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Impact of climate changes on crop yields of winter rye in Halle (southeastern Germany), 1901 to 1980

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ABSTRACT: This study attempts to answer the question whether observed recent climatic changes have had an impact on the crop yields of winter rye in this century, using grain yields from a long-term fertilization experiment in Halle (southeastern Germany). Using the statistical method of factor analysis it was possible to show that the long-term yield variations in Halle were associated with recent climate changes (i.e. on a time scale from years to decades) between 1901 and 1980. During this period annual climate fluctuations from October (sowing) to August (harvest) were significantly correlated with crop yields. A clear difference between years with high and low yields was discernible with respect to the corresponding annual climatic anomalies. Generally it was easier to explain high yields than low ones, because there are various possible reasons for low yields. The results of this study show that relatively small climate changes in this century have affected crop yields; it is therefore probable that the expected climate change due to the increase of trace gases in the atmosphere will have a substantial impact on crops and therefore on agriculture, unless new crop varieties become available which are well adapted to the new climatic situation.

INTRODUCTION

An essential quality of climate is its variability. Climate variations occur over a wide range of scales, from inter-annual fluctuations (here called 'climate fluctuations') to recent variations ('recent climate changes') to historical climate changes. The latter type of variation has significantly altered flora and fauna, e.g. the marked climate changes during the Pleistocene and in the Holocene warm phase led to successions of forest belts (Bolin 1980).

Recent climate changes occur over a time scale from years to decades. They are clearly discernible in time series of air temperature, as well as for other meteorological variables. The amplitude of these variations is rather modest and differs among regions, seasons and months (Grabau 1985, Kleber 1985). However, such small changes can also influence vegetation.

The beginning, end and length of the growing season are associated with temperature. According to Flohn (1985), a change in global yearly mean air temperature by only 1 °K is tantamount to a lengthening or shortening of the growing season in high latitudes by about 3 or 4 wk. This could be important for the profitability of agriculture in these regions; for example, crop yields in Finland approximately doubled during the warmest decade in this century, and those in Iceland were about 4 times above average during the warmest 10 years since 1939 (Parry et al. 1988). A decrease in rainfall may adversely affect yields, especially in the semi-arid tropics. During 1910 to 1914, 1940 to 1945 and 1968 to 1984 in the Sahel region there was either no rain or so little that crops could not be harvested in some areas. The northern border of the Sahara (Morocco, Tunisia, Algeria) has also been subjected to periods of drought in the last decade (Anhuf 1989).

Recent climate changes are also reflected in phenological events. In connection with climate variations, Rudloff (1967) showed that periodic spring phases in Austria were premature from 1946 to 1952, leading to frequent warmer and drier springs. Keil & Schnelle (1981) found a good correspondence between annual temperature variations and the opening of chestnut-tree leaves.

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In the present study I show that long-term crop variations of winter rye in Halle (southeastern Germany; ca 51° 30' N, 12° 00' E) are related to recent climate changes.

DATA

Crop yields. For impact studies such as this, observations from long-term yield experiments should be used. Such an experiment was established in Halle by Julius Kühn in 1878; its original aim was to demonstrate how different types of fertilization affected soil fertility and winter rye crop yields. This experiment, like similar studies in England (Rothamsted) and Denmark (Askov), was undertaken because of the growing interest in the use of mineral fertilizers. The Halle experiment was started using 5 different plots: (1) farmyard manure (ST1), (2) mineral fertilization (NPK), (3) N fertilization, (4) PK fertilization, and (5) unmanured.

For the present study only crops with sufficient fertilization were of interest; thus, results for Plots 3 to 5 were not used. Fig. 1 shows the yields of winter rye for Plots ST1 and NPK from 1880 to 1988. The 2 time series are significantly correlated with each other and exhibit the same long-term yield variations, despite the different fertilizer used. Therefore it appears as though these variations could be the result of climate changes. The most important features in Fig. 1 are the low yield level around 1920, a higher level between 1925 and 1940, and an increase in yields since 1945, with 2 peaks around 1950 and 1970.

For the analyses described below, only the grain yields from Plot 1 (the standard plot in the experiment) were used. Table 1 summarizes the experiment in this plot. The increasing C content of the soil hardly influenced yields, and the negative effects of monoculture were compensated for by new varieties (Garz 1979); further details about this experiment are given in Kühn (1901), Roemer & Ihle (1925), Schmalfuss (1950), Merker (1956), Müller & Reiher (1966), Rauhe & Lehne (1966), Kolbe & Stumpe (1969), and Stumpe & Hagedorn (1979).

It is interesting that both the highest and lowest yields occurred in the most recent part of the record (Table 1). This could have been due to a greater sensitivity of the newer varieties to climate fluctuations in Halle. In the meteorological time series, however, increasing climate variability is not discernible.

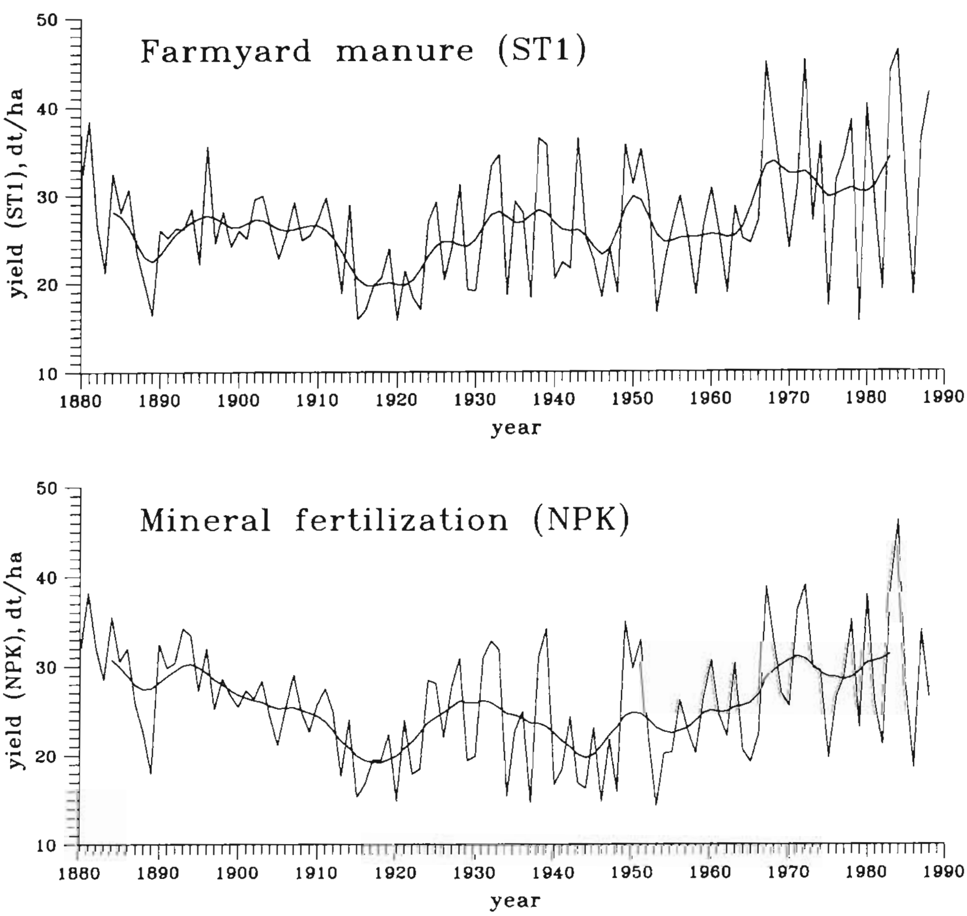

Fig. 1. Grain yields of winter rye in Halle, 1880 to 1988, for 2 kinds of fertilization. Annual yields and 11 yr running means are shown

Table 1. Details of the long-term fertilization experiment in Halle (Plot ST1, farmyard manure); 1 dt = 100 kg

Crop:	Winter rye
Experiment began:	1878 (first sowing)
Soil:	Loamy sand
Annual fertilization:	12000 kg farmyard manure ha^{-1}
Soil C content[a]:	1878: 1.24 %
	1929: 1.64 %
	1949: 1.66 %
	1953: 1.68 %
	1958: 1.69 %
Varieties[b]:	1878–1921: Saaleroggen
	1922–1952: Petkuser
	1953–1971: Petkuser Normalstroh
	1972–1974: Danae
	1975–1981: Dankowskie Zlote
	1982–1986: Janos
	1987–present: Pluto
Mean grain yield, 1879–1988:	26.9 dt ha^{-1}
Standard deviation:	7.0 dt ha^{-1}
Highest yield, 1984:	46.2 dt ha^{-1}
Lowest yield, 1979:	15.6 dt ha^{-1}

[a] According to Schmalfuss (1950) and Garz (1979)
[b] According to Müller & Reiher (1966) and Stumpe (1988 pers. comm.)

Table 2. Meteorological variables (M_i) used in this study (daily observations)

i	M_i	Abbreviation
1	Max. air temperature	T_{max}
2	Min. air temperature	T_{min}
3	Average relative humidity	H_r
4	Total precipitation	PP
5	Average cloudiness	Cl
6	Average duration of sunshine	D_s

Previous weather/yield studies for this site have been conducted by Holdefleiss (1929) and Mäde (1975). Holdefleiss (1925) used grain yields from Plot NPK from 1900 to 1924 for his investigations. He was able to show that a relatively dry period from January to March during these years supported high yields. The study by Mäde was more extensive and involved grain yields in Plot ST1 from 1900 to 1939. On the basis of correlation analysis he selected meteorological input parameters (primarily temperature and precipitation values) for a multiple regression analysis. With this regression equation it was possible to explain 80 % of the annual yield variance. Interestingly, in the equation from February to March temperature was determining, while from May onwards the influence of precipitation was dominant.

Meteorological observations in Halle. Daily meteorological observations made by the German Federal Weather Service from 1900 to 1980 were used for this survey. The weather station is not far from the experimental site. The variables used are given in Table 2; for this study the daily observations were summed or averaged to yield data for months and decades (periods of 10 d).

METHODS

To a certain extent, yearly crop yields depend on annual weather conditions from sowing (October) to harvest (August). These conditions vary somewhat from year to year, representing annual climate fluctuations. However, recent climate change is superimposed on these annual fluctuations, so that meteorological parameters also display long-term variations. Fig. 2 shows the long-term variations in seasonal temperature and precipitation in Halle from 1885 to 1950. The most important features with respect to temperature variations are the warming in summer and autumn between 1930 and 1950. This warming is also discernible in time series of surface air temperature in the Northern Hemisphere, and is probably a response to increasing atmospheric transparency from 1920 to 1960 (Pitovranov et al. 1984). Precipitation shows high variability in all seasons, but is amplified in summer by convection. Between 1940 and 1960 summer precipitation was higher. One aim of the present study was to show that long-term yield variations were associated with these climate changes.

On the other hand, the influence of meteorological variables on crops is not the same for different developmental stages. For instance, temperature or precipitation may be correlated positively with yield at one stage and negatively at another (Chmielewski 1989a). Thus, yearly crop yields depend on annual climate fluctuations in a complex way.

Therefore a complex statistical method is necessary to describe the observed crop variations in Halle during this century. In this study factor analysis was applied. This method attempts to simplify complex and diverse relationships existing among a set of observed variables, by revealing common dimensions or factors that link seemingly unrelated variables; consequently, it provides insight into the underlying structure of the data (Dillon & Goldstein 1985). A summary of the individual steps in this method is given in Fig. 3. The final step (special transformation) is described in Jahn & Vahle (1970).

Usually factor loadings represent the ordinary correlation between a variable and a factor. After the special transformation it is possible to determine the extent of the connections between the in-

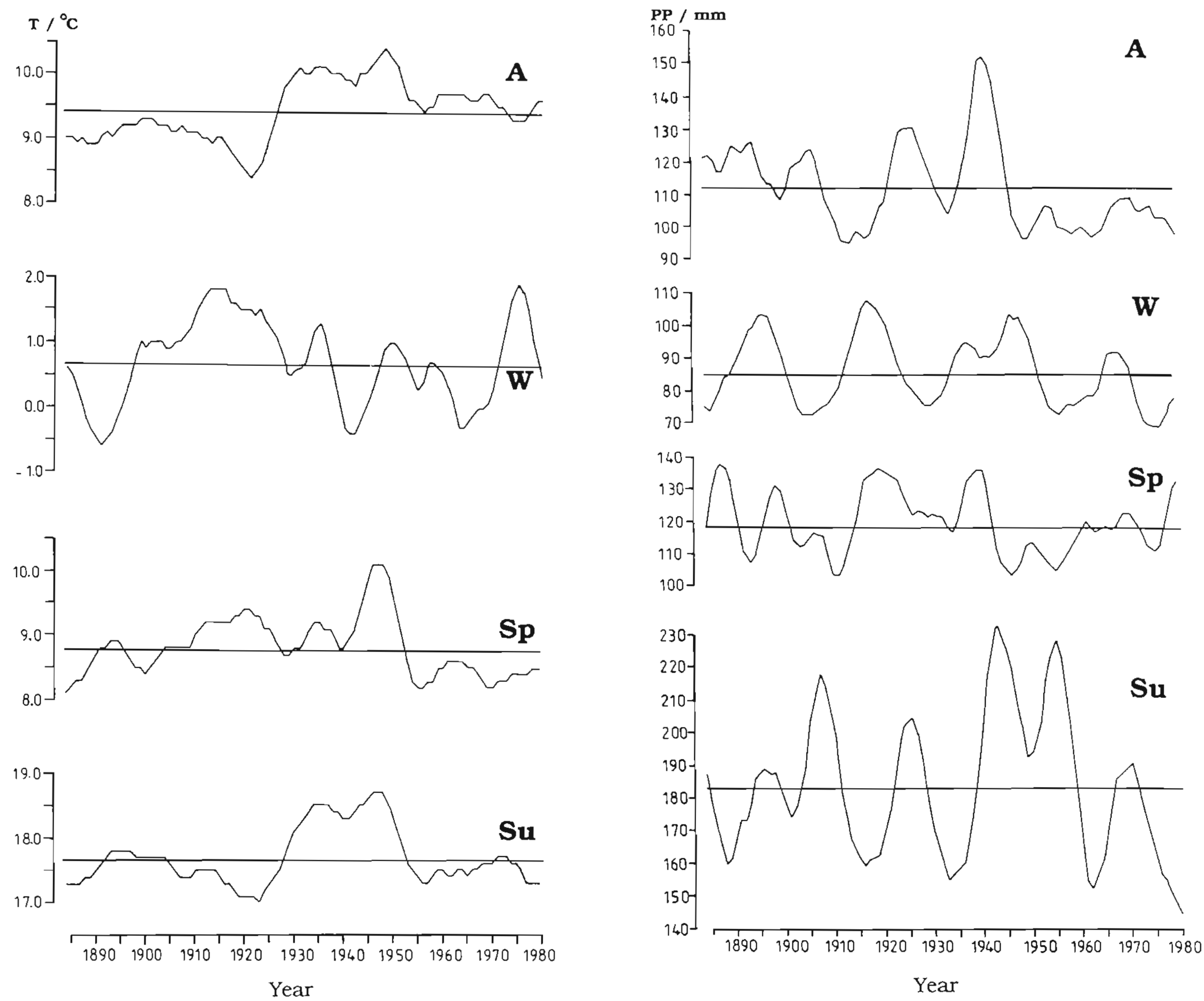

Fig. 2. Average seasonal air temperatures (T) and total precipitation (PP) from 1885 to 1980 in Halle (11 yr running means). A: Autumn (Sep, Oct, Nov); W: winter (Dec, Jan, Feb); Sp: spring (Mar, Apr, May); Su: summer (Jun, Jul, Aug)

dependent variables and the dependent variable (in this case the grain yield). The independent variable with the highest loading has the greatest influence on the dependent variable. Additional information about this method is given in Überla (1971) and Weber (1974).

An advantage of factor analysis is that it allows within-year variability and any number of independent meteorological variables to be collapsed into a single 'climate index' (here termed standardized climate fluctuations). Thus, it enables comparison of climate changes with long-term yield variations. One disadvantage of this method, however, is that the calculated climate index is difficult to interpret.

RESULTS

Influence of climate changes on crop yields

To determine the influence of climate variations on crop yields in Halle (Plot ST1), factor analysis was used twice.

In the first step, the analysis was carried out for every month from October to August. The input parameters for the statistical procedure were the annual grain yield (Y) and the set of selected meteorological variables between 1900 and 1980 (Table 2). Four factors were extracted for every month, with an average common variance of 71.1 % (SD = 3.1 %). Table 3a shows the rotated loadings

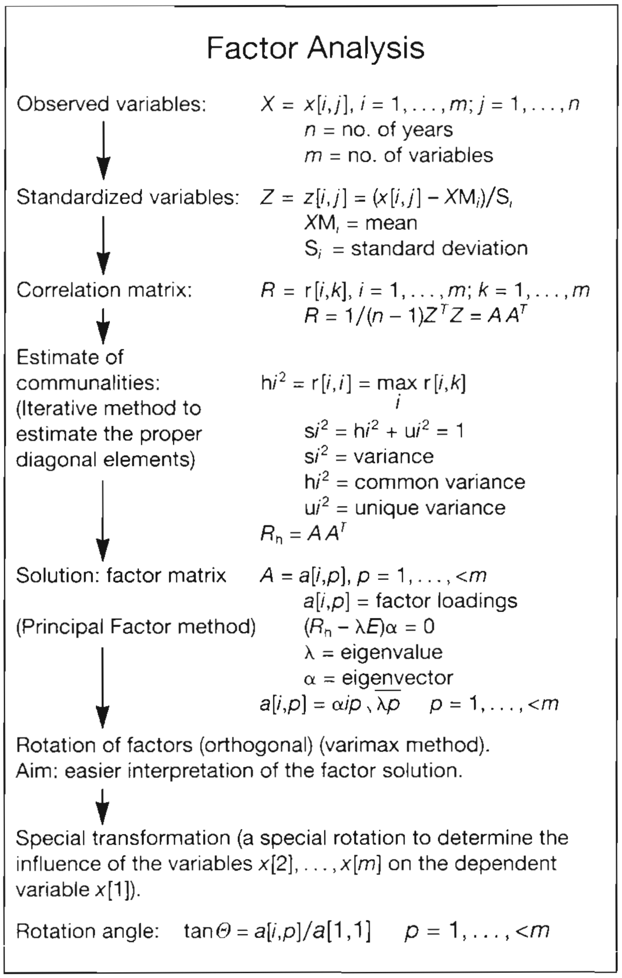

Fig. 3. Steps in factor analysis

after the special transformation. The loadings in bold print are significant ($p < 0.05$) and describe the influence of each meteorological variable on the yield.

Generally the temperature loadings are negative from April through June and positive during other months. In addition, precipitation showed a moderately positive influence on crops only in May, June and August. Higher temperatures from April to June lead to a reduced duration of developmental stages and thus probably to lower crop yields; furthermore, important developmental stages of winter rye occur during May and June (see below). During this period a sufficient water supply is important for plant development. These findings were also partly established in the previous studies at this site (Holdefleiss 1929, Mäde 1975).

The months October (sowing and emergence), January (main winter stage), May and June (shooting, ear formation, full bloom) have the highest loadings for the dependent variable (Table 3a, first row).

Altogether the effect of weather conditions in each individual month is small, i.e. the variance in annual yields is explainable only by the variability in meteorological parameters over all months. Therefore factor analysis was applied a second time for all months. This time the input variables were the time series of the specially transformed components [$PC_j(t)$] from October to August which are received in the first step for every month.

$$PC_j(t) = \sum_{i=1}^{6} M_i(t)\, a_i^{\bullet} \quad (1)$$

where j = 1,...,11 (months); M_i = meteorological variables (i = 1 to 6); and $a_i^{\bullet}$ = factor loadings after special transformation. Table 3b shows the factor loadings after this calculation. The loading of the yield variable (Y, 0.81) indicates that 66 % of the annual yield variability is associated with monthly climate fluctuations.

The influence of each month on the yields is slightly different, with values ranging from 0.19 (November) to 0.42 (October). Here as well the highest loadings were

Table 3. Factor loadings after special transformation in 2 steps of factor analysis: (a) Step 1, $a_i^{\bullet}$; (b) Step 2, $a_j^{\bullet}$. Values in **bold** print are significant ($p < 0.05$); highest loadings are underlined

(a)	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Y	**0.59**	**0.36**	**0.44**	**0.54**	**0.45**	**0.49**	**0.40**	**0.55**	**0.55**	**0.41**	**0.41**
T_{max}	**0.64**	**0.41**	0.05	0.11	**0.30**	**0.24**	−0.23	**−0.55**	−0.21	0.17	**0.32**
T_{min}	**0.41**	**0.30**	0.14	0.20	**0.39**	0.14	**−0.37**	**−0.45**	−0.16	0.03	**0.34**
H_r	−0.07	−0.04	−0.02	**0.34**	−0.06	**−0.49**	−0.12	**0.37**	**0.54**	**0.24**	0.07
PP	−0.21	**−0.25**	**−0.34**	**−0.32**	**−0.27**	**−0.24**	−0.20	0.07	0.20	−0.11	0.06
Cl	**−0.44**	**−0.33**	0.04	**0.33**	0.07	**−0.35**	0.10	**0.31**	**0.34**	0.04	−0.07
D_s	**0.42**	0.18	**−0.24**	**−0.43**	−0.07	0.20	−0.20	**−0.42**	**−0.35**	−0.09	−0.16

(b) Y	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
0.81	**0.42**	0.19	**0.34**	**0.38**	**0.30**	0.24	0.20	**0.37**	**0.36**	**0.33**	0.22

found for October, the winter, and May, June and July. The high loadings in the winter months (December, January, February) could reflect the negative influence of strong winters on the yields.

The calculated time series of components for standardized climate fluctuations [CF(t)] are given in Fig. 4. These data represent the monthly weighted climate variables from October to August according to their influence on the grain yields:

$$CF(t) = \sum_{j=1}^{11} PC_j(t)\, a_j^{*} \qquad (2)$$

There was a good correspondence between the yearly yields (Fig. 1) and the standardized climate fluctuations. The long-term variations in both time series (deep-pass filtered) were also similar (Fig. 5). As with the crop yields, long-term values of CF(t) display a minimum around 1920, a higher level between 1925 and 1940, and an additional increase since about 1945. The 2 maxima in the 1950s and 1970s are also discernible. The course of the time series suggests that the observed long-term variations in crop yields in Halle are probably caused by climate changes.

Fig. 6 shows the regression of annual grain yields vs calculated climate fluctuations. The correlation coefficient between these data series is 0.64. The statistical connection between both parameters was approximated both by a linear regression (Fig. 6) and a polynomial estimation (Fig. 7). The root mean square error (RMSE) was somewhat smaller for the latter (linear regression: RMSE = 5.25; 2nd degree polynomial: RMSE = 5.11).

In Fig. 6 it can also be seen that the average yields from 1901 to 1980 (26.3 dt ha^{-1}) are accompanied by a mean climate fluctuation of 0.0, which means that the calculated statistical equations describes the mean climate/crop connection for this period.

Climate anomalies in years with high and low yields

In Figs. 6 & 7 the high and low yields are indicated by filled circles [high yields are defined here as crops above the 75 % quantile (31 dt ha^{-1},1901 to 1980) and low yields as crops below the 25 % quantile (21.7 dt ha^{-1} in the same period)]. The average yield between these 2 groups was significantly different (Table 4).

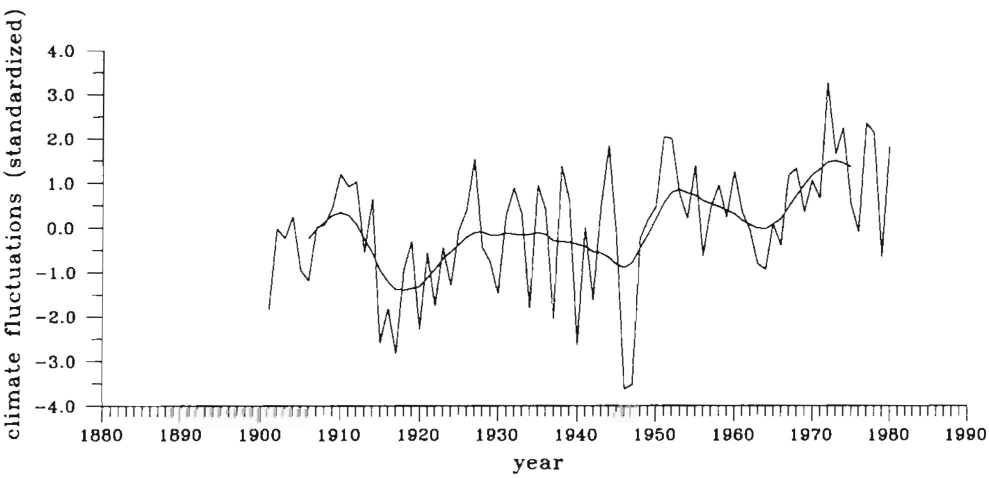

Fig. 4. Time series of components for standardized climate fluctuations in Halle, 1901 to 1980, on the basis of monthly weighted climate variables (yearly data and 11 yr running mean)

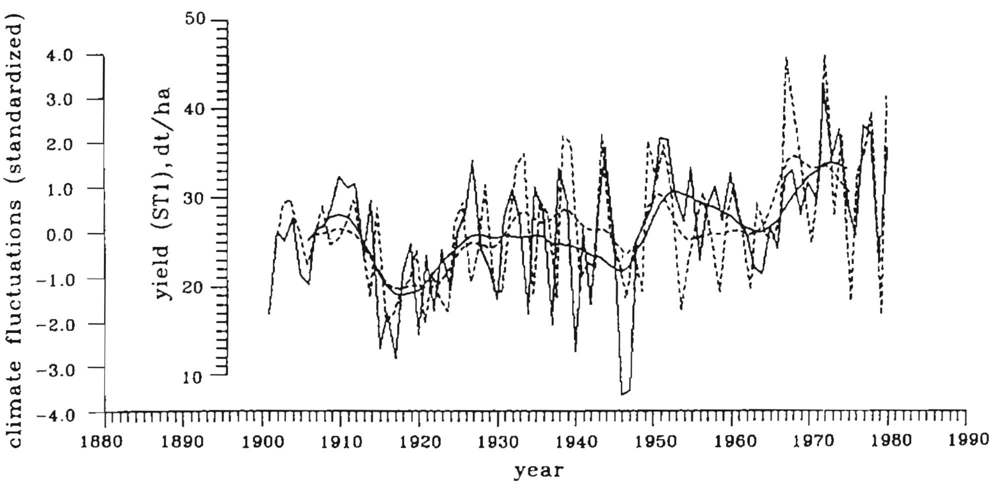

Fig. 5. Time series comparing components for standardized climate fluctuations (——; on a monthly basis) and winter-rye yields (----) in Halle, 1901 to 1980 (yearly data and 11 yr running mean)

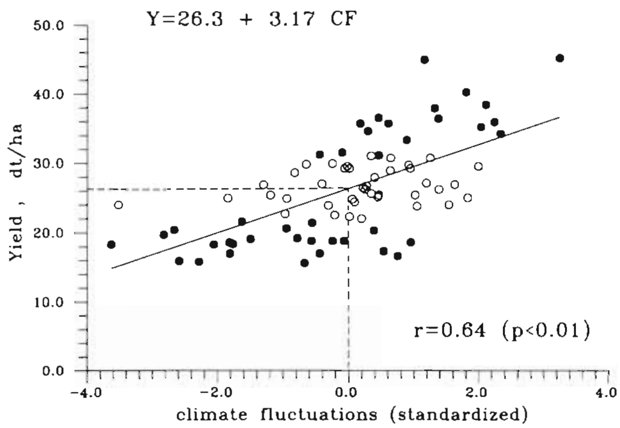

Fig. 6. Linear approximation of the correlation between climate fluctuations (CF) and winter-rye-yields (Y) in Halle, 1901 to 1980, on the basis of monthly weighted climate variables. Filled circles indicate low and high yields

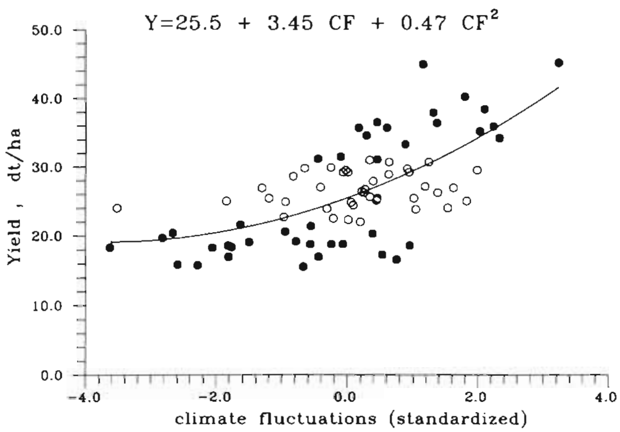

Fig. 7. Polynomial approximation of the correlation between climate fluctuations (CF) and winter-rye yields (Y) in Halle, 1901 to 1980, on the basis of monthly weighted climate variables. Filled circles indicate low and high yields

Fig. 6 indicates that, apart from a few exceptions, climate fluctuations in years with high yields are connected with positive climate anomalies, and those in years with low yields are connected with negative anomalies; the average standardized climate anomaly for high yields is 1.17, for low yields −1.14 (Table 4). The difference between these variables is significant. Thus, the weather conditions in years with high and low yields are clearly different.

In 4 cases, however, low yields were connected with moderately positive climate fluctuations. This may be due to the fact that the reasons for low yields are diverse (harvesting method, pests, diseases, etc.). Only 2 years with high yields showed negative climate anomalies, which were small.

Table 4. Statistical parameters for low and high grain yields. (For 1901 to 1980, mean Y = 26.3 dt ha^{-1}, SD = 6.84 dt ha^{-1})

	$\bar{x}$	SD	n	Sig.	Max., Min.
High yields (dt ha^{-1})	36.3	4.09	17	*	45.1
Low yields (dt ha^{-1})	18.5	1.07	23		15.6
CF ($Y > 31.0$)	1.17	1.01	17	*	3.24
CF ($Y < 21.7$)	−1.14	1.24	23		−3.63

*$p < 0.01$

The average monthly climate anomalies for years with high and low yields are shown in Fig. 8. It is apparent that the climate fluctuations in every month were > 0 in years with high yields, and < 0 in years with low yields. There were statistically significant differences ($p < 0.05$) between the climate anomalies in both groups in October, December, January, February, March, April, May and July.

A better approach

The statistical equation relating crop yields to climate fluctuations was calculated on the basis of monthly climate variables. However, the developmental stages of crop plants cannot be expected to conform to calendar months (e.g. Chmielewski 1989, Dharmadhikari et al. 1990). Some developmental stages between sowing and harvest are shorter than

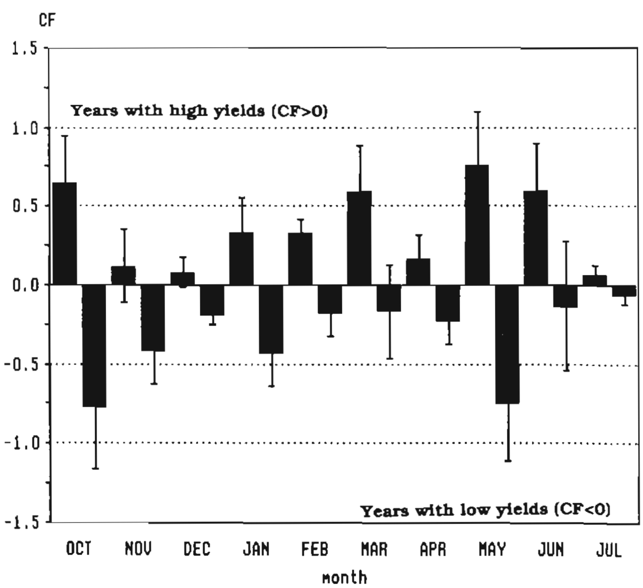

Fig. 8. Average monthly climate fluctuations (CF) in years with high (> 31.0 dt ha^{-1}) and low (< 21.7 dt ha^{-1}) winter-rye yields in Halle, 1901 to 1980

1 mo (Table 5). Thus, to obtain a more meaningful CF/yield regression, the year should be subdivided into phenological stages; unfortunately, phenological observations were not made during the long-term field experiment in Halle.

In order to achieve a better approximation of the relation between climate fluctuations and crop yields, the same 2-step factor analysis was applied to periods of 10 d (decades) instead of months, i.e. to shorter stages. Thus the average meteorological variables (M_i) were calculated for 33 decades from October to August. Fig. 9 presents the results of the factor analysis (cf. Fig. 6). The regression shows a stronger correlation than before between the yields and standardized climate fluctuations (r = 0.73). It is therefore likely that the use of phenological stages to divide the year leads to a better explanation of variance. For this purpose the average meteorological variables could be calculated for each developmental stage.

The time series of components for the standardized climate fluctuations [CF(t); Fig. 10] is similar to that shown in Fig. 4.

Table 5. Average duration of developmental stages of winter rye in Germany (Potsdam, 1951 to 1980)

Developmental stage	$\bar{x}$ (d)	SD (d)
Sowing to emergence	12.5	3.1
Sprouting to end of growing season	35.4	14.8
Winter break	131.3	18.5
Start of growing season to shooting	34.9	11.6
Shooting to ear formation	21.0	4.1
Ear formation to full bloom	16.1	4.1
Full bloom to harvest	58.2	4.2

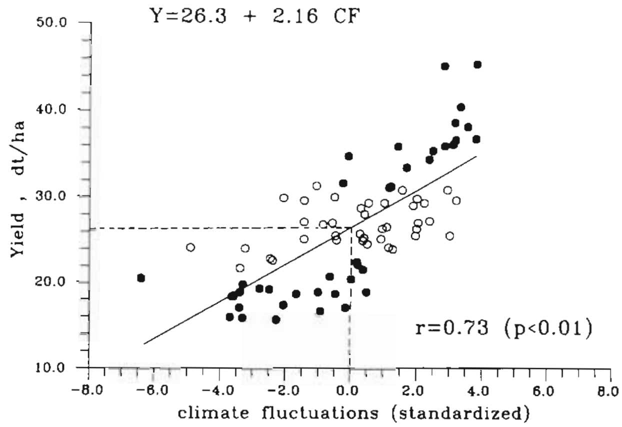

Fig. 9. Linear approximation of the correlation between climate fluctuations (CF) and winter-rye yields (Y) in Halle, 1901 to 1980, on the basis of 10 d weighted climate variables. Filled circles indicate low and high yields

Influence of single variables

The above findings show that yield variability depends on climate fluctuations in a complex way. In addition, the climate conditions in some months have a greater influence on yields than those in other months. With the complex statistical method employed, it was not possible to show how individual meteorological variables affected crops, which represents a disadvantage. However, we may suspect that any single variable only describes a small amount of the yearly yield variance.

It was found that the climate fluctuations in May and June had a clear effect on yields (Table 3a). Furthermore, the precipitation in these 2 months was positively correlated with grain yields. Therefore, in this section the relationship between crops and several individual variables is discussed.

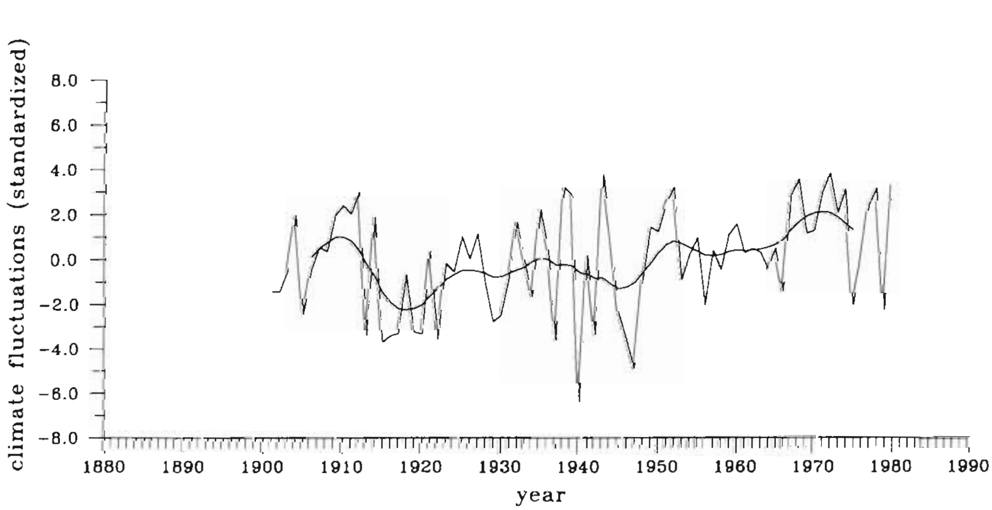

Fig. 10. Time series of components for standardized climate fluctuations in Halle, 1901 to 1980, on the basis of 10 d weighted climate variables (yearly data and 11 yr running mean)

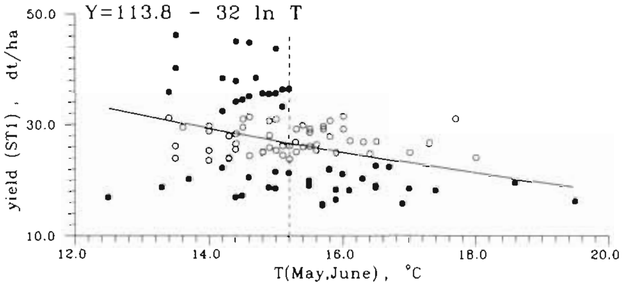

Fig. 11. Relationship between winter-rye yields and average temperature (T) in May and June in Halle, 1880 to 1985

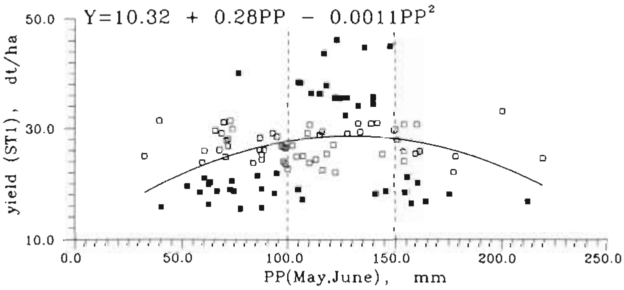

Fig. 12. Relationship between winter-rye yields and total precipitation (PP) in May and June in Halle, 1880 to 1985

Figs. 11 & 12 show the influence of average temperature and total precipitation on yields in Halle in May and June, for the period 1880 to 1985. During this period the threshold for high yields was 31.5 dt ha^{-1} (75 % quantile) and for low yields was 22.1 dt ha^{-1} (25 % quantile). Fig. 11 indicates that average air temperature (May and June) in years with high yields was always < 15.2 °C. A connection between low yields and temperature could not be detected. The effect of precipitation in these months was also interesting (Fig. 12). In most cases high yields were observed during years with between 100 and 150 mm precipitation in May and June. The majority of low yields were connected with precipitation on either side of this range. Table 6 summarizes these relations.

Table 6. Relationships of high and low yields to temperature (*T*) and total precipitation (PP) in May and June, 1880 to 1985

	Y (dt ha^{-1})	*T* (°C)	PP (mm)
High yields			
$\bar{x}$	37.9	14.5	127
SD	4.2	0.6	24
Range	32.5–46.2	13.4–15.2	77–201
Optimal, ca		< 15.3	100–150
Low yields			
$\bar{x}$	18.7	15.7	104
SD	1.8	1.4	46
Range	15.6–22.0	13.3–19.5	42–213

We have already seen that long-term yield variations are probably caused by climate changes on the same scale. It is also worth considering whether such variations may be detected for single variables as well.

For winter cereals, the end and the beginning of the growing season are important. A growing season of short duration occurs when the season begins late and ends early. An earlier end of the growing season leads to insufficient plant development in autumn, and a later beginning results in a shorter generative stage. Neither effect is advantageous for a successful grain yield. To address this factor, the duration of the growing season in Halle was calculated on the basis of daily temperatures between 1900 and 1985. The beginning of the season was defined as the day of the year on which average air temperature was > 5.0 °C, with the proviso that on the following days the sum of differences

$$\sum_i (T_i - 5\ °C) > 0\ °C \quad (i = 2, 3, ...) \tag{3}$$

remains positive. Correspondingly, the end of the growing season was defined as the day of the year on which the average temperature was < 5.0 °C, under the condition that

$$\sum_i (T_i - 5\ °C) < 0\ °C \quad (i = 2, 3, ...). \tag{4}$$

The duration of growing seasons in Halle between 1900 and 1985 is shown in Fig. 13. The absolute differences in season length between years were considerable (shortest duration = 189 d, 1922; longest = 286 d, 1934). Long-term variation in this variable also showed a significant minimum around 1920, similarly to crop yields. Thus, the short duration of the growing season could be one reason for the low yields in this period.

COMPARISON WITH CROPS OF ANOTHER LONG-TERM EXPERIMENT

Similar types of climatic changes occur over large spatial scales. Thus, recent climate changes at one site may similarly effect long-term variation in crop yields at another site, such as Halle. Fig. 14A shows average yields in Askov (Denmark) from 1894 to 1972 (Kofoed & Nemming 1976) for crops in sandy loam. Running means of annual yields (winter cereals, root crops, spring cereals, and a clover-grass mixture) are presented as

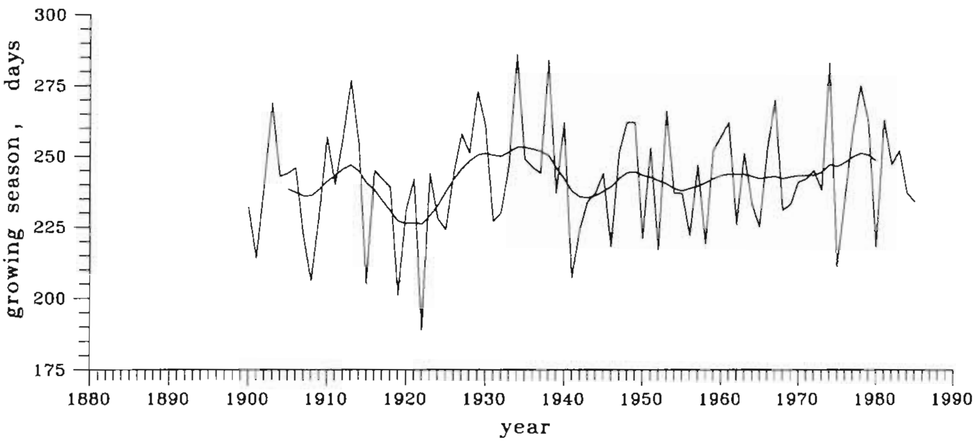

Fig. 13. Duration of growing season in Halle, 1900 to 1985 (yearly data and 11 yr running mean)

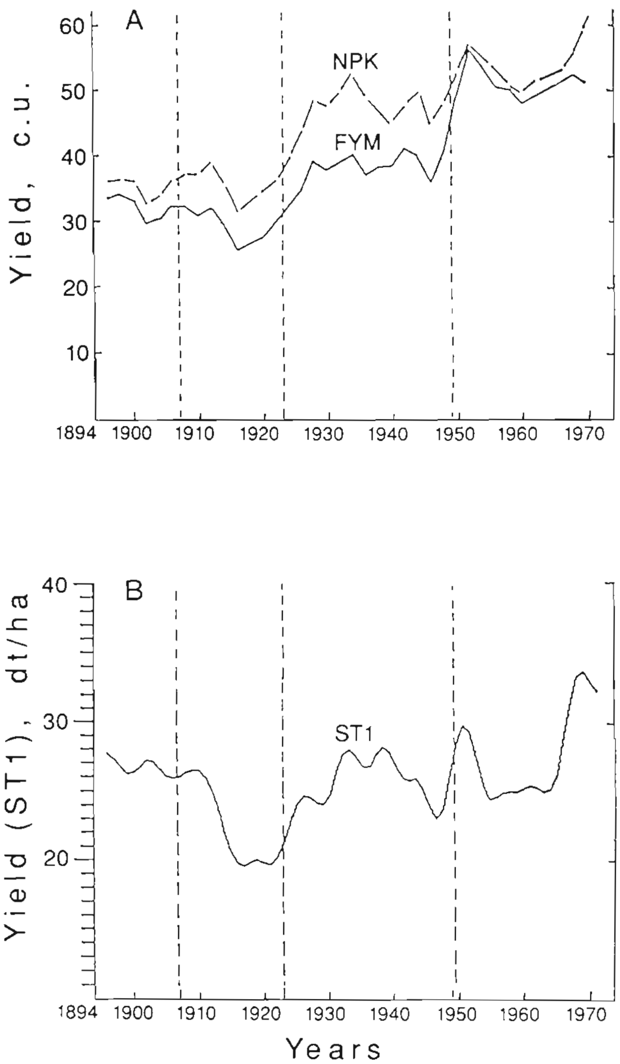

Fig. 14. Average crop yields (running means) from 1894 to 1972, in (A) Askov (winter cereals, root crops, spring cereals, clover-grass mixture) on a loam field (according to Kofoed & Nemming 1976), and (B) Halle (winter rye). c.u.: crop units; NPK: Mineral fertilization; FYM: farmyard manure

crop units*; vertical dashed lines indicate an increase in fertilization. The increasing crop yields from 1894 to 1972 at this site resulted from a periodical increase of fertilization. For comparison purposes, winter-rye yields in Halle are also presented (Fig. 14B; dashed lines are included here only to aid comparison). The correspondence in long-term yield variations is impressive. To a certain extent, the yield variations in Denmark may also be related to climate change.

CONCLUSIONS

That annual weather conditions affect crops is scarcely a matter of controversy. This study represents an attempt to show whether long-term yield variations are also related to climatic variations on a greater scale. The results suggest that this is probably true. The relatively small climatic changes in this century have had an impact on crop yields. Analogously we may assume that future expected climate change will have a substantial impact on crops and therefore on agriculture, if no new crop varieties are developed which are well adapted to the changed climate.

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* 1 crop unit = 100 kg grain yield; use of crop units permits the yield of different crops to be expressed uniformly

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