

Effects of Rainfall and Fertilization on the Yield of a Winter Rye (*Secale cereale* L.) Monoculture in a Long-Term Experiment

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Introduction

Climate change is recognized as a serious environmental issue (JOHNSTON, 2000). It has repeatedly affected much or all of the Earth (LÁNG, 2005). Available evidence suggests that such changes are not only possible, but likely in the future, potentially with large impacts on ecosystems and societies (BARROW et al., 2000; NRC, 2002; RAJENDRA, 2004; MÁRTON, 2004, 2005a,b). During the 20th century the atmosphere greenhouse gases, especially CO₂, increased markedly (SZÁSZ, 2005). Nearly concurrently with this, relative global temperatures of the 19th century increased by 0.6 °C (LÁNG et al., 2004; JOLÁNKAI, 2005; VÁRALLYAY, 2005).

In the coming decades global plant production faces the prospect of a changing climate and environment, as well as the known challenge of feeding the world's population, predicted to double the present six billion by about the year 2050. The prospective climate change is global warming with associated changes in hydrological regimes and other climatic variables induced by the increasing concentration of radiatively active greenhouse gases. Climate change could have far-reaching effects on patterns of trade among nations, development, and food security. These changes (largely caused by human activities) are likely to affect crop yields differently from region to region across the globe (MÁRTON, 2005a,b; SETH & JEFFREY, 2005). A significant issue that becomes apparent from even a cursory summary of existing knowledge is that from the crop's perspective the important point is the net effect of all the environmental changes that occur, or might occur, at any given place and time.

At present, plenty of agricultural investigations focus on understanding the relation between mean climate change and crop production (VÁRALLYAY, 1992). Few investigations, however, have studied the effects of climate variability on agricultural crop yields (NÉMETH, 2004). The response of agricultural crop yields to changes in climate variability have been attributed primarily to changes in the frequency of extreme climatic events (EU, 2003). Recent studies demonstrated the greater effect of the frequency of extreme climatic events than changes in the mean

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climatic response (EM, 2004). Hence, in studying the effects of climatic change on crop production, the changes in the climatic variability and associated weather patterns should be included (BARROW et al., 2000).

Changes in weather patterns were observed throughout Europe (including Hungary) as early as 1850. Among the natural consequences of changing weather patterns, years of drought (rainfall deficit) and wet (rainfall excess) conditions, resulted in problems among plant nutrition and field crop production (EU, 2003). Whereas rye (*Secale cereale* L.) is a crop of worldwide importance, limited research has been carried out on the effects of climate change on these crops (KÁDÁR et al., 1984; MÁRTON, 2002, 2003). These crops react sensitively to the prevailing weather conditions (such as rainfall) and, for this reason, understanding the effects of anthropogenic climate change on its production bears great importance. In addition to rainfall, crops require an optimal level of soil macronutrients: nitrogen, phosphorus and potassium (KÁDÁR, 1992; KÁDÁR et al., 1984).

Most environmental research focus on only one, or very few changes instead of the concomitant multiple changes occurring in our world. Unfortunately, however, the bulk of past research has focused on one factor at a time. As a result for example, much is known about the effects of a change in a geochemical element (macro, meso, micro or trace) loading on yield of some crops, but much less information is available about the effects of a change in a geochemical element in combination with a change in rainfall quantity and distribution on the yield of those same crops. It is obviously the effects of all the environmental changes occurring, rather than just a geochemical element (or just other geochemical elements, or just rainfall quantity and distribution etc.), that is of importance to any crop. Although much of this paper focuses on single factors (rainfall quantity, rainfall distribution, N, P, K fertilization), it was our intent to emphasize that the net effect of multiple environmental changes on rye is far more important than the effect of a single factor on that crop.

So, findings are presented on interactions related to rainfall quantity, rainfall distribution changes and N, P, K fertilization effects on the yield of rye grown on a calcareous sandy soil with a low humus content in an ecologically fragile experimental site at Örbottyán in Hungary from 1961 to 2004 for 44 years.

Materials and Methods

The effect of rainfall (quantity and distribution) on crop fertilization factors, such as macronutrients and yield, were studied during a long-term (1961 to 2004) field experiment on a calcareous sandy soil with low humus content in North Hungary at the Örbottyán Experimental Station of RISSAC. In 1959, at the time the experiment was set up (LÁNG, 1973) the ploughed layer of the experimental soil could be characterized as follows: pH(H₂O): 7.5–7.8, pH(KCl) 6.9–7.1, humus content: 0.6–1.0%, clay content: ~ 5%, CaCO₃ content: 3–7%, AL (ammonium lactate) soluble P₂O₅ and K₂O content: 40–60 and 50–100 mg·kg⁻¹. The experiment in-

Table 1
 Values of the crop-specific drought index (CDI) for rye grown in monoculture during various periods of the experimental years (1961–2004)
 (Long-term fertilization experiment, calcareous sandy soil, Órbottyán)

Year	Period					
	Winter half year	Summer half year	Month (Oct.-Sept.)	Month prior to sowing (Aug.)	Vegetation period (Sept.-Jul.)	Harvesting month (July)
<i>Average years</i>						
1969	-9	-3	1	-3	1	1
1976	-1	2	1	-5	1	7
1978	-9	6	1	-6	1	6
1979	-9	-9	1	-3	1	-4
1980	9	-9	1	-5	1	-2
1981	9	-9	1	1	1	-4
1982	4	-9	1	-4	-1	1
1985	-8	9	1	5	-1	-5
1987	-1	2	1	1	-1	-6
1989	-9	9	-1	1	-1	-3
1994	-9	-3	1	3	1	-8
2001	-9	9	1	-7	2	9
Mean	-3.5	-0.4	0.9	-1.8	0.4	-0.7
<i>Dry years</i>						
1961	-9	-4	-1	-9	-1	1
1962	9	-9	-1	-9	-1	-2
1964	-9	-2	-1	1	-2	-1
1967	-1	-9	-1	-9	-1	-7
1971	-9	-6	-1	-4	-2	1
1984	-9	-7	-1	2	-3	-9
1995	-9	1	-1	6	-2	-3
Mean	-5.3	-5.1	-1.0	-3.1	-1.7	-2.9
<i>Droughty years</i>						
1968	-9	3	-1	9	-4	-2
1973	-9	-4	-1	-7	-3	-3
1974	-9	-9	-1	2	-5	-6
1983	1	-9	-1	-7	-2	-7
1986	-3	-9	-1	-5	-4	-8
1988	-7	-9	-1	-2	-4	-8
1990	-9	-9	-1	-7	-5	-6
1992	-9	-9	-1	-9	-4	-4
1993	-9	-9	-1	-9	-5	4
1996	-9	-9	-1	-6	-2	-5
1997	-9	-9	-1	-9	-3	-3
1998	-9	3	-1	-7	-2	1
2000	-9	-9	-1	-9	-4	3
2002	-9	5	-1	9	-4	-2

Table 1 cont.

Year	Period					
	Winter half year	Summer half year	Month (Oct.-Sept.)	Month prior to sowing (Aug.)	Vegetation period (Sept.-Jul.)	Harvesting month (July)
2003	-9	-9	-1	-8	-4	-1
2004	9	-9	-1	3	-5	-5
Mean	-6.8	-6.3	-1.0	-3.9	-3.8	-3.3
<i>Wet year</i>						
1991	-9	9	1	-1	2	9
<i>Very wet years</i>						
1965	9	9	1	9	5	9
1966	9	9	1	9	5	9
1972	-9	9	1	9	2	9
1975	4	-9	1	-1	4	9
1977	9	9	1	7	8	2
1999	-9	9	1	8	3	9
Mean	2.2	6.0	1.0	6.8	4.5	7.8
Grand mean	-4.5	0.6	0.2	-0.6	0.3	2.0

Remarks: Average years: Equivalent to the 30-year (1961–1990) rainfall mean at Örbottyán Experimental Station; dry year: -10 – -20%; droughty year: above -20%; wet year: +10 – +20%; very wet year: above +20%

cluded ten treatments in five replications, giving a total of 50 plots (35 m² each) arranged in a Latin square design.

From the 1st to the 25th year the fertilization rates (per hectare per year) were: 0, 50 and 100 kg N; 0 and 54 kg P₂O₅; 0 and 80 kg K₂O and their combinations. From the 26th year on these rates (per hectare per year) were 0 and 120 kg N; 0, 60 and 120 kg P₂O₅; and 0, 60 and 120 kg K₂O and their combinations in the form of 25% calcium ammonium nitrate, 18% superphosphate, 40% potassium chloride. The groundwater table was at a depth of 2–3 m below the surface.

Rainfall amounts, deviation in rainfall from the average over many years (dry year: -10 – -20%, droughty year: above -20%; wet year +10 – +20%; year with excess rainfall: above +20%) and other related data were determined based on traditional Hungarian standards (HARNOS, 1993; MÁRTON, 2004) (Tables 1 and 2), and MANOVA (Multivariate Analysis of Variance) by SPSS test (SPSS, 1988).

Table 2

Frequency of critical months following each other during the vegetation period and in the whole year between 1961–2004 (Long-term fertilization experiment, Órbottyán)

Year	Frequency		Year	Frequency	
	No. of consecutive critical months, during the			No. of consecutive critical months, during the	
	vegetation period (Sept.-July)	whole year (Oct.-Sept.)		vegetation period (Sept.-July)	whole year (Oct.-Sept.)
1961	2(-3), 2(5)	2(-3), 2(5)	1984	–	–
1962	3(9)	3(9), 2(-9)	1985	–	–
1964	–	–	1986	2(3)	2(3)
1965	2(5), 2(9)	2(5), 3(9)	1987	2(-6)	2(-6)
1966	–	2(9)	1988	2(-6)	2(-6)
1967	2(6)	2(6)	1989	2(-8)	2(-8)
1968	–	–	1990	–	–
1969	–	–	1991	–	–
1971	2(-8)	2(-8)	1992	2(-4)	2(-4), 2(-9)
1972	2(9)	2(9), 2(9)	1993	2(-9)	2(-9)
1973	–	–	1994	–	–
1974	–	–	1995	–	–
1975	2(-9)	2(-9)	1996	–	–
1976	–	–	1997	2(-6), 2(-9)	2(-6), 2(-9)
1977	2(9), 4(9), 2(2)	2(9), 4(9), 2(2)	1998	2(-9), 2(9)	2(-9), 2(9)
1978	–	–	1999	2(9)	2(9)
1979	2(6)	2(6)	2000	2(-9)	2(-9)
1980	2(3), 2(-2)	2(3), 2(-2), 2(-5)	2001	2(-9), 3(9)	2(-9), 3(9)
1981	2(9)	2(9)	2002	–	–
1982	2(6)	2(6)	2003	2(3)	2(3)
1983	2(-2)	2(-2), 2(-7)	2004	–	–
1961	2(-3), 2(5)	2(-3), 2(5)	1984	–	–

Results and Discussion

In *average years* the yield in the control plots stabilized at around $0.8 \text{ t}\cdot\text{ha}^{-1}$ (Table 3). The yield doubled ($1.8\text{--}1.9 \text{ t}\cdot\text{ha}^{-1}$) in the N, NP and NK treatments, while the full NPK doses gave the maximum yield of $2.1 \text{ t}\cdot\text{ha}^{-1}$.

In *dry years* yields of $0.7 \text{ t}\cdot\text{ha}^{-1}$ were harvested in the control plots. This was a 13% yield reduction as compared to the many years' mean. Yield depressions of 33, 16, 21 and 20% were caused by drought in the N, NP, NK and NPK treatments.

In *wet years* the yield was little more than $0.5 \text{ t}\cdot\text{ha}^{-1}$ ($0.6 \text{ t}\cdot\text{ha}^{-1}$) in the control plots, representing a yield loss of 25%, compared with average years. The N, NP, NK and NPK treatments led to yield depressions of 28, 26, 26 and 26%. Rye grown in a monoculture has approx. 5% less tolerance to wet years than to drought.

Table 3
Effect of mineral fertilization on the yield ($t \cdot ha^{-1}$) of winter rye (*Secale cereale* L.) grown in monoculture in average, dry, droughty, wet and very wet years between 1961 and 2004 (Long-term fertilization experiment, calcareous sandy soil, Örbottyán)

Year	Treatment									LSD _{5%}	Mean
	0	NP ₁	NP ₂	NK ₁	NK ₂	NP ₁ K ₁	NP ₁ K ₂	NP ₂ K ₁	NP ₂ K ₂		
	1.	2.-3.	4.	5.	6.	7.	8.	9.	10.		
<i>Average years</i>											
1969	0.6	0.8	0.9	0.8	0.8	1.1	1.3	1.4	1.6	0.3	1.0
1976	0.6	0.7	0.4	0.4	0.4	1.2	1.1	1.1	1.1	0.2	0.8
1978	0.7	0.7	0.7	0.6	0.7	1.9	1.5	1.9	1.7	0.2	1.2
1979	0.5	0.5	0.4	0.4	0.4	1.0	0.8	0.9	0.9	0.3	0.6
1980	1.1	2.6	2.5	1.5	1.6	3.0	2.9	3.1	2.9	0.5	2.4
1981	0.5	1.8	1.8	1.0	1.0	1.9	1.9	2.0	1.9	0.2	1.5
1982	0.9	1.5	1.5	0.7	1.7	1.7	1.5	1.6	1.6	0.3	1.4
1985	0.6	1.8	2.1	0.8	1.5	1.7	2.0	2.2	2.3	0.4	1.7
1987	0.7	1.8	2.0	0.9	1.0	1.9	2.0	2.0	2.0	0.6	1.6
1989	1.3	2.9	2.8	2.4	2.4	3.3	3.5	3.2	3.4	0.8	2.8
1994	0.8	2.3	2.6	1.9	2.0	2.6	2.9	2.9	2.6	0.7	2.3
2001	0.9	1.9	1.9	1.4	1.4	2.1	2.1	2.2	2.3	0.5	1.8
LSD _{5%}	0.4									–	0.4
Mean	0.8	1.6	1.7	1.2	1.3	2.1	2.1	2.1	2.1	0.4	1.7
<i>Dry years</i>											
1961	0.6	1.0	1.2	1.7	1.5	1.4	1.2	2.1	1.6	0.2	1.4
1962	0.6	0.6	0.8	0.8	0.9	0.7	1.1	1.1	1.5	0.2	0.9
1964	0.6	0.8	1.0	0.9	0.9	1.1	1.2	1.4	1.3	0.6	1.0
1967	0.6	0.8	1.2	1.3	1.3	1.1	1.6	1.9	2.1	0.2	1.3
1971	0.8	1.0	1.5	1.3	1.9	1.5	2.3	2.2	2.4	0.4	1.7
1984	1.6	3.9	3.8	2.1	2.5	3.4	4.2	3.6	3.6	0.8	3.2
1995	1.3	2.4	2.2	1.8	1.9	2.7	2.6	2.8	2.7	0.5	2.3
LSD _{5%}	0.4									–	0.4
Mean	0.8	1.5	1.7	1.4	1.6	1.7	2.0	2.2	2.2	0.4	1.7
<i>Droughty years</i>											
1968	0.5	0.9	0.9	0.8	0.7	1.5	1.2	1.5	1.5	0.2	1.1
1973	0.9	1.4	1.4	1.4	1.5	2.0	1.7	1.9	2.1	0.3	1.6
1974	0.7	0.6	0.5	0.5	0.6	1.0	1.1	1.2	1.3	0.2	0.8
1983	1.5	2.7	2.9	2.3	2.7	3.1	3.0	3.2	3.2	0.5	2.7
1986	0.9	1.8	2.0	1.4	1.4	1.7	2.0	2.0	2.1	0.3	1.7
1988	1.3	3.0	3.1	2.4	2.6	3.3	3.5	3.5	3.4	0.6	2.9
1990	0.7	1.5	1.8	1.3	1.1	1.8	2.0	1.9	2.3	0.6	1.6
1992	1.1	1.9	2.0	1.5	1.5	2.2	2.2	2.2	2.3	0.4	1.9
1993	0.5	0.6	0.7	0.3	0.4	0.8	0.8	0.8	0.9	0.7	0.6
1996	0.7	1.2	1.2	1.0	1.1	1.3	1.2	1.2	1.3	0.3	1.1
1997	0.9	1.6	1.6	1.5	1.6	2.0	2.0	2.0	2.1	0.5	1.7
1998	0.6	1.0	1.1	1.0	0.9	1.5	1.6	1.5	1.8	0.4	1.2
2000	0.5	0.9	0.9	0.6	0.7	0.8	0.9	1.0	1.1	0.3	0.8
2002	0.2	0.3	0.3	0.3	0.2	0.5	0.5	0.5	0.5	0.2	0.4

Table 3 cont.

Year	Treatment									LSD _{5%}	Mean
	0	NP ₁	NP ₂	NK ₁	NK ₂	NP ₁ K ₁	NP ₁ K ₂	NP ₂ K ₁	NP ₂ K ₂		
	1.	2.-3.	4.	5.	6.	7.	8.	9.	10.		
2003	0.6	1.2	1.4	0.6	0.7	1.4	1.2	1.3	1.3	0.3	1.1
2004	0.4	0.7	1.0	0.6	0.7	1.0	1.4	1.0	1.4	0.4	0.9
LSD _{5%}	0.4									–	0.4
Mean	0.7	1.3	1.4	1.1	1.2	1.6	1.6	1.7	1.8	0.4	1.4
<i>Wet years</i>											
1991	0.9	2.5	2.7	1.6	1.5	2.6	2.9	3.1	2.9	0.7	2.3
LSD _{5%}	0.7									–	–
Mean	0.9	2.5	2.7	1.6	1.5	2.6	2.9	3.1	2.9	0.7	2.3
<i>Very wet years</i>											
1965	0.6	0.7	1.8	1.6	2.3	0.8	2.1	2.3	3.0	0.2	1.7
1966	0.6	0.7	1.1	0.9	0.9	0.7	1.5	1.7	1.7	0.1	1.1
1972	0.9	1.5	1.5	1.3	1.5	2.5	2.2	2.2	2.5	0.2	1.8
1975	0.3	0.2	0.4	0.2	0.5	0.4	0.7	1.2	1.3	0.3	0.6
1977	0.6	0.6	0.6	0.6	0.5	0.9	1.0	1.2	1.4	0.2	0.8
1999	0.6	1.1	1.1	0.9	0.9	1.5	1.4	1.5	1.3	0.4	1.1
LSD _{5%}	0.2									–	0.2
Mean	0.6	0.8	1.1	0.9	1.1	1.1	1.5	1.7	1.9	0.2	1.2

Remarks: Average years: Equivalent to the 30-year (1961–1990) rainfall mean at Örbottyán Experimental Station; dry year: -10 – -20%; droughty year: above -20%; wet year: +10 – +20%; very wet year: above +20%; For treatments: See Materials and Methods

Depending on the nutrient supplies, significant quadratic correlations were established between rainfall quantity and yield (0: $R=0.7489^{***}$, N: $R=0.8974^{***}$, NP: $R=0.8020^{***}$, NK: $R=0.7370^{***}$, NPK: $R=0.9047^{***}$, mean $R^2=0.8180$; 66.9%) during the vegetation period.

The increase in grain yield per mm rainfall ranged from 3.0 to 6.4 kg·ha⁻¹ in the case of optimum rainfall supplies, while the quantity of rainfall during the vegetation period required for the production of 1 kg air-dry yield ranged between 1529 and 3360 litres in the case of maximum yield.

Based on the meteorological database for the 44 years of the long-term experiment (1961–2004) the frequency of years in which the rainfall was optimum for various levels of nutrient supply was as follows: control: 2%, N: 7%, NP: 7%, NK: 9%, NPK: 7%, giving an average of 6% over the treatments. This suggests that the occurrence of optimum rainfall supplies and the possibility of achieving optimum yields in a rye monoculture will decline in the future.

The yield average of rye grown in a monoculture on calcareous sandy soil (Örbottyán) was 86% less than that achieved in a biculture on acidic sandy soil (Nyírlugos) under similar fertilization and rainfall conditions.

The results show that rye production is totally (66.9%) dependent on rainfall and fertilization changes.

Summary

The effect of rainfall on crop fertilization factors, such as macronutrients and yield, were studied during a long-term field experiment on a calcareous sandy soil with low humus content in North Hungary at the Örbottyán Experimental Station of RISSAC from 1961 to 2004. At the time of the set-up of the experiment, in 1959, the soil's ploughed layer had the following characteristics: pH(H₂O): 7.5–7.8, pH(KCl) 6.9–7.1, humus content: 0.6–1.0%, clay content: ~ 5%, CaCO₃ content: 3–7%, AL soluble P₂O₅ and K₂O content: 40–60 and 50–100 mg·kg⁻¹. The experiment included ten treatments in five replications, giving a total of 50 plots (35 m² each) arranged in a Latin square design. From the 1st to the 25th year the fertilization rates were 0, 50 and 100 kg N·ha⁻¹·year⁻¹; 0 and 54 kg P₂O₅·ha⁻¹·year⁻¹; 0 and 80 kg K₂O·ha⁻¹·year⁻¹ and their combinations. From the 26th year on these rates were 0 and 120 kg N·ha⁻¹·year⁻¹; 0, 60 and 120 kg P₂O₅·ha⁻¹·year⁻¹; and 0, 60 and 120 kg K₂O·ha⁻¹·year⁻¹ and their combinations. The major findings can be summarized as follows:

In *average years* the yield in the control plots stabilized at around 0.8 t·ha⁻¹. The yield doubled (1.8–1.9 t·ha⁻¹) in the N, NP and NK treatments, while the full NPK doses gave the maximum yield of 2.1 t·ha⁻¹. In *dry years* 0.7 t·ha⁻¹ yields were harvested in the control plots. This meant a 13% yield reduction as compared to the many years' mean. Yield depressions of 33, 16, 21 and 20% were caused by *drought* in the N, NP, NK and NPK treatments. In *wet years* the yield was little more than 0.5 t·ha⁻¹ (0.6 t·ha⁻¹) in the control plots, representing a yield loss of 25% in comparison to average years. The N, NP, NK and NPK treatments led to yield depressions of 28, 26, 26 and 26%. Rye grown in a monoculture has approx. 5% less tolerance to wet years than to drought. Depending on the nutrient supplies, significant quadratic correlations were observed between the rainfall quantity and the yield (Control: R=0.7489***, N: R=0.8974***, NP: R=0.8020***, NK: R=0.7370***, NPK: R=0.9047***, mean R²=0.8180; 66.9%) during the vegetation period. The increase in grain yield per mm rainfall ranged from 3.0 to 6.4 kg·ha⁻¹ in the case of optimum rainfall supplies, while the quantity of rainfall during the vegetation period required for the production of 1 kg air-dry yield ranged from 1529 to 3360 litres in the case of maximum yield. Based on the meteorological database for the 44 years of the long-term experiment (1961–2004) the frequency of years in which the rainfall was optimum for various levels of nutrient supply was as follows: control: 2%, N: 7%, NP: 7%, NK: 9%, NPK: 7%, giving an average of 6% over the treatments. This suggests that the occurrence of optimum rainfall supplies and the possibility of achieving optimum yields in a rye monoculture will decline in the future. The yield average of rye grown in a monoculture on calcareous sandy soil (Örbottyán) was 86% less than that achieved in a biculture on acidic sandy soil (Nyírlugos) under similar fertilization and rainfall conditions. These results show that rye production is totally (66.9%) dependent on rainfall and fertilization changes.

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Key words: rye, monoculture, rainfall, fertilization, yield

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