Effect of Crop Rotation and Fertilization on Maize and Wheat Yields and Yield Stability in Long-term Experiments

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Introduction and Literary Review

In recent decades the interest shown in long-term experiments has increased world-wide, since suitable indicators of production sustainability (yield trends, parameters characteristic of the quality of the ecosystem), capable of serving as an early warning system, can only be obtained in such experiments (LEIGH & JOHNSTON, 1994; DEBRECZENI & DEBRECZENI, 1994).

Crop sequences represent a systems approach in crop production research, enabling the available natural resources to be preserved and more efficiently utilized. In crop rotation experiments a monoculture is generally compared to various crop sequences. The fact that in most cases the yields of the cultivated crops increase in crop rotation, as compared with a monoculture under identical conditions, is explained by the rotation effect. This rotation effect has been demonstrated irrespective of whether the crop rotation contains legumes or non-leguminous plants. Numerous factors contribute to the rotation effect (GYŐRFFY, 1975). The major factors inducing typical yield differences are well known, but the importance of the various factors may be substantially modified by the experimental conditions.

When comparing monocultures with crop sequences, studies are generally made not only on yields, but also on their effect on soil fertility, pH, N requirements, soil organic matter, soil tilth, rainfall utilization, pest, disease and weed control, the efficiency of plant protection, and soil erosion. The direct, residual and cumulative effects of a rotation system on soil fertility are often expressed in terms of cycles.

The analysis of crop rotation data is generally more complicated (due to yearly replications, cycles and crop orders, and correlational errors) than that of 1-year experiments. The evaluation of several decades of data series requires a specific order of data processing and biometric analysis (annual and combined analysis of variance, trend calculations, simulation models). A detailed discussion of the special problems encountered during the biometrical analysis of crop rotation experiments was given by YATES (1954). Further valuable details are found in the papers of PATTERSON (1953) and CADY (1991).

The first step in the biometrical analysis of long-term crop rotation data is annual variance analysis. The aim of this preliminary analysis is to determine whether all the experimental years can be included in a single combined analysis, or whether it is necessary either to transform the data or to divide the experimental years into more or less homogeneous groups. If the variances are homogeneous on the basis of the Bartlett test, combined analysis can be carried out using the data of the various experimental years. Emphasis continues to be put on the examination of the treatment x year interaction and the analysis can be extended to cycles and series (CADY & MASON, 1964).

The significant treatment x environment interactions observed in variance analysis are difficult to interpret using traditional variance analysis due to the complexity of the factors influencing the environment. The significant treatment x environment interactions observed in the variance analysis models of long-term experiments can be interpreted simply using stability analysis.

The measurement of yield stability over time involves at least three components: (1) the correlation of yield with the local environment, (2) the mean yield level and (3) the variability of the yield (MEAD et al., 1986). The most important variance parameters are the mean square deviation *(s^2)*, the coefficient of variation *(CV%)*, the ecovalence parameter *(W^2)* described by WRICKE (1962) and the stability variance parameter *(σ^2)* elaborated by SHUKLA (1972). The two latter parameters measure the contribution of the treatment to the treatment x environment interaction (CALLOWAY & FRANCIS, 1993). Recently KANG (1993) combined yield and stability in a single selection criterion, yield stability *(YS)*.

The most frequently applied stability indices are based on the regression model. In this case the stability index is the slope of the linear function *(b)*. The use of regression to estimate the yield stability of genotypes in different environments was first suggested by YATES & COCHRAN (1938), followed later by FINLAY & WILKINSON (1963) and EBERHART & RUSSELL (1966). When applying this method the environmental index, which usually consists of the yield average calculated for each genotype in each environment, is compared to the yields of the various genotypes tested.

A stable system can be defined as that which changes least as the result of environmental factors. EBERHART & RUSSELL (1966) characterised a stable genotype as one which had a linear regression coefficient of 1, while its deviation from the regression function was 0. FINLAY & WILKINSON (1963) proposed that a regression coefficient value of $b<1.0$ should indicate better adaptation to poorer environments, while genotypes with a value of $b>1.0$ could best be grown in an excellent environment.

Stability analysis has rarely been applied other than in the field of plant breeding. HILDEBRAND (1984) and RAUNN et al. (1993) employed stability analysis in long-term experiments to evaluate fertilization treatments. The extrapolation of this method to characterize the stability of agronomic treatments instead of genotypes can be regarded as a practical application for the separation of responses to treatments dependent in time on the environment.

The *aim of the present paper* was (a) to evaluate the effect of various crop sequences and fertilization treatments on maize and wheat yields in comparison with maize and wheat monocultures on the basis of more than 35-year data, and (b) to use the variance and regression methods of stability analysis to characterize the effect of experimental treatments on yield stability.

Material and Methods

Treatments in the crop rotation experiment. - The crop rotation experiment was set up by Győrffy and co-workers in 1961 in the field nursery of the Agricultural Research Institute of the Hungarian Academy of Sciences on a chernozem soil with forest residues. The experiment is a bifactorial split plot with four replications. The main plots are the crop sequences and the subplots the fertilizer treatments, in a random design. The subplots measure 7x7 m = 49 m^2 and the main plots 49x5 m = 245 m^2.

The main plot consists of 7 crop sequences, namely maize and wheat monocultures, periodic monocultures of maize and wheat, dicultures, tricultures and a Norfolk crop rotation. The 7 treatments in the experiment consisted of the following 2 monocultures and 5 crop sequences:

1. Maize monoculture;
2. Wheat monoculture;
3. 3 years alfalfa - 5 years maize;
4. 3 years alfalfa - 5 years wheat;
5. 2 years wheat - 2 years maize;
6. 3 years alfalfa - 3 years maize - 2 years wheat;
7. Maize - spring barley - peas - wheat.

Each cycle of treatments 3, 4 and 6 takes 8 years, while that of treatments 5 and 7 takes 4 years, so the full experimental cycle is 8 years. Four complete cycles have taken place since the start of the experiment. The effects of the various sequences are compared with each other and with the monocultures. The various plant species represent the treatments and it follows from the structure of the experiment that the plots being compared do not always contain the same crops in the same years. However, due to the long period which has passed since the experiment was set up, it is possible to compare the treatments over an adequate number of years.

The subplots in the experiment represent 5 different fertilization systems:

A: Control, without fertilizer;

B: 60 t/ha stable manure every 4 years + NPK supplementation;

C: 5 t/ha straw or 7 t/ha maize stalks each year + NPK supplementation;

D: NPK fertilizer;

E: Extracted NPK for a yield of 15 t/ha maize and 10.5 t/ha wheat.

In treatments B, C and D, 720 kg/ha N, 360 kg/ha P and 600 kg/ha K were applied over 4 years. In treatment E, calculations were based on 2.3 kg N, 1.1 kg P and 2.0 kg K per 100 kg yield (+ by-products) for maize and 2.5 kg N, 1.2 kg P and 1.0 kg K for wheat. The NPK requirements are modified according to the crops and previous crops. It should be noted that since autumn 1984 the fertilizer treatments have been revised: the quantity of active agents applied over 4 years has been doubled. Since the experiment was set up the standard agrotechnical measures have not changed to any great extent and the varieties have only been changed every 6-8 years. The proportions of maize and wheat were 25.0, 37.5, 50.0, 62.5 and 100 %, depending on the type of crop sequence.

Variance analysis. - The analysis is based on the combined evaluation of yield data from the maize and wheat monocultures and from the various crop sequences for comparable years. Thus, depending on the type of crop sequence, the combined analysis could be carried out for 9, 12, 15 or 20 years for maize and 8, 9, 18 or 20 years for wheat. On the above principles the effect of 3 and 4 sequences, respectively, was evaluated using combined variance analysis, taking into consideration 12, 8, 9 and 4 comparable years, respectively.

Prior to combined analysis, bifactorial variance analysis was carried out for each experimental year (with crop order as main plots and fertilization as subplots) and the heterogeneity of the experimental errors was examined. The homogeneity of the error variance for the different years was studied using the Bartlett test (SVÁB, 1981).

The structure of the combined variance analysis was determined on the basis of GOMEZ & GOMEZ (1984) and the analysis was carried out using the MSTAT-C programme. This combined variance analysis provided an overview of the magnitude of variation between the experimental years, the variation between the treatments and especially the treatment x year interaction. As a continuation of variance analysis, it is possible to extend the analysis to include cycles and series (CADY & MASON, 1964), but this was not the aim of the present work.

Stability analysis. - The stability analysis of the experimental treatments was conducted using the variance and regression methods. Among the variance methods, WRICKE's (1962) ecovalence index (W^2), SHUKLA's (1972) stability variance index (σ^2) and KANG's (1993) yield stability index (*YS*) were calculated using the STABLE model elaborated by KANG & MAGARI (1995). This model made it possible to use a covariant (rainfall quantities) to eliminate heterogeneity (the non-additive or linear effect of the covariant) from the interaction; the stability variance was then calculated from the residual interaction. The ecovalence (W^2), and stability variance (σ^2) indices measure the contribution of the treatment to the treatment x environment interaction. The two indices are equivalent (KANG & MAGARI, 1995).

Linear regression analysis was carried out according to the method of FINLAY & WILKINSON (1963). In the present studies the stability of the treatments was not only characterized by the steepness of the lines, but the effect of the treatments under various environmental conditions was also illustrated by linear functions, after RAUNN et al. (1993). In this sense stability analysis is one way of visually breaking down the treatment x environment interaction, by illustrating the effect of agronomic treatments on the yield under varying environmental conditions.

The data were processed on an IBM-compatible computer using the MSTAT-C and SPSS 6.1 for Windows programmes.

Results

Effect of crop rotation and fertilization on soil properties

The 28-year long-term effect of the crop rotation and fertilization treatments on major soil properties is summarized in *Table 1*. The *humus content* was sig-

Table 1

28 year long-term effect of crop rotation and fertilization treatments on major properties in the 0-20 cm soil layer*

Treatments	Humus %	pH (KCl)	P_2O_5 mg $100g^{-1}$	K_2O mg $100g^{-1}$
Crop sequences				
1. Maize monoculture	2.81 d	5.91 ab	5.33 c	27.25 b
2. Wheat monoculture	3.24 ab	5.79 ab	7.60 ab	31.75 a
3. 3 years alfalfa - 5 years maize	3.39 a	5.51 b	4.33 c	26.49 b
4. 3 years alfalfa - 5 years wheat	3.31 a	6.06 ab	4.07 c	26.77 b
5. 2 years wheat - 2 years maize	2.99 cd	6.33 ab	7.27 b	33.53 a
6. 3 years alfalfa - 3 years maize - 2 years wheat	3.07 bc	6.01 ab	4.12 c	25.58 b
7. Norfolk crop rotation	2.96 cd	6.56 a	9.28 a	31.30 a
Fertilization treatments				
A: Unfertilized control	3.05 b	6.23 a	2.58 d	25.12 c
B: Organic manure and NPK fertilizer	3.21 a	6.25 a	6.73 b	30.91 a
C: Straw or stalks and NPK fertilizer	3.11 ab	5.93 b	5.77 c	28.33 b
D: NPK fertilizer	3.08 b	5.89 b	5.72 c	29.19 b
E: NPK fertilizer taken up	3.10 ab	5.82 b	9.19 a	31.20 a

* Data followed by the same letter within a column or group of treatments do not differ significantly at the P = 5% level.

nificantly the greatest in treatments 3 and 4 (where alfalfa was grown for 3 years as a previous crop to maize and wheat, respectively) and in the wheat monoculture. It was lowest in the maize monoculture. As regards the effect of fertilization, the humus % was greatest in plots where both stable manure and NPK were distributed. The *soil pH* was greatest in the Norfolk rotation and lowest in the alfalfa-maize sequence. The pH was significantly higher in control plots and in those treated with stable manure than in the other fertilizer treatments. The *P_2O_5 and K_2O contents of the soil* were highest in the Norfolk rotation, in the wheat monoculture and in the wheat-maize diculture, and the data also provided a good reflection of the effect of the fertilizer treatment.

Evaluation of the main effects and interactions of maize and wheat sequences and fertilization by means of variance analysis

The results of comparable years in the long-term experiments were evaluated using bifactorial combined variance analysis (main plots were crop sequences, subplots were fertilization) (Tables 2 and 3). In the variance analysis the effects of crop sequences containing various proportions of maize and wheat were compared to the maize and wheat monocultures. The main effects (year, crop sequence, fertilization) were significant in all cases at the 0.1% level, but their relative importance on the basis of MQ values varied according to the type of crop sequence.

Table 2

Combined variance analysis of a long-term, two factorial, split-plot experiment taking into account the years (2 years maize - 2 years wheat vs. maize monoculture and 3 years alfalfa - 5 years maize vs. maize monoculture)

Factor	Wheat-maize diculture vs. maize monoculture		Alfalfa-maize diculture vs. maize monoculture	
	FG	MQ	FG	MQ
Years (Y)	16	63.32***	19	57.78***
Replication within the year R (Y)	51	3.55**	60	4.48**
Crop rotation (A)	1	17.80***	1	13.49**
Y x A	16	3.15*	19	2.21 NS
Pooled error (a)	51	1.52	60	2.23
Fertilization (B)	4	116.45***	4	110.22***
Y x B	64	1.10***	76	1.33***
A x B	4	2.10***	4	5.44***
Y x A x B	64	0.24 NS	76	0.52 NS
Pooled error (b)	408	0.34	480	0.45

Significant at ***P: 0.1% level; **P: 1% level; *P: 5% level. NS: Non-significant.

Table 3

Combined variance analysis of a long-term, two-factorial, split-plot experiment taking into account the years (3 years alfalfa - 3 years maize - 2 years wheat vs. maize monoculture and Norfolk crop rotation vs. maize monoculture)

Factor	Alfalfa-maize-wheat vs. maize monoculture		Norfolk crop rotation vs. maize monoculture	
	FG	MQ	FG	MQ
Years (Y)	11	56.80***	8	62.54***
Replication within the year R (Y)	36	1.71*	27	1.90
Crop rotation (A)	1	52.97***	1	77.55***
Y x A	11	3.22**	8	3.02^{NS}
Pooled error (a)	36	0.97	27	1.74
Fertilization (B)	4	75.35***	4	66.66***
Y x B	44	0.98***	32	1.85***
A x B	4	0.60^{NS}	4	2.35***
Y x A x B	44	0.58^{NS}	32	0.62^{NS}
Pooled error (b)	288	0.43	216	0.44

Significant at ***P: 0.1% level; **P: 1% level; *P: 5% level. NS: Non-significant.

In the case of *wheat-maize diculture vs. maize monoculture* and *alfalfa-maize diculture vs. maize monoculture* the greatest effect was recorded for fertilization, followed by the year effect and the crop sequence effect (Table 2). In the *3 years alfalfa - 3 years maize - 2 years wheat triculture vs. maize monoculture*, too, the effect of fertilization was the greatest, but the effect of crop sequence increased substantially, becoming similar in magnitude to that of the year. When comparing the *Norfolk rotation* with the *maize monoculture* the effect of crop rotation became the most important, followed by fertilization and year, with similar magnitudes (Table 3).

The importance of interactions appears on the basis of MQ values to be far less than that of the previous effects. The crop rotation x year interaction was significant at the 5% level in the *2 years wheat - 2 years maize* and the *3 years alfalfa - 3 years maize - 2 years wheat* sequences compared to the maize monoculture. The fertilization x year interaction was significant at the 0.1% level for all the crop sequences. The crop sequence x fertilization interaction was significant at the 0.1% or 1% level for all crop sequences except the Norfolk rotation. The triple interaction (YxBxC) was not significant for any of the sequences, i.e. the effect of none of the three factors depends on the level of the other two.

In the variance analysis crop sequences containing various proportions of wheat were all compared with the wheat monoculture (Tables 4 and 5). The main effects (year, crop sequence and fertilization) were significant at the 0.1% level in all cases, but their relative importance on the basis of MQ values depended on the type of crop rotation.

Table 4

Combined variance analysis of a long-term, two-factorial, split-plot experiment taking into account the years. (2 years maize - 2 years wheat vs. wheat monoculture and 3 years alfalfa - 5 years wheat vs. wheat monoculture)

Factor	Wheat-maize diculture vs. wheat monoculture		Alfalfa-wheat diculture vs. wheat monoculture	
	FG	MQ	FG	MQ
Years (Y)	17	42.65***	19	33.44***
Replication within the year R (Y)	54	0.84*	60	0.99*
Crop rotation (A)	1	86.11***	1	24.55***
Y x A	17	3.54***	19	3.56***
Pooled error (a)	54	0.51	60	0.58
Fertilization (B)	4	58.07***	4	62.89***
Y x B	68	0.96***	76	0.69***
A x B	4	1.84***	4	0.21^{NS}
Y x A x B	68	0.36***	76	0.31**
Pooled error (b)	432	0.14	480	0.20

Significant at ***P: 0.1% level; **P: 1% level; *P: 5% level. NS: Non-significant.

Table 5

Combined variance analysis of a long-term, two-factorial, split-plot experiment taking into account the years. (3 years alfalfa - 3 years maize - 2 years wheat vs. wheat monoculture and Norfolk crop rotation vs. wheat monoculture)

Factor	Alfalfa-maize-wheat vs. wheat monoculture		Norfolk crop rotation vs.wheat monoculture	
	FG	MQ	FG	MQ
Years (Y)	7	10.36***	8	45.90***
Replication within the year R (Y)	24	0.55	27	0.58
Crop rotation (A)	1	90.36***	1	208.33***
Y x A	7	2.90**	8	4.61***
Pooled error (a)	24	0.69	27	0.47
Fertilization (B)	4	31.42***	4	32.82***
Y x B	28	0.45**	32	1.06***
A x B	4	0.24^{NS}	4	0.68**
Y x A x B	28	0.62***	32	0.33***
Pooled error (b)	192	0.23	216	0.15

Significant at ***P: 0.1% level; **P: 1% level; *P: 5% level. NS: Non-significant.

When comparing the *3 years wheat-5 years alfalfa diculture* with the *wheat monoculture* the effect of fertilization was the most important, followed by that of year and crop sequence. In the case of *wheat-maize diculture vs. wheat monoculture* the effect of crop sequence was the most important; on the basis of MQ values the effect of fertilization was only two-thirds and that of the year only half that of crop sequence (Table 4). In the case of *3 years alfalfa - 3 years maize - 2 years wheat triculture vs. wheat monoculture* the effect of crop sequence was three times that of fertilization and almost ten times that of the year. When comparing the *Norfolk rotation* with the *wheat monoculture* the effect of crop sequence was more than six times that of fertilization and more than four times that of the year (Table 5).

The importance of *interactions* is shown by the MQ values to be substantially less than that of the main effects. The crop sequence x year interaction was significant at the 0.1% level for all crop sequences and was the most important of the interactions on the basis of MQ values. The fertilization x year interaction was significant at the 1% level in the triculture and at the 0.1% level in the other crop sequences. The crop sequence x fertilization interaction was significant at the 0.1% level in the wheat-maize diculture and at the 1% level in the Norfolk rotation. The triple interaction (YxAxB) was significant at the 0.1% or 1% level for all the sequences, which means that the effect of one of the three factors depends on the levels of the other two.

Effect of various crop sequences on maize and wheat yields at different fertilization levels

The effect of crop rotation and fertilization on the yield and yield stability of maize was evaluated on the basis of data from 9, 12, 15 or 20 comparable years, depending on the type of crop sequence (Tables 6 and 7).

It can be seen from the data in Table 6 that without fertilization the yield in the *2 years maize - 2 years wheat diculture* was 0.59 t/ha higher than in the maize monoculture. Averaged over the "B-E" fertilizer treatments the yield difference was 0.257 t/ha. Differences were observed in the maize yield depending on whether it was grown in the first or second year after wheat. In the first year the maize yield was 0.396 t/ha higher than that of maize grown in a monoculture, while this figure dropped to 0.267 t/ha in the second year.

In the *3 years alfalfa - 5 years maize* sequence the yield average of maize without fertilization was 0.875 t/ha higher than in a maize monoculture, while it was only 0.107 t/ha greater when a satisfactory level of fertilization was applied (mean of treatments B-E) (Table 6). A detailed analysis of the data indicates that the yield of maize after alfalfa, averaged over fertilizer treatments A-E, was 0.346 t/ha greater than that in maize monoculture during the first 2 years, but

Table 6

Stability parameters of a maize monoculture vs. maize-wheat diculture and maize monoculture vs. maize-alfalfa diculture in various fertilization systems, 1961-1996.

Fertilizer treatments	Yield response t/ha	CV% (1)	W² (2)	σ² (3)	YS (4)	Yield response t/ha	CV% (1)	W² (2)	σ² (3)	YS (4)
	Maize monoculture					*Maize monoculture*				
A	4.797	10.89	17.09	1.21**		4.546	11.84	24.10	1.45**	
B	6.890	4.26	8.06	0.51 NS		6.584	8.04	21.13	1.26**	
C	6.912	6.44	15.74	1.11**		6.744	6.58	14.92	0.85**	
D	7.180	5.76	11.85	0.81**	+	6.863	4.96	8.92	0.45 NS	+
E	7.001	6.48	14.21	0.99**		6.882	6.02	14.76	0.84*	+
	Maize-wheat diculture					*Maize-alfalfa diculture*				
A	5.387	9.80	25.08	1.84**		5.421	13.73	40.06	2.50**	
B	6.812	5.47	12.29	0.84**	+	6.807	6.81	24.15	1.46**	+
C	7.346	4.59	7.47	0.46 NS	+	6.778	6.51	19.13	1.13**	
D	7.476	5.33	10.02	0.66**	+	6.786	3.93	5.42	0.22 NS	+
E	7.377	7.14	16.97	1.21**	+	7.127	4.72	9.33	0.48 NS	+
$LSD_{5\%}$	*0.164*					*0.174*				

Table 7

Stability parameters of a maize monoculture vs. alfalfa-maize-wheat triculture and maize monoculture vs. Norfolk crop rotation in various fertilization systems, 1961-1996.

Fertilizer treatments	Yield response t/ha	CV% (1)	W² (2)	σ² (3)	YS (4)	Yield response t/ha	CV% (1)	W² (2)	σ² (3)	YS (4)
	Maize monoculture					*Maize monoculture*				
A	4.521	11.34	19.13	2.04**		4.825	14.75	29.41	4.42**	
B	6.470	6.96	12.56	1.30**		7.136	5.32	4.59	0.54 NS	+
C	6.594	8.19	13.18	1.37**		7.089	8.42	10.48	1.46**	
D	6.721	4.51	4.05	0.33NS	+	7.243	6.37	6.04	0.77 NS	+
E	6.772	7.51	13.85	1.44**		7.224	8.60	13.43	1.92**	
	Maize-alfalfa-wheat triculture					*Norfolk crop rotation*				
A	5.420	10.85	15.25	1.60**		6.086	10.31	15.28	2.21**	
B	7.207	5.34	7.14	0.68 NS	+	8.280	5.41	5.65	0.70 NS	+
C	7.199	5.71	9.48	0.95**	+	8.243	6.13	7.41	0.98*	+
D	7.204	3.83	4.09	0.33 NS	+	7.869	3.92	3.09	0.30 NS	+
E	7.370	4.72	5.08	0.45 NS	+	7.680	5.76	7.72	1..03*	+
$LSD_{5\%}$	*0.219*					*0.258*				

Significant at: ***P: 0.1% level; **P: 1% level; *P: 5% level. NS = Non-significant. (1) Variance coefficient. (2) Wricke's ecovalence index. (3) Shukla's stability variance index. (4) Kang's yield stability index.

only 0.204 t/ha greater in the 3rd-5th years (without fertilization the yield increase over the same periods was 1.123 t/ha and 0.709 t/ha, respectively).

In the *3 years alfalfa - 3 years maize - 2 years wheat triculture* (Table 7) the mean yield surplus compared with the maize monoculture was 0.899 t/ha without fertilization and 0.606 t/ha at a satisfactory nutrient supply level (mean of treatments B-E).

The greatest maize yield surplus was obtained in the *Norfolk rotation* (maize-spring barley-peas-wheat), where the maize yield average exceeded that achieved in the maize monoculture by 1.261 t/ha without fertilization and by 0.845 t/ha in fertilized treatments (Table 7).

Neither the magnitude of the yield-increasing effect of the previous crop compared to the maize monoculture nor the order of the various crop sequences was modified even in the stage of analysis when the effect of the monoculture was compared with that of 2 or 3 crop sequences simultaneously.

When the *effect of the fertilizer treatments* was compared in various crop sequences, it was found on the basis of variance analysis that the alfalfa-maize and alfalfa-maize-wheat rotations produced significantly higher yields at high NPK fertilizer rates (treatment "E"), while in treatments "B-D" there was no significant difference in the maize yields. In the Norfolk rotation the highest yield was obtained when stable manure was applied, and this was significantly better than the yield of treatment "E". By contrast, in the maize-wheat diculture the effect of stable manure was significantly smaller than that of the other fertilizer treatments.

The effect of crop sequence and fertilization on the grain yield of maize over the average of the years 1961-1995 without fertilization and at optimum nutrient supply levels is illustrated in Figure 1. It can be seen that the effect of the

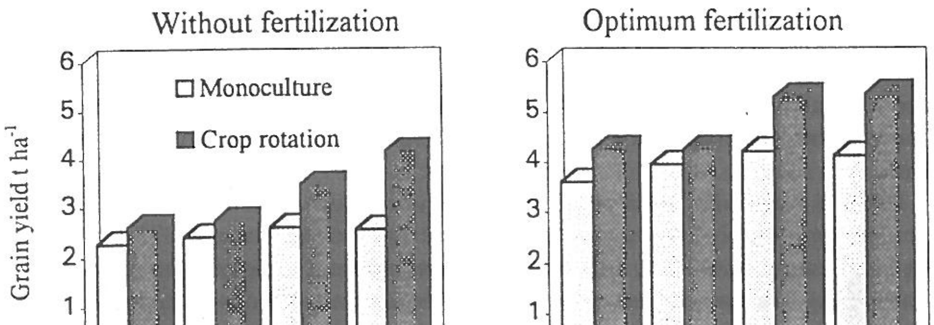

Figure 1

Effect of crop rotation and fertilization on maize grain yield (1961-1996).
WM: 2 years wheat-2 years maize; AM: 3 years alfalfa-5 years maize; AMW: 3 years alfalfa-3 years maize-2 years wheat; NF: Norfolk crop rotation

previous crop without fertilization was greatest in the Norfolk rotation, followed by the alfalfa-maize-wheat triculture and the alfalfa-maize diculture, with similar magnitudes, and by the maize-wheat diculture. Over the average of the fertilized treatments the yield-increasing effect of the previous crop was smaller, and there was a slight change in order, as the effect of the wheat-maize diculture surpassed that of the alfalfa-maize diculture.

The effect of crop sequence and fertilization on *wheat yield and yield stability* was evaluated for the data of 8, 9, 18 or 20 comparable years depending on the type of crop rotation (Tables 8 and 9).

It can be seen from the data in Table 8 that in the *2 years maize - 2 years wheat diculture* the yield without fertilization was 0.343 t/ha higher than in the wheat monoculture. Averaged over the "B-E" treatments the yield difference was 0.779 t/ha. A comparison of the main effects of the experiment shows that in the diculture, when averaged over the fertilizer treatments, the yield was 0.692 t/ha higher than in the monoculture. An examination of the fertilization systems indicates that the yield was highest in treatments with high levels of NPK fertilization and significantly the lowest in the unfertilized "A" treatment. Among treatments which received both organic material (manure or residuum) and fertilizer the yield was significantly higher in treatment "C" than in treatment "B". A slight difference was found in the wheat yields depending on whether it was grown in the first or second year after maize (0.704 vs. 0.682 t/ha).

In the *3 years alfalfa - 5 years wheat diculture* the wheat yield average was 0.33 t/ha greater without fertilization and 0.367 t/ha greater at adequate fertilizer levels (average of treatments B-E) than in wheat monoculture. A comparison of the main effects of the experiment shows that the yield in the wheat-alfalfa diculture was 0.35 t/ha greater than in the wheat monoculture. There was a difference in the effect of the crop sequence, however, depending on which year the wheat was grown after alfalfa. The yield surplus of wheat after alfalfa, averaged over treatments A-E, was 1.084 t/ha in the first year, 0.55 t/ha in the second year and only 0.055 t/ha in the 3rd-5th years compared to the wheat monoculture (the magnitude of the yield increase was similar without fertilization).

In the *3 years alfalfa - 3 years maize - 2 years wheat triculture* (Table 9) the average yield surplus compared to the wheat monoculture was 0.878 t/ha without fertilization and 1.116 t/ha with adequate nutrient supplies (mean of treatments B-E). Differences were observed in the wheat yield depending on whether it was grown in the 1st or 2nd year after maize. In the triculture the yield of wheat after maize was 1.354 t/ha greater in the 1st year and 0.78 t/ha greater in the 2nd year than in the monoculture.

The greatest wheat yield surplus was obtained in the *Norfolk rotation* (maize-spring barley-peas-wheat), where the wheat yield average exceeded that of the monoculture by 1.714 t/ha without fertilization and by 1.554 t/ha in fertilized plots (Table 9).

Table 8

Stability parameters of wheat monoculture vs. maize-wheat diculture and wheat monoculture vs. wheat-alfalfa diculture in various fertilization systems, 1961-1996

Fertilizer treatments	Yield response t/ha	CV% (1)	W^2 (2)	σ^2 (3)	YS (4)	Yield response t/ha	CV% (1)	W^2 (2)	σ^2 (3)	YS (4)
	Wheat monoculture					*Wheat monoculture*				
A	2.261	28.35	27.36	1.89**		2.403	17.75	19.04	1.15**	
B	3.246	13.64	12.85	0.82**		3.553	8.49	6.55	0.33^{NS}	+
C	3.413	10.62	8.74	0.52**		3.764	10.95	13.89	0.81**	
D	3.464	10.04	7.74	0.45**		3.825	10.78	12.27	0.70**	
E	3.584	8.82	6.95	0.39*	+	3.948	13.26	19.84	1.20**	
	Wheat-maize diculture					*Wheat-alfalfa diculture*				
A	2.604	17.13	17.14	1.14**		2.733	23.37	29.65	1.85**	
B	3.943	7.69	6.28	0.34^{NS}	+	4.000	7.91	7.86	0.41^{NS}	+
C	4.272	11.59	17.13	1.14**	+	4.095	9.77	11.87	0.68**	+
D	4.356	11.43	15.78	1.04**	+	4.221	9.11	12.44	0.72**	+
E	4.252	15.93	29.26	2.03**	+	4.242	7.64	7.88	0.41^{NS}	+
$LSD_{5\%}$	0.132					0.138				

Table 9

Stability parameters of wheat monoculture vs. alfalfa-maize-wheat triculture and wheat monoculture vs. Norfolk crop rotation in various fertilization systems, 1961-1996.

Fertilizer treatments	Yield response t/ha	CV% (1)	W^2 (2)	σ^2 (3)	YS (4)	Yield response t/ha	CV% (1)	W^2 (2)	σ^2 (3)	YS (4)
	Wheat monoculture					*Wheat monoculture*				
A	2.586	18.30	5.43	0.87**		2.422	22.57	12.79	1.42**	
B	3.770	13.50	6.31	1.03**		3.702	12.54	5.43	0.85**	
C	3.888	9.24	3.15	0.46^{NS}	+	3.727	15.59	9.04	1.43**	
D	4.128	9.35	3.84	0.59*		3.930	8.09	3.21	0.38*	
E	4.208	8.67	3.87	0.59*	+	4.073	6.72	2.41	0.27^{NS}	+
	Wheat-maize-alfalfa triculture					*Norfolk crop rotation*				
A	3.464	15.79	7.18	1.18**		4.136	12.78	9.31	1.38**	
B	4.884	11.33	7.72	1.28**	+	5.343	4.97	2.25	0.19^{NS}	+
C	5.075	5.57	5.41	0.87**	+	5.436	6.76	4.17	0.54**	+
D	5.210	7.23	3.47	0.52^{NS}	+	5.444	8.51	6.28	0.91**	+
E	5.291	6.46	3.16	0.47^{NS}	+	5.340	7.39	4.89	0.77**	+
$LSD_{5\%}$	0.221					0.149				

Significant at: ***P: 0.1% level; **P: 1% level; *P: 5% level. NS = Non-significant. (1) Variance coefficient. (2) Wricke's ecovalence index. (3) Shukla's stability variance index. (4) Kang's yield stability index.

Neither the magnitude of the yield-increasing effect of the previous crop compared to the wheat monoculture nor the order of the various rotations was modified even when the monoculture was compared with the effects of 2 or 3 crop sequences simultaneously.

When comparing the *effect of fertilization treatments* in various crop sequences, it was found on the basis of variance analysis that a significantly higher yield was obtained at high rates of NPK fertilization (treatments D-E). The joint application of organic manure and fertilizer proved efficient for wheat fertilization, though the yield level in treatment B, involving stable manuring every 4 years, was slightly lower than in treatments D and E.

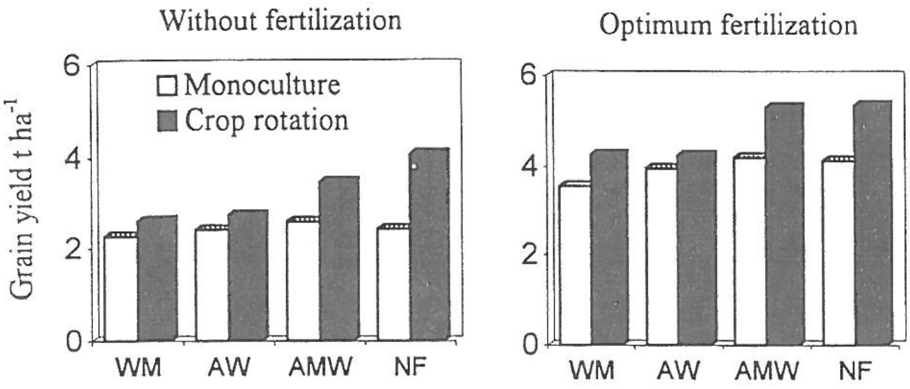

Figure 2

Effect of crop rotation and fertilization on wheat grain yield (1961-1969).
WM: 2 years wheat-2 years maize; AW: 3 years alfalfa-5 years wheat; AMW: 3 years alfalfa-3 years maize-2 years wheat; NF: Norfolk crop rotation

The effect of crop rotation and fertilization on the grain yield of wheat over the average of the years 1961-1996, without fertilization and under optimum nutrient supply conditions, is illustrated in Figure 2. It can be seen that the effect of crop rotation without fertilization was greatest in the Norfolk rotation (1.714 t/ha) followed by the alfalfa-maize-wheat triculture (0.878 t/ha), with the poorest effect for the two dicultures (0.37 and 0.34 t/ha). When averaged over the fertilizer treatments the yield-increasing effect of crop rotation remained at a similar level (there was a slight reduction for the Norfolk rotation, an increase for the triculture and the wheat-maize diculture and no change for the wheat-alfalfa diculture).

Yield stability of maize and wheat in various crop sequences at different fertilizer levels

Variance indices characteristic of the yield stability of maize were calculated for comparable years for crop rotation and monoculture for each fertilizer treatment (Tables 6-7).

Of these variance indices, the smaller the *coefficient* of *variance* (CV %), the more stable the treatment is. There was a tendency for CV % values to be higher in the maize monoculture than in the crop sequences. The highest CV % was obtained in the non-fertilized treatment (A), for both the monoculture and the crop sequences. The lowest CV % values were generally recorded in treatments B and D.

The significance level and numerical size of the stability variance index *(σ^2)* expresses the extent to which different treatments are responsible for the interaction. It can be seen that the effect of treatments B and D was not usually significant. In sequences including alfalfa the stability variance index was not significant in treatment E either.

On the basis of mean yield response and stability, the *yield stability index (YS)* elaborated by KANG (1995) selected fertilizer treatments D, E, C and B in the crop sequences and treatment D in the monoculture.

The effect of crop rotation and fertilization on maize yield stability, as shown by the *linear regression model*, is illustrated in Figure 3 for treatments A (non-fertilized) and E (optimum nutrient supplies). The effect of crop sequences and fertilizer levels in *different environments* are characterized by parallel or intersecting linear functions. In various crop sequences at the same fertilization level the points of intersection of the lines indicates the environmental average above which the crop sequence becomes superior to the monoculture. It was established from the data that for crop sequences and in fertilized treatments, if the regression coefficient *(b)* tended to have a higher value this indicated that a greater yield increase was obtained in a favourable environment.

When comparing the *wheat-maize diculture* with the maize monoculture, the diculture became superior at above 4.1 t/ha environmental average without fertilization and above 4.6 t/ha at optimum nutrient supply levels.

The superiority of the *3 years alfalfa - 5 years maize* crop sequence could be demonstrated above an environmental average of 2.3 t/ha without fertilization, and increased at higher environmental indices. With satisfactory nutrient supplies the diculture was only slightly superior, but this could be demonstrated in all environments.

The advantage of the *3 years alfalfa - 3 years maize - 2 years wheat triculture* over the maize monoculture could be observed above an environmental average of 2.9 t/ha at optimum nutrient supply levels and above 4.5 t/ha without fertilization. At high environmental averages the effect of the crop sequence increases.

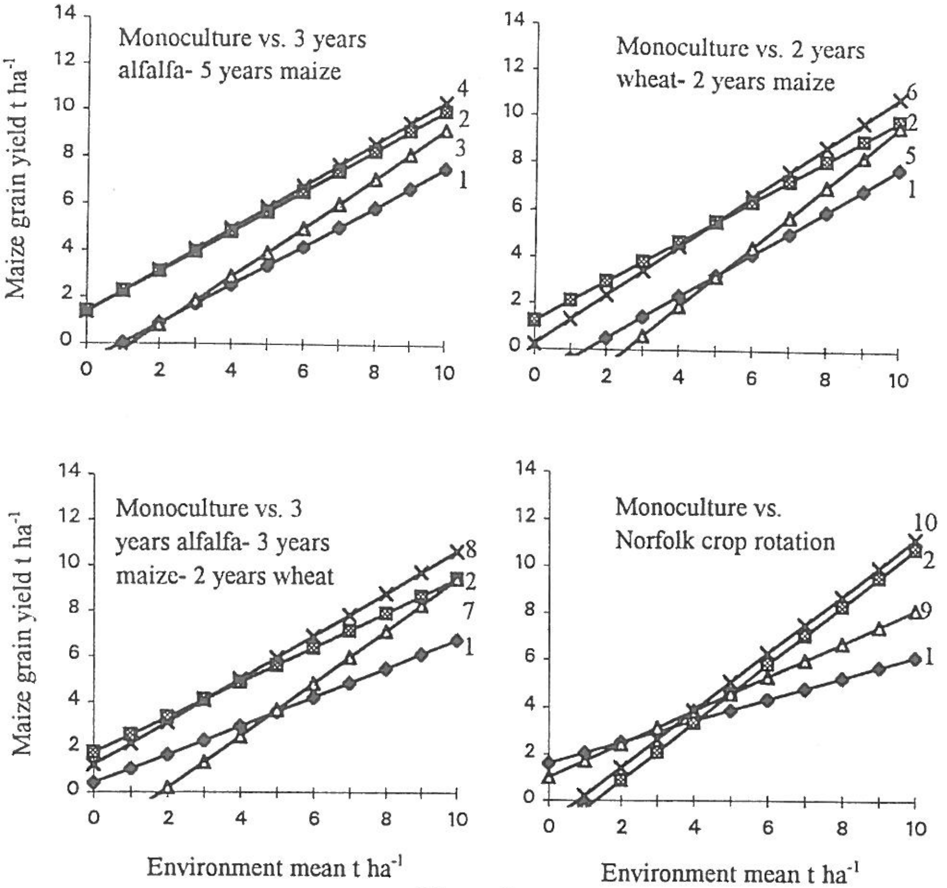

Figure 3

Maize monoculture vs. various crop rotations and the regression of the environment mean at various fertilizer levels. 1-2: maize monoculture; 3-4: 3 years alfalfa-5 years maize; 5-6: 2 years wheat-2 years maize; 7-8: 3 years alfalfa-3 years maize-2 years wheat; 9-10: Norfolk crop rotation, all at fertilizer levels A and E. Fertilizer level A: without fertilization (treatments 1, 3, 5, 7, 9), fertilizer level E: optimum nutrient supplies (treatments 2, 4, 6, 8, 10)

The *Norfolk rotation* became superior to the monoculture even at an environmental average of 1.3 t/ha without fertilization, while at optimum nutrient supply levels the advantage of the Norfolk rotation could be seen in all environments.

The variance indices characteristic of *wheat yield stability* for comparable years were calculated for crop sequences and monoculture for each fertilizer treatment (Tables 8-9). The CV % values tended to be higher in the wheat monoculture than in the crop sequences. The CV % value was greatest in the non-fertilized treatment (A) for both the monoculture and the crop rotation. The lowest CV % values were usually recorded in treatments B and E. It can also be seen from the significance level and numerical size of the stability variance indices (σ^2) that treatments B and E were usually the least responsible for the interactions.

On the basis of mean yield response and stability, the yield stability index *(YS)* defined by KANG (1993) selected fertilizer treatments E, D, C and B as the

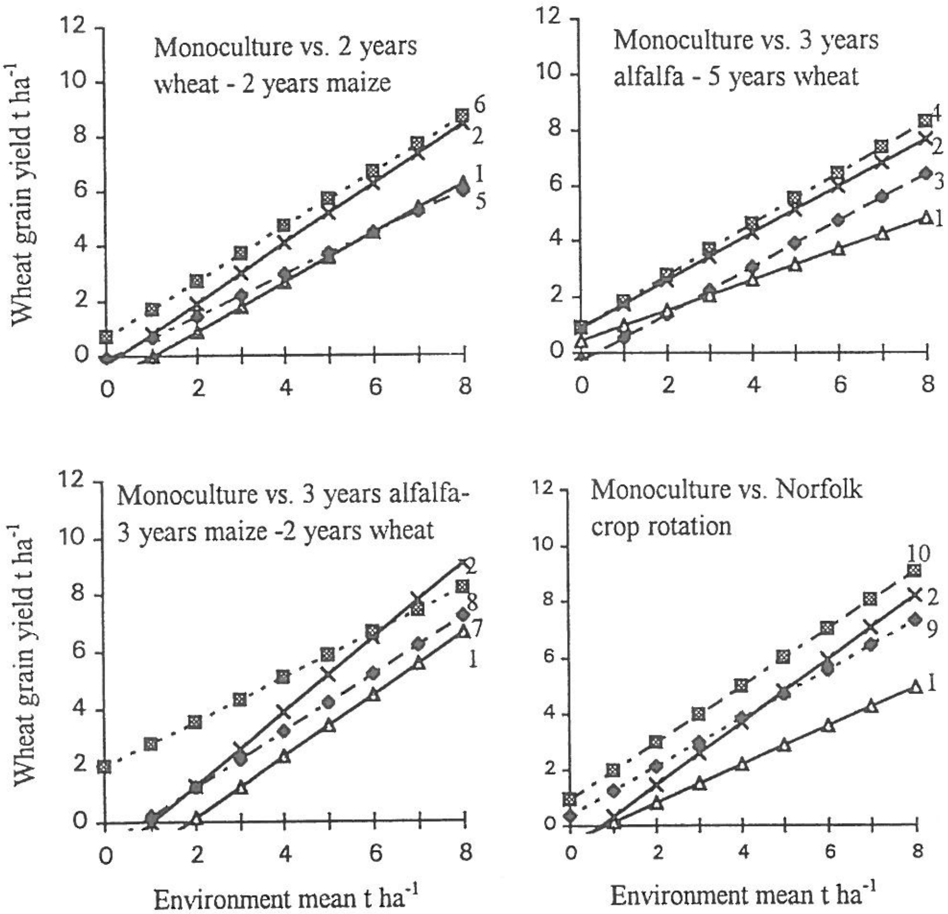

Figure 4

Wheat monoculture vs. various crop rotations and the regression of the environment mean at various fertilizer levels (1991-1996). 1-2: wheat monoculture; 3-4: 3 years alfalfa-5 years wheat; 5-6: 2 years wheat-2 years maize; 7-8: 3 years alfalfa-3 years maize-2 years wheat; 9-10: Norfolk crop rotation; all at fertilizer levels A and E. Fertilizer level A: without fertilization (treatments 1, 3, 5, 7, 9), fertilizer level E: optimum nutrient supplies (treatments 2, 4, 6, 8, 10) best treatments for crop sequences and most frequently treatment E for the monoculture.

The effect of crop rotation and fertilization on wheat yield stability, calculated using the *linear regression model*, is illustrated in Figure 4 for treatments A (non-fertilized) and E (optimum nutrient supplies). In the crop rotation and the fertilized treatments a tendency for higher values of the regression coefficient *(b)* indicates a greater extent of yield increase in a favourable environment. In various crop sequences at identical fertilization levels the points of intersection of the lines demonstrate the environmental average values above which the crop rotation becomes superior to the monoculture.

When comparing the *wheat-maize diculture* and the wheat monoculture, the diculture exhibited superiority up to an environmental average of 6.0 t/ha without fertilization and in all environments at optimum nutrient supply levels.

The superiority of the *3 years alfalfa-5 years wheat* sequence could be demonstrated above an environmental average of 2.5 t/ha without fertilization and increased at higher environmental indices. At satisfactory nutrient supply levels the diculture only exhibited a slight advantage, but this could be observed in all environments.

The advantage of the *3 years alfalfa - 3 years maize - 2 years wheat* triculture over the wheat monoculture could be characterized in the non-fertilized treatment by parallel straight lines at higher yield levels, which means that it was manifested in all environments. At optimum levels of fertilization the advantage of the triculture could be demonstrated up to an environmental average of 6.0 t/ha.

The *Norfolk rotation* (maize-spring barley-peas-wheat) was superior to the wheat monoculture at both fertilization levels in all environments. Even at fertilizer level A the Norfolk rotation surpasses the yield of the wheat monoculture at fertilizer level E up to an environmental average of 4.6 t/ha.

Conclusions

1. The yield of maize in a monoculture was always lower than in crop rotation. Larger yields were obtained in crop sequences after leguminous previous crops, and also after non-leguminous crops.

The yield-increasing effect of crop rotation was inversely proportional to the ratio of maize in the sequence. Averaged over the fertilizer treatments (A-E) the yield-increasing effect was greatest in the Norfolk rotation (0.929 t/ha), followed by the alfalfa-maize-wheat triculture (0.664 t/ha), the wheat-maize diculture (0.324 t/ha) and the alfalfa-maize diculture (0.26 t/ha). These results are in agreement with previous examinations by GYŐRFFY (1975) who found that wheat was often a better previous crop for maize than alfalfa. When employing alfalfa as a previous crop attention must be given to its effect on the water management of the soil.

2. The effect of crop rotation on the maize yield was greater without fertilization than in fertilized treatments, and in the first two years after alfalfa as previous crop than in the 3rd-5th years. The results of variance analysis show that the crop rotation effect was the greatest in the Norfolk rotation, followed by the alfalfa-maize-wheat triculture, while it was lowest in the two dicultures.

Year and crop rotation had significant effects on the fertilized treatments (B-E), though the yield differences were not great. It can be concluded from the experimental data that stable manuring and the returning of plant residues (maize stalks, wheat straw), combined with NPK supplementation, are efficient methods of nutrient replenishment in maize. Stable manuring also improved yield stability.

3. An analysis of the 35-year data of the long-term experiment leads to the conclusion that wheat yields were always lower in a monoculture than in a crop sequence. The yield-increasing effect of the crop rotation was inversely proportional to the ratio of wheat in the sequence. The greatest yield-increasing effect (in t/ha) was observed in the Norfolk rotation (1.505), followed by the alfalfa-maize-wheat triculture (1.069), the wheat-maize diculture (0.692) and the wheat-alfalfa diculture (0.35).

Compared to the wheat monoculture the yield increase in the alfalfa-wheat diculture was smaller than that in the maize-wheat diculture. This was due partly to the fact that the favourable previous crop effect of alfalfa was only perceptible in the first two years. It is also probable, however, that the yield-decreasing effect of a monoculture was also manifested more strongly after the third year of growing wheat after wheat.

Maize is a good previous crop for wheat, and this is doubly important since wheat and maize are the two major field crops in Hungarian crop production. In a maize-wheat diculture the yield of wheat was 0.692 t/ha higher than in a monoculture. In an alfalfa-maize-wheat triculture the yield increase was 1.069 t/ha compared with the wheat monoculture. Differences were also noted in the wheat yields depending on whether it was grown in the 1st or 2nd year after maize.

4. When comparing the advantages of crop sequences over a wheat monoculture in non-fertilized plots and averaged over the fertilized treatments it can be seen that the yield-increasing effect of the crop rotation was not greatly modified by fertilization. It can thus be concluded that the rotation effect was manifested in the various wheat crop sequences both without fertilization and at optimum nutrient supply levels, in contrast to the maize crop sequences, where fertilization reduced the rotation effect to almost half.

Variance analysis of the effect of fertilizer treatments in the various crop rotations indicated that a significantly higher yield was obtained at high NPK fertilizer levels (treatments D-E). The combined application of organic manure and fertilizer (treatments B-C) was an efficient way of fertilizing wheat, though the yield level in treatment B, which involved stable manuring every 4 years, was significantly lower than in treatments D and E. It can be suggested, however, that the joint application of manure and fertilizer may provide more favourable conditions for the manifestation of the rotation effect. This can be concluded from the fact that the rotation effect compared to the monoculture was consistently slightly higher in treatments B and C than in treatments D and E, which received only NPK fertilization (27.4% and 22.9% over the average of the crop sequences). Yield stability was greatest in treatments E and B.

5. In the long-term crop rotation experiment bifactorial combined variance analysis proved to be a satisfactory method for the evaluation of the main effects (year, crop rotation and fertilization) and the interactions when comparing crop sequences and monocultures.

The results show that stability analysis is a suitable method for the interpretation of the significant environment x treatment interactions observed in variance analysis models of long-term crop rotation experiments. Both the variance and regression methods of stability analysis contributed to the characterization of the stability of the experimental treatments in different environments.

Summary

In a long-term crop rotation experiment set up in 1961 the effects of 7 crop sequences and 5 fertilization treatments were studied on the yields of maize and wheat and on yield stability. The soil of the experimental area was a humous loam of the chernozem type with forest residues, slightly acidic in the ploughed layer, poorly supplied with available phosphorus and well supplied with potassium.

The crop sequences included maize and wheat monoculture, periodic monocultures, dicultures, a triculture and a Norfolk crop rotation. Apart from the control the fertilizer treatments represented various fertilization systems, namely organic manuring (stable manure or plant residues supplemented with NPK) and high levels of NPK fertilization.

The yields were evaluated with bifactorial variance analysis and with the variance and regression methods of stability analysis.

The yields of maize and wheat were lower in all cases in monoculture than in a crop sequence. The yield-increasing effect of crop rotation was inversely proportional to the ratio of maize or wheat in the sequence. Averaged over the fertilizer treatments the yield-increasing effect for both maize and wheat was greatest in the Norfolk rotation, followed by the alfalfa-maize-wheat triculture, the wheat-maize diculture, and the alfalfa-maize and alfalfa-wheat dicultures.

It can be concluded from the experimental data that stable manuring and the returning of plant residues (maize stalks, wheat straw) with NPK supplementation are efficient ways of fertilizing maize and wheat. Stable manuring also improves yield stability. A comparison of the effects of the fertilizer treatments shows that significantly higher yields of maize and wheat were obtained in the various crop sequences at high levels of NPK fertilization.

The yield-increasing effect of crop sequences compared to the wheat monoculture was not modified greatly by fertilization: the rotation effect was manifested both without fertilization and at good nutrient supply levels. By contrast, in maize crop sequences fertilization reduced the rotation effect by almost half.

Both the variance and regression methods of stability analysis contributed to the characterization of the stability of the experimental treatments in various environments.

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