Thesis of doctoral (PhD) dissertation

EFFECT OF PLANT DENSITY ON THE YIELD AND YIELD COMPONENTS OF MAIZE HYBRIDS

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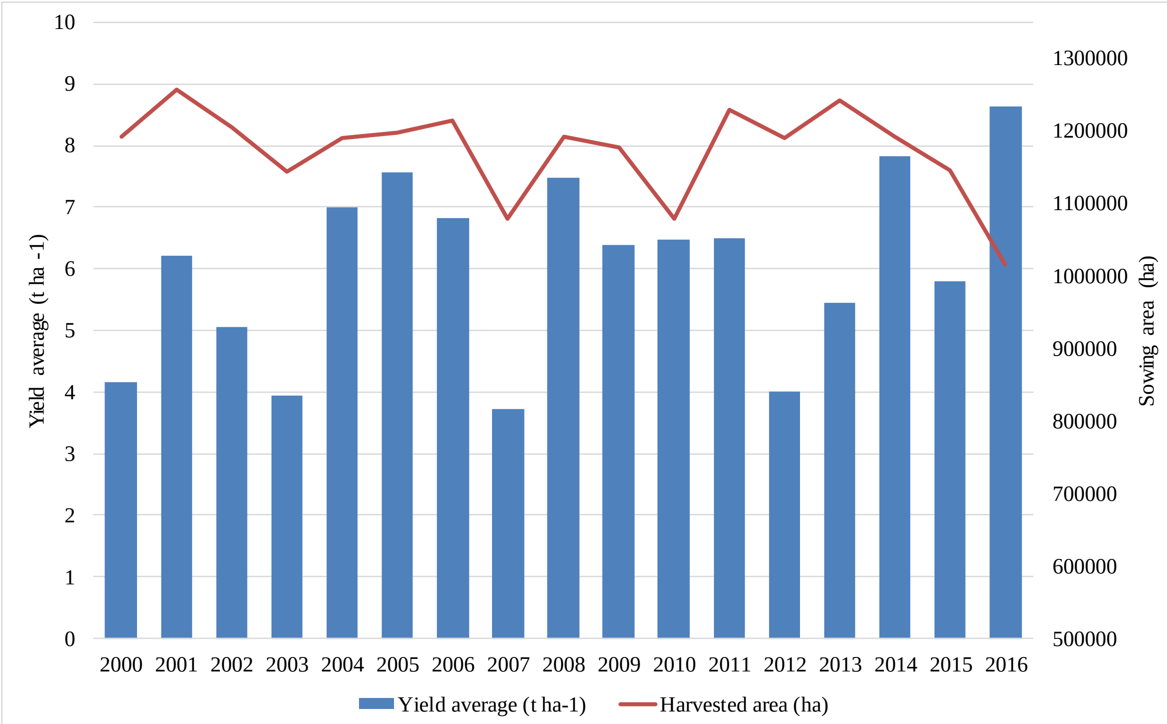
What we eat starts with the seed we plant and the food system we have in place."

Jose Graziano da Silva – FAO Director General

1. BACKGROUND AND AIMS

Maize (*Zea mays* L.) is one of the most important fodder crops in the world. Maize used to be grown on 1.2–1.3 million ha in Hungary, but in recent years, partly due to global over-production and the consequent drop in market prices, the growing area has fallen to below 1.1 million ha.

Nowadays maize has a wide range of applications, being produced for food, feed and industrial purposes. Thanks to continuous improvements in the germplasm and to competition between breeding companies, the yield potential of the species is clearly increasing, but when grown under the continental climate characteristic of Hungary the increasing frequency of extreme environmental conditions means that yield averages have risen only slightly and exhibit great instability. The national yield average over the last 15 years was 5.89 t ha^{-1}. In addition to the low average, the yield also exhibits substantial fluctuation, which has a negative influence on the medium- and long-term economic safety of maize production, on complex farm management based on maize, and on economic growth. Over the last 15 years the best yield was achieved in 2014, with a national average of 7.82 t ha^{-1}, representing 132.8% of the 15-year mean, while the worst year was 2007, when the average yield was 3.73 t ha^{-1}, only 63.2% of the 15-year mean (Fig. 1). The primary goal of modern maize production is sustainability, in which a wise choice of genotypes and technologies plays an outstanding role. The plant density, a component of the maize production technology which has been widely studied but is still not exploited sufficiently in farm practice, has a great influence on the success of maize production, especially when weather conditions are unpredictable. This contributes to the fact that farmers are often reluctant to change their choice of hybrids.



1. Figure Trends in maize yield averages and sowing area in Hungary (2000–2016)

Consequently, higher plant density is not always justified, but there is nevertheless a chance of obtaining higher yields from hybrids with better yield potential, based on knowledge of the growing area, a wise choice of genotype and the rational use of production technologies. This question has long been the subject of research and a large body of information is available, both in Hungary and abroad. However, this information is not always comprehensible to maize growers, so the results, however good, are rarely translated into practice.

The agronomic experiments performed over the last ten years were aimed at promoting a successful choice of hybrids. Plant density experiments set up in different years at various yield levels make it possible to draw general and specific conclusions and to obtain detailed knowledge on the individual responses of genotypes. In addition to plant density, seasonal differences also had diverse effects on the yield components, having a significant but varying influence on the final yield.

The aim of the present experiments was to obtain knowledge on the genotypes tested and to interpret how they were affected by environmental factors and the components of the production technology, in the hope that the information acquired would provide guidelines for breeding and selection and for the improvement of the germplasm.

A further aim was to evaluate the effect of plant density on the yield. The maize yield is jointly determined by numerous components, so the influence of plant density on each of these components was also an important subject of research. An insight was also sought on the relationship between individual yield components and the yield, i.e. the extent to which each yield component was responsible for the final yield. The work included investigations on the relationship between plant density and yield, the analysis of correlations between plant density and individual yield components, and the use of these results to describe various ear types and to obtain a better understanding of them.

A major aspect of the work was to maximise the profits gained by maize farmers. An income calculation model was used to calculate for each plant density in each year the profit that could be achieved with a given genotype under the given production conditions.

The research was aimed at more than simply determining hybrid-specific plant density optima and giving recommendations for growing maize at different yield levels. One important factor for sustainable farming and the future success of Hungarian maize production will be a complex knowledge of the available germplasm, its rational use and how to exploit its latent potential to the maximum in an environmentally sound manner.

2. MATERIALS AND METHODS

The experiments were performed between 2009 and 2015 in the experimental network of Monsanto Hungária Kft. The data were obtained from field experiments and laboratory analyses.

2.1. Factors considered when selecting experimental locations

One important consideration when choosing the locations was that the fields should be characteristic of those used for maize production in Hungary and should allow the experiments to reflect farm conditions. Plant density experiments were performed during this period in the following agro-ecological regions: the Mezőföld region of Transdanubia, found previously to be an excellent location, though with many conditional challenges. We had locations on meadow and meadow chernozem soil on plains neighbouring the River Danube; also on plains neighbouring the River Dráva, and in the Tolna-Baranya hills in Transdanubia. The last three locations were situated in the most important maize-growing region of Hungary, where high yield levels are usually attained, though they are exposed to drought in some years. Another important location was Hort, on an alluvial fan in the Tiszai-Alföld region, where heat or drought stress was experienced in almost every year in one or other phenophase. Hajdúböszörmény in the Hajdúság district of the Tiszai-Alföld region, was also an important location, where the experiments were conducted on high quality chernozem soil. Other locations were Szeged, in the Lower Tisza region, and in the region between the Rivers Körös and Maros with high quality chernozem soils.

2.2. Hybrids included in the tests and the selection criteria

We analysed 17 hybrids in thesis. Ten hybrids tested each year, divided into two maturity groups, one containing very early (FAO 200) and early (FAO 300) hybrids and the other consisting of hybrids in the medium maturity group (FAO 400). Important criteria for the choice of hybrids were diverse plant density responses, different ear types and the importance of the hybrid in farm cultivation. General information on the hybrids is presented in Table 1.

1. Table General information on the hybrids tested in the experiments

Hybrid	Year of regsitration or single year testing	FAO number	RM number	Hybrid type
DKC3623	2012	280	86	Single cross (SC)
DKC3705	2010	290	87	Single cross (SC)
DKC4014	2011	290	90	Single cross (SC)
DKC3939	2015	310	89	Single cross (SC)
DKC4025	2012	310	90	Single cross (SC)
DKC4590	2009	330	95	Single cross (SC)
DKC4541	2014	360	95	Single cross (SC)
DKC4490	2007	360	94	Single cross (SC)
DKC4717	2012	380	97	Single cross (SC)
DKC4795	2010	380	97	Single cross (SC)
DKC4964	2006	400	99	Single cross (SC)
DKC4943	2014	450	99	Single cross (SC)
DKC5031	2013	450	100	Single cross (SC)
DKC5007	2010	490	100	Single cross (SC)
DKC5190	2010	460	101	Single cross (SC)
DKC5222	2012	480	102	Single cross (SC)
DKC5276	2010	480	102	Single cross (SC)

2.3. Design and implementation of the field experiments; evaluation methods

The small-plot experiments were laid out in a split-plot design with three replications per hybrid and five plant densities at each location. The plant densities were as follows: 50,000, 60,000, 70,000, 80,000 and 90,000 plants ha^{-1}. Each plot was 6.8 m in length and consisted of four rows, with a row distance of 0.76 m and a path measuring 0.8 m between each plot. Observations and harvesting were performed on the middle two rows of each plot, but the same plant density was applied in all four rows. Sowing was carried out using a HEGE 95 DT plot planter and in later years with a Wintersteiger 8-row seed drill with hydraulic drive, at the date usual for the given agro-ecological region, generally between April 20 and May 5. Simultaneously with sowing, granulated FORCE 1.5 G pyrethroid soil disinfectant (15 g kg^{-1} teflutrin) was applied at a rate of 15 kg ha^{-1} to minimise soil-borne pests, and the seed were dressed with MAXIM XL 035 FS (25 g l^{-1} fludioxonil + 9.7 g l^{-1} metalaxil-M) fungicide prior to sowing. Early post- and post-emergence weed control was performed where necessary. The plant density was adjusted after successful weed control and the labelling of the plots.

The following agronomic traits were scored during the growing season: start of pollen shedding, date of tasselling (days from sowing), date of silking (days from sowing), plant height (cm), height of ear attachment (cm), root lodging (No./plot or %), stalk breakage (No./plot or %), yield (kg $plot^{-1}$ or t ha^{-1}), grain moisture content at harvest (%) and test weight (kg hl^{-1}). The two latter traits were recorded using a Wintersteiger twin combine (converted Sampo Rosenlew combine).

The yields of the individual hybrids were not compared; in all cases the hybrid mean was taken as the basis for evaluating the effect of plant density, so the experimental design was excellent for the purpose of the experiments and the use of 4-row plots helped to eliminate the border effect. In this factorial experiment, the plant densities were the main factors, placed in the main plots, with three random replications at each location, after which the hybrids were randomised in the subplots, as recommended by Berzsenyi (2015).

The processing and statistical evaluation of the data was performed using the Microsoft Excel program and MINITAB 17 software. Analysis of variance (ANOVA) was applied to interpret the year * location * plant density * hybrid interactions, while the type and strength of correlations between the individual traits was evaluated by means of correlation analysis. The effect of the year was investigated using ANOVA and the general linear model. As a large number of diverse data were available, dissection was also possible for yield levels. After evaluating all the data, three artificial yield level groups were formed: low (yields of below 7 t ha^{-1}), average (7–11 t ha^{-1}) and high (above 11 t ha^{-1}).

Based on the yields of the hybrids in the plant density experiment, the plant density responses of the genotypes were determined over the whole experiment and for the separate yield levels. Significant differences ($LSD_{5\%}$) were calculated between the plant density treatments, after which the optimum plant density and the range of optimum densities were calculated for each hybrid by adding or subtracting half the $LSD_{5\%}$ value from the maximum yield and then using regression equations to obtain the exact plant density associated with the range. From this it was possible to deduce the range of optimum plant densities for each hybrid, i.e. the plasticity of the hybrid.

The effect of changes in plant density on the yield components was revealed by means of correlation analysis, after which a two-sample t-test was used to analyse significant differences between the treatments. After analysing the yield components, cluster analysis was also performed with the aim of forming homogeneous groups of hybrids on the basis of the traits tested. The data within each group were similar to each other for some dimension or another but differed from those in other clusters. The aim of this analysis was to classify the hybrids according to their ear characteristics and to confirm the statistical analysis and field observations.

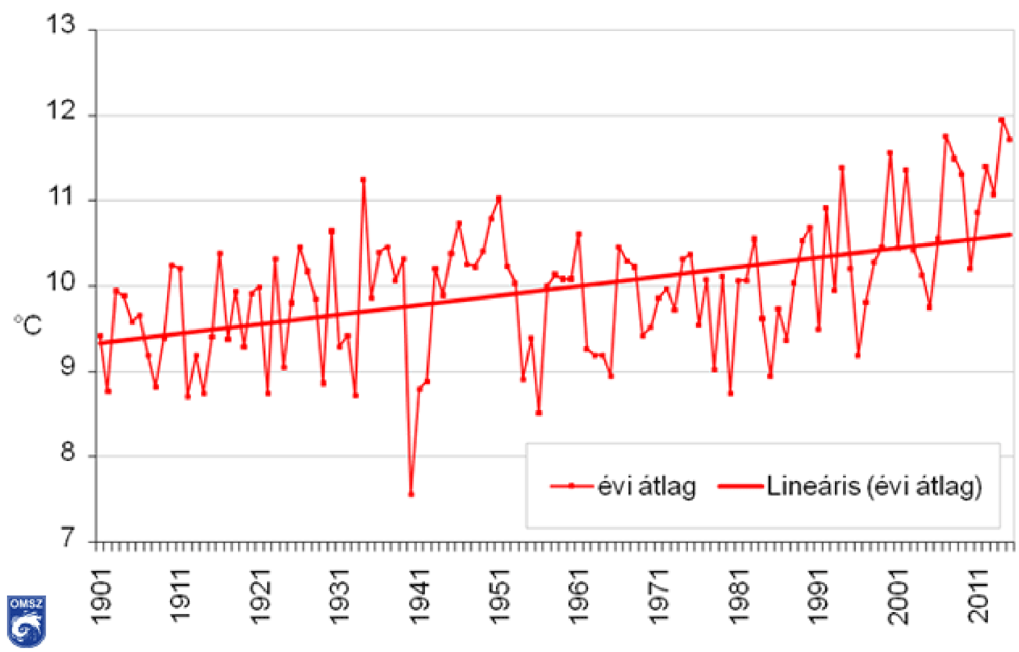
2.4. Methods used to analyse yield components

The sample ears required for the analysis of yield components were collected from the two outer rows of each plot, which were not harvested. The last five ears in each row were not included in the measurements in order to reduce the border effect. Measurements were made on the ear length (cm), circumference (cm) and diameter (cm), the cob diameter (cm), the number of kernel rows, the number of kernels per row and, after shelling, the thousand-kernel weight of three samples formed from the grand sample. The yield, grain moisture and test weight data obtained from the combine harvesting of the plant density experiments were also used for the analysis.

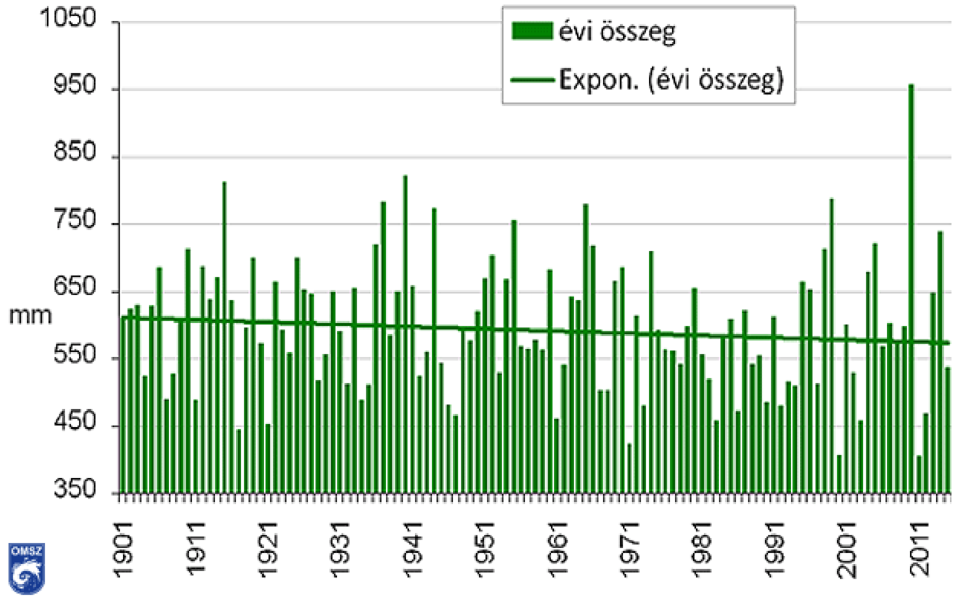
2.5. Climatic conditions during the experimental period

In Hungary the annual mean temperature is between 10 °C and 11 °C, the hottest month being July. The annual rainfall quantity ranges from 500–700 mm. The experimental network covered practically the whole of the maize-growing area in Hungary. Due to the strong effect of the very diverse weather conditions in the individual years, the effect of the location was not analysed separately; the hybrids were evaluated on the basis of their specific plant density responses and their performance at different yield levels.

Over the last 100 years the temperature has exhibited a gradually increasing tendency in Hungary, though with great fluctuations (Fig. 2), leading to an increase of 1 °C in the annual mean temperature. An analysis of the quantity, distribution and evenness of rainfall showed that, like the temperature trend, changes of an unfavourable nature could be detected over the last 100 years (Fig. 3). The quantity of rainfall is declining and the distribution is becoming more and more erratic. From the point of view of maize water requirements, the period from June to August is critical, and the length of rainless periods during these months has substantially increased, making the reliability of maize production unpredictable.



2. Figure Annual mean temperatures in Hungary between 1901 and 2015 (based on the homogenised, interpolated data of 15 meteorological stations)



3. Figure Annual rainfall sums in Hungary between 1901 and 2015 (based on the homogenised, interpolated data of 58 meteorological stations)

Table 2 summarises the main weather parameters for the flowering period of maize, including July rainfall data and the number of very hot days, together with their deviations from the long-term mean.

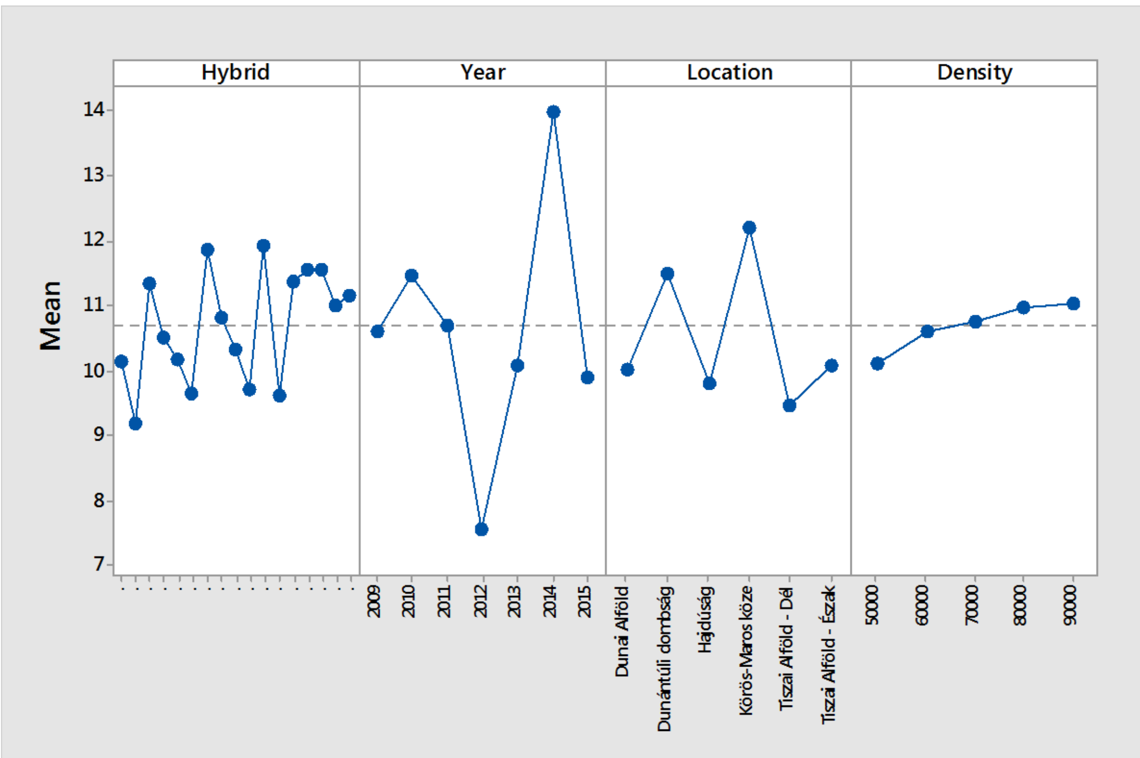
2. Table Weather parameters for the critical flowering period (2009–2015)

Year	Rainfall		Annual mean temperatures - deviation from the 30 year mean	No. of very hot days ($t_{max} > 30^oC$)		Mean temperature in July - deviation from the 30 year mean	Mean rainfall in July - in % of the 30 year mean
	mm	As a % of the last 30 years		No. of days	Deviation from the 30 year mean		
2009	598.00	105%	1.30	28.00	8.00	1.80	-66%
2010	959.00	169%	0.20	23.00	3.00	2.10	121%
2011	407.40	72%	0.90	32.00	12.00	0.10	149%
2012	470.40	83%	1.40	49.00	29.00	2.90	101%
2013	649.60	114%	1.10	33.00	13.00	2.00	-37%
2014	739.80	130%	1.90	19.00	-1.00	1.30	189%
2015	538.90	92%	1.40	46.00	26.00	2.30	-61%

3. RESULTS

3.1. General results

Experiments were performed to examine how the year, the location (agro-ecological region), the plant density and the hybrid, and interactions between these factors, influenced the yield of maize hybrids. The results of analysis of variance revealed that all four factors had a significant effect on the yield (Fig. 4). The year had the greatest effect, followed by the location, the plant density and finally the hybrid. The combined effect of these factors was also significant.



4. Figure The effect of the factors on the yield results (2009-2015)

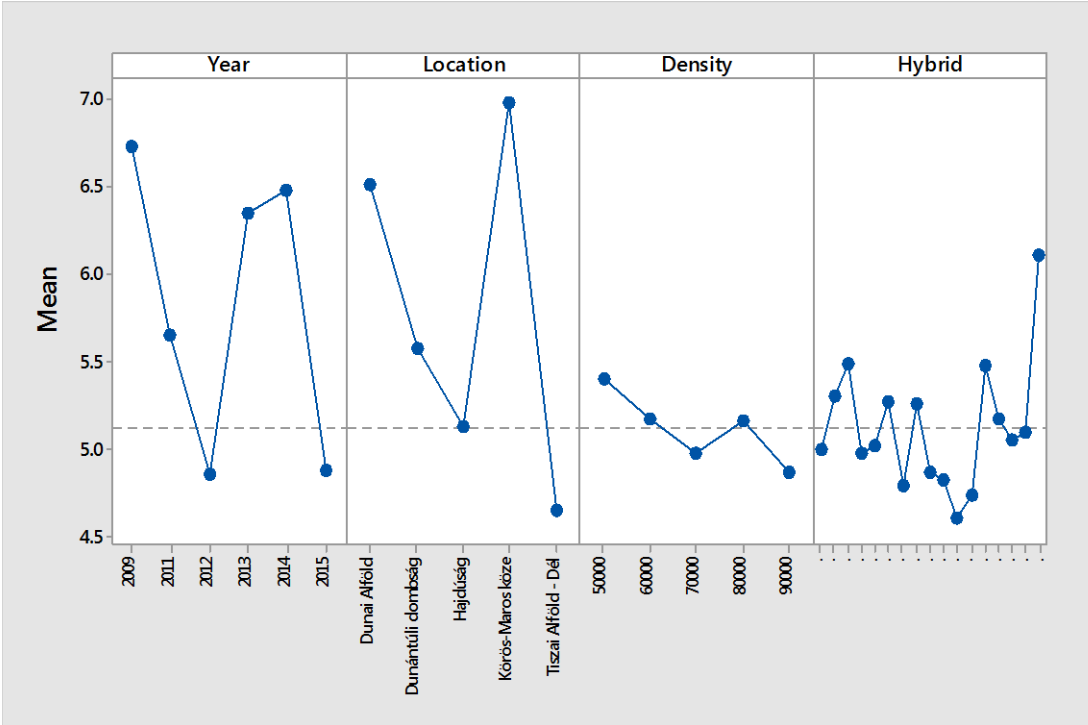
It was found that, apart from the significant effect of the main factors, the agro-ecological region * hybrid interaction was also significant, while the agro-ecological region * plant density, plant density * hybrid and agro-ecological region * plant density * hybrid interactions were not (Table 3). In order to obtain more precise knowledge on the interactions, the data were further dissected and analysis of variance was performed at various yield levels.

3. Table Interaction of the factors, effect on yield results (2009-2015)

ANOVA Factors	SQ	df	MQ	F	P
Corrected Model	27715.784[a]	465.00	59604	9502.00	<.001
Intercept	42142844.00	1.00	42142844	6718049.00	<.001
Year	15744911.00	1.00	15744911	2509918.00	<.001
Location (Agro-ecological region)	2882460.00	5.00	576492	91899.00	<.001
Density	146344.00	4.00	36586	5832.00	<.001
Hybrid	937815.00	16.00	58613	9344.00	<.001
Location * Density	119741.00	20.00	5987	0.95	0.516
Location * Hybrid	1993852.00	71.00	28082	4477.00	<.001
Density * Hybrid	106281.00	64.00	1661	0.27	1.000
Location * Density * Hybrid	460799.00	284.00	1623	0.26	1.000
Error	28348039.00	4519.00	6273		
Total	625426854.00	4985.00			
Corrected Total	56063823.00	4984.00			

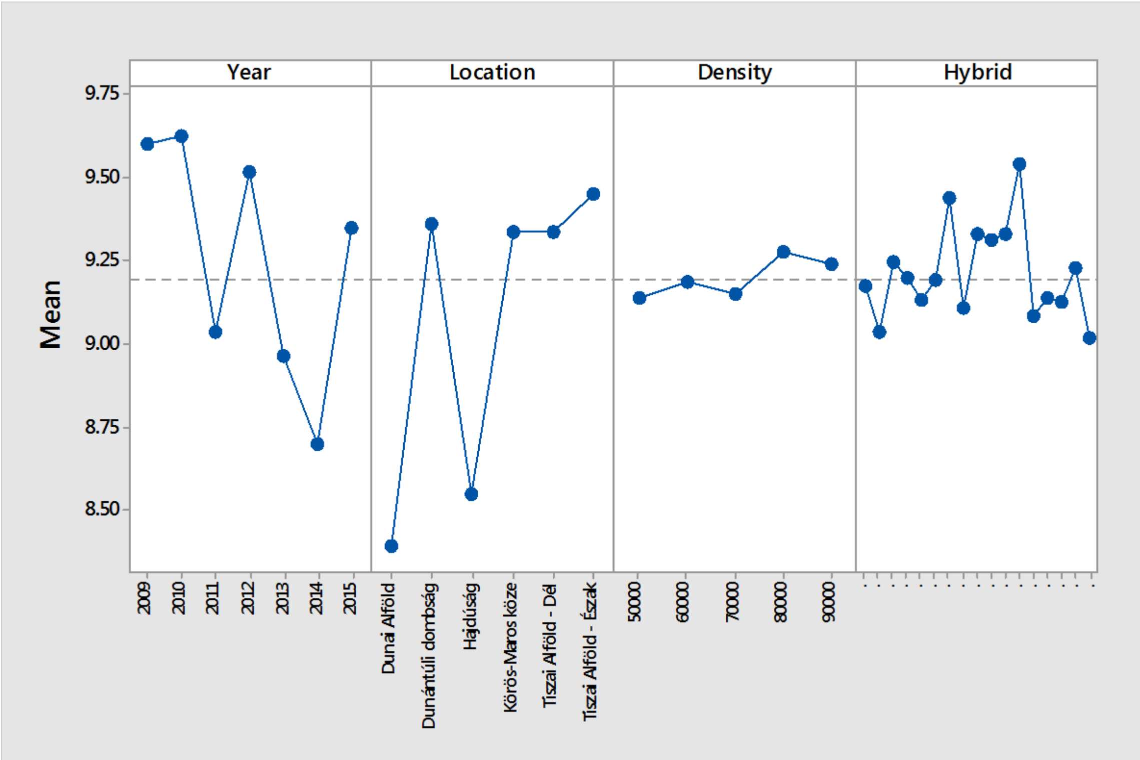
a. R Squared = ,494 (Adjusted R Squared = ,442)

At low yield level (< 7 t ha^{-1}) the location had the greatest effect and the average yields at the various locations differed substantially from each other and from the grand mean (Fig. 5). This was followed by the year, the plant density and finally the hybrid. It is clear from this that in dry years or under more adverse conditions the choice of growing site, hybrid and plant density are particularly important for the success of maize production. At low yield level, an unwise choice of plant density may lead to considerably lower yields and thus to economic losses.



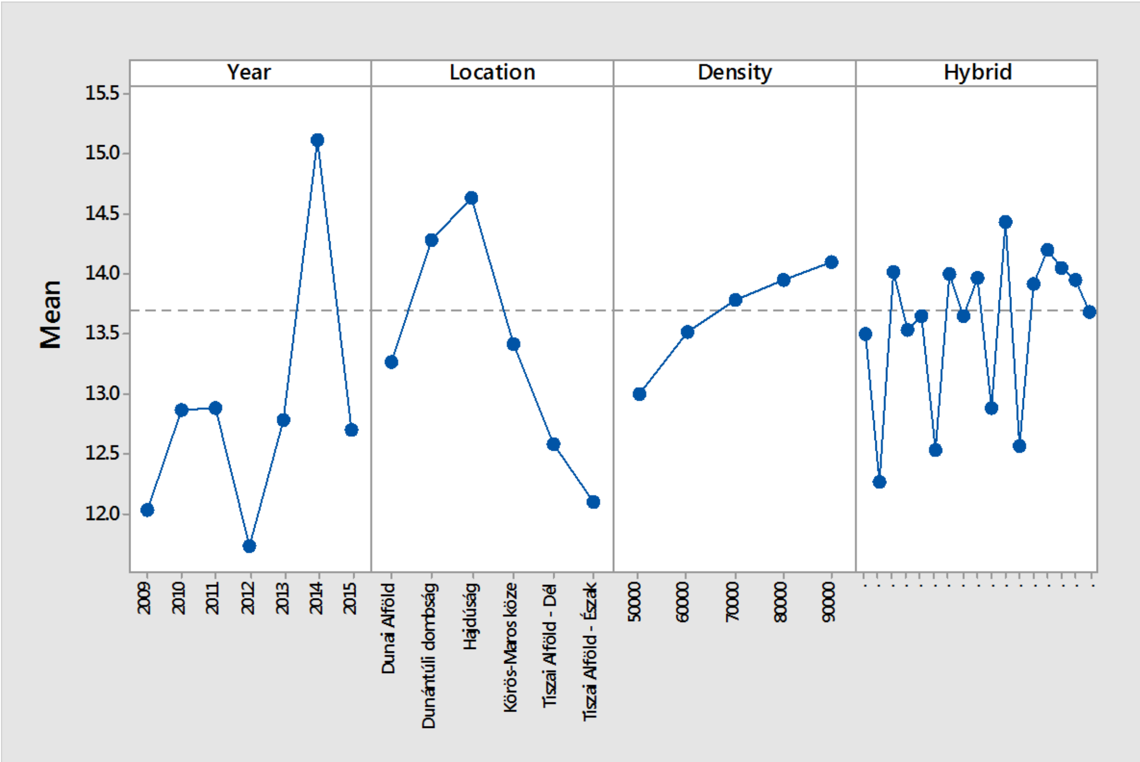
5. Figure The influence of the factors on the yield results at low yield level (2009-2015)

At average yield level (7–11 t ha^{-1}) a significant effect was detected for the location, followed by the year and the hybrid, but not for the plant density (Fig. 6). The year * plant density, agro-ecological region * plant density and plant density * hybrid interactions were non-significant, as were the other interactions. If the yield averages recorded in Hungary are taken into consideration, it can be seen that this is the yield level most frequently achieved. The importance of choosing the best hybrid for the given area should be emphasised, as this is decisive for the success of maize production at this yield level.



6. Figure The influence of the factors on the yield results at average yield level (2009-2015)

At high yield level (> 11 t ha^{-1}) the year had the greatest effect, followed by the agro-ecological region, but the hybrid and the plant density also had a significant effect (Fig. 7). Among the interactions, the agro-ecological region * plant density and the year * plant density had a significant effect, while the other interactions were non-significant. The agro-ecological area and the year also interacted with each other and jointly influenced the yield. Although the effects of the plant density and the hybrid were not considerable in themselves, the results clearly showed that under favourable conditions (on soils with better potential and under good weather conditions) the choice of genotype and plant density played a greater role in determining the yield average.



7. Figure The influence of the factors on the yield results at high yield level (2009-2015)

3.1.1. Effect of the year

Plant density has a substantial effect on both the yield and yield stability of maize. The achievement of the genetic potential of the hybrids is determined to the greatest extent by environmental factors. In the Central European region water is the yield-forming factor that most frequently limits the success of production.

The experiments were set up between 2009 and 2015 in the major maize-growing regions of Hungary. The mean yields achieved during these years (in the experiments and on farms on a national scale) are presented in Table 4 in relationship to environmental factors. When the yields were analysed as a function of environmental factors, it could be seen that the rainfall quantity in July was closely correlated with the yield (r=0.85), while the effect of the number of very hot days exhibited a looser correlation (r=0.40).

4. Table Mean yields in the experiment and on a national scale as a function of the annual precipitation, rainfall in July and the number of very hot days (2009–2015)

Year	National mean yield (t ha^{-1})	Experimental yield (t ha^{-1})	Farm mean/Experimental mean (t ha^{-1})	Grain moisture at harvest (%)	Annual precipitation (mm)	July rainfall in the % of the mean	No. of very hot days
2009	6.39	10.59	0.60	18.30	598.00	-66.00	28.00
2010	6.47	11.47	0.56	21.96	959.00	121.00	23.00
2011	6.50	10.70	0.61	15.86	407.40	149.00	32.00
2012	4.00	7.55	0.53	16.28	470.40	101.00	49.00
2013	5.44	10.06	0.54	19.72	649.60	-37.00	33.00
2014	7.82	13.99	0.56	23.97	739.80	189.00	19.00
2015	5.79	9.99	0.58	15.83	538.90	61.00	46.00

The highest yield was recorded in 2014, when the experimental mean was 13.99 t ha^{-1} and the rainfall sum in July exceeded the 30-year mean by 89%. In this year the national mean temperature and the July mean temperature exceeded the long-year mean by 1.9°C and 1.3°C, respectively. The largest quantity of precipitation (959 mm) fell in 2010, when the temperature was not much higher than the long-term mean and the number of very hot days was fairly low. The lowest yield was observed in 2012, with an experimental mean of 7.55 t ha^{-1}. This was reflected by the national data, as the yield average achieved on Hungarian farms was 4 t ha^{-1}. Over the last 30 years yields lower than this were only obtained in 2003 and 2007. In 2012 the annual mean temperature was 1.4°C higher than the 30-year mean, while the number of very hot days was 49.

The effect of the year was analysed using the general linear model, an amalgamation of conventional analysis of variance and linear regression analysis. This model revealed that the plant density and the year had a significant influence on the yield. The years 2010 and 2014 could be classified as favourable, leading to significantly higher yields. 2011 was also a favourable year, but the yield did not differ significantly from the mean. The years 2012 and 2013 had a significantly negative effect, while 2009 was also unfavourable, but the difference was not significant. In 2012, as well as the anomalies noted above, the mean temperature in July was 2.9°C higher than the 30-year mean and the total precipitation was the second lowest in the experimental period, after 2011.

3.1.2. Effect of location on the yield

In recent years plant density experiments have been performed on six agro-ecological regions of Hungary. The results of analysis of variance showed that, after the year, the location had the second greatest influence on the yield. The region between River Körös and River Maros had the greatest positive significant effect on the yield, with an average of 12.20 t ha^{-1}, which was significantly higher than the grand mean of 10.69 t ha^{-1}. The effect of the location in the Transdanubian hills was also favourable and significant, having a yield average of 11.48 t ha^{-1}, which was again significantly higher than the grand mean. The yield achieved in the northern part of the Tiszai-Alföld region, was also higher than the grand mean, but not significantly. The yields recorded in the Dunai Alföld region and in the Hajdúság region, were somewhat below the grand mean, but not significantly so, while those obtained at locations in the Tiszai Alföld region, the Alsó-Tisza regions and in the neighbourhood of Szeged were significantly lower than the grand mean.

3.1.3. Effect of plant density on the yield

The plant density experiments were carried out between 2009 and 2015 to investigate the tolerance of various genotypes to denser sowing and their response to plant densities between 50,000 and 90,000 plants ha^{-1} at different yield levels. The results indicated that, in the given years, the yields of the tested hybrids increased with a rise in plant density (Table 5).

5. Table Yields recorded at different plant densities for the tested hybrids, averaged over the experimental locations (2009–2015)

Hybrids	All yield data			Low yield level (0-7 t ha^{-1})			Average yield level (7-11 t ha^{-1})			High yield level (11< t ha^{-1})		
Density	Yield (t ha^{-1})	Yield (%)	Deviation from the meam (%)	Yield (t ha^{-1})	Yield (%)	Deviation from the meam (%)	Yield (t ha^{-1})	Yield (%)	Deviation from the meam (%)	Yield (t ha^{-1})	Yield (%)	Deviation from the meam (%)
50000	10.10	94.52	-5.48	5.40	105.48	5.48	9.14	99.39	-0.61	13.00	94.96	-5.04
60000	10.61	99.24	-0.76	5.17	100.93	0.93	9.19	99.91	-0.09	13.51	98.65	-1.35
70000	10.74	100.52	0.52	4.98	97.20	-2.80	9.15	99.50	-0.50	13.77	100.60	0.60
80000	10.96	102.52	2.52	5.16	100.79	0.79	9.28	100.90	0.90	13.94	101.82	1.82
90000	11.03	103.22	3.22	4.87	95.03	-4.97	9.24	100.48	0.48	14.09	102.93	2.93
Average	**10.69**	100.00		**5.12**	100.00		**9.19**	100.00		**13.69**	100.00	

On average the highest yield was obtained at the highest plant density (3.22% higher than the mean) and the lowest at the 50,000 plants ha^{-1} density (5.49% less than the mean), suggesting that the yield-reducing yield effect of the lowest plant density was greater than the yield-increasing effect of the highest density. The yield closest to the mean was recorded for a plant density of 70,000 plants ha^{-1}, where the deviation from the mean was 0.52%.

A total of 4985 yield data were collected from the tested hybrids between 2009 and 2015. The mean yield over the whole experiment was 10.69 t ha^{-1} and the mean grain moisture content at harvest was 18.92%. The highest yield was recorded in 2014 in the neighbourhood of Dalmand, where hybrid DKC5007 produced a yield of 19.30 t ha^{-1} at a plant density of 80,000 plants ha^{-1}, with a grain moisture content of 32.6%. The lowest yield was measured near Szeged in the extremely dry year of 2012, when hybrid DKC4795 yielded only 1.17 t ha^{-1} at a plant density of 80,000 plants ha^{-1}, with a moisture content of 24.7%.

Averaged over the plant densities, the hybrids yielded 10.10 t ha^{-1} at 50,000 plants ha^{-1}, 10.61 t ha^{-1} at 60,000 plants ha^{-1}, 10.74 t ha^{-1} at 70,000 plants ha^{-1}, 10.96 t ha^{-1} at 80,000 plants ha^{-1} and 11.03 t ha^{-1} at 90,000 plants ha^{-1}. The regression coefficient for the fitted curve indicated that the correlation was very close (Fig 8).

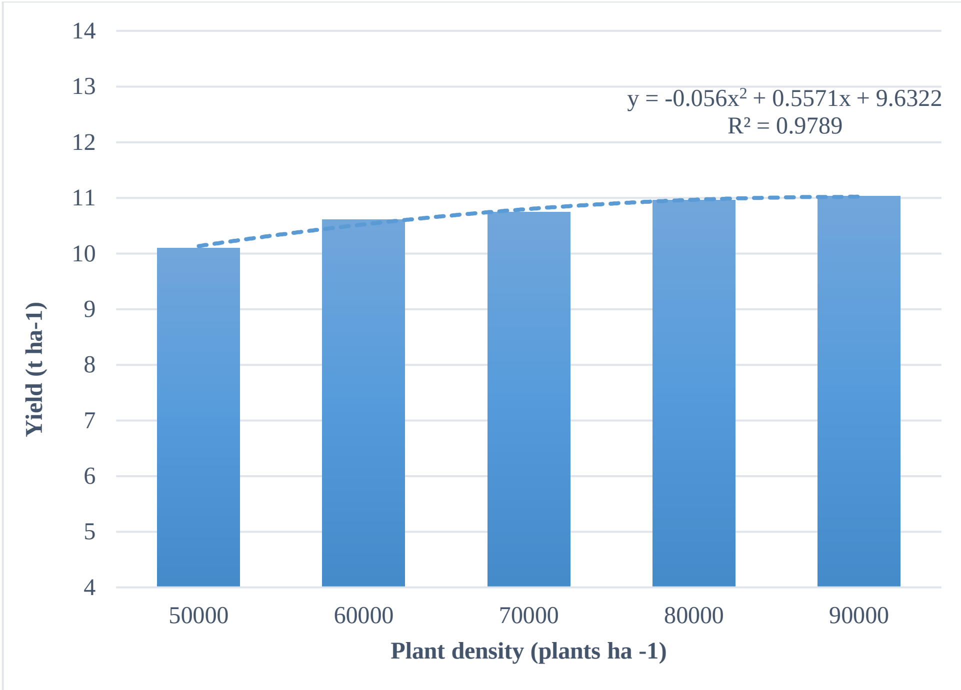


Figure 8 Yields achieved at different plant densities by the tested hybrids, averaged over the locations (2009–2015)

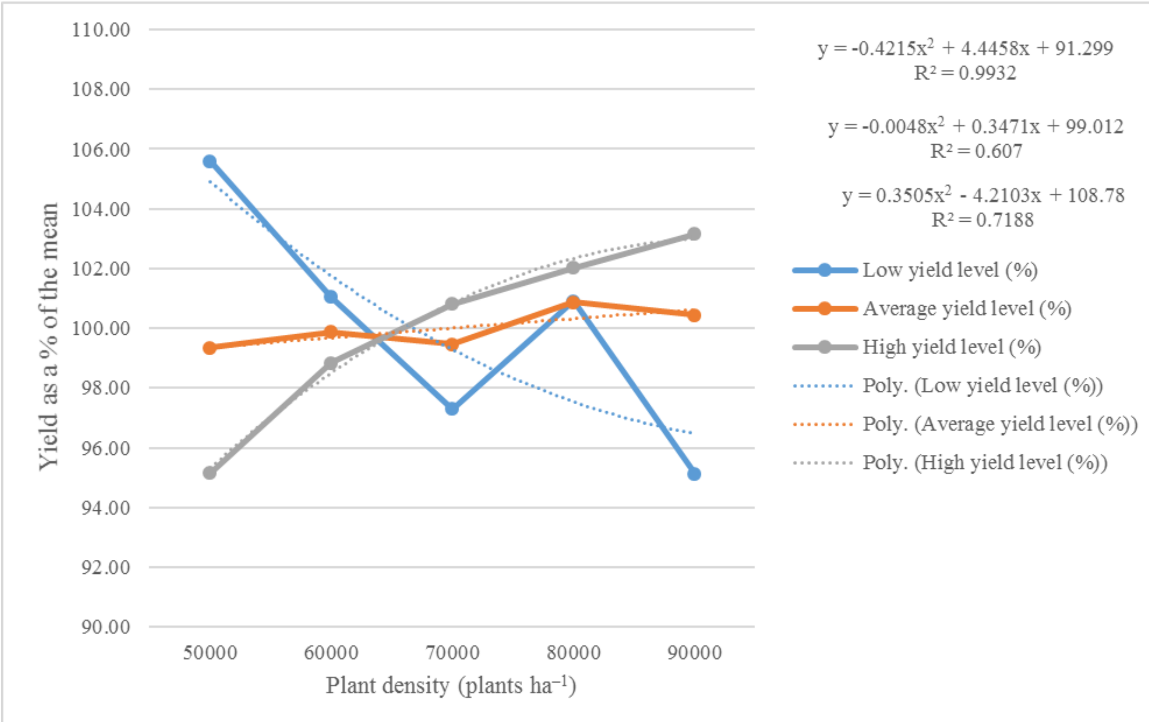
During the experimental period, 674 yield data were collected for the low yield level (<7 t ha^{-1}), 2045 for the average level (7–11 t ha^{-1}) and 2266 for the high level (>11 t ha^{-1}).

At low yield level the experimental mean was 5.12 t ha^{-1} and, based on all the data, the highest yield (5.40 t ha^{-1}) was recorded at the lowest plant density (50,000 plants ha^{-1}) and the lowest (4.86 t ha^{-1}) at the highest plant density (90,000 plants ha^{-1}). At this yield level a rise in the plant density resulted in yield losses, chiefly as the consequence of heat and drought stress.

At average yield level (7–11 t ha^{-1}) the experimental mean was 9.19 t ha^{-1} and the highest yield (9.28 t ha^{-1}) was obtained at 70,000 plants ha^{-1}. However, there were no significant differences between the yields measured at the different plant densities. While at low yield level there was a difference of over 10% between the lowest and highest grain yields, at average yield level this difference was only 1.09%.

At high yield level (>11 t ha^{-1}) the experimental mean was 13.69 t ha^{-1}, the highest yield of 14.09 t ha^{-1}, which was 2.93% higher than the mean, was obtained at the highest plant density (90,000 plants ha^{-1}) and the lowest (13 t ha^{-1}) at the lowest plant density. At this yield level there was a difference of 7.97% between the extreme values, and the grain yield rose consistently as the plant density was increased.

The effects of the plant density treatments at different yield levels and the problems arising in the field due to the incorrect choice of plant density are illustrated for all the data in Figure 9. At average yield level the classic plant density curve was obtained: after an initial rise there was a slight drop in yield, but at higher plant densities, despite the reduction in individual plant production, higher yields were recorded due to the compensating effect of greater plant density. At high yield levels all the hybrids gave better yields in response to greater plant density, while at low yield level the highest yields were found in the lowest plant density treatment. At this yield level an increase in plant density would definitely be risky under farm conditions. At the low yield level the highest yield was recorded at a plant density of 50,000 plants ha^{-1}. At average yield level, an optimum yield was reached as the plant density rose, after which a decline was observed. At still higher plant densities, however, the yield increased again, as the lower yields per plant were compensated for by the higher number of plants. A plant density curve of this shape was found for several hybrids even at low yield level. (Due to the narrow range of plant densities tested, the difference was not significant in most cases, but this statement was confirmed if the calculated optimum was taken into consideration.) As the plant density increased, the fact that more ears mean more kernels leading to higher yields was manifested, leading to higher yields at higher plant densities, with significant differences between the yields recorded in the individual plant density treatments.



9. Figure Deviation in the yields of the tested hybrids from the mean of the experimental locations at different plant densities and for three yield levels (2009–2015)

Data in the literature indicate that hybrids in different maturity groups exhibit different plant density responses. The present results suggest that hybrids belonging to early maturity groups (FAO 200 and FAO 300) respond well to greater plant density. Based on 2955 yield data the highest yield (10.63 t ha^{-1}) was measured at the highest plant density and the lowest (9.75 t ha^{-1}) at the lowest plant density. The experimental mean was 10.35 t ha^{-1} and the regression coefficient of the fitted curve demonstrated a close correlation. In recent years experience has shown that early and very early hybrids can be grown more successfully under dry conditions, as they can be sown earlier and therefore flower earlier, giving them a better chance of avoiding the periods most prone to drought.

A total of 2030 yield data were processed for hybrids in the medium maturity group (FAO 400). In this maturity group the experimental mean was 11.17 t ha^{-1}, which was 0.82 t ha^{-1} higher than for the very early and early hybrids. The highest yield (11.66 t ha^{-1}) was obtained at the highest plant density and the poorest (10.65 t ha^{-1}) at the lowest plant density.

3.1.4. Effect of plant density on agronomic traits

A total of 7102 agronomic trait data were collected in the plant density experiments during the period 2009–2015. The largest number of data were obtained for plant height (1821 data), ear height (1821 data) and flowering (1596). Where possible the number of lodged plants and stalk breakage was also recorded (709 data for each).

Based on field observations and data processing it can be stated that a rise in plant density exerted an effect on the agronomic traits (Table 6). The results of correlation analysis on how an increase in plant density influenced individual agronomic traits are summarised in Table 7.

An analysis of all the data revealed that **plant height** rose to a plant density of 80,000 plants ha^{-1}, after which it declined. However, the correlation coefficient indicated that plant density was not correlated with this trait (r=–0.01). The **ear height** gradually increased with a rise in plant density, but this too declined at the highest plant density. The differences were significant, the greater plant density was not correlated with changes in this trait (r=0.08), what we can explain by the lower values at the highest density.

Increasing the plant density had no influence on **flowering**: the number of days from sowing to silking and tasselling did not change and the regression coefficient revealed only a weak relationship between plant density and these traits (r=0.03 for silking and r=0.02 for tasselling). At low yield level (<7 t ha^{-1}) a rise in plant density led to slightly earlier flowering, so the sign of the correlation changed, presumably due to the greater heat sum or the drought stress, but the relationship was still weak (r=–0.03 for silking and r=–0.08 for tasselling).

The **test weight** was reduced by a rise in plant density (r=–0.06) at all yield levels, but the decrease was more pronounced at low yield level (r=–0.27). Here, too, the correlation was weak and negative. Higher plant density also had a measurable influence on the stalk and root characteristics of the hybrids in the field.

6. Table Values of agronomic traits at various plant densities, averaged over the experimental locations (2009–2015)

Agronomic traits	50.000 plants ha^{-1}	60.000 plants ha^{-1}	70.000 plants ha^{-1}	80.000 plants ha^{-1}	90.000 plants ha^{-1}	$LSD_{5\%}$
Plant height (cm)	236.28	237.89	237.27	238.89	234.37	3.23
Ear hight (cm)	104.77	106.88	108.23	109.65	107.92	2.19
Silking (Days After Planting)	70.02	69.85	69.99	70.34	70.49	1.35
Tasseling (DAP)	70.66	70.34	70.43	70.74	70.99	1.29
Stalk lodging (No./plot)	2.37	1.86	2.88	5.29	5.3	2.07
Rootlodging (No./plot)	2.05	2.94	4.03	5.54	7.22	2.04
Test weight (kg hl^{-1})	76.37	76.47	75.78	75.54	75.35	1.24

7. Table Correlation coefficients between agronomic traits and plant density, averaged over the experimental locations for various yield levels (2009–2015)

Agronomic traits	All data	Low yield level (<7 t ha^{-1})	Average yield level (7-11 t ha^{-1})	High yield level (11< t ha^{-1})
Density	1			
Plant height (cm)	-0.016	-0.120	0.018	-0.007
Ear height (cm)	0.085	0.071	0.107	0.077
Silking (Days After Planting)	0.033	-0.031	0.063	-0.011
Tasselling (DAP)	0.025	-0.081	0.053	-0.017
Stalk lodging (No./plot)	0.190	0.272	0.271	-0.102
Root lodging (No./plot)	0.342	0.510	0.343	0.130
Test weight (kg hl^{-1})	-0.062	-0.272	-0.070	-0.104

The **stalk** and **root lodging** gradually increased with a rise in plant density, significantly higher problems detected at higher densities (80-90,000). The correlation between plant density and **stalk breakage** was weak (r=0.19), while in the case of **root lodging** it was slightly stronger (r=0.34). At low yield level (<7 t ha^{-1}) these correlations were more pronounced (r=0.27 for stalk breakage and a medium-strength correlation of r=0.50 for root lodging).

An analysis of all the data for all the hybrids showed that plant density had significant effect on the agronomic traits, as also reported in the literature.

3.1.5. Effect of plant density on yield components

The **number of kernel rows** proved to be a constant trait for all the hybrids, as this parameter was not influenced by changes in plant density. For the majority of the hybrids the **ear length** and the **number of kernels per row** exhibited a close negative correlation with the plant density. The only exception was hybrid DKC4795, where the correlation was only of medium strength. The **circumference** and **diameter** of the ear and the **thousand-kernel weight** were found to be in medium negative correlation with the plant density except in the case of hybrids DKC4014 and DKC4590, where the correlation between ear circumference and plant density was close and negative.

3.2. Detailed results

This chapter of the thesis presents all the results and means obtained in the plant density experiments, including the plant densities resulting in the highest and lowest yields, and the sign and strength of the correlations between plant density and the yield. The data were also evaluated for the separate yield levels. Significant differences were calculated in order to demonstrate real differences between the plant density treatments, and calculations were made on the optimum plant density for each hybrid and the yield that can be achieved at the optimum plant density. The plasticity of each hybrid can be seen from the range of values.

The results obtained from the analysis of yield components are described both in writing and in tabular form. The effect of plant density on the yield components was statistically analysed using correlation analysis and the two-sample t-test. The yield component data, especially the ear length, were also examined using cluster analysis in order to perform a statistical check on field observations and previously formed opinions about the genotypes. In the course of this analysis the hybrids were grouped according to their ear characteristics, based on their diverse responses to changes in plant density. The results were illustrated with a dendrogram.

The analysis of profitability was not included in the PhD thesis, so these results, which will be important for recommendations on choice of hybrid and plant density, are only briefly illustrated, in order to give a complete picture of the work performed. The plant density recommendations are based mainly on the experimental results, while in some cases the cultivation recommendations for a given hybrid are also a function of the fertility of the growing area.

Table 8 contains the grain yields obtained for each hybrid at each plant density, averaged over the locations, and also gives the yields as a percentage of the mean for each hybrid over all the plant densities (%). The hybrids were only evaluated compared with their own mean yields, not with other hybrids in the maturity group or with the group mean, as the aim was to investigate the individual plant density responses of the hybrids. Changes in agronomic traits at different plant densities help in the compilation of plant density recommendations that do not endanger yield safety, while the analysis of yield components allows the individual nature of the plant density responses to be evaluated.

8. Table Yields of the tested hybrids in different plant density treatments, averaged over the locations (2009–2015)

Hybrid	50 000 plants ha^{-1}	%	60 000 plants ha^{-1}	%	70 000 plants ha^{-1}	%	80 000 plants ha^{-1}	%	90 000 plants ha^{-1}	%	Average	$LSD_{5\%}$	
DKC3623	9.45	93.27	10.01	98.72	10.00	98.62	10.50	103.63	10.75	106.13	10.14	1.09	**
DKC3705	8.78	95.71	8.78	95.68	9.34	101.79	9.37	102.14	9.63	104.92	9.17	0.84	**
DKC3939	10.37	91.41	11.05	97.43	11.53	101.59	11.81	104.05	11.96	105.39	11.35	1.38	**
DKC4014	10.26	97.51	10.71	101.87	10.41	98.97	10.69	101.63	10.52	99.98	10.52	1.11	NS
DKC4025	9.70	95.45	9.92	97.63	10.15	99.96	10.80	106.29	10.25	100.93	10.16	1.16	NS
DKC4590	10.24	94.66	10.45	96.59	11.13	102.91	11.12	102.85	11.15	103.06	10.81	1.01	NS
DKC4541	10.99	92.62	12.00	101.11	11.76	99.76	12.16	102.46	12.42	104.63	11.87	1.42	NS
DKC4490	9.17	95.19	9.63	99.97	9.59	99.61	10.00	103.79	9.76	101.35	9.64	1.42	NS
DKC4717	9.59	92.93	10.65	103.15	10.58	102.60	10.48	101.59	10.34	100.20	10.32	1.07	NS
DKC4795	9.15	94.30	9.56	98.47	9.78	100.85	9.78	100.80	10.25	105.63	9.70	1.15	NS
Average - early maturity group (t ha^{-1})	9.77	100.00	10.25	100.00	10.41	100.00	10.65	100.00	10.68	100.00	10.35		
DKC4964	9.53	99.05	9.14	94.95	9.46	98.31	9.75	101.35	10.37	107.76	9.63	1.29	NS
DKC4943	11.24	94.15	11.95	100.15	12.00	100.58	12.12	101.53	12.36	103.54	11.93	1.50	NS
DKC5031	10.80	93.57	11.56	100.07	11.71	101.41	11.66	100.95	12.00	103.83	11.55	1.18	**
DKC5007	10.73	94.47	11.43	100.63	11.49	101.16	11.62	102.31	11.52	101.43	11.36	1.08	NS
DKC5190	10.80	93.58	11.70	101.37	11.36	98.43	11.62	100.72	12.26	106.20	11.55	1.11	**
DKC5222	10.32	93.72	11.05	100.35	11.07	100.59	11.21	101.80	11.39	103.44	11.01	1.14	NS
DKC5276	10.63	95.34	10.89	97.61	11.31	101.36	11.74	105.28	11.27	101.01	11.15	1.05	**
Average -mid maturity group (t ha^{-1})	10.58	100.00	11.10	100.00	11.20	100.00	11.38	100.00	11.58	100.00	11.17		

3.2.1. Plant density treatments and ear types

An important aspect of the hybrid evaluation was the determination of the plant density optimum (Table 9). These values were calculated and then compared with the results obtained for yield components and agronomic traits. The final characterisation of the hybrids and the plant density recommendations were formulated after a joint consideration of the results of the plant density experiments, the corresponding agronomic information and the evaluation of yield component data.

Among the yield components the **ear length** (and consequently the number of kernels per row) was found to be in close negative correlation with the plant density, except in the case of hybrid DKC4795. When evaluating this trait it was found that hybrids where the difference in ear length between the lowest and highest plant densities (50,000 and 90,000 plants ha^{-1}) was less than 20% could be classified as being of **fixed ear type**, even if the difference was significant (Table 10). Such varieties were DKC4795 and DKC4025. Genotypes where the change in ear length at the extreme plant densities was greater than 20% and the difference was significant were classified as being of **flexible ear type**. Hybrids of this type were DKC4943, DKC5007, DKC5276 and DKC5031. Hybrids where the difference in ear length at the extreme plant densities was around 20% or less and significant, and where the ear length did not drop to less than 90% of the mean ear length for the hybrid even at the highest plant density, were classified as being of **flexible ear type, able to maintain good ear length** even at high plant density. This was true of hybrids DKC3705, DKC4014 and DKC4590. Hybrids where the change in ear length between the extreme plant densities was around 20% but the difference was not significant were classified as having stable, **preserved ear type**. This group included hybrids DKC3939, DKC3623, DKC4541 and DKC4717.

9. Table Optimum plant densities calculated for the tested hybrids and the range of optimum values (2009–2015)

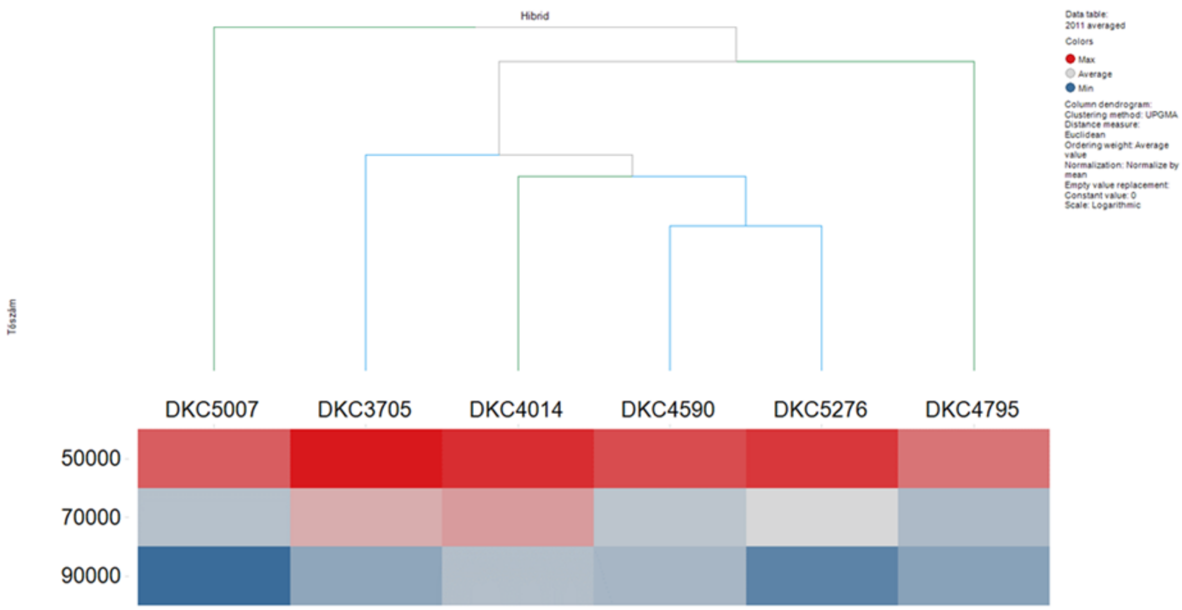
Hybrid	Linear equation	Calculated optimum (plants ha^{-1})	Calculated yield at optimum plant density (t ha^{-1})	Calculated minimum plant density (plants ha^{-1})	Minimum recommendation (plants ha^{-1})	Calculated maximum plant density (plants ha^{-1})	Maximum recommendation (plants ha^{-1})	Calculated range of optimum densities (plants ha^{-1})	Recommended range	Range characteristics
DKC3623	$y = -0.000000000057116x^2 + 0.000039053534817x + 7.700992739820680$				60000.00		90000.00		30000	Non-evaluable/wide (based on $LSD_{5\%}$)
DKC3705	$y = -0.000000000008408x^2 + 0.000023980373751x + 7.542966698221790$				70000.00		90000.00		20000	Non-evaluable/narrow (based on $LSD_{5\%}$)
DKC3939	$y = -0.000000000900000x^2 + 0.000165400000000x + 4.355999999999920$	91888.88	11.95	66951.18	70000.00	116826.58	90000.00	49875.4	20000	narrow
DKC4014	$y = -0.000000000484938x^2 + 0.000072826418515x + 7.892426098488780$	75088.38	10.62	41115.33	50000.00	109061.00	90000.00	67945.67	40000	very wide
DKC4025	$y = -0.000000000804203x^2 + 0.000132536500752x + 4.986960163542920$	82402.39	10.45	55547.02	50000.00	109247.8	90000.00	53700.78	40000	very wide
DKC4590	$y = -0.000000000758400x^2 + 0.000131124749236x + 5.507591545705820$	86448.27	11.17	59282.1	60000.00	113614.45	90000.00	54332.35	30000	wide
DKC4541	$y = -0.000000000614286x^2 + 0.000116200000000x + 6.864857142856930$	94581.35	12.36	64396.27	60000.00	124766.43	90000.00	60370.16	30000	wide
DKC4490	$y = -0.000000000680149x^2 + 0.000110772054044x + 5.348862847059920$	81432.19	9.85	52745.82	50000.00	110118.56	90000.00	57372.74	40000	very wide
DKC4717	$y = -0.000000001746587x^2 + 0.000257917152018x + 1.183968877008200$	73834.00	10.7	55933.39	60000.00	91735.82	90000.00	35802.43	30000	wide
DKC4795	$y = -0.000000000077075x^2 + 0.000035027239599x + 7.644899792816440$				50000.00		90000.00		40000	Non-evaluable/very wide (based on $LSD_{5\%}$)
DKC4964	$y = 0.000000001423100x^2 - 0.000176297482482x + 14.736023024697800$				60000.00		90000.00		30000	Non-evaluable/wide (based on $LSD_{5\%}$)
DKC4943	$y = -0.000000000642857x^2 + 0.000114000000000x + 7.226571428571360$	88666.68	12.28	59159.99	60000.00	118173.37	90000.00	59013.38	30000	wide
DKC5031	$y = -0.000000000761962x^2 + 0.000131618805072x + 6.218921627301630$	86368.35	11.9	59265.74	60000.00	113470.95	90000.00	54205.21	30000	wide
DKC5007	$y = -0.000000001093935x^2 + 0.000170834648106x + 4.984864571402070$	78082.63	11.65	55463.18	60000.00	100702.07	90000.00	45238.89	30000	wide
DKC5190	$y = 0.000000000050844x^2 + 0.000021267216691x + 9.804598151164370$				50000.00		90000.00		40000	Non-evaluable/very wide (based on $LSD_{5\%}$)
DKC5222	$y = -0.000000000710141x^2 + 0.000122440603318x + 6.060829625711370$	86208.65	11.33	58134.58	60000.00	114282.72	90000.00	56148.14	30000	wide
DKC5276	$y = -0.000000001028513x^2 + 0.000165204905627x + 4.848509272880600$	80312.5	11.48	56984.75	60000.00	103640.24	90000.00	46655.49	30000	wide

10. Table Changes in ear length, averaged over plant densities, and the determination of ear type (2011, 2015)

Hybrid	Year	Difference in ear length (%)	Ear type
DKC4025	2015	15.86**	fix
DKC4795	2011	16.07**	fix
DKC4943	2015	26.41**	flexible
DKC5007	2011	21.17**	flexible
DKC5031	2015	24.85**	flexible
DKC5276	2011	25.06**	flexible
DKC3705	2011	20.90**	flexible, preserved
DKC4014	2011	15.32**	flexible, preserved
DKC4590	2011	15.16**	flexible, preserved
DKC3623	2015	22.49 ^{NS}	stable length
DKC3939	2015	21.42 ^{NS}	stable length
DKC4541	2015	21.44 ^{NS}	stable length
DKC4717	2015	19.85 ^{NS}	stable length

Accordingly, it can be said that hybrid DKC3623 is tolerant to greater plant density, has a significantly higher yield at high plant densities at the average and high yield levels, has a wide optimum range for plant density, and has stable, preserved ear length. Hybrid DKC3705 needs not be grown with higher plant density at low and average yield levels, can only be grown in a narrow range of plant densities and regularly produces long ears. Significant differences in ear length were recorded at different plant densities. Hybrid DKC3939 tolerates higher plant density well, but has a narrow optimum range. The ear length is stable. The optimum plant density is stable, with a wider range, at average and low yield levels. Hybrid DKC4014 has a wide range of optimum plant densities, not requiring a denser stand. It is prolific, with a flexible ear type, and has great compensation ability at low and average yield levels. Hybrid DKC4025 tolerates a denser stand well and has a wide range of optimum density. The ear is of the fixed type. At high yield level the genotype responds well to higher plant density, but also yields reliably at low and average yield levels. Hybrid DKC4590, which has a flexible ear type, does not require a denser stand, having a wide range of optimum plant densities and great stability. Higher plant density is only justified at high yield levels if the crop is to be harvested early due to root lodging risks. Hybrid DKC4541 has a wide range of optimum plant densities and great stability, so it is unnecessary to increase the plant density. The ear length is of the preserved type. At low yield levels the hybrid compensates well with its stable ears, but at high yield levels higher plant density may be justified. Hybrid DKC4490 responds well to greater plant density, but has a wide range of optimum densities and fixed ear type. Thanks to its good agronomic traits it can be grown satisfactorily in denser stands. Hybrid DKC4717 only requires a denser stand at high yield levels. It has a wide range of optimum plant densities, regularly produces long ears and compensates well at low plant densities. Hybrid DKC4795 responds well to greater plant density, and has a wide range of optimum densities. It has fixed ear type and excellent agronomic traits. Hybrid DKC4964 is a long-eared genotype with a wide range of optimum plant densities, not requiring a denser stand at low and average yield levels, where it compensates well. Hybrid DKC4943 has a wide range of optimum plant densities and flexible ear type. At low yield levels it compensates well with its stable ears, but at high yield levels a denser stand may be justified. Hybrid DKC5031 has a wide range of optimum plant densities and flexible ear type. It can be grown successfully at higher plant densities. At average and low yield levels it compensates well with its long ears. Hybrid DKC5007 has a wide range of optimum plant densities and flexible ear type. Hybrid DKC5190 responds well to greater plant density at average and high yield levels, and can be grown reliably with low plant density at low yield levels. It has a wide range of optimum plant densities. Hybrid DKC5276, which has flexible ear type, responds well to higher plant density and has a wide range of optimum plant densities.

In order to supplement these descriptions, cluster analysis was performed to evaluate the extent to which the yield components, particularly the ear length, resembled each other within the clusters and differed from those in different clusters. The aim was to classify the hybrids according to their ear characteristics, providing a different approach to the statistical results and field observations and to the conclusions and hybrid classifications based on these. The dendrogram presented in Figure 10 illustrates how the hybrids are clustered based on ear length and plant density. The analysis and dendrogram visualisation of the 2011 data confirmed the classification given above regarding both the ear type and the plant density responses related to these ear types. The red color represents the higher values, since the blue the lower ones, the shorter ears. The intensity of the colorization means the deviation from the mean. In the dendogram the flex eared type hybrids are close to each other, like DKC3705, DKC4014, DKC4590 and DKC5276. DKC4795 and DKC5007 that have fixed ear types, can be clearly differenciated, although there was no significant difference on the extreme densities.



10. Figure Differences between the hybrids in terms of ear length in response to plant density treatments, 2011

3.2.2. Plant density recommendations and income calculations based on the plant density experiments

From the farmer's point of view, the final aim of crop production is to increase farm income and to make farming sustainable and profitable. When making recommendations on hybrids and plant densities an important aim is to improve the economic position of farmers following these recommendations. Table 11 presents the potential income attainable with hybrid DKC3623 grown with various plant densities at different yield levels. At low yield level (<7 t ha^{-1}) this hybrid produced the highest grain yield at the greatest plant density (90,000 plants ha^{-1}), but the investments required were not economical at this yield level.

At average yield level (7–11 t ha^{-1}) the yield was highest at the greatest plant density (90,000 plants ha^{-1}), but maximum income was achieved at the lowest plant density (50,000 plants ha^{-1}). At high yield level (>11 t ha^{-1}) the highest yield was again recorded at the greatest plant density (90,000 plants ha^{-1}), but the maximum profit was obtained at medium plant density (70,000 plants ha^{-1}). The income calculations demonstrate that the highest possible grain yield does not always provide the farmer with the greatest income. Plant density recommendations must be part of a complex advisory service that takes into account the potential of the growing site, the expected yield level based on the yields previously recorded on the area, the yield potential, plant density response, plant density optimum, range of optimum plant densities and agronomic traits of the hybrid and the potential income. If all these factors are considered, it becomes possible to prepare a precise, hybrid-specific plant density recommendation for the given location.

11. Table Potential income attainable with hybrid DKC3623 at various yield levels as a function of the plant density treatments (2009–2015)

Income calculation based on all data - DKC3623										
Plant density (plants ha^{-1})	**Yield (t ha^{-1})**	**Grain moisture content (%)**	**Farm gate price (Ft t^{-1})**	**Drying costs (removal of 1% H2O/t maize) (Ft)**	**Total cost ha^{-1} (Ft)**	**Seed price sales unit^{-1} (Ft)**	**Seed price ha^{-1} (Ft)**	**Drying costs (Ft)**	**Market value (Ft)**	**Profit (Ft)**
50000	9.45	16.05	45700	680	250000	48000	30000	9964	432023.161	142059
60000	10.01	16.12	45700	680	250000	48000	36000	11023	457282.713	160260
70000	10.00	16.24	45700	680	250000	48000	42000	11828	456844.466	153016
80000	10.50	16.04	45700	680	250000	48000	48000	10999	479995.012	170996
90000	10.76	16.1	45700	680	250000	48000	54000	11705	491633.037	175929
Income calculation for low yield level (<7 t ha^{-1}) - DKC3623										
Plant density (plants ha^{-1})	**Yield (t ha^{-1})**	**Grain moisture content (%)**	**Farm gate price (Ft t^{-1})**	**Drying costs (removal of 1% H2O/t maize) (Ft)**	**Total cost ha^{-1} (Ft)**	**Seed price sales unit^{-1} (Ft)**	**Seed price ha^{-1} (Ft)**	**Drying costs (Ft)**	**Market value (Ft)**	**Profit (Ft)**
50000	5.19	14.92	45700	680	240000	48000	30000	1483	237239.015	-34244
60000	5.10	15.73	45700	680	240000	48000	36000	4269	233268.947	-47000
70000	4.78	16.2	45700	680	240000	48000	42000	5531	218648.992	-68882
80000	4.72	15.27	45700	680	240000	48000	48000	2474	215900.657	-74573
90000	5.20	15.86	45700	680	240000	48000	54000	4808	237604.814	-61203
Income calculation for average yield level (7-11 t ha^{-1}) - DKC3623										
Plant density (plants ha^{-1})	**Yield (t ha^{-1})**	**Grain moisture content (%)**	**Farm gate price (Ft t^{-1})**	**Drying costs (removal of 1% H2O/t maize) (Ft)**	**Total cost ha^{-1} (Ft)**	**Seed price sales unit^{-1} (Ft)**	**Seed price ha^{-1} (Ft)**	**Drying costs (Ft)**	**Market value (Ft)**	**Profit (Ft)**
50000	8.97	13.69	45700	680	240000	48000	30000	-4939	409786.569	144726
60000	8.94	13.55	45700	680	240000	48000	36000	-5772	408336.016	138108
70000	9.22	14	45700	680	240000	48000	42000	-3134	421306.617	142441
80000	9.35	13.56	45700	680	240000	48000	48000	-5977	427326.489	145303
90000	9.40	13.47	45700	680	240000	48000	54000	-6582	429482.855	142065
Income calculation for high yield level (>11 t ha^{-1}) - DKC3623										
Plant density (plants ha^{-1})	**Yield (t ha^{-1})**	**Grain moisture content (%)**	**Farm gate price (Ft t^{-1})**	**Drying costs (removal of 1% H2O/t maize) (Ft)**	**Total cost ha^{-1} (Ft)**	**Seed price sales unit^{-1} (Ft)**	**Seed price ha^{-1} (Ft)**	**Drying costs (Ft)**	**Market value (Ft)**	**Profit (Ft)**
50000	12.56	20.07	45700	680	240000	48000	30000	47575	574023.223	256448
60000	12.90	18.51	45700	680	240000	48000	36000	35163	589308.689	278146
70000	13.96	19.19	45700	680	240000	48000	42000	44511	637830.406	311319
80000	14.01	18.99	45700	680	240000	48000	48000	42770	640176.926	309407
90000	14.02	18.9	45700	680	240000	48000	54000	41951	640761.151	304810

4. NEW SCIENTIFIC RESULTS

The aims of the agronomic experiments carried out over the last ten years were to gain better knowledge on the tested genotypes and to interpret how they were influenced by environmental factors and the production technology, especially the plant density. It was hoped that the information thus obtained would provide guidelines for breeding and selection and for the improvement of the germplasm. The achievement of sustainable farming and the future success of maize production in Hungary will depend in part on a sound knowledge of the genetic material, its rational use and the maximum exploitation of its latent potential in an environmentally sound manner.

In the course of this work the following new scientific results were obtained:

1. The data acquired for the tested genotypes proved that, despite the unpredictability of the weather, modern hybrids can be successfully grown at higher plant densities.
2. This was the first time that hybrid * plant density interactions were examined separately for three yield levels, making it possible to obtain more precise knowledge on the responses of the hybrids.
3. It was established that different hybrids have specific plant density responses, which also differ at different yield levels. Accordingly, the separate evaluation of these results is critical for a better knowledge of the genotypes and for their use in Hungarian farm practice.
4. The statistical analysis showed that the effect of plant density on agronomic traits was significant, the negative effect of an increase in the plant number per unit area could be detected in the field.
5. The evaluation of plant density responses was complemented with the analysis of the yield components of the hybrids, which revealed that the number of kernel rows was a fixed property, completely unaffected by the environment or changes in plant density.

6. An increase in plant density was found to have a negative effect on all the other yield components (ear length, number of kernels per row, ear circumference and diameter, and thousand-kernel weight).
7. The combined analysis of plant density responses, agronomic traits and yield components made it possible to perform a complex investigation on the hybrid-specific plant density response at the whole plant level.
8. Different hybrids employ various strategies to maximise the yield per unit area, which can generally be expressed as the number of ears per unit area times the number and weight of the kernels per ear. The highest possible yield at a given plant density is achieved via a different yield component in each hybrid. Knowledge on these specific strategies was important for the elaboration of hybrid-specific plant density recommendations that also took into consideration the fertility of the given location.
9. On the basis of their plant density responses, tolerance of greater plant density and ear length the tested hybrids could be classified in the following groups:
    a. Hybrids with a sensitive response to greater plant density, which can only be grown over a narrow range of plant densities: DKC3705.
    b. Hybrids tolerant of greater plant density:
        i. Hybrids tolerant of a wide range of greater plant densities, having stable ear length: DKC3623, DKC4541;
        ii. Hybrids tolerant of a narrow range of greater plant densities, having stable ear length: DKC3939;
        iii. Hybrids tolerant of a wide range of greater plant densities, having fixed ear length: DKC4025, DKC4490, DKC4795, DKC5190, DKC5222.
    c. Hybrids that can be grown over a wide range of plant densities:
        i. Hybrids with flexible ear type, not requiring greater plant density as they can be grown over a wide range of plant densities: DKC4014, DKC4590, DKC4964, DKC4943, DKC5031, DKC5276;

ii. Hybrids that can be grown over a wide range of plant densities, with preserved ear length: DKC4717, DKC5007.

10. A new system was elaborated for plant density experiments and hybrid evaluation to promote precise recommendations based on the nature of the location. The system includes the following components:

a. A plant density experiment network with its own methodology, including the analysis of agronomic traits;

b. Study and evaluation of yield components in various plant density treatments;

c. Joint evaluation of plant density responses and ear length, followed by hybrid classification;

d. Evaluation of hybrids at different yield levels in order to provide science-based practical hybrid-specific information not only on mean yields but on those attainable under extreme conditions;

e. Provision of profit calculations for farmers, who need to maximise profits, not yields.

5. RESULTS SUITABLE FOR PRACTICAL APPLICATION

Due to the unpredictable weather conditions and the low level of inputs, the national maize yield in Hungary has averaged 5.89 t ha^{-1} over the last 15 years. Even more importantly, there are great fluctuations in yield, which means that it is impossible to predict farm incomes. Maize production plays a key role in the Hungarian agricultural structure, so it is a national priority to achieve yield reliability and profitability. The results achieved in the present work could have the following practical applications:

1. Growing the right hybrid at the right plant density is responsible for almost 50% of the success of maize production (Győrffy and Berzsenyi, 1995), so the present findings could contribute to the achievement of rational choices of genotype.
2. With the help of the database compiled during this research, hybrid and plant density recommendations can be made for different yield levels.
3. The complex information available for specific hybrids and plant densities can be utilised directly in the framework of precision agriculture.
4. The hybrids tested in the experiments were grouped according to plant density response, tolerance of greater plant density and ear type; this information can be used directly by those seeking a suitable hybrid for a given location.
5. The system elaborated for plant density experiments and complex hybrid evaluation can be put directly into practice.
6. The models developed for plant density experiments, hybrid evaluation and income calculation could become daily practice in maize production, not only for determining the correct plant density, but also for planning income levels.
7. The results will contribute to the elaboration of a complex, successful genotype–environment–management system to promote future hybrid breeding efforts

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List of publications related to the dissertation

Foreign language scientific articles in Hungarian journals (1)

1. **Könczöl, P.**: The effect of plant density to the yield results and the yield components of maize hybrids.
   Agrártud. közl. 72, 89-93, 2017. ISSN: 1587-1282.

Foreign language scientific articles in international journals (1)

2. **Könczöl, P.**, Ágner, Z., Sovány, C., Fehérvári, S.: Effect of plant density on grain yield, yield components and agronomic traits of maize (Zea mays L.) hybrids.
   Maydica. [Epub], [18], 2018. ISSN: 0025-6153.
   IF: 0.375 (2016)

Other journal articles (1)

3. **Könczöl, P.**: A tőszám, mint a kukorica termesztéstechnológia lényeges, de ki nem használt eleme.
   Agroforum. 67, 56-59, 2016. ISSN: 1788-5884.

Hungarian abstracts (1)

4. **Könczöl, P.**: A tőszám- és terméskomponens-vizsgálatok eredményeinek felhasználása a kukorica gyakorlati nemesízői munkában.
   In: XXIII. Növénynemesítési Tudományos Nap : Összefoglalók. Szerk.: Veisz Ottó, Magyar Tudományos Akadémia, Budapest, 53, 2017.

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List of other publications

Informational/educational articles (1)

5. **Könczöl, P.**, Csajbók, J.: Éghajlati anomáliák hatásai a kukorica genetikai és termesztéstechnológiai fejlesztésére.
   Agroforum. *19* (Extra), 20-21, 2008. ISSN: 1788-5884.

Patents (5)

6. **Könczöl, P.**: 91DUQ1 X 0997. 2017
   Country: Russia
   Application Date: 2014.12.25
   Application number: 66453 (2014.12.25)
   Registration number: 9285 (2017.10.20)

7. **Könczöl, P.**: EP3919. 2017
   Country: Russia
   Application Date: 2017.08.24
   Application number: 72529 (2017.08.24)

8. **Könczöl, P.**: EP4224. 2017
   Country: Russia
   Application Date: 2017.10.24
   Application number: 72791 (2017.10.24)

9. **Könczöl, P.**: EP4313. 2017
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   Application number: 72790 (2017-10-24)

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10. **Könczöl, P.**: V4265Z. 2017
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