Theses of the PhD dissertation

THE IMPACT OF ECOLOGICAL AND AGROTECHNICAL FACTORS ON THE WATER MANAGEMENT OF THE CROP PRODUCTION SPACE AND ON THE YIELD OF MAIZE

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1. INTRODUCTION, PREVIOUS RESEARCH

In multifunctional, sustainable crop production, an optimum yield of good quality meeting the market requirements with a high yield safety is targeted under the given ecological conditions. The efficacy of production, the yield and yield safety are determined by the combination of the biological bases, the agrotechnical elements (crop rotation, soil cultivation, water and nutrient supply etc.) and the agro-ecological factors (soil, weather). From these three groups, the first two can be greatly influenced by man, while the ecological factors (especially weather) make the production quite vulnerable. In the crop production space, one of the most important elements is water, which is present in several ways and participates in plant metabolism in several forms, without it, assimilation, respiration, evapotranspiration and numerous other metabolic and physiological processes in plant tissues and cells would not function. The water stock of the soil ensures the water requirements of the plants (and thereby their nutrient uptake, which serves as a basis for the physiological, dry matter and yield formation processes.

In crop production, water has a prominent role as it can influence the effect of the different natural and production technology factors and thereby, the efficacy of production. Therefore, the extreme water management situations and their effects on the crop stand are of great significance for the experts. The aim is the prevention or the quickest possible elimination of these water management situations detrimental to crop production.

Water has a very complex cycle in the soil-plant-atmosphere system. It is called the hydrological cycle which is influenced by man via its crop production activities; we modify certain elements of the cycle in order to create favourable conditions for enhancing the quality and quantity of the yield, the 'end-product'. These efforts together with other human activities can have a detrimental effect on certain elements of the hydrological cycle in many cases and thereby create unforeseeable, often irreversible consequences in the environment and within this the water cycle of the crop production space. The changes mostly have repercussions on the ecologica, agro-ecological systems and their subsystems which weakens the efficacy of agricultural production and accordingly the profit of those earning their living from this sector.

Global climate change, which has been a current topic for years, is a proven fact by now. In the past hundred years, the temperature rose by 0.7 ºC. The warming has mainly been a result of the human activities, at least since the middle of the twentieth century (HARE, 2009). The 'macroclimatic' change which started several years ago has shifted also the climate of

Hungary from the typical features of the continental climate. The future possibilities of crop production will probably be widened or limited by the level of adaptation to the changes in the climate. The weather phenomena of the past six years verify the forecasts. Not only the dry or wet periods are more frequent, but the probability of weather extremes and the strength of their effects are increasing even within a year or a vegetation period (KESZTHELYI, 2005; SÁRVÁRI, 2005; BIRKÁS, 2006; LÁNG et al. 2007; ANDA, 2008; POLYÁK, 2008; JOLÁNKAI és BIRKÁS, 2009).

2. RESEARCH OBJECTIVES

Within my research, I focused on the analysis of the water cycle processes of the crop production space and the parametrization of these processes with respect to the extreme climate-weather conditions of Hungary, especially those of the eastern Great Plain region, the Trans-Tisza region. The study was carried out in maize, which has the largest sowing area among crops in this region and its sensitivity to water supply and water balance also justified the research.

In accordance with the above factors, weather and climate changes and processes, the followings were to be investigated:

- Study of the effects of crop rotation, fertilization, plant density and irrigation from among the agrotechnical elements;
- Determination of soil moisture by gravimetry in the maize season and off-season
- Determination of the dynamic changes in soil moisture and the actual water deficiency;
- Analysis of the effect of the different agrotechnical elements (crop rotation, fertilization, plant density, irrigation) on the water management of the soil;
- To define the exact relationship between the water deficiency of the season, the influencing meteorological, biological and agrotechnical elements and the yield and yield stability of maize.

By using the research results, the yield and yield safety of maize can be enhanced in the production and recommendations can be made for production technologies in dry and irrigation farming.

3. MATERIALS AND METHODS

3.1. Experimental site

The examinations were carried out in 2007, 2008 and 2009 in the polyfactorial long-term experiment set up by Prof. László Ruzsányi † in 1983 and directed by Prof. Péter Pepó since

2004 at the experimental farm of the University of Debrecen Centre for Agricultural and Applied Economic Sciences at Látókép located about 15 km from Debrecen along the main road No. 33 in the loess region of Hajdúság.

The experimental soil was calcareous chernozem soil (formed on loess) with a deep humus layer, good general state, it was medium-heavy soil (plasticity index according to Arany: 43) belonging to the loam category.

The fertile layer was 80-90 cm, out of which the layer with uniform humus content was 40-50 cm. The average humus content was 2.76 %. The carbonated lime occured at the transitional level at 75 cm depth, but it was also present coating the soil grains, in this layer the $CaCO_3$ content was between 10 and 13 %. The pH of the cultivated layer (KCl) ranged between 6.3 and 6.5.

The N supply of the experimental area was medium, the total nitrogen content of the top 50 cm layer was 0.12-0.15 %.

Based on the P_2O_5 and K_2O contents determined by the ammonium-lactate method, the phosphorus content of the experimental soil was variable, it could be qualified as medium as an average of the samples (133 mg kg^{-1}). The potassium supply was good with a value of 240 mg kg^{-1}.

The experimental soil can be classified into group IV according to the soil classification system of Várallyai, which means a medium water permeating and good water-holding capacity. The available water is about 50% of the field capacity, the minimum field capacity (WC_{min}) was 275 mm in the 0-100 cm layer and 265 mm in the 100-200 cm layer. The minimum water capacity was 33.65-46 %, the water content at wilting point (WP) was 8.5-15.7 % expressed as volume percentage in the 0-200 cm layer of the soil. The ground water level was 3-5 m, not increasing above 2 m even in rainy years.

Table 1. Water management parameters of the experimental site
(Debrecen, 1983, results of Martin B. – Győri Z.)

Soil layer cm	**Volume weight g/cm^3**	**Volume of pores P %**	**Capillary-gravitational pore space %**	**Gravitational pore space+ air inclusions Pg+a%**	**Capillary pore space %**	**Capillary water capacity V %**	**Minimum field capacity FC_{min} %**	**Wilting point WP %**
5-25	1.34	49.6	17.9	0.9	30.8	31.7	30.8	15.55
27-33	1.53	42.2	3.9	1.2	37.1	38.3	37.1	15.70
47-53	1.31	50.5	12.0	3.1	35.4	38.5	35.4	14.75
72-78	1.45	45.4	6.4	3.3	35.7	39.0	35.7	11.13
97-103	1.57	40.8	3.7	1.5	35.6	37.1	35.6	9.38
122-128	1.6	39.8	2.6	1.1	36.1	37.2	36.1	9.03
147-153	1.65	37.7	1.3	0	36.4	36.4	36.4	8.50

3.2. Experimental set-up

The experimental set-up and the size of the plots are inclued in Annex 1. The size of the experimental plots was 9.2x5 m, 46 m^2.

The studied factors: The long-term experiment is a four-factorial experiment, where the main plots are the crop rotation experiments. The sub-plots within the crop rotation are the irrigation treatments and the sub-sub plots are the plant densities, and the different fertilization treatments are the sub-plots of plant densities:

Factor 'A': crop rotation

Treatments: a_1 monoculture

a_2 biculture (maize-wheat)

a_3 triculture (maize-pea-wheat)

Factor 'B': irrigation

Treatments: b_1 non-irrigated (I_1)

b_2 irrigated (I_3)

Factor 'C': plant density

Treatments: c_1 40000 plants ha^{-1}

c_2 60000 plants ha^{-1}

c_3 80000 plants ha^{-1}

Factor 'D': fertilization

In the experiment, five fertilization levels were used (Table 2).

Table 2. Fertilizer treatments applied in the experiment

	Control	**Fert. treatment 1**	**Fert. treatment 2**	**Fert. treatment 3**	**Fert. treatment 4**
	kg active ingredient ha^{-1}				
Nitrogen	0	60	120	180	240
Phosphorus	0	45	90	135	180
Potassium	0	45	90	135	180

In the irrigated treatment (I_3), the irrigation water dosages applied were as follows:

2007: 50 mm irrigation water on 4 May

50 mm irrigation water on 23 May

50 mm irrigation water on 4 June

50 mm irrigation water on 30 June

2008: no irrigation was applied as the distribution of precipitation was favourable for maize.

2009: 50 mm irrigation water on 4 May

50 mm irrigation water on 23 May

The irrigation was performed with a Valmont linear irrigation system.

The plant densities were 40000 plants ha^{-1}, 60000 plants ha^{-1} and 80000 plants ha^{-1}. The examinations were performed at plant densities of 60000 plants ha^{-1} and 80000 plants ha^{-1}. Soil cultivation, crop protection and harvest were uniform in the experiment. The tested hybrid was Reseda (PR37M81).

To study the water cycle, soil samples were collected on six occassions in all three years from each 20 cm layer until 200 cm depth from mono-, bi- and triculture from the 60000 plants ha^{-1} and 80000 plants ha^{-1} plots from the irrigation treatments I_1 and I_3. The first sampling was done pre-sowing at the beginning of the season, while the sixth sample was taken post-harvest, the four interim samplings were at the major maize phenophases (3-4-leaf stage, tasseling, fertilization, maturity).

The sampling dates in the experimental years were as follows:

2007	2008	2009
20 March	3 April	3 April
27 April	9 May	24 April
4 June	25 June	26 May
4 July	18 July	1 July
16 August	10 September	31 August
5 October	2 October	29 September

The wet weight of soil samples was measured, then the samples were dried in a drying cabinet at 105 ^{o}C until reaching constant mass. The dry samples were weighed and the difference between the wet and dry mass gave the soil moisture content expressed as mass percent. The obtained results were expressed also as a volume percentage by using the volume weight of the given soil layer.

$$WD=(WC_f-SM_v) \times S_v$$, where :

WD – water deficiency

WC_f – field capacity

SM_v – soil moisture in volume percentage

S_v – volume weight of the soil.

The calculations were done for the 200 cm layer of the calcareous chernozem soil for each 20 cm layer, that is 10 results were obtained about the water management status for one plot until 2 m depth.

In parallel with this, the amount of the maize yield was also measured in all three crop rotations in both irrigation treatments at both plant densities and for all three fertilization treatments. Yield samples were taken from all plots, which were measured and then dried in a drying cabinet until reaching constant weight and after that they were measured again, in this way, the grain moisture content of the samples was determined. The per-plot yields were standardized, that is the yield was expressed for 1 ha area for 14% moisture content in the different treatments.

For writing the thesis and for constructing the tables, figures and diagrams, the programs *Microsoft Office Word®* and *Excel®* were used. The statisticak analysis of the data was done using the program *SPSS for Windows 13.0*.

4. RESULTS AND DISCUSSION

4.1. Evaluation of the experimental years with respect to the water balance of maize

I compared the monthly precipitation values of the seasons of 2007, 2008 and 2009 with the 30-year average data (Table 3). From the three studied years, 2007 and 2009 were dry as indicated by the deviations from the 30-year average in the table. At the end of the season in 2007 in August and in September, the difference was positive, thereby, the lack of precipitation in the previous months was balanced and the total precipitation of the season was 61. 3 mm lower than the 30-year average. In spite of the fact that it was dry, 2009 was distinctly different. Except for June, the amount of precipitation was lower in each month of the season than the 30-year average. This is also demonstrated by the sum of precipitation in the 6 months (176.3 mm deviations from the 30-year average).

As opposed to the other two years, 2008 was very wet. The amount of precipitation in the season was 483.9 mm, which was 138.8 mm higher than the 30-year average. The amount of precipitation was lower than the 30-year average only in May and August, in the other months the precipitation was much higher (33 – 79 mm) than the average of 30 years. The precipitation was near the 30-year average (38 mm) only in September with 42.2 mm, but this did not have a significant influence on the development of maize.

Table 3. Monthly precipitation values in the season of maize and deviations from the 30-year average (Debrecen, 2007, 2008, 2009)

	2007		2008		2009		30-year
	value (mm)	**deviation (mm)**	**value (mm)**	**deviation (mm)**	**vakue (mm)**	**deviation (mm)**	
April	3.6	-38.8	74.9	32.5	9.9	-32.5	*42.4*
May	54	-4.8	47.6	-11.2	20.1	-38.7	*58.8*
June	22.8	-56.7	140.1	60.6	96.6	17.1	*79.5*
July	39.7	-26	144.9	79.2	9.2	-56.5	*65.7*
August	77.6	16.9	34.2	-26.5	11.3	-49.4	*60.7*
September	86.1	48.1	42.2	4.2	21.7	-16.3	*38*
Total	**283.8**	**-61.3**	**483.9**	**138.8**	**168.8**	**-176.3**	***345.1***
Average temp	**18.8**	**2.0**	**17.4**	**0.6**	**19.5**	**2.7**	***16.8***
Max water deficiency (mm)	**336**		**227**		**314**		**-**

The last row of the table shows the maximum water deficiency values of the season, calculated from the combined results of the experiment. The values reflect the nature of the different years, the maximum water deficiency values were the highest in the dry year of 2007. As opposed to that, the values were more than 100 mm lower in 2008. The water deficiency value in 2009 was similar to that of 2007.

4.2. Changes in the moisture content of the soil layers in the experimental years

The majority of the maize roots (70-80%) are in the top 100-120 cm layer, but roots can be found in greater depths too. Therefore, we found it worthwhile to study the effects of the year and the different agrotechnical elements on the plant, its water use and thereby, on the soil moisture content.

The changes in the water stock of the 200 cm soil profile were studied in the non-irrigated (I_1) and irrigated (I_3) treatments of the different crop rotations in 2007, 2008 and 2009 (Figures 1-3). The figures show the soil moisture content in volume percent at the six sampling dates in monoculture at 60000 plants ha^{-1} plant density at N_{120}+PK fertilization level. The first date represents the soil moisture content directly before the maize season, while the last one stands for the post-harvest state. The interim four samplings were at the major maize phenophases. The respective soil layer was divided into three levels based on the rooting depth of maize: 0-60 cm – where the majority of maize roots is located; 61-120 cm – about one third of the roots reaches this layer as the plant grows; 121-200 cm – this layer is not of determining importance as regards maize roots, but is important for the water cycle of the soil profile.

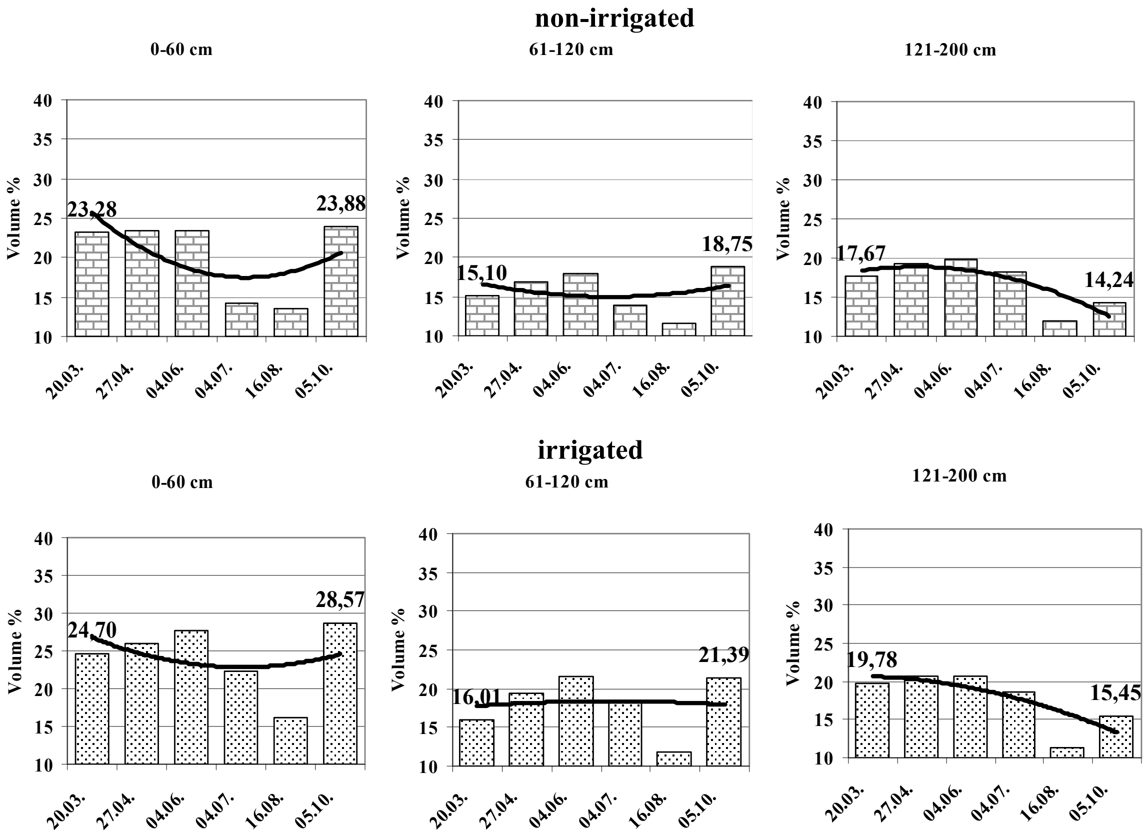
In the water cycle of the studied soil profile, the changes in the water stock of the three layers should be studied. First, I observed the water cycle in the non-irrigated plots. The water loss in the top 0-60 cm layer was moderate (with small fluctuations) but continuous in 2007 at all fertilization levels for both plant densities. This slight, continuous reduction accelerated in July and the soil moisture reached its minimum by August (12-16 v %). The small increase at the last samling was due to the early autumn rains and due to the significant reduction in the intensity of life processes in maize, its assimilation and transpiration surfacee was much smaller and the grain filling processes also decelerated and were finished.

In the 61-120 cm soil layer, the processes were similar to those of the top layer. The roots reached this layer at the mid-season in June at flowering, which is indicated also by the moisture values (12- 16 v %). At the end of the season, a remoisturization (24-28 v %) could be observed also here, but this was lower than that of the top layer.

In the bottom layer (121-200 cm), a reducing trend could be observed with small fluctuations. The explanation for this is that the water loss of the upper soil layers was supplemented from this layer via the movement of water vapor and water lifting via capillary action. The slight remoisturization (14-17 v %) of the middle layer (61-120 cm) was partly due to this mechanism.

In the irrigated plots, the changes in the moisture content of the top 0-60 cm layer were similar to those of the non-irrigated plots. However, the values were higher throughout the whole season (4-5 v % higher on average). The moisture increasing effect of irrigation was the most intensive in the top layer, but it also had a beneficial effect in the middle layer, the minimum values of irrigated treatments in August were significantly higher by 2-3 % than in the non-irrigated treatments. No moisture increasing effect of irrigation could be detected in the bottom soil layer (Figure 1).

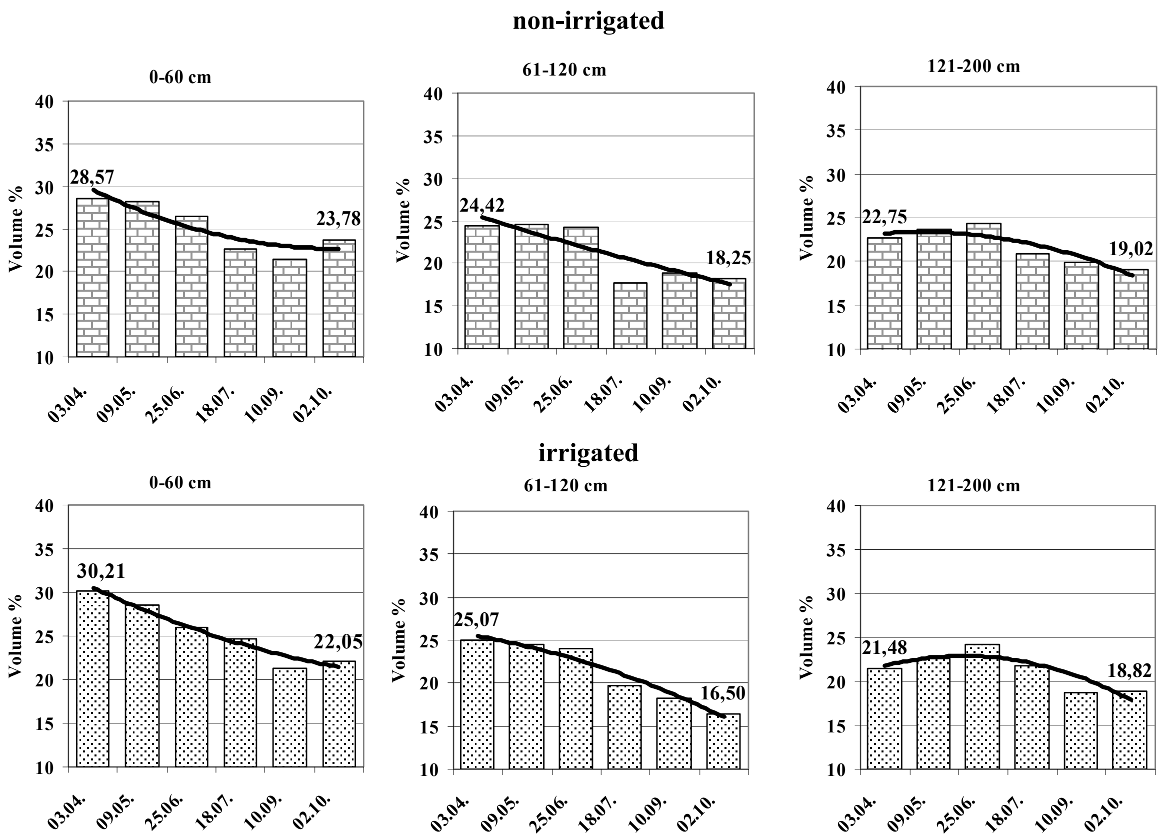
Figure 1. Soil moisture content (v%) in monoculture in 2007 (60000 plants ha^{-1}, N_{120}+PK)



When studying the changes in the water stock of the soil in the three crop rotation systems in the irrigated (I_1) and non-irrigated (I_3) treatments in the 200 cm soil profile in 2008 (Figure 2), we can state that the water stock was favourable for maize in all three crop rotations (18-30 v%), the wilting point (17-24 v%) was approached only at the end of the summer in certain layers. The water content of the soil was favourable (22-31 v%) already before the pre-sowing period, which provided optimum water supply conditions for emergence and early development of maize. The results also support that the year was optimal for maize growth with proper water supply in the different phenological stages, the soil moisture values were higher throughout the whole season as compared to the extremely dry year of 2007 (in 2007- the measured moisture values in the season were between 11 and 18 v%, while in 2008, the values varied between 18 and 27 v %). However, by the end of the season, the water stock was near the wilting point (16-23 v %) in the root zone (0-60 cm), but at this stage, it did not have an unfavourable effect on plant development, yield formation and grain filling that is on the amount of yield.

The dynamics of water loss in the 0-60 cm layer showed a slightly decreasing trend. The sudden reduction of 3-4 v% in moisture content observed in the grain-filling period was due to the water demand of the great vegetative and generative plant biomass. In 2008, the distribution of the precipitation was favourable, by harvest the water stock of the soil in the top layer started to increase again.

Figure 2. Soil moisture content (v%) in monoculture in 2008 (60000 plants ha^{-1}, N_{120}+PK)

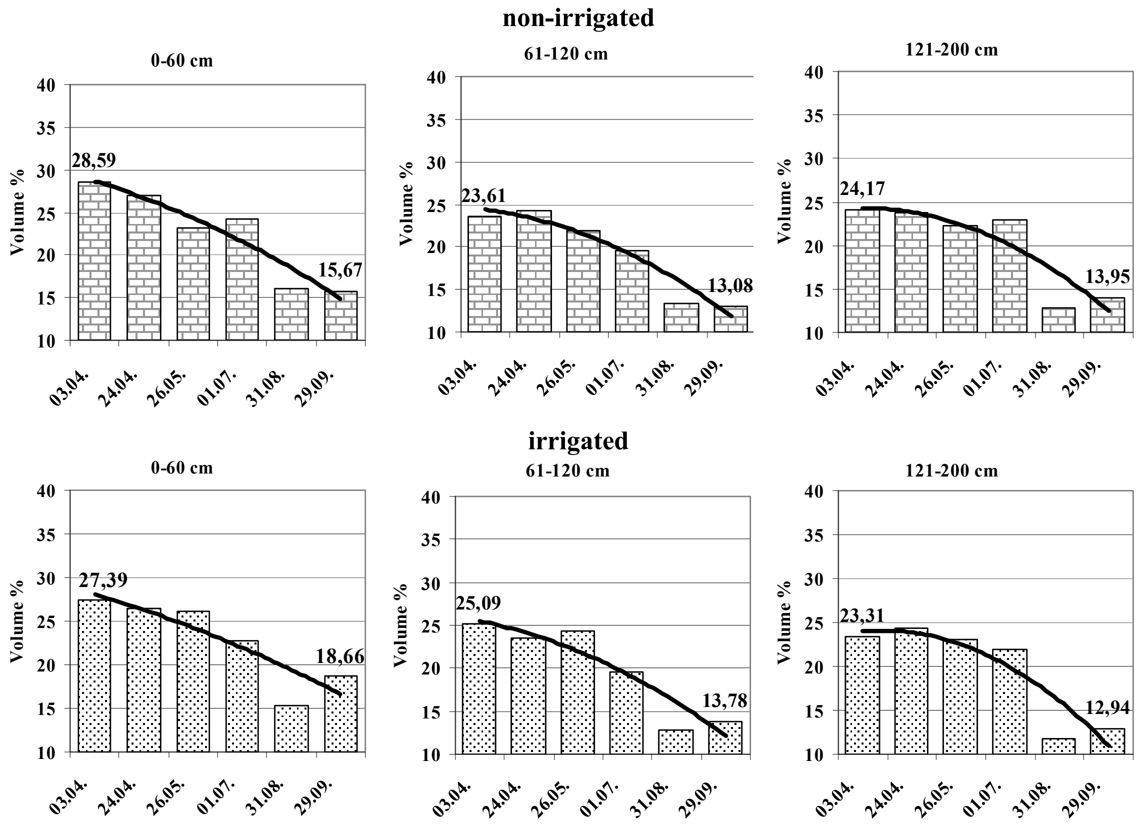


In the 61-120 cm layer, the same trend could be observed, the difference being that there was no increase at the last sampling date, the moisture content remained at the same level as at the end of August-beginning of September (16-21 v%), because this layer also contributed to the filling of the top layer due to the different water movement processes in addition to the natural precipitation.

The 121-200 cm layer showed a similar trend to the upper two layers, except for the end of the season, when it supplemented water for the upper, relatively drier layers, therefore, its values stagnated due to supplying the 61-120 cm via vapour movement and capillary action.
As there was no need for irrigation in 2008 due to the favourable precipitation, there were no significant differences between the moisture values of irrigated and non-irrigated plots.
In 2009, the original soil water stock at pre-sowing (Figure 3) was similar to that of 2007 and 2008 (24-29 v%) in all three crop rotation systems, in all fertilization and irrigation treatments at both plant densities.
In the top 0-60 cm layer, the water stock reduced with small fluctuations in the first half of the season. As a result of precipitation exceeding 100 mm in June, the stand still had enough water in the period of flowering. By August, a reduction of 8-9 v % occurred, resulting in the lowest value, as a remoisturization of 2-3 v % resulted from the upward movement of moisture from lower layers.
The trend in the 61-120 cm layer was similar to the upper layer. However, the values did not increase significantly around harvest, but they rather stagnated (13-15 v %), as it fed the water stock of the upper layer and the upward moving moisture could not be supplemented from the layer below due to the drought.
The same trend could be observed in the 121-200 cm soil layer.
A favourable after-effect of irrigation could be detected in 2008, the soil moisture values were higher not only in the top, but also in the second root zone.
Based on our examinations, the plant density had a small (2-3 v%), but significant effect on soil moisture in all layers, except for August, the most critical period of maize as regards water demand, when no significant difference could be found in the 0-60 and 61-120 cm layers. In sum, it can be concluded that a higher plant density increases only the trend of water consumption.
The effect of fertilization was not dependent upon the year, there were significant differences in soil mositure at all soil layers between the fertilization treatments. In very dry and partially dry years, the differences were smaller due to the smaller biomass, while in 2008 with good water supply, the increasing fertilizer dosages reduced the soil moisture more strongly. It proves, that if there is enough water in the soil to satisfy the plant requirements, then the higher fertilizer dosages result in higher water uptake, the plants ’waste’ the water.
If we study the changes in soil moisture for the three years combined, then we can state that the changes during the season are the greatest in the top 0-60 cm layer. The diagrams and the trend lines demonstrate well that irrigation water has the largest impact in this layer and the

moisture-increasing effect of precipitation is the greatest and the water uptake by the large root mass of maize is also the most intensive here. The soil moisture content of the 61-120 cm layer is more balanced, the reduction of water content is lower than in the top layer. The 121-200 cm layer participated indirectly in the water movement processes of the soil and in the water supply of maize via capillary action, therefore, soil moisture content was the most balanced here as shown by the trendlines and columns of the diagrams. A great reduction could be observed in August in the grain-filling period, when the soil moisture movement and supplementation start from this layer with the drying of the medium layer.

Figure 3. Soil moisture content (v%) in monoculture in 2009 (60000 plants ha^{-1}, N_{120}+PK)



In the trends of the three experimental years, the good water management, water-holding and permeating capacity of the chernozem soil can be observed. As a result of this, it can moderate the climate effects and compensate for the unfavourable water cycle conditions to a certain extent.

As a result of the extreme climate, drastic impacts could be detected in the upper soil layer. In all three years, the water stock reduced from the beginning of the season with small fluctuations reaching a bottom value at flowering and yield formation and then, depending upon the amount and distribution of precipitation, starts to increase in September.

The second layer (61-120 cm) showed a decreasing trend from April to early June. From the beginning of July until mid- or late August, the roots of maize reach this zone, accordingly, the moisture of this layer is drastically reduced. The extent of reduction is dependent upon the water supply of the year. In 2007 and 2009, the water loss was high, 8-10 v%, while in 2008, this value was only 3-4 v %.

From among the three layers, the 121-200 cm layer is the least influenced by the water consumption of the plants and the effects of precipitation and irrigation. The water stock of this layer is determined mostly by the ’refilling’ effect of the autumn-winter period. In the three studied years, the values started from 20-24 v% with a slight reduction along with the season, the drastic reduction occurred in July and August in this layer also. Via water vapour movement and capillary action, this layer provides water for the 61-120 cm layer above it. When analyzing the effects of irrigation, it can be concluded that it had the major effect in the 0-60 cm root zone in 2007 and 2009, it filled up the upper layer of the soil almost to field capacity, thereby, favourable water and nutrient supply conditions were created for the crop stand. As soon as the irrigation had been stopped, and we relied on the precipitation only, the soil moisture content started to reduce. The moisture values of the 61-120 cm layer were very similar to those of the non-irrigated plots, which supports the conclusion, that irrigation has a moisture enrichment effect mainly in the top layer. In a very dry year (2007), the effect of irrigation water appears also below the 0-60 cm layer, more strongly in the 61-120 cm layer and very moderately in the bottom layer (1-3 v %).

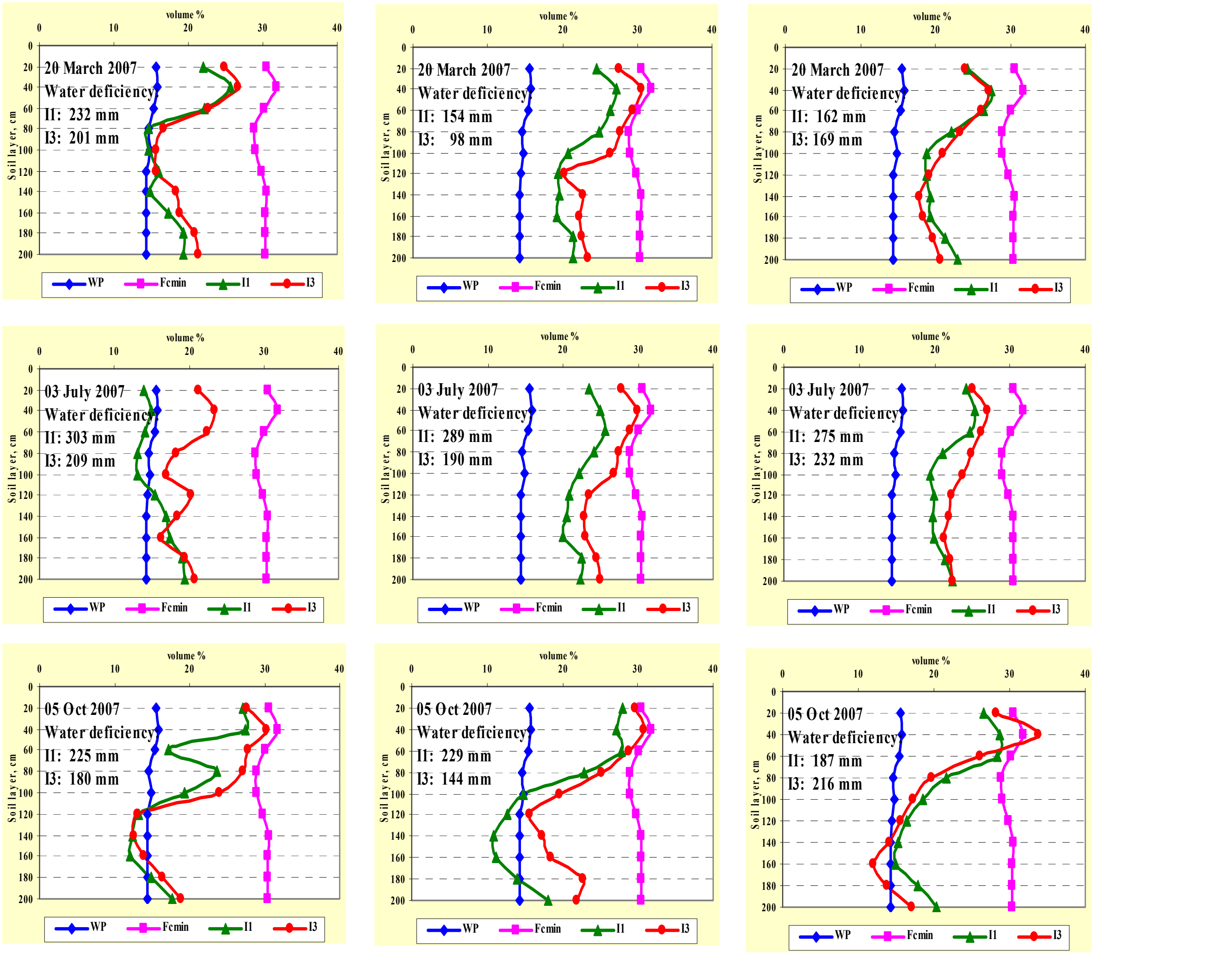
Similar trends, tendencies were observed in the soil moisture content in the other two crop rotation systems, in biculture and in triculture. The difference was that the initial water stock values were already 3-4 v% higher in bi- and triculture as compared to monoculture and this trend remained the same throughout the whole season in both the irrigated and non-irrigated treatments.

4.3. Dynamics of changes in the moisture content in the studied soil profile (0-200 cm)

In addition to the changes in the moisture content of the different layers, it is reasonable to study the changes in the water stock of the whole soil profile of 0-200 cm during the season. We compared the changes in the water stock of the 0-200 cm layer in the non-irrigated(I_1) and irrigated plots (I_3) at the plant density (60000 plants ha^{-1}) and fertilization level (N_{120}+ PK) applied in field practice in 2007, 2008 and 2009 (Figures 4, 5 and 6). In the analysis, the soil moisture contents at the beginning of the season, at the flowering-fertilization phenophase when the water-uptake is the highest and at the post-harvest period (water left after the crop is removed) are included, the diagrams show the wilting point and minimum water capacity curves which show the pattern characteristic to chernozem soils. The results showed that the water stock of the soil significantly reduced by the end of the season in all three crop rotation systems and all years in the non-irrigated plots (10-14 v% 20 2007, 11-17 v% in 2009).

Figure 4. Changes in the water stock of the soil in 2007 in non-irrigated (I_1) and irrigated (I_3) treatments in mono-, bi- and triculture (Debrecen, 60000 plants ha^{-1}, N_{120}+P_{90}+K_{90})

Monoculture **Biculture** **Triculture**



In the non-irrigated plots, the reduction in water stock almost reached the wilting point by the beginning of July in monoculture (13-15 v% in 2007). In irrigated plots, this effect did not occur or only to a smaller extent (14-18 v%) (Figures 4 and 6).

Results of 2008 showed that the water stock of the soil (25-30 v%) was favourable for maize in all three crop rotation systems and the wilting point (13-19 v%) was approached only at the end of the season. As a result of the precipitation received at the proper time and in proper amount, the water stock of the non-irrigated and irrigated plots was similar from April to October (non-irrigated plots 13-30 v%, irrigated plots 17-32 v%) in all threee crop rotation systems, there was no significant difference (1-2 v%), the curves were almost parallel due to the favourable water supply of the season. In all the crop rotation systems, the upper layer 60 cm layer of the soil was almost saturated to FC_{min} in the spring in both the non-irrigated and irrigated plots, which greatly promoted the emergence and early development of maize. However, by the end of the season, the water stock in the root zone almost reached 13-14 v% in the non-irrigated treatment in triculture, while the soil moisture was 17-19 v% in both the non-irrigated and irrigated treatments in the other two crop rotations, but this did not have an unfavourable effect on stand development and yield formation processes (Figure 5).

Figure 5. Changes in the water stock of the soil in 2008 in non-irrigated (I_1) and irrigated (I_3) plots in mono-, bi- and triculture (Debrecen, 60000 plants ha^{-1}, N_{120}+P_{90}+K_{90})

Monoculture **Biculture** **Triculture**

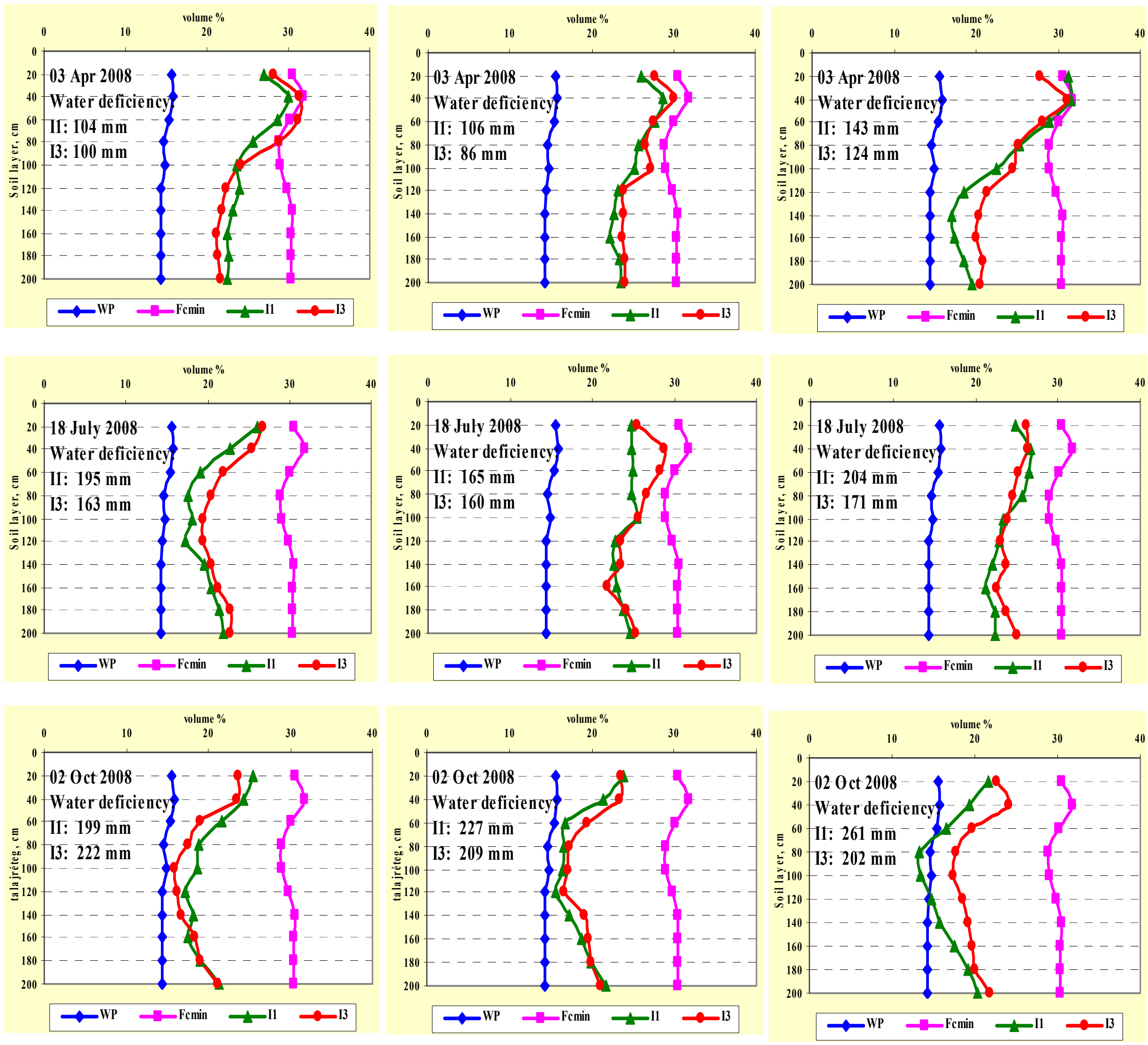
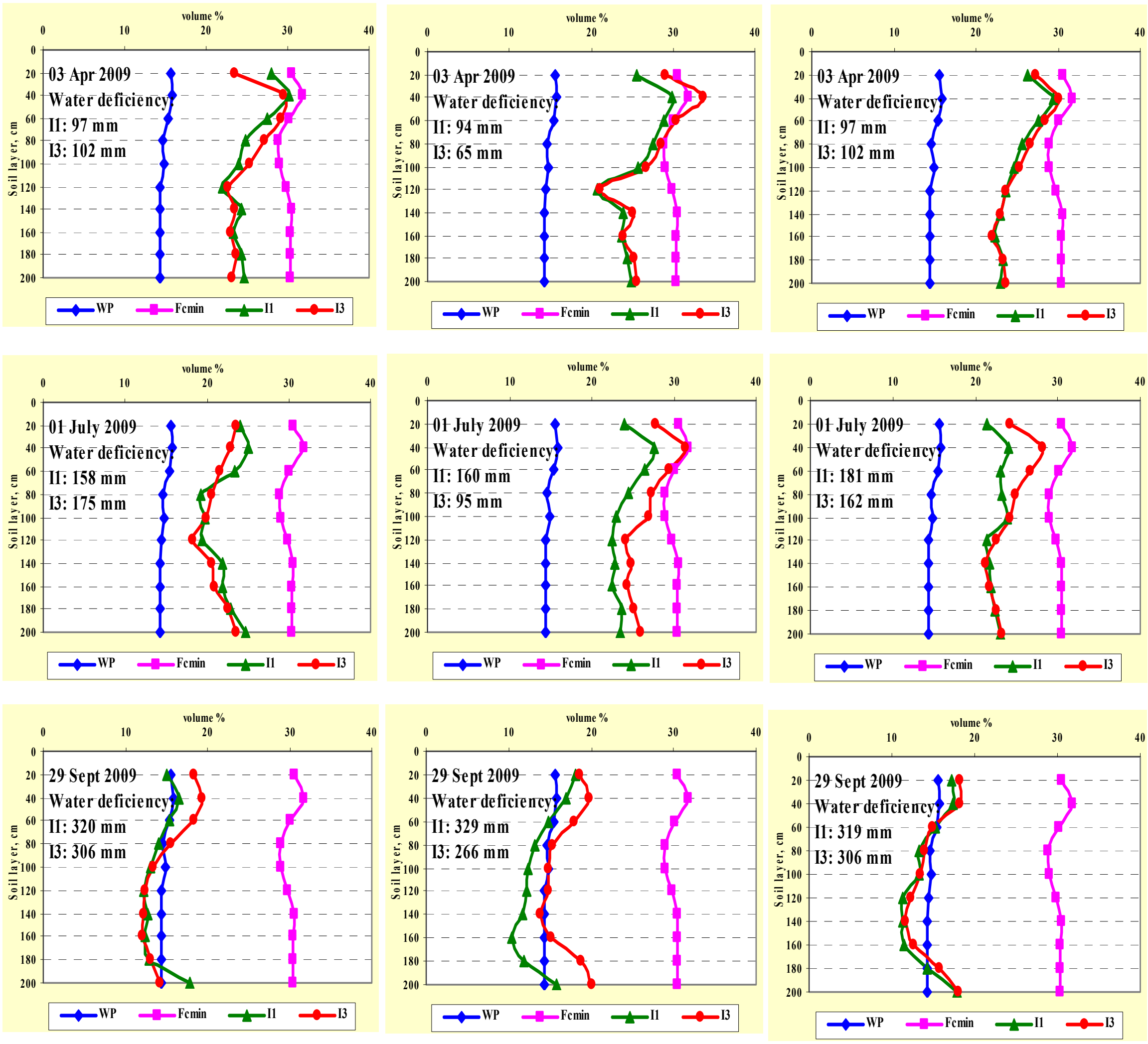


Figure 6. Changes in the water stock of the soil in 2009 in non-irrigated (I_1) and irrigated (I_3) plots in mono-, bi- and triculture (Debrecen, 60000 plants ha^{-1}, $N_{120}+P_{90}+K_{90}$)

Monoculture **Biculture** **Triculture**



4.4. The effect of agrotechnical factors on water deficiency of chernozem soil in the experimental years

In addition the changes in the water stock of the studied soil layer (0-200 cm), the dynamics of water deficiency in the maize stand the influence of the different irrigation treatments, fertilization levels, crop rotation systems and plant densities on the water cycle of the crop production space were also determined.

When analyzing the water deficiency values 2008 and the results of 2007 together, it can be concluded that the water deficiency values of the soil were much lower in 2008 than in the previous year in both the non-irrigated ($I_{1)}$ and irrigated treatments of the three crop rotations (70-376 mm in 2007, 78-271 mm in 2008). This great difference was due to the favourable amount and distribution of precipitation in 2008. In spite of the fact that water was available in the soil in proper amount and distribution for the undisturbed development of maize in this year and there was no need for irrigation, the water deficiency was smaller in the irrigated plots (I_3) than in the non-irrigated plots in mono-, bi- and triculture (differences between the water deficiency values of the non-irrigated and irrigated treatments were 1-201 mm). In all three crop rotations, the water deficiency values increased due to the higher temperature in July (from 78-152 mm to 131-254 mm), the increasing biomass of the stand and the higher water consumption of plants in the flowering and grain setting period also contributed to this pheonomenon. In spite of the optimum water supply for maize, the water stock of the soil greatly reduced by the first decade of September in both irrigation treatments. It can be explained by the large vegetative mass and high yields resulting from the favourable water supply, the maize stand used the available soil moisture for producing an exceptionally large vegetative and generative plant biomass.

The impact of the multi-year irrigation is shown by the fact that, although the experiment was not irrigated in 2008, the water stock of the soil was higher in the irrigated plots before the season and it remained higher throughout the whole season and even after harvest (water deficiency was 95-152 mm in the non-irrigated plots and 75-125 mm in the irrigated plots).

As opposed to 2007, the plant density significantly increased the water deficiency, it can be stated that under favourable water supply conditions, the water consumption of stands with higher plant density is also higher (60000 plants ha^{-1} 108 mm, 80000 plants ha^{-1} 124 mm as an average of crop rotations and the irrigation and fertilization treatments).

The differences between the water deficiency values of the crop rotations were very small and not significant (monoculture: 107 mm, biculture: 115 mm, triculture: 126 mm), which was due to the fact that the water stock in the soil was satisfactory for all the three crop rotation systems.

Based on the results of 2009, a water deficit of 100 mm was to be expected already in the pre-sowing period in all the three crop rotations due to the low precipitation in the winter-early spring period. The water deficiency values moderately increased with the advancement of the season until the beginning of July (the water deficiency starting from 100mm approached and even exceeded 200 mm in July in certain plots). If the values of May and June are compared, we can conclude that there had been no change in the water stock of the soil (water deficiency was 129-190 mm in June and 143-212 mm at the beginning of July), in spite of the fact that maize has a strongly increasing water demand in this period. The reason for this was the significant amount of rain (96.6 mm) in June, wchich was efficiently utilized by the stand for vegetative and later generative development. However, a strong reduction started in July in the water stock of the soil due to the increasing water demand of maize at flowering and grain setting, the water deficiency values approached or exceeded 300 mm in both the non-irrigated and irrigated plots in August. This process lasted until the end of August due to the extreme drought and high temperatures.

According to the water deficiency values in June, the effect of fertilization was also detectable in 2008, the increasing fertilizer dosages resulted in higher water deficiency values, although the differences were not significant (control: 143 mm, N_{120}+P_{90}+K_{90}: 158 mm, N_{240}+P_{180}+K_{180}: 172 mm).

The effect of plant density was not significant either, there were very small differences in water deficiency between the plant densities 60000 plants ha^{-1} and 80000 plants ha^{-1} (153 at 60000 plants ha^{-1}, 162 mm at 80000 plants ha^{-1} as an average of crop rotations, irrigation and fertilization treatments).

In the irrigated plots, the results of the experiments in the period from the end of April until the beginning of July demonstrated the positive effect of irrigation. While the water deficiency values greatly increased in the non-irrigated plots in this period (from 89-112 mm in April to 139-190 mm), there had been a great reduction in the water stock of irrigated plots as a result of the irrigation performed in May (water deficiency ranging between 65 and 135 mm in April and 51-135 mm at the end of May). The proper timing of irrigation is proved by the fact that the water deficiency values stagnated in this period. The maize stand received the irrigation in its growth phase, therefore it could be used completely for vegetative development.

When analyzing the effect of irrigation on the water cycle, it can be concluded that the difference in water deficiency between the non-irrigated and irrigated plots at the beginning of the season was the smallest in monoculture (10-98 mm). As a result of the lack of precipitation starting from July and the monthly average temperature being higher by 3 C^{o} than the 30-year average, only very small differences could be observed between the water deficiency values of non-irrigated and irrigated plots by the end of August. By the end of August, the water deficiency values of the non-irrigated plot in triculture were almost the same as those in the irrigated treatment (difference of 2-21 mm). In monoculture, the values of the irrigated treatment were even higher than those of the non-irrigated treatment (by 5-17 mm). This can be explained by the larger water uptake of the larger vegetative and generative plant biomass resulting from the irrigation and the increasing atmospheric and soil drought.

With respect to crop rotation systems, the water deficiency values biculture were significantly lower than those of the others (monoculture: 163 mm, biculture: 138 mm, triculture: 172 mm).

4.5. The effect of agrotechnical elements on maize yield

Changes in the water cycle of the crop production space have a great impact on yields. The water cycle processes are influences and determined both by agro-ecological and agrotechnical factors. In this chapter, we studied the relationships between agrotechnical factors (crop rotation, fertilization, plant density, irrigation), yield and the water deficiency values in the pre-sowing period in April, at flowering at the end of June and at grain filling (the highest value of the season, in Mid-August-early September) in three different years.

In 2007, great differences were found when comparing the results of the two plant densities in all the crop rotations in all fertilization treatments (control, $N_{120}P_{90}K_{90}$, $N_{240}P_{180}K_{180}$). In both the non-irrigated (I_1) and irrigated (I_3) treatments, higher yields were obtained at lower plant densities: yields were higher by 250-870 kg ha^{-1} in monoculture, 520-530 kg ha^{-1} in biculture, 200-630 kg ha^{-1} in triculture in the non-irrigated treatments and by 360-1100 kg ha^{-1} in monoculture, 14-570 kg ha^{-1} in biculture and 39-440 kg ha^{-1} in triculture in the irrigated treatments. There were two exceptions only, yields were higher at 80000 plants ha^{-1} plant density in the non-irrigated treatment of biculture in the control plot (by 74 kg ha^{-1}) and int he irrigated treatment of triculture in the control plot (by 425 kg ha^{-1}). It proved, that under such dry conditions the optimum plant density of maize is smaller. The maximum yield was obtained in the $N_{120}P_{90}K_{90}$ fertilization treatment in the applied crop rotation systems.

As a result of irrigation (I_3=4x50 mm) a significant yield increment was obtained as compared to the non-irrigated plots, it varied between 2-5.5 t ha^{-1} depending upon the applied crop rotation, plant density and fertilization level (Tables 4 and 5).

According to our results, fertilization had a significant yield-increasing effect in all crop rotations and all irrigation treatments. In the long-term experiment set up in 1983, each plot receives the same treatment in each year, that is the control plots do not receive fertilization, the nutrient stock of the soil is greatly reduced, therefore, the effect of fertilization in mono- and biculture was significant. The yield increment at the fertilization level of $N_{120}P_{90}K_{90}$ was 1-1.5 t ha^{-1}, 1.1-1.5 t ha^{-1} and only 0.05-0.1 t ha^{-1} in mono-, bi- and triculture, respectively. Based on the results, the $N_{120}P_{90}K_{90}$ fertilization treatment proved to be the agro-ecological optimum in the different irrigation and plant density treatments.

Table 4. The effect of agrotechnical factors on maize yield (Debrecen, 2007-2009)

	2007			2008			2009		
	Yield (kg ha^{-1})		Yield increment due to irrigation (kg ha^{-1})	Yield (kg ha^{-1})		Yield increment due to irrigation of the previous year (kg ha^{-1})	Yield (kg ha^{-1})		Yield increment due to irrigation (kg ha^{-1})
	Non-irrigated	Irrigated		Non-irrigated	Irrigated		Non-irrigated	Irrigated	
MONOCULTURE									
Ø									
60 000	2667	5277	2610	9049	8580	-469	6009	6438	429
80 000	2348	4914	2566	8819	7559	-1260	5447	6404	957
N_{120}+$P_{90}K_{90}$									
60 000	4228	8233	4005	13809	12893	-916	8774	10973	2199
80 000	3364	6889	3525	12095	11444	-651	8795	10595	1800
N_{240}+$P_{180}K_{180}$									
60 000	2361	7858	5497	12909	13292	383	8704	11173	2469
80 000	2109	6757	4648	12464	11657	-807	7792	11256	3464
BICULTURE									
Ø									
60 000	5983	8680	2697	11514	12709	1195	10112	10491	379
80 000	6057	8106	2049	11577	13294	1717	9674	9958	284
N_{120}+$P_{90}K_{90}$									
60 000	7696	10694	2998	14056	14158	102	12329	13968	1639
80 000	7159	10241	3082	14396	14703	307	11517	13005	1488
N_{240}+$P_{180}K_{180}$									
60 000	7026	8761	1735	13360	13736	376	11055	12651	1596
80 000	6504	8747	2243	13803	13849	46	10090	12656	2566
	5983								
TRICULTURE									
Ø									
60 000	6761	7833	1072	11321	11154	-167	8556	9225	669
80 000	6560	8258	1698	11714	11293	-421	8335	8801	466
N_{120}+$P_{90}K_{90}$									
60 000	6890	11031	4141	13622	14089	467	10160	12858	2698
80 000	6614	10992	4378	13465	14236	771	9205	12648	3443
N_{240}+$P_{180}K_{180}$									
60 000	6630	10026	3396	13358	13219	-139	9565	10664	1099
80 000	6003	9586	3583	14192	14362	170	8759	10750	1991

Table 5. Variances for the yields of 2007-2009

	2007			2008			2009		
	Mono-culture	Bi-culture	Tri-culture	Mono-culture	Bi-culture	Tri-culture	Mono-culture	Bi-culture	Tri-culture
$LSD_{5\%}$ plant density	124	233	244	418	502	468	322	533	492
$LSD_{5\%}$ fertilization	152	285	299	512	615	573	394	653	602
$LSD_{5\%}$ irrigation	124	233	244	418	502	468	322	533	492
$LSD_{5\%}$ plant density x fertilization	214	403	423	724	870	811	557	924	852
$LSD_{5\%}$ plant density x irrigation	175	329	345	591	710	662	455	754	695
$LSD_{5\%}$ fertilization x irrigation	214	403	423	724	870	811	557	924	852

Based on the yields, it can be concluded that in addition to representing a great environmental burden, the fertilizer dose of $N_{240}P_{180}K_{180}$ also had a yield-reducing effect. The very hot and dry weather in 2007 contributed to this effect since plants need a proper water supply in addition to proper nutrient supply.

Agro-ecological and agrotechnical factors have an effect on yield via influencing the water cycle of the crop production space. Among the experimental years, two were of opposing character, therefore, we studied the relationships between irrigation, yield and water deficiency in a dry year (2007) and in a year with optimum water supply (2008). In 2007, the abiotic stress caused by the draught resulted in very low yields in the non-irrigated treatments. Due to the permanent draught, irrigation had a significant yield-increasinf effect: 2566-5497 kg ha^{-1} in monoculture, 2049-3082 kg ha^{-1} in biculture, 1072-4378 kg ha^{-1} in triculture. The proper timing of irrigation is justified by the fact that the water deficiency values did not reduce either in the irrigated treatment, the maize stand used the water with proper efficacy in the yield formation processes.

In 2008 (when there was no irrigation), there were no significant differences in water deficiency values and yields between the non-irrigated and irrigated plots. In spite of the optimum water supply of maize, the water stock of the soil was significantly reduced in both irrigation variates: water deficiency values were 180-262 mm in monoculture, 167-391 mm in biculture and 174-254 mm in triculture depending upon the irrigation, fertilization and plant density treatments. Due to the favourable water supply of 2008, the maize stands used the available soil moisture for producing an exceptionally large vegetative and generative plant biomass, consequently, the high water deficiency values occurring in the second half of the season can be explained by the large plant biomass and excellent yields.

However, there were great differences in yields between mono-, bi- and triculture. The positive effect of biculture on the water cycle of the soil is well indicated by the high yields and by the yield surplus of the plots which had been regularly irrigated for years. While in monoculture and triculture, the yields of non-irrigated plots were higher, the formerly irrigated plots had higher soil moisture content already in the pre-sowing period in the first days of April in biculture (wheat-maize) and this trend remained the same in the period of flowering and grain setting. This statement is especially obvious in the $N_{120}P_{90}K_{90}$ fertilization treatment at 60000 plants ha^{-1} plant density. Due to its higher water consumption, the stand with 80000 plants ha^{-1} density had a lower initial water stock and it required more water to achieve high yields The effect of plant density on yield showed a tendency but was not significant.

Studying the relationships between irrigation and the soil water cycle in the season of 2009 at three fertilization levels and at two plant densities, it was found that the water deficiency was the highest in mono- and triculture among the three crop rotations. In parallel with increasing average temperature and lack of precipitation, the water stock of the soil started to decrease and accordingly increasing water deficiency values were measured reaching their maximum in August: water deficiency was 257-343 mm in monoculture in the control (non-fertilized) treatment under non-irrigated conditions at 60000 plants ha^{-1}, 240-324 mm in biculture and 291-355 mm in triculture in the control treatment under non-irrigated conditions at 60000 plants ha^{-1}plant density depending upon the level of irrigation, fertilization and plant density. In all the three crop rotation systems, the precipitation in June had a favourable effect on the water stock of the soil. From the end of April until the end of May, the water deficiency significantly increased, but this rate decelerated by June and a much smaller reduction was observed in the water stock. From the end of July, the amount of water stored in the soil greatly reduced due to the large evaporation and increasing water uptake by plants and this state was maintained until the end of the season.

From the three studied years, two vere dry (2007 and 2009), however, the lack of precipitation differed in the two years, its effect on the water cycle of the crop production space should be evaluated differently. If we compare the yields and maximum water deficiency values of 2007 and 2009, it can be stated that the water deficiency values were similar in both years. In 2009, the precipitation received at the critical development phase of maize (intensive vegetative growth) directly before the flowering-grain setting period saved the yield, while in 2007 the stand received the precipitation lately at mid-August, therefore, it did not have a yield-increasing effect.

The effect of plant density was manifested in yields in the two dry years. In the very dry years of 2007, the higher plant density (80000 plants ha^{-1}) was unfavourable, significantly lower yields were harvested from these plots as compared with those of the plots of 60000 plants ha^{-1} plant density.

In 2009 being only partially dry, there were no significant differences or the yields of the plots with 60000 plants ha^{-1} plant density were significantly higher than those at 80000 plants ha^{-1} plant density. It proved that increasing ferilizer dosages are not always accompanied by a yield increment, if the availability of water for nutrient uptake is limited. In the non-irrigated treatment (I_1) the highest yield was obtained in biculture (12329 kg ha^{-1}). Yield increased in all crop rotation systems in the I_3 treatment as compared to the non-irrigated plots. The largest increment (3464 kg ha^{-1}) was obtained in monoculture (non-irrigated: 7792 kg ha^{-1}; irrigated: 11256 kg ha^{-1}).

4.6. Analysis of the interactions between the yield-influencing factors in maize during the experimental years

Year has a great effect on the water cycle of soils and their water stock, thereby, also on the crop yields. In 2007 and 2009, the lack of precipitation was reflected in the water cycle of the soil, water deficiency was 338 mm in monoculture, 357 mm in biculture and 327 mm in triculture in the grain-filling period of maize in non-irrigated plots, which also had an effect on yields which were 2846 kg ha^{-1} in monoculture, 6738 kg ha^{-1} in biculture and 6576 kg ha^{-1} in triculture. In 2008, there were significant differences between the two irrigation treatments in biculture both in water deficiency and in yields, which proved the good water management of the crops applied in this crop rotation. In spite of its dry nature, 2009 had very different results. The soil water stock also indicated a large water deficiency with values of 314 mm in monoculture, 316 mm in biculture and 334 mm in triculture in the non-irrigated treatments at the end of August – beginning of September. However, there were no great differences in yields: yields were lower by 3937 kg in monoculture, 2322 kg in biculture and 3848 kg in triculture as compared to 2008.

However, yields were significantly higher in bi- and triculture than in monoculture in dry years (2007 and 2009): as compared to monoculture, yields were higher by 3468 kg ha^{-1} and 2662 kg ha^{-1} in non-irrigated bi- and triculture and by 2461 kg ha^{-1} and 1793 kg ha^{-1} in irrigated bi- and triculture in 2007 and by 3555 kg ha^{-1} and 1386 kg ha^{-1} in non-irrigated bi- and triculture and by 2995 kg ha^{-1} and 1885 kg ha^{-1} in irrigated bi- and triculture in 2009. Results of the irrigated treatments also support the above. In the exceptionally dry and hot year of 2007, irrigation resulted in a significant yield increment. As a result of irrigation, a yield increment of 3809 kg ha^{-1}, 2467 kg ha^{-1} and 3045 kg ha^{-1} was observed in mono-, bi- and triculture, respectively. This indicates that the efficacy of monocultural production is more dependent upon the water supply conditions. In 2009, a smaller, but significant yield increment was observed as a result of irrigation: 2199 kg ha^{-1} in monoculture, 1639 in biculture (and 2698 kg ha^{-1} in triculture).

There were no significant differences between the water deficiency values of non-irrigated and irrigated plots in the two dry years (2007, 2009). This can be explained by the fact that the maize stand utilized the applied irrigation water efficiently in the vegetative, but mainly in the generative growth phase as proved by the significantly higher yields of the irrigated plots as compared to the non-irrigated plots (Table 6).

Table 6. The effects of irrigation and crop rotation on maize yields as an average of the fertilization and plant density treatments in the experimental years (Debrecen, 2007-2009)

	Monoculture		**Biculture**		**Triculture**	
	Non-irrigated	**Irrigated**	**Non-irrigated**	**Irrigated**	**Non-irrigated**	**Irrigated**
2007						
max. water deficiency (mm)	338	314	357	354	327	329
yield (kg ha^{-1})	2846	6655	6738	9205	6576	9621
$SD_{5\%}$ max. water deficiency	24		21		32	
$SD_{5\%}$ yield	124		233		244	
2008						
max. water deficiency (mm)	223	212	278	220	238	220
yield (kg ha^{-1})	11524	10919	13118	13741	12945	13059
$SD_{5\%}$ max. water deficiency	24		18		23	
$SD_{5\%}$ yield	418		502		468	
2009						
max. water deficiency (mm)	314	315	316	277	334	336
yield (kg ha^{-1})	7587	9473	10796	12122	9097	10824
$SD_{5\%}$ max. water deficiency	17		24		13	
$SD_{5\%}$ yield	322		533		492	

We have studied the effect of the different agrotechnical factors on the yield differences in maize. It was found that irrigation has a stronger yield-increasing effect at the optimum fertilization level, if there is a lack of nutrients the efficacy of irrigation is not appropriate. The optimum water (irrigation) and nutrient (fertilization) supply interaction resulted in a significant yield increment. This is proven by Table 7, the largest yield difference (2873 kg ha^{-1}) was measured in 2008, when the water supply was favourable for maize.

Regarding crop rotations, the yields of bi- and triculture were compared to those of monoculture. As Table 7 shows the largest yield difference as an average of the three years was observed for biculture (2786 kg ha^{-1}).

The differences were the smallest in the case of plant density, but there was a yield reduction at the plant density of 80000 plants ha^{-1} as compared to the plant density of 60000 plants ha^{-1}- in all the three years as an average of the treatments.

Table 7. Evaluation of the effect of agrotechnical factors based on yield differences (kg ha^{-1}) (Debrecen, 2007-2009)

Agrotechnical factor	2007		2008		2009		Average of 3 years	
Irrigation	Ø	Nopt+PK	Ø	Nopt+PK	Ø	Nopt+PK	Ø	Nopt+PK
	2115	3688	-	-	1080	2292	1598	2990
Fertilization	1716		2873		1833		2141	
Crop rotation	Bi	Tri	Bi	Tri	Bi	Tri	Bi	Tri
	3221	3348	2208	1780	2929	1431	2786	2186
Plant density	-413		-111		-445		-323	

The relationships between water deficiency values, yield, irrigation, fetrilization, precipitation before the season (October-March), precipitation during the season (April-September) and precipitation in June-July (a critical period for maize) were studied per year and per crop rotation using Pearson's correlation.

In 2007, irrigation had a strong effect on yield (0.649), the relationship was significant. In dry years, the correlation between fertilization and yield was of medium strength (0.335). In 2008, the values were the opposite due to the optimum water supply. As a result of proper water supply for maize in all phenophases, there was a tight, significant correlation between fertlization and yield (0.597).

In 2009, a medium, significant correlation was found between irrigation and yield (0.397), the explanation for this is that the stand received the artificial water supply in May, so irrigation water was used for the processes of vegetative development.

The correlation between fertilization and yield was medium and significant (0.422). The correlation between plant density and yield was not significant in either year.

In the crop rotations, the correlations between yield, water deficiency, irrigation, fertilization, precipitation and temperature before the season, during the season and in June-July were studied in the experimental years (2007, 2008 and 2009) (Table 8).

Based on the results of the three years, it can be concluded that the period of June-July (when maize has the highest water requirements) has the strongest effect on yield and accordingly on water deficiency, at this time, temperature also has a great impact on yields in addition to water supply. A very strong significant correlation was found between precipitation in the period of June-July and yield in mono-, bi- and triculture (monoculture: 0.711, biculture 0.754 and triculture: 0.781).

Table 8. Correlation coefficients between some agrotechnical elements, temperature, precipitation and yield (Debrecen, 2007-2008-2009)

	Monoculture	**Biculture**	**Triculture**
Year-yield	0.456**	0.540**	0.300**
Nutrient-yield	0.350**	0.183	0.233*
Water deficiency-yield	-0.423**	-0.668**	-0.562**
Plant density-yield	-0.104	-0.041	-0.013
Precipitation in June-July-yield	0.711**	0.754**	0.781**
Precipitation in June-July –water deficiency	-0.808**	-0.810**	-0.878**
Precipitation in October-March-yield	0.749**	0.832**	0.685**
Precipitation in October-March –water deficiency	-0.529**	-0.768**	-0.506**
Precipitation in April-September-yield	0.431**	0.427**	0.581**
Precipitation in April-September –water deficiency	-0.740**	-0.558**	-0.858**
Heat sum in June-July-yield	-0.782**	-0.848**	-0.788**
Heat sum in June-July-water deficiency	0.723**	0.847**	0.751**

Numbers marked by (**) indicate a significant correlation at P=1 %

The off-season precipitation of the autumn-winter months which fills up the soils is of determining importance in yield formation processes, it showed very tight (0.749, 0.832) and tight (0.685) correlation with yield in mono- and biculture and in triculture, respectively.

The correlation between precipitation during the season and water deficiency was very tight in mono and triculture (-0.740, -0.858) and tight in biculture (-0.558). The correlation between precipitation in the period of April-September and yield was medium in mono- and biculture (0.431, 0.427) and strong in triculture (0.581).

5. NEW SCIENTIFIC RESULTS

1. In chernozem soils, the soil layer of 0-60 cm is of determining significance int he water supply of maize during the vegetation period. The layer of 61-120 cm depth has a direct role in the water supply of the plant after the roots had reached this zone (July), while the 121-200 cm zone supplements the water loss of upper layers via capillary action and it participates indirectly in the water cycle of the crop production space.

2. For maize yield, the initial water stock (stored precipitation of the autumn-winter months x yield r=0.685-0.832) of spring (April) and the precipitation during the critical phases of the season (precipitation in June-July x yield r=0.711-0.781) are of determining importance.

3. The water stock and its changes in chernozem soil are determined basically by the weather conditions of the given year. The maximum water deficiency of the soil profile (in August) was 326-355 mm, 293-335 mm and 212-247 mm in an extremely dry year (2007), a dry year (2009) and in a year with favourable water supply(2009), respectively.

4. In addition to the determining effects of meteorological factors, the water deficiency of the soil is also modified by the agrotechnical elements applied in maize production (crop rotation, irrigation, fertilization, plant density). The differences in maximum water deficiency during the season in the 0-200 cm soil profile were 21-34 mm, in biculture amd 2-20 mm in triculture as compared to monoculture, 8-31 mm between the irrigation treatments, 2-31 mm between the plant densities of 60000 plants ha^{-1} and 80000 plants ha^{-1} and 20-35 mm in the N_{120}+PK treatment and 21-47 mm in the N_{240}+PK treatment as compared to the control as an average of the three years and the treatments.

5. There was a tight correlation between maize yield and the water deficiency of the 0-200 cm soil profile (r=-0.423-0.668) and yield and irrigation in a dry year (r=0.649), while the correlation between yield and fertilization was of medium strength (r= 0.335-0.597) on chernozem soil in the region of Hajdúság.

6. In addition to the direct effect (within the given vegetation period) of irrigation an indirect, after-effect could also be observed at the beginning of the following season (2008), when no irrigation was applied, the water deficiency values of the non-

irrigated plots were 17 mm, 34 mm and 16 mm higher than those of the irrigated plots (taken as the average of other agrotechnical treatments) in monoculture, biculture and triculture, resprectively, and this trend remained the same throughout the whole season.

7. On chernozem soil in Hajdúság, the agrotechnical elements (irrigation, fertilization, plant density, crop rotation) increased yields by different degrees. The yield increments in maize resulting from irrigation, fertilization, plant density treatments were 1.1-3.7 t ha^{-1}, 1.7-2.9 t ha^{-1} and 0.4 t ha^{-1}, respectively, while the yields of biculture and triculture were higher by 2.2-3.2 t ha^{-1} and 1.4-3.3 t ha^{-1} as compared to monoculture depending upon the year.

6. Practical applicability of the scientific results

1. Under the climate conditions of Hungary, the basis of maize production is the development of a water-saving production technology which efficiently utilizes precipitation and irrigation water. The yield and water uptake of maize was essentially determined by water supply (water stock in the soil, amount and distribution of precipitation during the season, irrigation).
2. In the water cycle of the crop production space and in the water supply of maize, the water stock of chernozem soil and the amount and distribution of precipitation during the season are of determining significance. The influencing effects of the agrotechnical factors (crop rotation, irrigation, fertilization, plant density) on the water stock of the soil were different.
3. In chernozem soil, the minimum water stock is reached in the period of grain filling (mid-August-early September). Precipitation and irrigation have an effect mainly on the water stock of the 0-60 cm soil layer, but in the water supply of maize the 61-120 cm layer and the 121-200 cm layer (via capillary action) also have a significant role. On chernozem soil with a deep fertile layer and without an impermeable layer, the whole soil profile of 0-200 cm contributes to the water supply of maize.
4. The water stock of chernozem soil was determined primarily by crop rotation, which was modified by irrigation and fertilization. Plant density had the smallest impact on the water stock of the soil in maize production.
5. The maize stand having a lower water stock in the spring is more dependent upon the amount and distribution of precipitation during the season.
6. The effect of regular, multi-year irrigation was detectable also in the succeeding vegetation season. The difference could be observed at the beginning and the later phases of the season and even after maize harvest.
7. The proper timing of irrigation is proven by the fact that the water deficiency values did not change in the periods between the irrigation dates. If the maize stand receives the water supply in proper time at the phenophase with high water requirements, then it can be used effectively for vegetative development and yield formation.

8. Via the optimization of the agrotechnical elements (crop rotation, fertilization, irrigation, plant density), the maximum yield of maize varied between 9.6 and 13.9 t ha^{-1} in a small-plot long-term experiment on chernozem soil in the region of Hajdúság. Therefore, the harmonization of agrotechnical elements is essential for achieving high yields in the practice of production.

LIST OF MAJOR PUBLICATIONS RELATED TO THE DISSERTATION

Scientific papers in foreign, peer-reviewed journals in foreign language::

- Peter Pepo - Laszlo Zsombik - Attila Vad - Sandor Berenyi - **Lajos Doka**. (2007): Agroecological and management factors with impact on the yield and yield stability of maize (*Zea mays L.*) in different crop rotation. Analele Universitatii Oradea. Facultatea de Pretectia Mediului. **13.** 181 – 187.

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- Sándor Berényi, Attila Vad, **Lajos Dóka**, Péter Pepó. (2007): Effect of fertilization and cropyears on maize (*Zea mays L.*) yields in different crop rotations. Cereal Research Communications. **35.2.** 241-244.
- **Dóka Lajos Fülöp** – Pepó Péter (2007): Role of watersupply in monoculture maize (*Zea mays L.*) production. Cereal Research Communications. **35.2**. 353-356.
- **Fülöp Lajos Dóka** (2008): Effect of some agrotechnical factors on water budget in maize (*Zea mays L.*) production. Cereal Research Communications. **36.3**. 747-750.
- Attila Vad **– Lajos Fülöp Dóka** (2009): Cropyear as abiotic stressor regarding yield of maize (*Zea mays L.*) in different crop rotations. Cereal Research Communications**. 37.** 253-256.
- **Dóka Lajos Fülöp** - Pepó Péter (2009): Yield and Water Balance of Maize Grown in Rotation on Chernozem Soil. Cereal Research Communications. **37. 4.** 611-621.

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- Pepó Péter - **Dóka Lajos -** Berényi Sándor - Vad Attila. (2008): Az öntözés hatása a kukorica (*Zea Mays L.*) termésére száraz évjáratban csernozjom talajon. Növénytermelés. **57.2.** 171-179.
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- **Dóka Lajos Fülöp** (2007): Agrotechnikai tényezők hatása a monokultúrás kukorica *(Zea mays L.*) vízfelvételére és termésére. Acta Agronomica Óváriensis. Vol. 49. No. 2. Mosonmagyaróvár. 581-589.
- **Dóka Lajos Fülöp** (2008): A kukoricaállomány 2007. évi szélsőséges vízforgalmának vizsgálata eltérő vetésváltási rendszerekben. Agrártudományi közlemények. Acta Agronomica Debreceniensis 2008/32. 33-41.

- **Dóka Lajos Fülöp** (2009): Talaj vízháztartási vizsgálatok különböző vetésváltású kukoricában. Agrártudományi közlemények. Acta Agronomica Debreceniensis 2009/36. 41-49.

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- **Dóka Lajos Fülöp** (2008): Néhány agrotechnikai tényező vízháztartásra és termésre gyakorolt hatása monokultúrás kukorica (*Zea mays L.*) termesztésben. [Effect of some agrotechnical factors on water husbandry and yield in monoculture maize (*Zea mays L.*) production]. Szerk.: Pepó Péter. Magyar-Szlovák Kormányközi TÉT Együttműködés (CD kiadvány), 133-137. ISBN 978-963-9732-33-9.
- **Dóka Lajos Fülöp** (2008): Néhány agrotechnikai tényező vízháztartásra és termésre gyakorolt hatása monokultúrás kukorica (*Zea mays L.*) termesztésben. [Effect of some agrotechnical factors on water husbandry and yield in monoculture maize (*Zea mays L.*) production]. Szerk.: Pepó Péter. Magyar-Szlovák Kormányközi TÉT Együttműködés, 133-137. ISBN 978-963-9732-34-6.

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- **Dóka Lajos Fülöp** (2009)**:** Évjárat és öntözés hatása a csernozjom talaj vízháztartására. V. Növénytermesztési Tudományos Nap Keszthely. 73-77. ISBN 978 963 05 8804 1.

PUBLICATIONS NOT DIRECTLY RELATED TO THE DISSERTATION

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- **Dóka Lajos Fülöp** – Szabó András (2009): Környezetkímélő tápanyag-gazdálkodási módok alkalmazása. Értékálló Aranykorona. IX. évfolyam1. sz. 16-17.
- Szabó András – **Dóka Lajos Fülöp** (2009): Nem mindegy a tőszám – A vetés kritikus elemei. Haszon agrár. III. évfolyam. 2009/2. március. 28-34.
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