube Lowland in the period 1961 – 1990 and 1991 – 2020

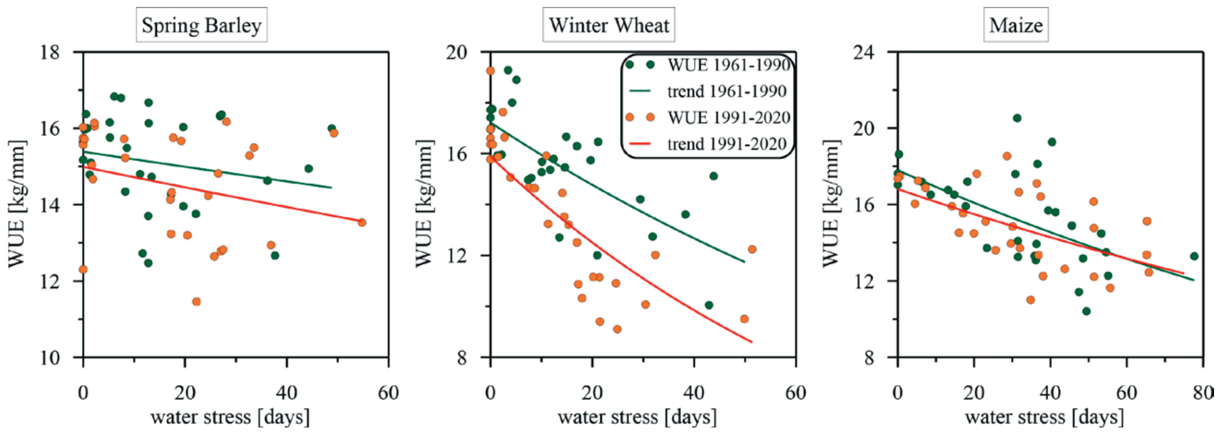

Figure 2 Relationship between the number of days with water stress and production efficiency of water use of selected crops of Danube Lowland in the period in the period 1961 – 1990 and 1991 – 2020

When there is a lack of usable water in the soil, crops suffer from water stress. According to the results of simulations using the DAISY model, winter wheat suffers from water stress in the Danube Lowland for an average of 8 days, spring barley for 10 days and maize for 19 days. Crops on Luvisols suffer the most from water stress. In two consecutive years, 1990 and 1991, maize on Luvisols in the Nitra region was affected by water stress for up to 73 days and 69 days, respectively. Water stress limits crop growth and thus also economic yields. With an increasing number of days with water stress, crop yields have a decreasing level.

According to the correlation coefficient values from the simulations performed for the locality Bratislava, a very high statistical dependence was found between the number of days with water stress and yields, which ranged from 0.76 to 0.82 (Fig. 1). In the case of the number of days with water stress and WUE (Fig. 2), the correlation coefficient for winter wheat and maize in the period 1961–1990 was 0.61 and in the period 1991–2020 it was 0.5, which corresponds to a high dependence. For spring barley, the correlation coefficient of 0.35 corresponds to a medium dependence.

In the period 1961–1990, the average WUE of the economic harvest of spring barley was 14.4 kg/mm, winter wheat 14.7 kg/mm, corn 16.4 kg/mm, sugar beet 20.6 kg/mm and potatoes 22.6 kg/mm. In the period 1991–2020, the average WUE of these crops decreased by approximately 1 kg/mm. The largest decrease in WUE was observed for most of the assessed crops in the northeast of the Danube Lowland in the Nitra region, for potatoes on the upper Žitný ostrov (Bratislava). The lowest WUE for densely planted cereals was recorded in the northeast of Slovakia (locality Medzilaborce), for corn on the upper Žitný ostrov and for sugar beet and potatoes in the southeast of the Danube Lowland (locality Mochovce). In general, it can be stated that below-average WUE values were calculated in western Slovakia and in the foothill areas. On the contrary, above-average WUE values were recorded in central and eastern Slovakia (Table 5). The WUE values of densely planted cereals and maize in individual years, depending on climatic conditions, fluctuated in the range from 10 to 19 kg/mm of sugar beet and potatoes from 11 to 27 kg/mm. The WUE histograms in Hurbanovo are shown in Fig. 3.

The average WUE value calculated for the dry matter of the aboveground biomass in the period 1961–1990 was 28.5 kg/mm for spring barley, 31.4 kg/mm for winter wheat, 37.2 kg/mm for corn, 27.1 kg/mm for sugar beet and 28 kg/mm for potatoes. As with the economic harvest, a decrease in the average WUE was recorded for the aboveground biomass in the period 1991–2020, from 0.75 kg/mm for winter wheat to 2.6 kg/mm for corn. Similarly to the economic harvest, above-average WUE values were calculated for central and eastern Slovakia, while below-average values prevailed in western Slovakia (Table 6).

Differences in WUE between regions are due to different climatic conditions. Soil properties also play an important role in crop water management and WUE. In the Danube Lowland, our most important agricultural region, the warm lowland climate and soil evaporation regime cause insufficient water supply to agricultural crops.

Regarding grain harvest, in the period 1961–1990 in the Danube Lowland, the average WUE of spring barley ranged from 14.8 kg/mm on Chernozems and Luvisols in the Bratislava region, to 16.6 kg/mm on Phaeozems in the Nitra region, of winter wheat from 13.0 kg/mm on Chernozems and Luvisols in the Bratislava region, to 15.2 kg/mm on Phaeozems soils in the Hurbanovo region, and of maize from 14.8 kg/mm on Luvisols in the Hurbanovo region, to 18.3 kg/mm on Fluvic Chernozems in the Nitra region. In the period 1991–2020, WUE decreased by an average of 1.4 kg/mm for spring barley, 2.4 kg/mm for winter wheat and 1.5 kg/mm for maize compared to the period 1961–1990 (Table 7). Differences in WUE of winter wheat in individual regions and on individual soil types are graphically shown in Fig. 4.

Table 5

Average water use efficiency for economic yield [kg/mm] of rainfed crops in selected locations in the period 1961–1990 and 1991–2020

Locality	Spring barley		Winter wheat		Maise		Sugar beet		Potatoes	
	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020
Kuchyňa	14.35	12.95	14.64	12.74	16.00	16.13	19.65	18.71	21.02	19.25
Stupava	14.90	13.60	15.28	13.10	15.97	16.08	19.44	18.61	20.22	18.51
Malacky	14.21	13.05	13.84	13.07	16.60	15.84	18.26	17.95	19.10	18.67
Holíč	12.83	12.05	12.67	10.95	15.86	13.85	18.17	16.65	18.43	16.33
Myjava	12.63	12.83	13.24	13.47	15.57	16.37	20.85	19.64	22.29	21.43
Bratislava	12.07	10.86	11.44	9.42	13.07	11.49	18.22	15.47	19.93	15.87
Hurbanovo	14.77	13.26	13.41	11.29	13.35	13.51	16.97	16.96	17.42	17.52
Kráľová pri Senci	12.81	12.29	12.25	10.96	14.02	13.52	18.87	18.03	20.36	18.21
Gabčíkovo	15.36	14.71	15.89	14.11	16.56	15.53	20.90	20.41	21.74	21.66
Žihárec	15.12	14.71	15.60	14.19	16.39	14.90	20.73	19.87	22.91	21.31
Jaslovské Bohunice	14.29	12.63	13.83	11.31	15.76	13.84	18.37	16.05	19.53	16.61

Locality	Spring barley		Winter wheat		Maise		Sugar beet		Potatoes	
	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020
Piešťany	14.35	13.71	14.47	13.39	16.68	15.30	18.29	17.12	18.78	18.33
Podhájska	15.74	13.76	14.56	12.18	15.08	14.37	18.84	17.54	20.76	18.72
Nitra	15.43	13.39	14.93	11.52	15.53	13.31	19.03	15.92	18.75	15.88
Mochovce	13.62	12.06	12.83	10.99	14.24	13.25	16.86	15.42	17.32	15.76
Želiezovce	15.9	14.22	14.41	11.95	14.86	13.68	17.59	17.13	18.2	17.42
Turčianske Teplice	13.47	13.82	14.75	13.56	15.39	16.75	21.31	21.59	24.69	26.18
Trenčín	15.26	14.06	15.34	14.36	16.63	15.28	20.06	18.25	21.87	19.34
Beluša	13.76	13.62	13.67	14.38	16.84	16.53	23.41	22.47	27.08	25.21
Topoľčany	15.69	14.51	15.23	12.87	16.50	15.11	18.66	17.87	19.41	18.54
Dudince	13.28	13.41	12.57	13.44	16.39	16.29	19.87	19.27	21.17	20.78
Dolné Plachtince	14.97	14.07	15.41	14.62	15.84	16.29	19.91	19.97	21.82	21.45
Bzovík	15.01	14.43	16.29	15.36	16.89	16.99	20.49	20.21	22.78	21.57
Žiar nad Hronom	16.27	15.49	15.07	16.62	18.44	17.41	23.75	22.03	26.47	24.29
Sliač	13.57	13.26	15.01	13.98	16.27	16.60	22.30	22.06	25.56	24.80
Lučenec	15.30	14.58	16.35	14.8	15.49	16.50	19.08	20.33	22.06	22.59
Rimavská Sobota	14.03	13.34	14.95	14.22	16.65	16.03	21.46	19.32	23.64	21.31
Rožňava	15.61	14.95	17.00	15.75	18.24	16.89	23.31	21.68	25.28	23.81
Moldava nad Bodvou	15.45	15.75	16.69	17.12	18.61	18.03	23.80	22.93	26.13	25.23
Košice	14.53	14.29	15.85	14.84	16.19	15.22	20.82	19.23	22.94	22.19
Prešov	15.15	15.03	16.35	16.52	17.12	18.06	21.85	22.64	24.34	25.17
Somotor	15.46	14.06	15.84	13.55	16.75	14.78	22.06	19.49	23.21	21.22
Michalovce	16.27	15.22	17.78	16.36	18.92	16.30	23.80	21.22	25.46	23.03
Trebišov	15.32	15.16	16.30	14.97	18.16	16.43	21.24	19.45	23.06	21.26
Vysoká nad Uhom	14.46	14.46	15.27	15.28	18.71	16.39	23.09	20.44	24.57	26.93
Orechová	15.32	14.31	16.92	15.37	17.82	16.14	23.09	21.01	25.08	22.85
Kamenica nad Cirochou	13.65	13.48	13.91	13.33	18.25	18.22	23.75	22.80	26.36	24.80
Medzilaborce	10.37	10.23	9.99	8.84					27.05	26.71
Stropkov	15.10	14.41	16.66	15.35	17.73	18.42	23.50	23.78	27.12	26.20
Spišské Vlachy	13.87	13.91	15.17	13.12					26.45	27.35
Liptovský Hrádok	13.55	12.70	13.43	11.40					23.78	25.27
Poprad	12.97	12.70	13.85	11.26					24.32	25.82

Original paper

Table 6
Average water use efficiency for the formation of dry matter of above-ground biomass [kg/mm] of rainfed crops at selected locations in the periods 1961–1990 and 1991–2020

Locality	Spring barley		Winter wheat		Maize		Sugar beet		Potatoes	
	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020
Kuchyňa	28.14	25.96	31.39	29.00	37.04	34.66	26.31	24.84	26.18	23.82
Stupava	28.27	26.38	31.95	29.71	36.88	34.81	26.18	24.80	25.16	22.85
Malacky	27.97	25.92	30.12	29.32	37.30	34.35	24.89	24.02	23.72	23.14
Holíč	28.57	26.52	30.80	28.93	34.41	31.42	24.66	22.56	22.95	20.32
Myjava	27.41	26.74	31.39	31.45	37.15	35.31	27.56	25.97	27.77	26.64
Bratislava	27.40	25.05	29.82	26.16	31.10	27.37	24.15	20.82	24.94	20.03
Hurbanovo	28.22	26.32	30.22	28.27	33.24	31.80	23.03	22.75	21.88	21.92
Kráľová pri Senci	29.34	27.36	31.64	29.19	33.19	30.51	25.40	24.07	25.51	22.76
Gabčíkovo	29.37	28.86	33.74	32.64	37.43	35.21	27.60	26.73	27.21	27.03
Žihárec	28.66	28.40	32.83	32.46	36.52	33.84	27.26	25.93	28.66	26.96
Jaslovské Bohunice	27.66	25.27	30.80	27.64	36.31	32.09	24.62	21.61	24.49	20.68
Piešťany	27.57	26.40	30.70	30.11	37.15	34.26	24.63	23.00	23.30	22.87
Podhájska	30.58	27.66	33.19	29.42	37.36	33.67	25.55	23.59	26.34	23.48
Nitra	28.86	26.18	32.39	28.09	36.00	31.66	25.63	21.49	23.51	19.79
Mochovce	29.72	25.94	32.29	28.66	33.57	30.63	22.86	20.92	21.86	19.62
Želiezovce	30.56	28.21	32.51	29.88	36.72	33.52	23.96	23.36	22.97	21.79
Turčianske Teplice	26.35	26.55	28.91	30.42	39.68	38.83	28.42	27.90	30.15	32.44
Trenčín	29.01	26.59	32.55	31.09	38.94	34.85	26.95	24.27	27.42	24.15
Beluša	29.13	27.71	31.90	32.12	38.67	36.31	30.11	28.51	33.24	31.02
Topoľčany	29.92	29.22	33.24	31.96	38.18	35.53	25.33	24.26	24.48	23.22
Dudince	29.44	28.29	31.15	32.68	36.14	34.77	26.50	25.61	26.58	25.82
Dolné Plachtince	29.23	27.18	33.52	32.40	37.35	36.11	26.29	26.09	27.45	26.63
Bzovík	28.88	27.44	32.15	32.83	39.86	36.90	27.20	26.25	28.50	26.57
Žiar nad Hronom	29.84	28.56	32.87	34.09	40.90	37.28	30.67	28.12	32.52	30.16
Sliač	28.59	27.01	31.26	31.52	37.66	35.56	28.99	27.92	31.54	30.68
Lučenec	29.12	28.07	33.02	32.55	36.39	35.87	25.00	26.33	27.68	27.90
Rimavská Sobota	29.36	27.52	32.02	32.59	36.54	34.45	27.74	24.97	29.19	26.40
Rožňava	28.79	27.43	32.14	32.31	39.00	35.58	29.84	27.59	30.90	29.40
Moldava nad Bodvou	28.90	29.03	32.21	34.58	38.79	37.12	30.19	28.97	31.95	31.12
Košice	27.15	26.51	31.08	31.05	35.33	32.95	26.85	24.73	28.19	27.54
Prešov	28.00	27.46	31.09	32.54	37.08	37.28	28.08	28.82	29.90	30.81
Somotor	29.61	28.08	33.77	31.80	36.56	33.87	28.41	25.34	28.87	26.44
Michalovce	30.10	28.23	34.28	33.83	39.27	35.21	30.40	27.08	31.29	28.64
Trebišov	29.31	28.54	33.03	32.56	38.73	35.81	27.97	25.69	28.54	26.28
Vysoká nad Uhom	28.11	27.39	31.67	33.02	38.52	35.45	29.56	26.46	30.15	26.93
Orechová	28.63	27.14	33.18	32.78	36.96	34.66	29.23	26.67	30.89	28.45

Locality	Spring barley		Winter wheat		Maize		Sugar beet		Potatoes	
	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020
Kamenica nad Cirochou	26.78	26.13	28.93	29.92	39.65	37.3	30.29	28.92	32.08	30.45
Medzilaborce	22.88	22.82	23.76	25.57					32.96	32.70
Stropkov	28.55	27.38	31.79	32.42	40.68	38.21	30.35	29.94	33.06	32.02
Spišské Vlachy	29.17	28.18	31.30	30.23					32.25	33.21
Liptovský Hrádok	26.40	25.25	26.42	26.08					28.96	30.87
Poprad	25.39	25.02	26.66	24.34					29.74	31.50

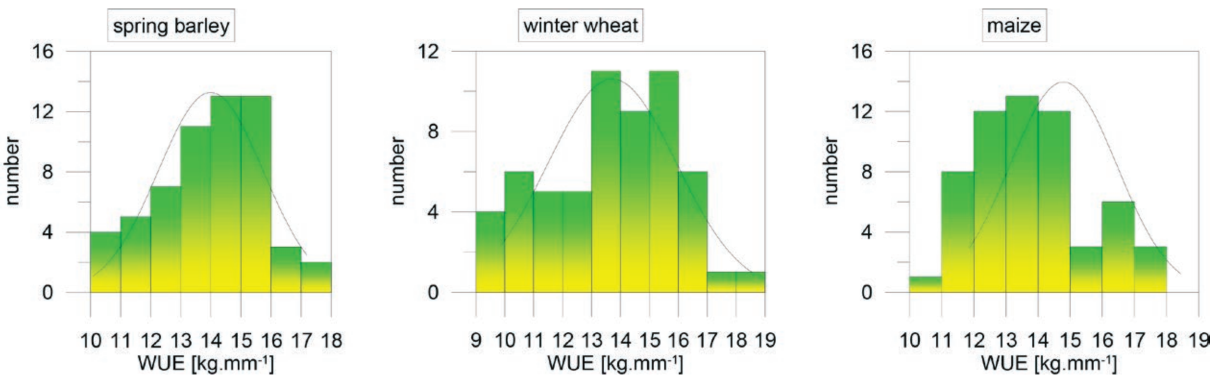

Figure 3 Histogram of WUE on Chernozems in Hurbanovo for the period 1961 – 2020

Table 7
Average water use efficiency of grain yield [kg/mm] of rainfed crops in the Danube Lowland in the period 1961–1990 and 1991–2020

Soil type	Spring barley		Winter wheat		Maize	
	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020
CA	15.72	14.50	16.34	13.83	17.73	16.19
CM	15.43	13.98	15.53	13.23	15.58	14.68
CMc	15.23	13.98	15.97	13.45	16.80	14.93
FM	15.49	14.59	16.55	14.45	17.31	15.39
HM	15.49	13.77	15.05	12.71	15.79	14.39

Original paper

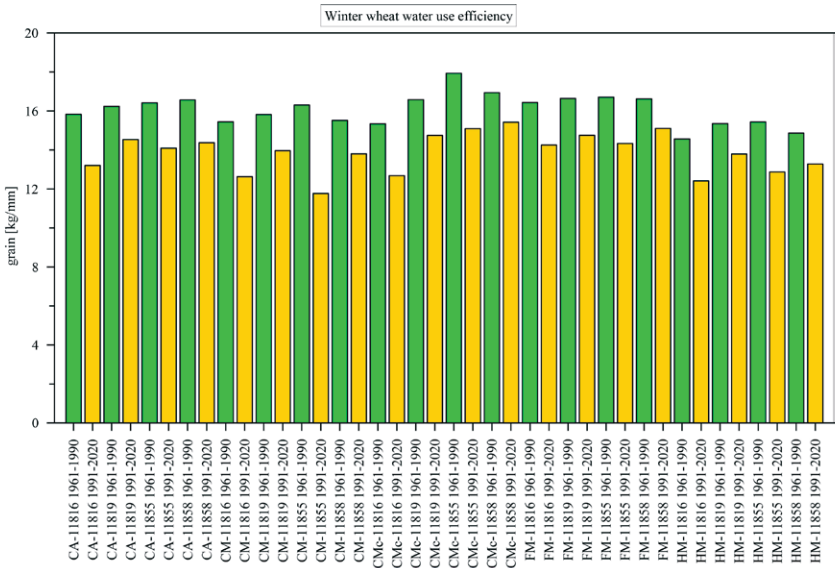

Figure 4 Water use efficiency of rainfed winter wheat crops by soil type and climate region in the period 1961 – 1990 and 1991 – 2020. Soil groups CA – Phaeozems, CM – Chernozems, CMc – Fluvic Chernozems, FM – Fluvisols, HM – Luvisols; regions: 11816 – Bratislava, 11819 – Jaslovské Bohunice, 11855 – Nitra, 11858 – Hurbanovo.

On irrigated land, WUE increased for densely planted cereals compared to rainfed crops, while it decreased for maize (Table 8). The most significant decrease in WUE was recorded on Chernozems and Luvisols in the Hurbanovo region.

Table 8
Average water use efficiency of grain water use [kg/mm] of irrigated crops in the Danube Lowland in the period 1961–1990 and 1991–2020

Soil type	Spring barley		Winter wheat		Maize	
	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020
CA	15.54	14.28	16.31	13.68	17.81	16.28
CM	15.53	14.76	16.74	14.75	17.73	16.44
CMc	15.43	14.59	16.68	14.59	17.68	15.94
FM	15.34	14.44	16.66	14.57	17.63	15.95
HM	15.58	14.28	14.76	12.77	17.82	16.39

Table 9
Average water use efficiency of above-ground biomass [kg/mm] of rainfed crops in the Danube Lowland in the period 1961–1990 and 1991–2020

Soil type	Spring barley		Winter wheat		Maize	
	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020
CA	27.74	26.22	29.73	27.11	31.58	29.45
CM	27.80	26.07	29.52	27.28	30.48	28.61
CMc	27.46	25.84	29.59	26.95	30.95	28.33
FM	27.34	26.21	29.85	27.75	31.26	28.79
HM	28.02	25.83	29.21	26.68	30.69	28.18

Table 10

Average water use efficiency of above-ground biomass [kg/mm] of irrigated crops in the Danube Lowland in the period 1961–1990 and 1991–2020

Soil type	Spring barley		Winter wheat		Maize	
	1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020
CA	27.28	25.47	29.45	26.55	31.25	28.92
CM	27.30	26.11	29.90	27.83	31.10	29.15
CMc	27.19	25.79	29.77	27.46	30.99	28.37
FM	26.97	25.51	29.71	27.36	30.92	28.40
HM	27.48	25.57	28.08	25.71	31.36	28.99

Regarding the total aboveground biomass (Table 9), in the period 1991–2020, compared to the period 1961–1990, the WUE of spring barley decreased by 1.7 kg/mm, winter wheat by 2.4 kg/mm and maize by 2.3 kg/mm, while the average differences for irrigated crops (Table 10) are close to rainfed. According to soil types, lower WUE was recorded on Phaeozems and Luvisols, while higher on other soil types. Simulations at the Rišňovce site confirmed that the nutrient supply in the soil also has a significant impact on WUE. At lower fertilization doses, WUE reaches lower values. The highest WUE values were recorded in the variants with the highest fertilization and automatic fertilization (Table 11).

Table 11

Average water use efficiency [kg/mm] at selected probes in the Rišňovce location according to fertilization options

Crop	Fertilization variant	R50		R163		R165	
		1961–1990	1991–2020	1961–1990	1991–2020	1961–1990	1991–2020
Spring barley	N0	1.14	0.82	1.63	1.10	1.45	0.60
	NA	15.76	12.33	16.28	13.28	16.12	12.01
	NN	7.17	10.18	9.53	11.9	8.05	10.48
	NS	12.61	12.68	14.83	13.82	13.37	12.93
	NV	15.88	13.59	16.81	14.29	16.15	13.84
Winter wheat	N0	1.78	1.50	2.52	2.07	2.23	1.82
	NA	17.71	15.73	18.23	16.01	17.77	15.81
	NN	5.51	6.04	6.80	7.21	6.19	6.42
	NS	8.59	9.21	10.40	11.38	9.17	9.59
	NV	13.92	14.33	16.8	15.89	14.87	14.39
Grain maize	N0	3.00	2.66	4.41	3.58	3.83	3.23
	NA	17.70	15.66	18.29	16.09	17.75	15.64
	NN	16.78	15.67	17.76	16.09	17.08	15.65
	NS	17.35	15.66	18.21	16.11	17.55	15.65
	NV	17.70	15.66	18.33	16.09	17.76	15.65

Simulations under emission scenarios for the Rišňovce and Milhostov sites showed an increase in WUE at higher CO_2 concentrations (RCP 8.5) for spring barley at both sites and for winter wheat at the Rišňovce site. In the case of winter wheat in Milhostov, there was a slight decrease in WUE under all emission scenarios due to increasing nitrogen stress caused by increased nitrogen leaching. In the case of maize, there was a slight increase under the RCP 2.6 emission scenario at both sites, while the WUE of maize decreased under the RCP 4.5 and 8.5 scenarios (Fig. 5 and 6, Tables 12 and 13). According to the simulation results for Rišňovce, the WUE of irrigated crops is higher than the WUE of rainfed crops (Table 12). Statistical analysis of the results according to the scenarios revealed higher variability in WUE values for all crops compared to the period 1961– 1990.

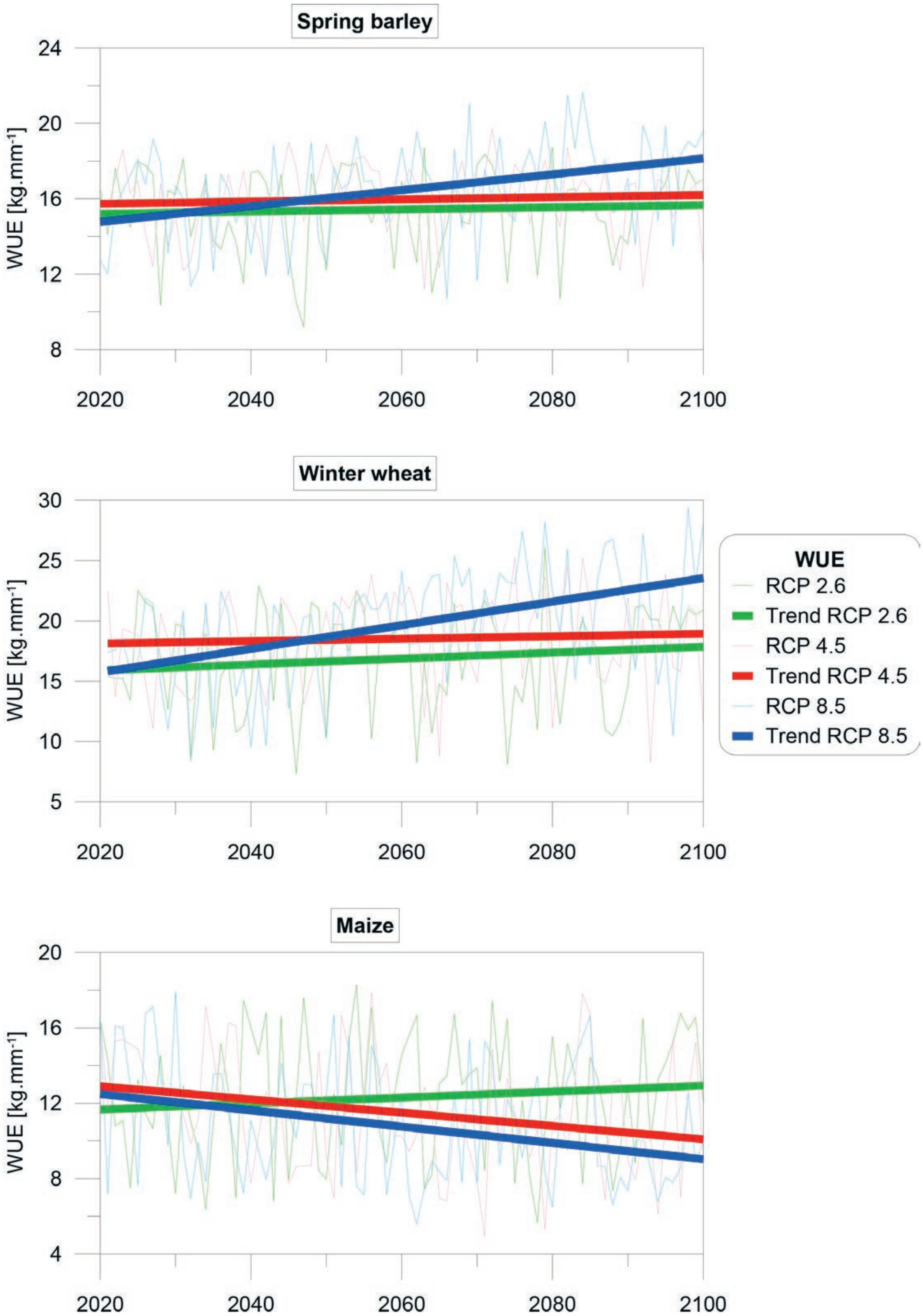

Figure 5 Water use efficiency of spring barley, winter wheat and maize according to the emission scenarios on Rišňovce site

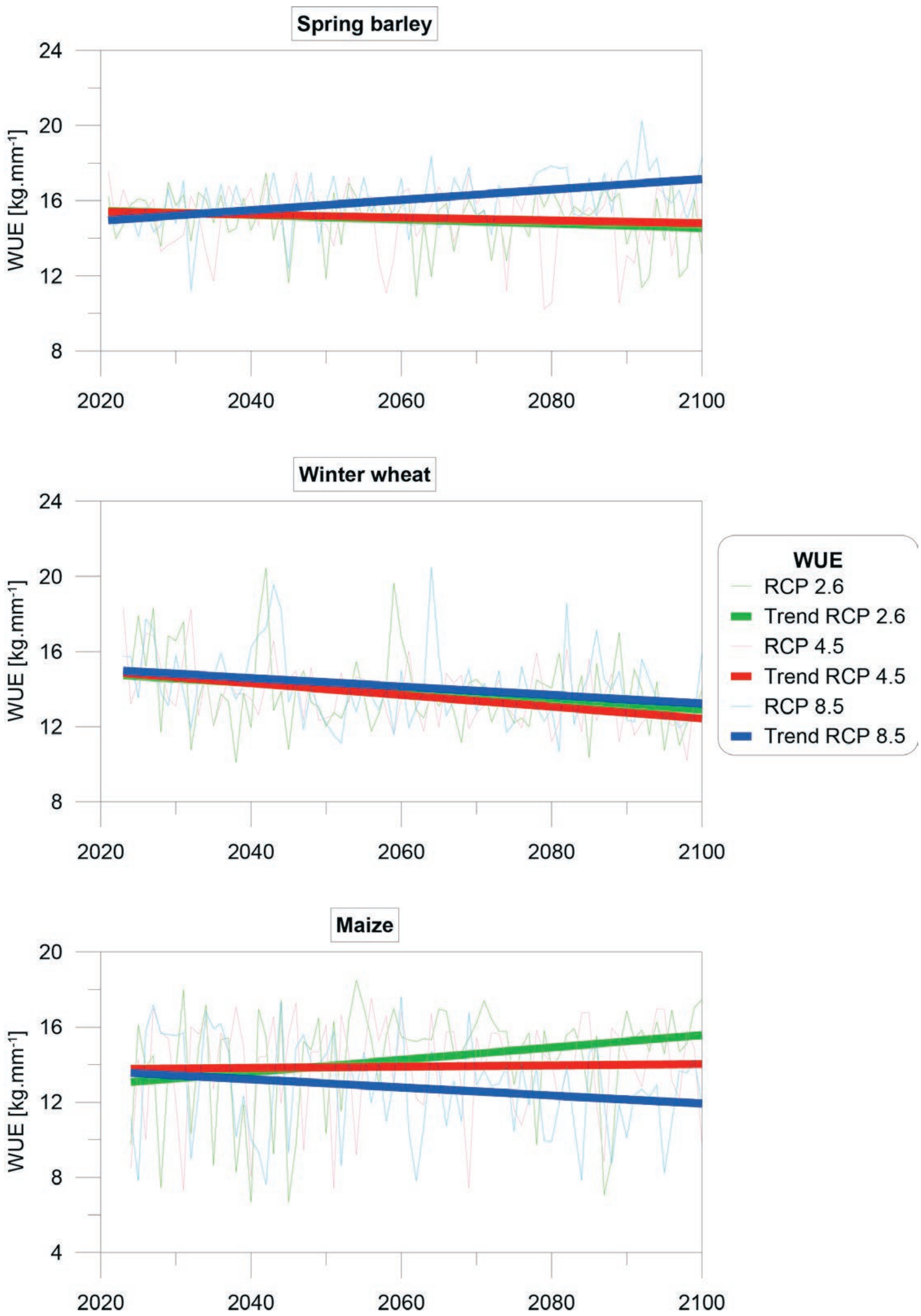

Figure 6 Water use efficiency of spring barley, winter wheat and maize according to emission scenarios at the Milhostov site

With the exception of winter wheat in Trebišov, the obtained WUE results are similar to the simulation results for Hurbanovo (southeast of the Danube Lowland) under the SRES A2 emission scenario, where the calculation results for dense-seeded cereals showed a significant increase in WUE and for maize a decrease in WUE under the SRES A2 scenario (Takáč *et al.* 2009). The increase in WUE of dense-seeded cereals was caused by a higher CO_2 fertilization effect. Unlike cereals, the dependence of WUE of maize as a C4 photosynthesis crop is not affected by the CO_2 concentration in the atmosphere.

Table 12

Average WUE values of spring barley, winter wheat and maize on irrigated and rainfed land according to emission scenarios at the Rišňovce site

Crop	Period	RCP 2.6		RCP 4.5		RCP 8.5	
		rainfed	irrigated	rainfed	irrigated	rainfed	irrigated
Spring barley	2026–2050	15.11	16.36	15.62	16.78	14.89	16.48
	2051–2075	15.64	16.53	16.48	16.86	16.65	17.23
	2076–2100	15.63	16.41	15.54	16.82	17.88	18.52
Winter wheat	2026–2050	15.40	19.00	17.21	19.68	16.37	19.24
	2051–2075	17.06	20.11	19.88	20.95	21.29	22.23
	2076–2100	17.57	19.83	18.27	18.66	20.23	23.60
Maize	2026–2050	11.78	15.12	12.32	15.25	11.83	15.24
	2051–2075	12.94	16.01	11.06	15.31	10.54	14.33
	2076–2100	12.33	15.42	10.89	14.62	9.67	13.45

Table 13

Average WUE values of spring barley, winter wheat and maize on irrigated and rainfed land according to emission scenarios at the Milhostov site

Crop	Period	RCP 2.6	RCP 4.5	RCP 8.5
Spring barley	2026–2050	15.18	15.32	15.37
	2051–2075	14.89	15.19	15.98
	2076–2100	14.89	14.75	16.95
Winter wheat	2026–2050	14.32	14.33	14.89
	2051–2075	13.67	13.55	13.62
	2076–2100	13.38	12.94	13.72
Maize	2026–2050	12.90	13.94	13.31
	2051–2075	15.61	13.86	12.79
	2076–2100	14.56	13.89	12.06

CONCLUSION

The WUE values of densely planted cereals and maize in individual years, depending on climatic conditions, fluctuated in the range from 10 to 19 kg/mm, sugar beet and potatoes from 11 to 27 kg/mm. In the period 1991–2020, compared to the period 1961–1990, the average WUE of crops decreased by approximately 1 kg/mm. The largest decrease in WUE was found for most of the evaluated crops in the northeast of the Danube Lowland in the Nitra region, for potatoes on the upper Žitný ostrov (Bratislava region).

In addition to climatic conditions, soil properties also play an important role in crop water management and WUE. In the Danube Lowland, the lowest average WUE of spring barley and winter wheat was recorded on Chernozems and Luvisols in the Bratislava region, in the case of spring barley the highest on Fluvic Chernozems in the Nitra region and in the case of winter wheat on Fluvic Chernozems in the Hurbanovo region. In the case of maize, the lowest WUE values were calculated on Luvisols in the Hurbanovo region and the highest on Phaeozems in the Nitra region.

Simulations at the Rišňovce site confirmed that the nutrient supply in the soil also has a significant impact on WUE. At lower fertilization rates, WUE reaches lower values. The highest WUE values were recorded in the variants with the highest fertilization and automatic fertilization.

Simulations according to emission scenarios for the Rišňovce and Milhostov sites showed an increase in WUE at higher CO_2 concentrations (RCP 8.5) for spring barley at both sites and for winter wheat at the Rišňovce site. In the case of maize, there was a slight increase at both sites under the RCP 2.6 emission scenario, while under RCP 4.5 and 8.5 there was a decrease in WUE of maize. Statistical analysis of the results according to the scenarios revealed a higher variability of WUE values for all crops compared to the period 1961–1990.

ACKNOWLEDGEMENT

This contribution was created thanks to the support of the Operational Program Integrated Infrastructure for the project: Sustainable systems of intelligent farming considering the challenges of the future 313011W112, co-financed from the resources of the European Regional Development Fund.

REFERENCES

Alcamo, J., Moreno, J.M., Nováky, B. *et al.* (2007). Europe. Climate change 2007: impacts, adaptation and vulnerability. In: *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E.), pp. 541–580. Cambridge University Press, Cambridge, UK.

Allen, R. G., Pereira, L. S., Raes, D., Smith, M. (1998). Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. *FAO Irrigation and Drainage*, Paper 56. FAO, Rome.

Bízik, J. (1999). Production Effect of Irrigation and Nutrition with a Special View to Environment. *Scientific Papers of the Research Institute of Irrigation*, Bratislava, vol. 24: 19–32, VÚZH, Bratislava, ISBN 80-85755-06-8.

Cambel, B., Takáč, J. (2000). Priestorová diferenciácia hydrofyzikálnych vlastností pôd na príklade modelového územia Šaľa. VI. *Zjazd Slov. Spol. pre poľnohospodárske, lesnícke, potravinárske a veterinárske vedy pri SAV.* Zborník prednášok. Sekcia pedologická. Zvolen 6.-7.9.2000. VÚPOP, Bratislava, s. 29–34.

Easterling, W.E., Aggarwal, P.K., Batima, P. *et al.* (2007). Food, fibre and forest products. Climate change 2007: impacts, adaptation and vulnerability. *Contribution of Working Group II. In: The Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E.),), pp. 273–313. Cambridge University Press, Cambridge.

Eitzinger, J., Trnka, M., Semerádová, D., Thaler, S., Svobodová, E., Hlavinka, P., Šiška, B., Takáč, J., Malatinská, L., Nováková, M., Dubrovský, M., Žalud, Z. (2013). Regional climate change impacts on agricultural crop production in Central and Eastern Europe – hotspots, regional differences and common trends. *Journal of Agricultural Science*, vol. 151(6): 782–812.

IPCC (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC.* Cambridge University Press. ISBN 978-0521-88010-7.

IUSS Working Group WRB (2015). *World Reference Base for Soil Resources 2015.* International soil classification system for naming and creating legends for soil maps. World Soil Resources Reports, No. 106. FAO, Rome.

Kostrej, A., Danko, T., Jureková, Z., Zima, M., Gaborčík, N., Vidovič, J. (1998). *Ekofyziológia produkčného procesu porastu a plodín*. (Ecophysiology of the production process of vegetation and crops). SPU v Nitre, Nitra. 187 p., ISBN 80-7137-528-4.

Larcher, W. (1988). *Fyziologická ekologie rostlin*. Vyd. 1. Academia, Praha, 368 s.

Leakey, A., Ainsworth, E., Bernacchi, C., Rogers, A., Long, S., Ort, D. (2009). Elevated CO_2 effects on plant carbon, nitrogen, and water relations: Six important lessons from FACE. *Journal of Experimental Botany*, vol. 60: 2859–2876, https://doi.org/10.1093/jxb/erp096.

Ministry of the Environment of the Slovak Republic. (2017). *The 7th National Communication of the Slovak Republic on Climate Change under United Nations Framework Convention on Climate Change and Kyoto Protocol*. Bratislava. 228 pp.

Palosuo, T., Kersebaum, K.C., Angulo, C., Hlavinka, P., Moriondo, M., Olesen, J.E., Patil, R.H., Ruget, F., Rumbaur, Ch., Takáč, J., Trnka, M., Bindi, M., Caldag, B., Ewert, F., Ferrise, R., Mirschel, W., Saylan, L., Šiška, B., Rötter, R. (2011). Simulation of winter wheat yield and its variability in different climates of Europe: A comparison of eight crop growth models. *European Journal of Agronomy,* vol. 35(3): 103–114. DOI: 10.1016/j.eja.2011.05.001.

Pohanková, E., Hlavinka, P., Orság, M., Takáč, J., Kersebaum, K.C., Gobin, A., Trnka, M. (2018). Estimating the water use efficiency of spring barley using crop models. *Journal of Agricultural Science*, 1–17. Doi:10.1017/S0021859618000060.

Pohanková, E., Hlavinka, P., Kersebaum, K.C., Rodríguez A., Balek, J., Bednařík, M., Dubrovský, M., Gobin, A., Hoogenboom, G., Moriondo, M., Nendel, C., Olesen, J.E., Rötter, R.P., Ruiz-Ramos, M., Shelia, V., Stella, T., Hoffmann, M.P., Takáč, J., Eitzinger, J., Dibari, C., Ferrise, R., Bláhová, M., Trnka, M. (2022). Expected effects of climate change on the production and water use of crop rotation management reproduced by crop model ensemble for Czech Republic sites. *European Journal of Agronomy*, vol. 134 126446. https://doi.org/10.1016/j.eja.2021.126446.

Rötter, R., Palosuo, T., Kersebaum, K.C., Angulo, C., Bindi, M., Ewert, F., Ferrise, R., Hlavinka, P., Moriondo, M., Nendel, C., Olesen, J.E., Patil, R.H., Ruget, F., Takáč, J., Trnka, M. (2012). Simulation of spring barley yield in different climatic zones of Northern and Central Europe: A comparison of nine crop models. *Field Crops Research,* vol. 13*:* 23–36, ISSN 0378-4290.

Takáč, J. (1999). Trends in Soil Water Regime in Model Conditions of Žitný Ostrov. *Scientific Papers of the Research Institute of Irrigation Bratislava*, vol. 24: 189–201, VÚZH Bratislava.

Takáč, J. (2001). *Dôsledky zmeny klímy na bilanciu vody v poľnohospodárskej krajine.* (The consequences of climate change on the water balance in agricultural landscapes). Národný klimatický program SR 10/01. SHMÚ, Bratislava, s. 16–26, ISBN 80-88907-24-1 (in Slovak).

Takáč, J. (2008). Produkčná účinnosť využitia vody poľnými plodinami – porovnanie výsledkov poľného pokusu a matematického modelu. (Production efficiency of water use by field crops – comparison of field experiment results and mathematical model). *16th International Poster Day. Transport of Water, Chemicals and Energy in the System Soil-Plan-Atmosphere System*, ÚH SAV, GFÚ SAV, Bratislava, 541–550. (in Slovak).

Takáč, J., Ilavská, B. (2021). Crop water sufficiency in Slovakia. *Pedosphere Research*, vol. 1(1): 20–39. NPPC – VÚPOP 2021. ISSN 2729–8728.

Takáč, J. Kotorová, D., Makovníková, J., Kováč, L. (2018). Validácia modelu DAISY v podmienkach Východoslovenskej nížiny. (Validation of the DAISY model in the conditions of the East Slovak Lowland). *Vedecké práce VÚPOP*, vol. 40: 100–113., Výskumný ústav pôdoznalectva a ochrany pôdy Bratislava. ISBN 978-80-8163-030-9 (in Slovak).

Takáč, J., Skalský, R., Dodok, R., Kusý, D. (2017). Bilancia využiteľnej vody v pôde v regióne Podunajskej nížiny v období 1961-2015. (Balance of usable water in the soil in the Danube Plain region in the period 1961-2015). *Vedecké práce VÚPOP*, vol. 39: 126–141. Bratislava. ISBN 978-80-8163-022-4 (in Slovak).

Takáč, J., Šiška, B. (2009). Climate Change Impact on Spring Barley and Winter Wheat Yields on Danubian Lowland. In: Strelcová, K., Matyas, C., Kleidon, A., Lapin, M., Matejka, F., Blazenec, M., Škvarenina, J., Holecy, J. (Eds.) *Bioclimatology and Natural Hazards*. 2009, XVI, Springer Science + Business Media B.V., 283–288p. ISBN: 978-1-4020-8875-9.

Takáč, J., Šiška, B. (2011). Kalibrácia a validácia modelu DAISY pre podmienky Slovenska. (Calibration and validation of the DAISY model for Slovak conditions) *Vedecké práce VUPOP*, vol. 33: 161–172. ISBN 978-80-89128-91-4 (in Slovak).

Takáč, J., Šiška, B., Lapin, M. (2009). Dôsledky zmeny klímy na vlahovú zabezpečenosť poľných plodín podľa scenárov SRES A2 a B1. (Consequences of climate change on the moisture security of field crops according to SRES A2 and B1 scenarios). *Vedecké práce VÚPOP,* vol: 31: 187–200. Bratislava. ISBN 978-80-89128-59-4 (in Slovak).

Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvag, A.O., Eitzinger, J., Seguin, B., Peltonen Sainio, P., Rötter, R., Iglesias, A., Orlandini, S., Dubrovský, M., Hlavinka, P., Balek, J., Eckersten, H., Cloppet, E., Calanca, P., Gobin, A., Vučetic, V., Nejedlík, P., Kumar, S., Lalič, B., Mestre, A., Rossi, F., Kozyra, J., Alexandrov, V., Semerádová, D., Žalud, Z. (2011). Agroclimatic conditions in Europe under climate change. *Global Change Biology* (2011) 17, 2298–2318, doi: 10.1111/j.1365-2486.2011.02396.x.