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Effects of climate change on wheat production potential in the European Community

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Abstract

Wheat grain production in the main arable areas of the EC was calculated with a simulation model, WOFOST, using historical weather data and average soil characteristics. The sensitivity of the model to individual weather variables was determined. Subsequent analyses were made using climate change scenarios with and without the direct effects of increased atmospheric CO_2. The impact of crop management (irrigation and cultivar type) in a changed climate was also assessed.

Sensitivity analyses show that water-limited grain production of winter wheat increased with increasing vapour pressure, rainfall and atmospheric CO_2 concentration and decreased with increasing windspeed, temperature (except for southern EC) and solar radiation. The various climate change scenarios that were used yielded considerably different changes in production, both for each location and for the EC as a whole. For example, the average water-limited grain production in the EC may remain constant or may decrease by about 1 000 kg ha^{-1} depending on scenario. If the direct effect of increasing CO_2 is also taken into account, the average water-limited grain production in the EC increased by about 1 000 kg ha^{-1}or more. Management analyses showed that for both the present and scenario generated climates the largest water-limited grain production will be attained by cultivars with an early start of grain filling, that average irrigation requirements to attain potential grain production will increase with climate change in northern EC and decrease in southern EC, and that with both increasing CO_2 and climate change irrigation requirements in northern EC remain unchanged and decrease further in southern EC.

Key-words : climate change, winter wheat, simulation model, crop production, EC, scenario analysis.

INTRODUCTION

Since agricultural production is greatly affected by climate, any changes in climate which may result from increasing concentration of greenhouse gases in the atmosphere could have dramatic consequences for agricultural production potential. In this study the effects of climate change on the production of winter wheat in the EC (European Community) and the implications for crop management were analysed.

The relationship between climate, crop growth and production is complicated as a large number of climate, soil, landscape and crop characteristics are involved. As a result, the effects of climate change on crop production cannot be described in terms of simple and average relations between the two. In the last two decades methods have been developed for estimating the production levels of crops grown under well-specified conditions. These methods are based on the application of crop growth simulation models, combining knowledge about crop characteristics and their interactions with the environment.

Prior to evaluation of the effects of climate change the sensitivity of wheat production to separately changed weather variables was determined. To analyse the effects of climate change on the production potential of winter wheat in the EC, 20 locations, representative of the main agro-climate conditions in the EC, were chosen. The production was calculated for current and changed climate conditions, using climate change scenarios (Barrow, 1993). The direct effect of increasing atmospheric CO_2 concentrations was incorporated in the production calculations for the changed climate and the impact of changes in crop management were also determined.

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METHODOLOGY

Model description

A dynamic crop growth model WOFOST, developed for calculating agricultural production potential on the basis of physiological, physical and agronomic information, was used. This model can easily be applied to a large number of combinations of different weather data, soil characteristics and crop species. The principles underlying this model have been discussed in detail by van Keulen and Wolf (1986) and the implementation and structure have been described by van Diepen *et al.* (1988, 1989). Its application for quantitative land evaluation and for regional analysis of the physical potential of crop production has been described by van Keulen *et al.* (1987) and van Diepen *et al.* (1990) and its use for analysis of the effects of climate change on crop production has been discussed by van Diepen *et al.* (1987) and Wolf and van Diepen (1991).

In the model, crop growth is simulated from sowing to maturity on the basis of physiological processes as determined by the crop's response to environmental conditions. The simulation is carried out in time-steps of one day. The major processes considered are CO_2 assimilation, respiration, partitioning of assimilates to various plant organs, transpiration and phenological development.

Two levels of crop production are calculated. Firstly, the potential production which is determined by crop characteristics, temperature and solar radiation, and can be realized in situations where the supply of water and plant nutrients, and crop management are optimum. Secondly, the water-limited production, determined by crop characteristics, temperature, solar radiation and water availability (dictated by rainfall pattern and soil physical properties), which can be realized in situations where the supply of plant nutrients and crop management are optimum.

Available soil moisture in the root zone follows from quantification of the water balance including rainfall, surface runoff, soil-surface evaporation, crop transpiration and leaching from the root zone. If the moisture content in the root zone is too low or too high, water uptake by the plant roots is reduced, stomata close and the water-limited growth is reduced : in a dry soil due to water shortage, in a wet soil due to oxygen shortage.

Data

In order to apply the model, data that specify crop growth and phenological development are required, including information on initial crop weight, properties that determine assimilation and respiration processes and response to moisture stress, partitioning of assimilates to plant organs, life span of leaves, and death rates of plant organs. For the most part a standard crop data set was used (van Heemst, 1988). Information from field experiments in the Netherlands and UK (Darwinkel, 1985 ; Green and Ivins, 1985 ; Green *et al.*, 1985 ; Groot, 1987 ; PAGV, 1987 ; Porter *et al.*, 1987) was used to assess data specifying the rate of phenological development, the level of production and the partitioning of assimilates to the plant organs. These data were used for all locations in the EC. Comparison of model output with information on production levels and grain/straw ratios from variety trials in other countries (France, Italy and Spain) and on the rate of phenological development in all regions in Europe (Thran and Broekhuizen, 1965) indicated that this Europe-wide use of crop data was quite realistic.

The direct effect of increasing atmospheric CO_2 concentration on the CO_2 assimilation and growth of the wheat crop was incorporated into the model by increasing the maximum value and initial angle of the CO_2 assimilation — light response curve of single leaves, by increasing the thickness of leaves, and by slightly decreasing the transpiration rate. These changes in model parameters were based on studies by Allen *et al.* (1990), Goudriaan *et al.* (1984), Goudriaan *et al.* (1985), Goudriaan (1990), Goudriaan and Unsworth (1990), Goudriaan and de Ruiter (1983) and Idso (1990), and on literature surveys on crop responses to CO_2 doubling by Cure (1985), Cure and Acock (1986) and Kimball (1983).

In order to calculate CO_2 assimilation rates, daily minimum and maximum air temperatures, atmospheric CO_2 concentration and solar radiation are required (Goudriaan and van Laar, 1978). To calculate the components of the water balance, daily rainfall, windspeed and vapour pressure are also required. For example, the calculations of potential rates of evaporation and transpiration that are made with the Penman formula require data on radiation, average daily air temperature, vapour pressure and windspeed (Frère and Popov, 1979). Daily weather data for 20 meteorological stations, representative of the main arable land areas in all EC countries (Figure 1) except Greece (for which no sets of daily weather data were available), were used. For most stations the sets of historical weather data covered a period of 20 years (1966-85).

In order to calculate soil water balance, the soil's infiltration, retention and transport properties must be known. These soil physical characteristics are defined by effective soil depth, soil moisture characteristics (notably soil porosity and volumetric moisture contents at field capacity and wilting point, respectively), maximum infiltration rate or surface runoff fraction, and the hydraulic conductivity of the subsoil. For each meteorological station the main soil types that occur on arable land areas within a radius of 100 to

150 km around the station (Figure 1), were obtained from the soil map of the European Communities (CEC, 1985). This map gives information per unit on soil type, texture class, characteristics such as gravelliness, stoniness, shallow rocks etc., and slope gradient. By interpreting this information (mainly based on King and Daroussin, 1989 and Reinds *et al.*, 1992) quantitative terms for use in the simulation model could be obtained : fraction of precipitation lost by surface runoff, maximum effective rooted soil depth (≤ 100 cm for winter wheat) and available volumetric moisture content in the soil. Areas with a slope gradient of more than 15 per cent. were left out, as being too steep for arable farming. For all soil types the ground water table was assumed to be at such a depth that it did not influence the water balance and that excess water drained rapidly to the subsoil, so that growth reduction due to oxygen shortage did not occur.

Model validation

Potential grain production was calculated for weather data from Wageningen and de Bilt (about 40 km west of Wageningen), the Netherlands, over the period 1980-88. Going back in time from 1980, grain production from field trials appeared to decrease rapidly with time as a result of less optimum crop management and less productive crop varieties. Therefore, these production data could not be used for comparison with calculated grain production. Calculated potential grain production levels were compared with actual results from variety trials (Figure 2) that were carried out over the period 1980-88 in Randwijk (in the neighbourhood of Wageningen) and in Wieringerwerf (about 130 km north of Wageningen), both on clay soils with a relatively high groundwater level and no water shortage in summer.

The comparison showed that the calculated variation in grain production over time was much smaller than the variation in grain production found in the variety trials. In years with a high level of solar radiation during grain filling, actual grain production was relatively large. In those years losses by diseases mainly associated with ripening (fungi such as mildew) were limited and hence calculated and actual grain production levels were comparable. In years with abundant rainfall and a low level of solar radiation during grain filling both calculated and actual grain production levels were relatively low. However, grain production levels in variety trials were found to be 10 to 20 per cent lower than calculated ones, which has to be explained by the considerable losses due to ripening diseases in those wet years. Unfortunately, the production-reducing effects of diseases could not be calculated with the crop growth simulation model.

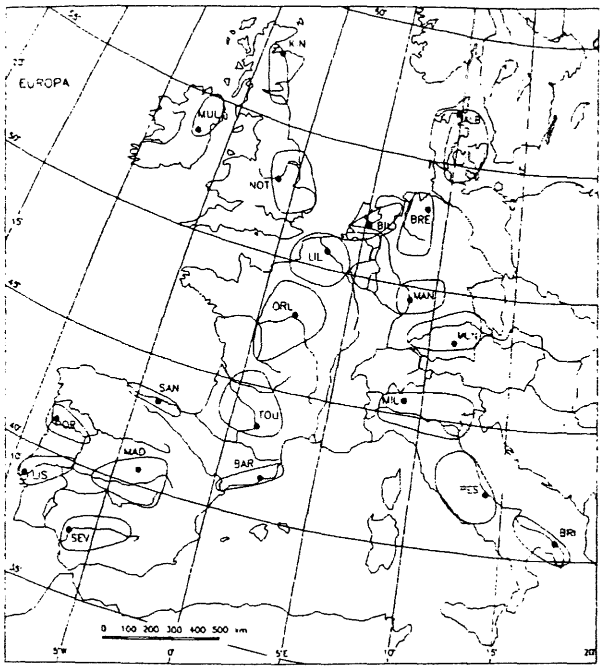


Figure 1. *Sets of historical weather data used for calculating the wheat production potential in the EC, were available for the following meteorological stations : Kinloss and Nottingham in the U.K. ; Mullingar in Ireland ; Ålborg in Denmark ; de Bilt in the Netherlands ; Bremen, Mannheim and München in Germany ; Lille, Orleans and Toulouse in France ; Santander, Barcelona, Madrid and Sevilla in Spain ; Porto and Lisbon in Portugal ; Milan, Pescara and Brindisi in Italy. Data for each station can be considered representative of the arable land area around that station, as roughly indicated (exclusive of areas of sea, wetlands, mountains etc.).*

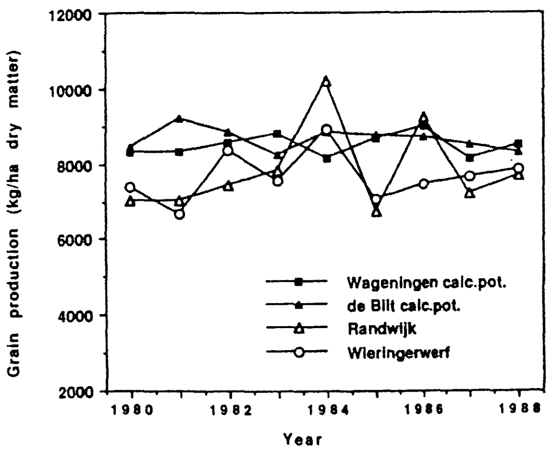


Figure 2. *Potential grain production of winter wheat calculated for Wageningen and de Bilt, Netherlands and actual grain production from variety trials on clay soils in the Netherlands.*

RESULTS

Baseline

Potential production was about 9 000 kg ha^{-1} dry matter of grain. Higher grain production levels were calculated for locations where the level of solar radiation was high during grain-filling and the average temperature was relatively low, which resulted in a long period of grain-filling. On the other hand, lower production levels were calculated for locations with higher temperatures and less solar radiation. This explains the relatively large production in Lisbon and Porto and the relatively small production in Milan and Madrid (Table 1). Water-limited grain production varied widely among locations and also among cultivated soil types. Largest production was found at locations with a relatively large ratio between precipitation and potential evapo-transpiration and a large amount of available soil moisture. By lowering the amount of available soil moisture (e.g. sandy, gravelly and/or shallow soils instead of deep, loamy or clay soils) water-limited grain production often decreased greatly.

Table 1. *Duration of grain filling (days) and average potential grain production for winter wheat (kg ha^{-1} dry matter).*

Location	Period of grain filling	Grain production
Milan	40	7770
Madrid	42	8720
Lisbon	50	10420
Porto	53	11130

For each location average soil characteristics were calculated from the characteristics of each soil type and in proportion to its relative area. Water-limited grain production levels, calculated for average soil characteristics, were similar to average grain production levels calculated for the various soil types per location, with a difference of 10 per cent at most. To limit the number of calculations and results, the subsequent sensitivity, scenario and management analyses were done for these average soil characteristics.

Sensitivity analyses

Sensitivity analyses were carried out for three locations representative of the main differences in climate in the EC : Kinloss in the UK (cool temperate), Orleans in France (continental), and Brindisi in Italy (Mediterranean). For each location, calculations were made using historical weather data for a period of 20 years. Data for one weather variable were varied separately, while others were held constant. Weather variables that determine crop production directly are solar radiation and temperature. Those that affect the water balance and hence the duration and degree of drought stress are rainfall, windspeed, vapour pressure, solar radiation and temperature. Atmospheric CO_2 concentration also has direct and indirect effects on crop production. These variables were adjusted separately, in a stepwise manner, in order to gauge the sensitivity of crop production to changing values of each.

Table 2 summarizes the sensitivity of potential and water-limited grain production to changing values of each weather variable. Potential grain production increased with increasing atmospheric CO_2 and solar radiation, and generally decreased with rising temperatures. Potential production was not influenced by the water balance and was thus insensitive to changes in windspeed, vapour pressure and rainfall. Water-limited production increased with increasing atmospheric CO_2, rainfall and vapour pressure, and decreased with increasing solar radiation, temperature (except for Brindisi) and windspeed.

Table 2. *Sensitivity of potential (POT) and water-limited (WAT) grain production of winter wheat at Kinloss in UK, Orleans in France, and Brindisi in Italy to increasing values of atmospheric CO_2 concentration (C), temperature (T), rainfall (R), solar radiation (S), windspeed (W) and vapour pressure (V)[1].*

	C	T	R	S	W	V
POT	++	– –, 0[2]	0	+, ++	0	0
WAT	++	– –, +[3]	++	–	– –	++

[1] 0, +, ++ : no, moderate, strong increase in grain production ; –, – – : moderate, strong decrease in grain production.
[2] Temperature effect varies from about zero in Kinloss to strongly negative in Brindisi.
[3] Temperature effect varies from strongly and moderately negative in Kinloss and Orleans respectively to moderately positive in Brindisi.

Scenario analyses without direct CO_2 effect

Composite time-dependent scenarios

Potential and water-limited grain production levels of winter wheat were calculated for historical weather data that were changed on the basis of composite scenario A (based on the business-as-usual emission scenario of Houghton *et al.* (1990)) for the years 2010, 2030 and 2050, and composite scenario A High (high estimate of scenario A) for the year 2050. These changes, as described by Barrow (1993), were specified per day over a period of one year. For precipitation and temperature the changes were location-specific. For solar radiation and vapour pressure only one set of changes was supplied for all locations, and for windspeed no changes could be made (Barrow, 1993).

Potential production in northern EC, e.g. in Kinloss, UK, increased slightly up to year 2030 (Figure 3), mainly due to rising temperatures. In southern EC, e.g. in Brindisi, Italy, potential production levels generally decreased over time, because rising temperatures advanced the period of grain-filling to a time of year with shorter days and lower solar elevation.

Water-limited production decreased over time at most locations, probably because rising temperatures caused larger water losses by soil evaporation and crop transpiration. However, these decreases in production were limited in magnitude (Figures 3 and 4). Weather conditions during the period of grain filling were influenced not only by the direct effects of climate change (as specified by the scenarios), but also considerably by the shift in time of the grain-filling period as a result of the changed climate. For example, at locations with dry summers such as Brindisi and Pescara, water-limited production was calculated to increase with time (Figures 3 and 4). The period of grain filling was advanced to a time of higher precipitation which resulted in increased grain production.

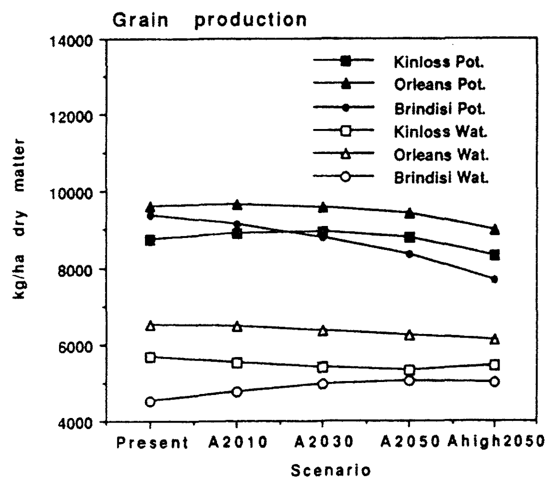


Figure 3. *Average potential (Pot.) and water-limited (Wat.) grain production of winter wheat cultivated at current and at future weather conditions in Kinloss, UK ; Orleans, France ; and Brindisi, Italy (direct effect of increasing atmospheric CO_2 in future not taken into account). Production has been established for historical weather data over a period of 20 years (1966-1985), for composite scenario A for the years 2010, 2030 and 2050, and for composite scenario A High for the year 2050.*

Individual GCM scenarios

Potential and water-limited grain production levels of winter wheat were also calculated for historical weather data that were changed on the basis of output from three equilibrium $2 \times CO_2$ general circulation models (GCMs), i.e. the GFDL, the GISS and the UKMO-L (low resolution) models. These changes, as described by Barrow (1993), were specified per day over a period of one year for each weather variable and were location-specific.

Potential grain production decreased at almost all locations for the changed weather data (Table 3), mainly due to higher temperatures. The lowest production level was generally calculated for the UKMO-L scenario, which tends to give the largest temperature increase, or for the GFDL scenario, which gives slightly smaller temperature increases but often combined with a decrease in the amount of radiation in winter and/or spring. The temperature increase given in the GISS scenario is generally the smallest. For the latter scenario the level of grain production was higher than for the other two scenarios, but generally lower than that for unchanged historical weather data.

Changes in temperature and radiation based on the scenarios influenced water-limited grain production in the same way as they influenced potential grain production (Table 3). The interaction between these changes and changes in the other weather variables is

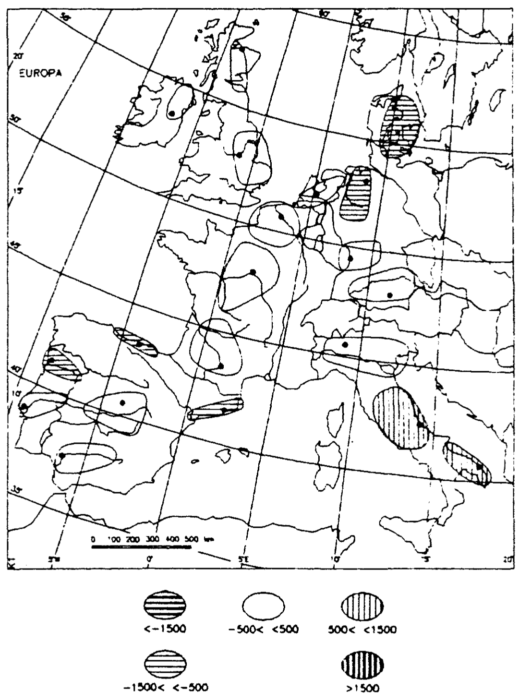


Figure 4. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of composite scenario A for the year 2050. Direct effect of increasing atmospheric CO_2 was not taken into account.*

Table 3. *Average potential (POT) and water-limited (WAT) grain production (kg ha^{-1} dry matter) of winter wheat established for historical weather data that were changed on the basis of GFDL, GISS and UKMO-L equilibrium 2 × CO_2 scenarios, with and without the direct effect of increased CO_2 (353 ppm → 560 ppm).*

Location	Historical weather	Scenario					
		GFDL		GISS		UKMO-L	
		− CO_2	+ CO_2	− CO_2	+ CO_2	− CO_2	+ CO_2
Brindisi POT	9370	6080	8360	5970	8180	5380	7530
Brindisi WAT	4510	5340	7350	5440	7410	4820	6690
Kinloss POT	8740	3110	3840	7680	9620	6540	8430
Kinloss WAT	5680	3110	3840	6990	8950	5670	7510
Orleans POT	9630	7850	10510	8380	11100	6620	8910
Orleans WAT	6510	6940	9350	5520	7700	6020	8120

very complex. In addition, the changes varied considerably among locations and over the year. Hence, simple and straightforward explanations of their effects on grain production cannot be derived. The GFDL scenario gave major decreases in water-limited grain production in the UK, Ireland, northern Spain, Portugal and northern Germany that can mainly be explained in the same way as the decrease in potential production via the higher temperatures and the lower level of radiation, while the moderate to major increase in central and southern Italy was probably due to relatively larger amounts of rainfall during the advanced period of grain-filling (Figure 5). The GISS scenario (smallest temperature increase) gave moderate decreases in production for Ireland, northern Germany, northern and central France, northern Spain and northern Portugal (Figure 6) and mainly moderate increases for Scotland, Denmark, central and eastern Spain and central and southern Italy. The UKMO-L scenario (highest temperature increase) gave major decreases in production for Ireland, England, northern Germany, northern and southern France, northern Spain and northern Portugal (Figure 7), and moderate decreases for central and southern Germany, northern Italy, eastern and southern Spain and central Portugal.

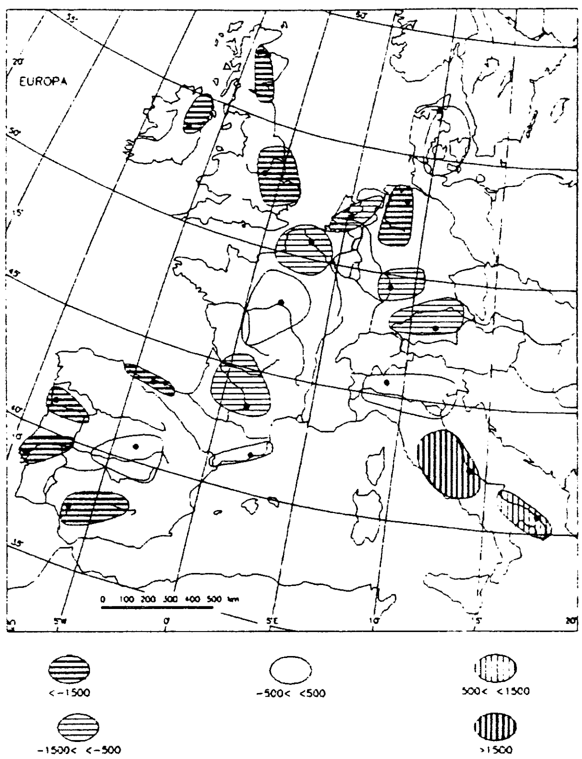


Figure 5. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of the GFDL equilibrium 2 × CO_2 scenario. Direct effect of increased CO_2 was not taken into account.*

Scenario analyses with direct CO_2 effect

Composite time-dependent scenarios

In these analyses the direct effect of increasing atmospheric CO_2, which results mainly in a higher CO_2 assimilation rate and thus larger crop production and in a somewhat lower transpiration rate, was taken into account. Potential production levels increased greatly over time at all locations, mainly due to increasing CO_2 (Figures 3 and 8). For water-limited production the same applied. For scenario A High for year 2050, which shows the largest increase in temperature, the increase in production was generally somewhat less than that for scenario A for the same year. The smallest relative increases in production were calculated for Denmark, northern Germany and Spain (Figure 9).

Individual GCM approach

In these analyses the effects of the GFDL, GISS and UKMO-L scenarios of climate change and of

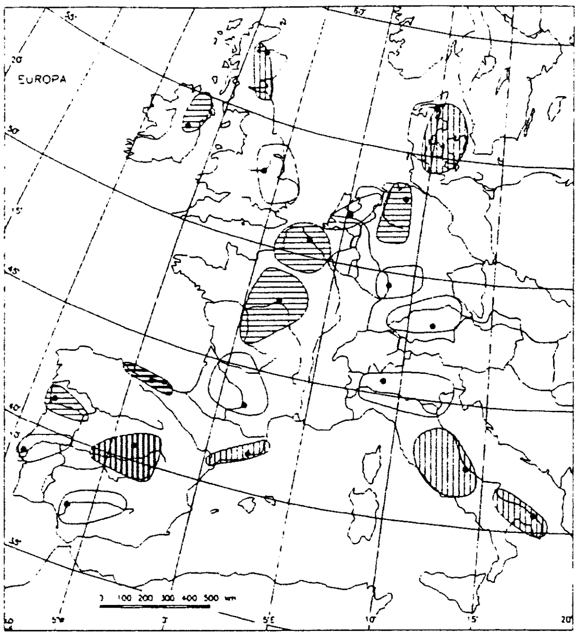
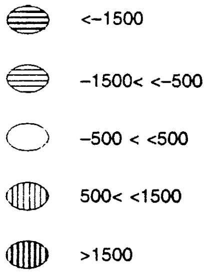


Figure 6. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of the GISS equilibrium $2 \times CO_2$ scenario. Direct effect of increased CO_2 was not taken into account.*



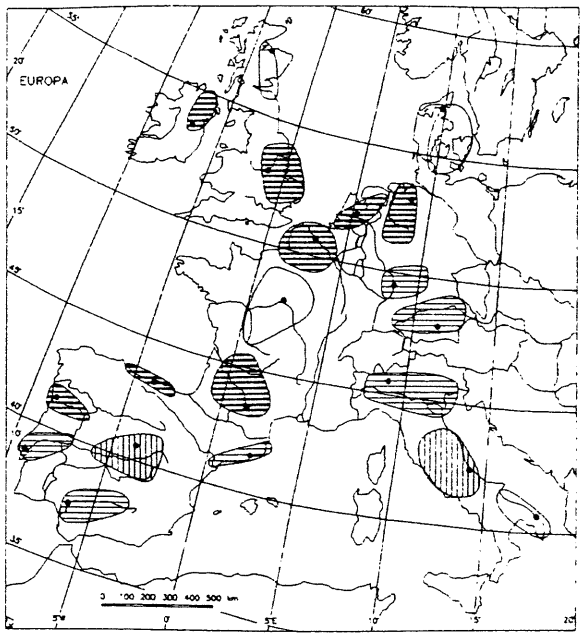


Figure 7. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of the UKMO-L equilibrium $2 \times CO_2$ scenario. Direct effect of increased CO_2 was not taken into account.*

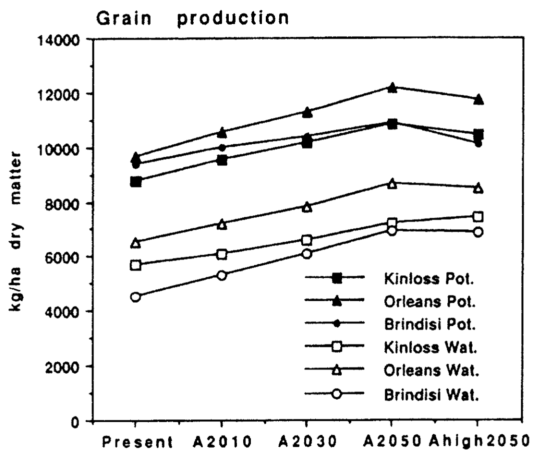


Figure 8. *Average potential (Pot.) and water-limited (Wat.) grain production of winter wheat cultivated at current and future weather conditions in Kinloss, UK ; Orleans, France ; and Brindisi, Italy, taking into account the direct effect of increasing atmospheric CO_2 in future. Production has been established for historical weather data over a period of 20 years (1966-85), for composite scenario A for the years 2010, 2030 and 2050, and for composite scenario A High for the year 2050.*

increasing CO_2 concentration (from 353 to 560 ppm) were taken into account. Increasing CO_2 resulted in an increase in potential grain production while the change in climate alone generally caused a decrease compared to production under the historical climate (Table 3). Hence, if the effect of the climate change scenario is larger, potential production will decrease, and if the direct effect of atmospheric CO_2 is larger, potential production will increase. The largest potential grain production was calculated generally for the GISS scenario which gives the smallest temperature rise and the smallest, generally, for the UKMO-L scenario and the GFDL scenario only at locations where radiation became limiting (e.g. Kinloss).

The GFDL scenario gave major decreases in water-limited grain production for Ireland, Scotland and northern Spain, due to an earlier start in spring (low radiation level) as a result of higher temperatures, and a reduced amount of solar radiation according to the scenario (Figure 10). Moderate production decreases were calculated for England, Portugal and southern Spain with constant productions for northern Germany and the Netherlands. At the other locations major increases in water-limited grain production were found as a result of the direct CO_2 effect. The GISS scenario gave major increases in water-limited grain pro-

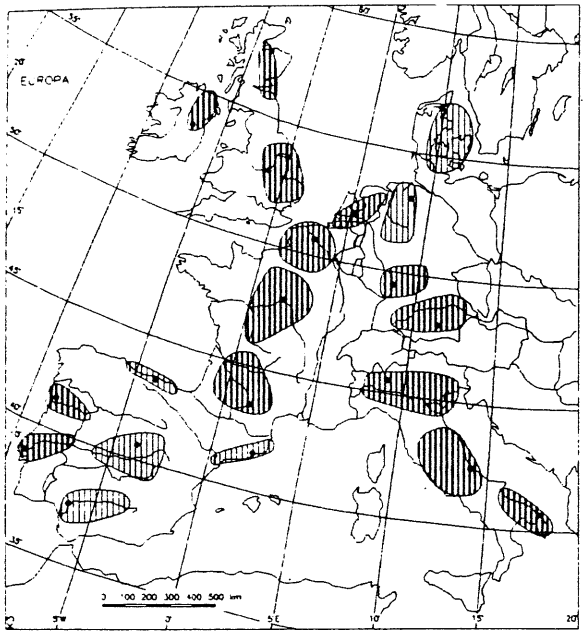
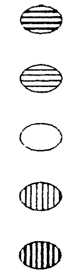


Figure 9. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather was changed on the basis of the composite scenario A for the year 2050 and the direct effect of increased atmospheric CO_2 was taken into account.*



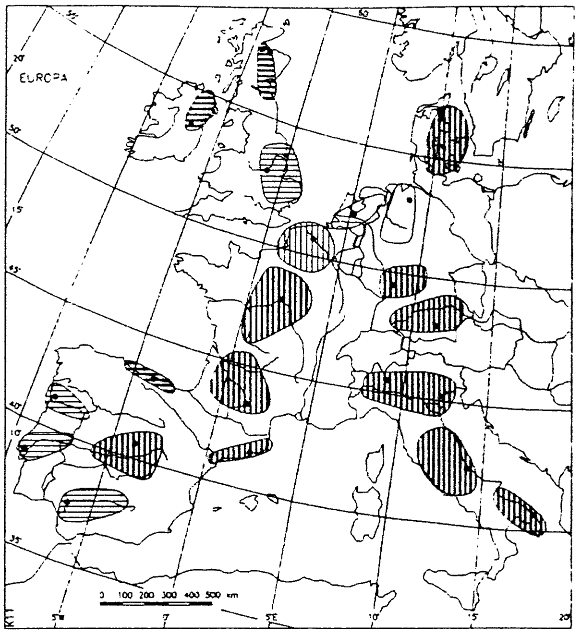


Figure 10. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather was changed on the basis of the GFDL equilibrium 2 × CO_2 scenario and the direct effect of increased CO_2 was taken into account.*

duction for most locations (Figure 11). Water-limited grain production also increased at most locations for the UKMO-L scenario. Exceptions were decreases in northern Spain, Ireland and England and constant production in the Netherlands and the northern parts of Portugal, France and Germany (Figure 12).

Management analyses

Crop temperature sums

The interactions between the temperature sum required for crop development and the effects of climate change and increasing atmospheric CO_2 were determined for the locations Kinloss, Orleans and Brindisi. It was assumed that, compared to the main wheat varieties grown at present, plant breeding might be able to produce varieties requiring 10 per cent greater or 10 per cent smaller temperature sums (°C days) for crop development until anthesis and from anthesis to the end-of-grain filling. For the average wheat variety grown at present and for these artificially constructed wheat varieties, average grain production was calculated for historical weather data, for the composite scenario A for the year 2050, both with and without the direct effect of increased atmospheric CO_2, and for the composite scenario A High for the year 2050 with the direct CO_2 effect.

For both potential and water-limited production optimum temperature sums until anthesis (T-anth) and from anthesis to the end-of-grain filling (T-ripe) were derived for the three locations for both historical and scenario weather data. The resulting optimum temperature sums are summarized in Table 4.

From these results it can be concluded that the largest potential production in changed climate, particularly that on the basis of scenario A High, will be attained with wheat varieties that need increased temperature sums for grain filling and hence have a longer period of grain filling. The largest water-limited production under projected future and also current conditions will be attained with wheat varieties that need smaller temperature sums until anthesis and hence have an early start to grain filling.

Irrigation requirements

The amount of irrigation water required to prevent drought stress during the growth of winter wheat and to attain the potential level of grain production in the

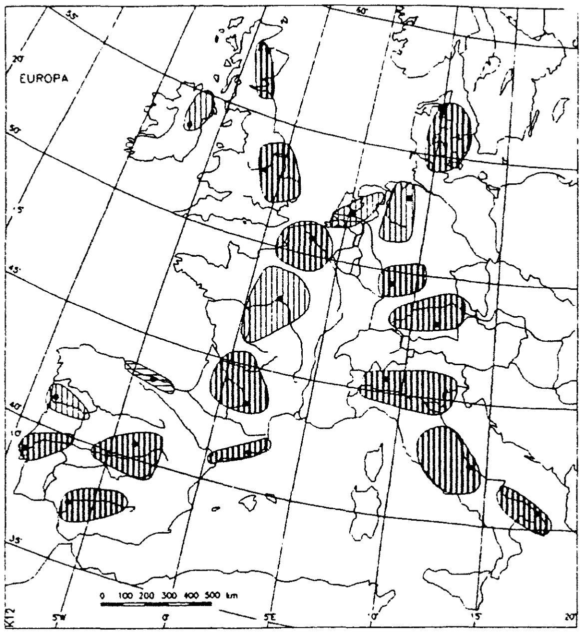
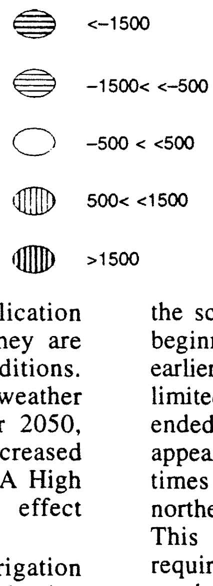


Figure 11. *Changes in water-limited grain production (kg ha⁻¹ dry matter) of winter wheat in the main arable land areas in the EC if the weather was changed on the basis of the GISS equilibrium 2 × CO_2 scenario and the direct effect of increased CO_2 was taken into account.*



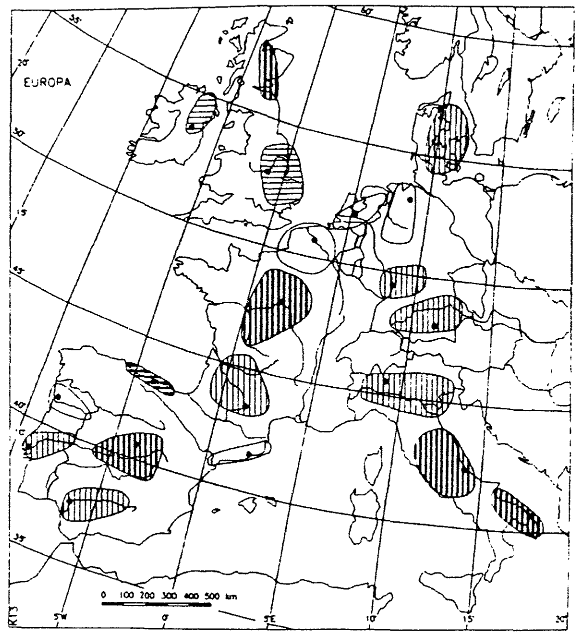


Figure 12. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather was changed on the basis of the UKMO-L equilibrium 2 × CO_2 scenario and the direct effect of increased CO_2 was taken into account.*

EC, was calculated. Conveyance and application losses are not included in the amount, as they are widely variable and dependent on local conditions. The calculations were made using historical weather data, the composite scenario A for the year 2050, both with and without the direct effect of increased atmospheric CO_2, and the composite scenario A High for the year 2050 with the direct CO_2 effect (Table 5).

Scenario A 2050 resulted in larger irrigation requirements in northern EC, but in smaller irrigation requirements in southern EC (Table 5). According to the scenario, temperatures will become higher so the beginning of crop growth in spring was shifted to an earlier date, particularly in northern EC and to a more limited extent in southern EC. Moreover, grain filling ended earlier. Therefore, a rise in temperature appeared to result in a shifted and constant, or sometimes even longer, period of 'effective'growth in northern EC and in a shorter period in southern EC. This explains the larger water use and irrigation requirements in northern EC and the smaller ones in southern EC. Increasing atmospheric CO_2 resulted in more efficient water use. This effect of CO_2 roughly

Table 4. *Optimum crop temperature sums (as a percentage of average temperature sums for present varieties) until anthesis (T-anth) and from anthesis to the end of grain filling (T-ripe) for Kinloss in Scotland, Orleans in France and Brindisi in Italy for historical and scenario weather data.*

Weather	Potential production T-anth & T-ripe[1]	Water-limited production T-anth & T-ripe[1]
Historical weather	100 % & 110 %, 90 % & 100 %	90 % & 100 %, 90 % & 90 %
Scenario A2050	100 % & 110 %, 100 % & 100 %, 110 % & 110 %[2]	90 % & 100 %, 90 % & 90 %
Scenario A2050 + CO_2 effect	100 % & 110 %, 100 % & 100 %, 110 % & 110 %[2]	90 % & 100 %, 90 % & 90 %
Scenario A High 2050 + CO_2 effect	100 % & 110 %, 110 % & 110 %, 100 % & 100 %[3]	90 % & 100 %, 90 % & 90 %

[1] Best temperature sums indicated first (starting from the left side), followed by second best sums.
[2] Only in Brindisi, Italy.
[3] Only in Orleans, France.

counteracted the increased water use and irrigation requirements in northern EC which resulted from climate change, and which caused a larger decrease in the irrigation water required in southern EC.

CONCLUSIONS

Sensitivity analyses showed that water-limited grain production of winter wheat increased greatly with increasing vapour pressure, rainfall and atmospheric CO_2 concentration, decreased greatly with increasing windspeed, and decreased moderately with increasing solar radiation and temperature, except for southern EC where there was a slight increase with rising temperature.

Increasing concentration of greenhouse gases in the atmosphere may cause changes in climate. Various climate change scenarios appeared to yield considerably different changes in production both for each location and for the EC as a whole. For example, for the equilibrium $2 \times CO_2$ scenarios (without a direct effect of CO_2), the average grain production of winter wheat in the EC remained roughly constant for the GISS scenario but decreased by about 1 000 kg ha^{-1} dry matter for the UKMO-L scenario.

The direct effect of increasing atmospheric CO_2 on wheat grain production appeared to be much greater than the effect of climate change. Moreover, the direct effect of CO_2 on production is more certain, whereas the effect of climate change is widely variable depending on the scenario and not yet established as fact. If both effects are taken into account, the average grain production of winter wheat in the EC increases by 1 000 kg ha^{-1} dry matter or more for the equilibrium $2 \times CO_2$ scenarios.

With climate change the highest level of potential production will generally be attained with wheat varieties that have larger temperature sum requirements for grain filling and hence a longer period of grain filling. If drought occurs at the end of the grain filling period, wheat varieties with smaller temperature sum requirements until anthesis, and hence an early start to grain filling, may yield the largest grain production, in both a current and a changed climate.

Irrigation requirements for attaining the potential level of wheat production increased at locations in northern EC with the climate changed on the basis of the composite scenario for the year 2050, and in southern EC they decreased. When the direct effect of increasing atmospheric CO_2 was also taken into account, this counteracted the increased irrigation requirements in northern EC and caused a larger decrease in required irrigation water in southern EC.

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Table 5. *Required average amounts of irrigation water (cm) for attaining the potential level of grain production for winter wheat at six locations in the EC for historical weather data and for scenario weather data with and without direct CO_2 effect.*

Location	Historical weather	Scenario A 2050	Scenario A 2050 + CO_2	Scenario A High 2050 + CO_2
Ålborg	14.4	18.0	16.2	16.3
Brindisi	15.7	13.1	12.1	10.8
Kinloss	8.7	11.3	9.7	9.5
Madrid	27.0	25.3	23.4	23.7
Mannheim	8.9	9.0	7.1	6.7
Orleans	14.5	14.8	12.9	12.6

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Effects of climate change on wheat production potential in the European Community

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Abstract

Wheat grain production in the main arable areas of the EC was calculated with a simulation model, WOFOST, using historical weather data and average soil characteristics. The sensitivity of the model to individual weather variables was determined. Subsequent analyses were made using climate change scenarios with and without the direct effects of increased atmospheric CO_2. The impact of crop management (irrigation and cultivar type) in a changed climate was also assessed.

Sensitivity analyses show that water-limited grain production of winter wheat increased with increasing vapour pressure, rainfall and atmospheric CO_2 concentration and decreased with increasing windspeed, temperature (except for southern EC) and solar radiation. The various climate change scenarios that were used yielded considerably different changes in production, both for each location and for the EC as a whole. For example, the average water-limited grain production in the EC may remain constant or may decrease by about 1 000 kg ha^{-1} depending on scenario. If the direct effect of increasing CO_2 is also taken into account, the average water-limited grain production in the EC increased by about 1 000 kg ha^{-1}or more. Management analyses showed that for both the present and scenario generated climates the largest water-limited grain production will be attained by cultivars with an early start of grain filling, that average irrigation requirements to attain potential grain production will increase with climate change in northern EC and decrease in southern EC, and that with both increasing CO_2 and climate change irrigation requirements in northern EC remain unchanged and decrease further in southern EC.

Key-words : climate change, winter wheat, simulation model, crop production, EC, scenario analysis.

INTRODUCTION

Since agricultural production is greatly affected by climate, any changes in climate which may result from increasing concentration of greenhouse gases in the atmosphere could have dramatic consequences for agricultural production potential. In this study the effects of climate change on the production of winter wheat in the EC (European Community) and the implications for crop management were analysed.

The relationship between climate, crop growth and production is complicated as a large number of climate, soil, landscape and crop characteristics are involved. As a result, the effects of climate change on crop production cannot be described in terms of simple and average relations between the two. In the last two decades methods have been developed for estimating the production levels of crops grown under well-specified conditions. These methods are based on the application of crop growth simulation models, combining knowledge about crop characteristics and their interactions with the environment.

Prior to evaluation of the effects of climate change the sensitivity of wheat production to separately changed weather variables was determined. To analyse the effects of climate change on the production potential of winter wheat in the EC, 20 locations, representative of the main agro-climate conditions in the EC, were chosen. The production was calculated for current and changed climate conditions, using climate change scenarios (Barrow, 1993). The direct effect of increasing atmospheric CO_2 concentrations was incorporated in the production calculations for the changed climate and the impact of changes in crop management were also determined.

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METHODOLOGY

Model description

A dynamic crop growth model WOFOST, developed for calculating agricultural production potential on the basis of physiological, physical and agronomic information, was used. This model can easily be applied to a large number of combinations of different weather data, soil characteristics and crop species. The principles underlying this model have been discussed in detail by van Keulen and Wolf (1986) and the implementation and structure have been described by van Diepen *et al.* (1988, 1989). Its application for quantitative land evaluation and for regional analysis of the physical potential of crop production has been described by van Keulen *et al.* (1987) and van Diepen *et al.* (1990) and its use for analysis of the effects of climate change on crop production has been discussed by van Diepen *et al.* (1987) and Wolf and van Diepen (1991).

In the model, crop growth is simulated from sowing to maturity on the basis of physiological processes as determined by the crop's response to environmental conditions. The simulation is carried out in time-steps of one day. The major processes considered are CO_2 assimilation, respiration, partitioning of assimilates to various plant organs, transpiration and phenological development.

Two levels of crop production are calculated. Firstly, the potential production which is determined by crop characteristics, temperature and solar radiation, and can be realized in situations where the supply of water and plant nutrients, and crop management are optimum. Secondly, the water-limited production, determined by crop characteristics, temperature, solar radiation and water availability (dictated by rainfall pattern and soil physical properties), which can be realized in situations where the supply of plant nutrients and crop management are optimum.

Available soil moisture in the root zone follows from quantification of the water balance including rainfall, surface runoff, soil-surface evaporation, crop transpiration and leaching from the root zone. If the moisture content in the root zone is too low or too high, water uptake by the plant roots is reduced, stomata close and the water-limited growth is reduced : in a dry soil due to water shortage, in a wet soil due to oxygen shortage.

Data

In order to apply the model, data that specify crop growth and phenological development are required, including information on initial crop weight, properties that determine assimilation and respiration processes and response to moisture stress, partitioning of assimilates to plant organs, life span of leaves, and death rates of plant organs. For the most part a standard crop data set was used (van Heemst, 1988). Information from field experiments in the Netherlands and UK (Darwinkel, 1985 ; Green and Ivins, 1985 ; Green *et al.*, 1985 ; Groot, 1987 ; PAGV, 1987 ; Porter *et al.*, 1987) was used to assess data specifying the rate of phenological development, the level of production and the partitioning of assimilates to the plant organs. These data were used for all locations in the EC. Comparison of model output with information on production levels and grain/straw ratios from variety trials in other countries (France, Italy and Spain) and on the rate of phenological development in all regions in Europe (Thran and Broekhuizen, 1965) indicated that this Europe-wide use of crop data was quite realistic.

The direct effect of increasing atmospheric CO_2 concentration on the CO_2 assimilation and growth of the wheat crop was incorporated into the model by increasing the maximum value and initial angle of the CO_2 assimilation — light response curve of single leaves, by increasing the thickness of leaves, and by slightly decreasing the transpiration rate. These changes in model parameters were based on studies by Allen *et al.* (1990), Goudriaan *et al.* (1984), Goudriaan *et al.* (1985), Goudriaan (1990), Goudriaan and Unsworth (1990), Goudriaan and de Ruiter (1983) and Idso (1990), and on literature surveys on crop responses to CO_2 doubling by Cure (1985), Cure and Acock (1986) and Kimball (1983).

In order to calculate CO_2 assimilation rates, daily minimum and maximum air temperatures, atmospheric CO_2 concentration and solar radiation are required (Goudriaan and van Laar, 1978). To calculate the components of the water balance, daily rainfall, windspeed and vapour pressure are also required. For example, the calculations of potential rates of evaporation and transpiration that are made with the Penman formula require data on radiation, average daily air temperature, vapour pressure and windspeed (Frère and Popov, 1979). Daily weather data for 20 meteorological stations, representative of the main arable land areas in all EC countries (Figure 1) except Greece (for which no sets of daily weather data were available), were used. For most stations the sets of historical weather data covered a period of 20 years (1966-85).

In order to calculate soil water balance, the soil's infiltration, retention and transport properties must be known. These soil physical characteristics are defined by effective soil depth, soil moisture characteristics (notably soil porosity and volumetric moisture contents at field capacity and wilting point, respectively), maximum infiltration rate or surface runoff fraction, and the hydraulic conductivity of the subsoil. For each meteorological station the main soil types that occur on arable land areas within a radius of 100 to

150 km around the station (Figure 1), were obtained from the soil map of the European Communities (CEC, 1985). This map gives information per unit on soil type, texture class, characteristics such as gravelliness, stoniness, shallow rocks etc., and slope gradient. By interpreting this information (mainly based on King and Daroussin, 1989 and Reinds *et al.*, 1992) quantitative terms for use in the simulation model could be obtained : fraction of precipitation lost by surface runoff, maximum effective rooted soil depth (≤ 100 cm for winter wheat) and available volumetric moisture content in the soil. Areas with a slope gradient of more than 15 per cent. were left out, as being too steep for arable farming. For all soil types the ground water table was assumed to be at such a depth that it did not influence the water balance and that excess water drained rapidly to the subsoil, so that growth reduction due to oxygen shortage did not occur.

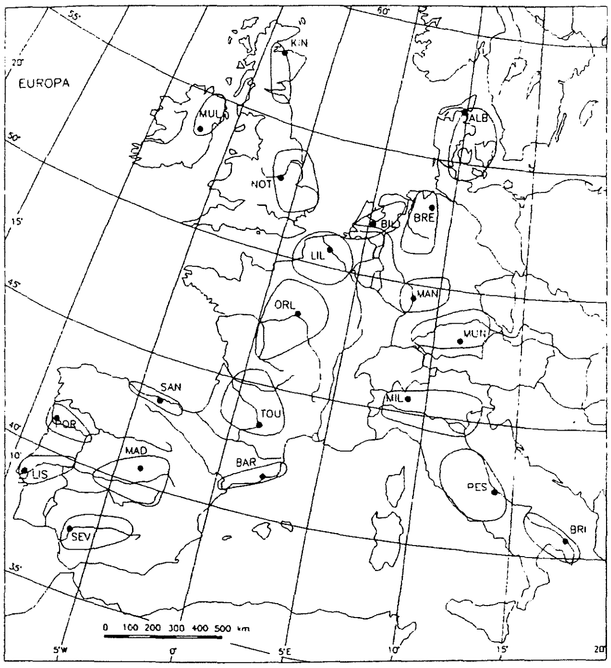


Figure 1. *Sets of historical weather data used for calculating the wheat production potential in the EC, were available for the following meteorological stations : Kinloss and Nottingham in the U.K. ; Mullingar in Ireland ; Ålborg in Denmark ; de Bilt in the Netherlands ; Bremen, Mannheim and München in Germany ; Lille, Orleans and Toulouse in France ; Santander, Barcelona, Madrid and Sevilla in Spain ; Porto and Lisbon in Portugal ; Milan, Pescara and Brindisi in Italy. Data for each station can be considered representative of the arable land area around that station, as roughly indicated (exclusive of areas of sea, wetlands, mountains etc.).*

Model validation

Potential grain production was calculated for weather data from Wageningen and de Bilt (about 40 km west of Wageningen), the Netherlands, over the period 1980-88. Going back in time from 1980, grain production from field trials appeared to decrease rapidly with time as a result of less optimum crop management and less productive crop varieties. Therefore, these production data could not be used for comparison with calculated grain production. Calculated potential grain production levels were compared with actual results from variety trials (Figure 2) that were carried out over the period 1980-88 in Randwijk (in the neighbourhood of Wageningen) and in Wieringerwerf (about 130 km north of Wageningen), both on clay soils with a relatively high groundwater level and no water shortage in summer.

The comparison showed that the calculated variation in grain production over time was much smaller than the variation in grain production found in the variety trials. In years with a high level of solar radiation during grain filling, actual grain production was relatively large. In those years losses by diseases mainly associated with ripening (fungi such as mildew) were limited and hence calculated and actual grain production levels were comparable. In years with abundant rainfall and a low level of solar radiation during grain filling both calculated and actual grain production levels were relatively low. However, grain production levels in variety trials were found to be 10 to 20 per cent lower than calculated ones, which has to be explained by the considerable losses due to ripening diseases in those wet years. Unfortunately, the production-reducing effects of diseases could not be calculated with the crop growth simulation model.

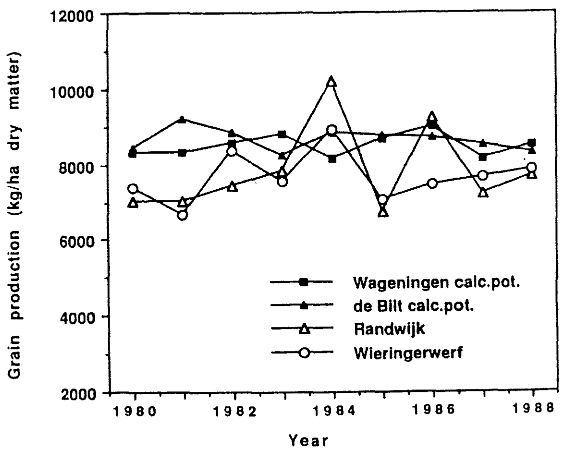


Figure 2. *Potential grain production of winter wheat calculated for Wageningen and de Bilt, Netherlands and actual grain production from variety trials on clay soils in the Netherlands.*

RESULTS

Baseline

Potential production was about 9 000 kg ha^{-1} dry matter of grain. Higher grain production levels were calculated for locations where the level of solar radiation was high during grain-filling and the average temperature was relatively low, which resulted in a long period of grain-filling. On the other hand, lower production levels were calculated for locations with higher temperatures and less solar radiation. This explains the relatively large production in Lisbon and Porto and the relatively small production in Milan and Madrid (Table 1). Water-limited grain production varied widely among locations and also among cultivated soil types. Largest production was found at locations with a relatively large ratio between precipitation and potential evapo-transpiration and a large amount of available soil moisture. By lowering the amount of available soil moisture (e.g. sandy, gravelly and/or shallow soils instead of deep, loamy or clay soils) water-limited grain production often decreased greatly.

Table 1. *Duration of grain filling (days) and average potential grain production for winter wheat (kg ha^{-1} dry matter).*

Location	Period of grain filling	Grain production
Milan	40	7770
Madrid	42	8720
Lisbon	50	10420
Porto	53	11130

For each location average soil characteristics were calculated from the characteristics of each soil type and in proportion to its relative area. Water-limited grain production levels, calculated for average soil characteristics, were similar to average grain production levels calculated for the various soil types per location, with a difference of 10 per cent at most. To limit the number of calculations and results, the subsequent sensitivity, scenario and management analyses were done for these average soil characteristics.

Sensitivity analyses

Sensitivity analyses were carried out for three locations representative of the main differences in climate in the EC : Kinloss in the UK (cool temperate), Orleans in France (continental), and Brindisi in Italy (Mediterranean). For each location, calculations were made using historical weather data for a period of 20 years. Data for one weather variable were varied separately, while others were held constant. Weather variables that determine crop production directly are solar radiation and temperature. Those that affect the water balance and hence the duration and degree of drought stress are rainfall, windspeed, vapour pressure, solar radiation and temperature. Atmospheric CO_2 concentration also has direct and indirect effects on crop production. These variables were adjusted separately, in a stepwise manner, in order to gauge the sensitivity of crop production to changing values of each.

Table 2 summarizes the sensitivity of potential and water-limited grain production to changing values of each weather variable. Potential grain production increased with increasing atmospheric CO_2 and solar radiation, and generally decreased with rising temperatures. Potential production was not influenced by the water balance and was thus insensitive to changes in windspeed, vapour pressure and rainfall. Water-limited production increased with increasing atmospheric CO_2, rainfall and vapour pressure, and decreased with increasing solar radiation, temperature (except for Brindisi) and windspeed.

Table 2. *Sensitivity of potential (POT) and water-limited (WAT) grain production of winter wheat at Kinloss in UK, Orleans in France, and Brindisi in Italy to increasing values of atmospheric CO_2 concentration (C), temperature (T), rainfall (R), solar radiation (S), windspeed (W) and vapour pressure (V)*[1].

	C	T	R	S	W	V
POT	++	– –, 0[2]	0	+, ++	0	0
WAT	++	– –, +[3]	++	–	– –	++

[1] 0, +, ++ : no, moderate, strong increase in grain production ; –, – – : moderate, strong decrease in grain production.
[2] Temperature effect varies from about zero in Kinloss to strongly negative in Brindisi.
[3] Temperature effect varies from strongly and moderately negative in Kinloss and Orleans respectively to moderately positive in Brindisi.

Scenario analyses without direct CO_2 effect

Composite time-dependent scenarios

Potential and water-limited grain production levels of winter wheat were calculated for historical weather data that were changed on the basis of composite scenario A (based on the business-as-usual emission scenario of Houghton *et al.* (1990)) for the years 2010, 2030 and 2050, and composite scenario A High (high estimate of scenario A) for the year 2050. These changes, as described by Barrow (1993), were specified per day over a period of one year. For precipitation and temperature the changes were location-specific. For solar radiation and vapour pressure only one set of changes was supplied for all locations, and for windspeed no changes could be made (Barrow, 1993).

Potential production in northern EC, e.g. in Kinloss, UK, increased slightly up to year 2030 (Figure 3), mainly due to rising temperatures. In southern EC, e.g. in Brindisi, Italy, potential production levels generally decreased over time, because rising temperatures advanced the period of grain-filling to a time of year with shorter days and lower solar elevation.

Water-limited production decreased over time at most locations, probably because rising temperatures caused larger water losses by soil evaporation and crop transpiration. However, these decreases in production were limited in magnitude (Figures 3 and 4). Weather conditions during the period of grain filling were influenced not only by the direct effects of climate change (as specified by the scenarios), but also considerably by the shift in time of the grain-filling period as a result of the changed climate. For example, at locations with dry summers such as Brindisi and Pescara, water-limited production was calculated to increase with time (Figures 3 and 4). The period of grain filling was advanced to a time of higher precipitation which resulted in increased grain production.

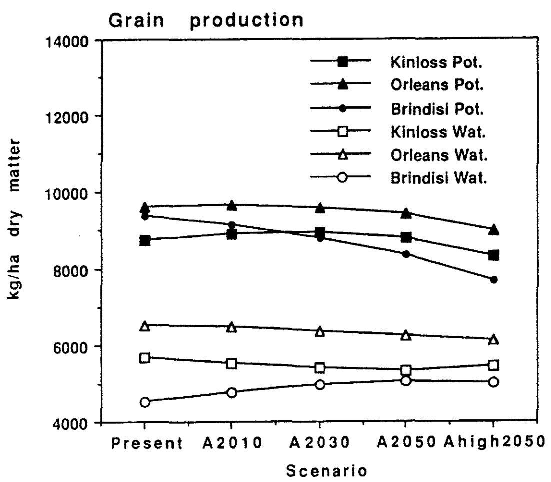


Figure 3. *Average potential (Pot.) and water-limited (Wat.) grain production of winter wheat cultivated at current and at future weather conditions in Kinloss, UK ; Orleans, France ; and Brindisi, Italy (direct effect of increasing atmospheric CO_2 in future not taken into account). Production has been established for historical weather data over a period of 20 years (1966-1985), for composite scenario A for the years 2010, 2030 and 2050, and for composite scenario A High for the year 2050.*

Individual GCM scenarios

Potential and water-limited grain production levels of winter wheat were also calculated for historical weather data that were changed on the basis of output from three equilibrium $2 \times CO_2$ general circulation models (GCMs), i.e. the GFDL, the GISS and the UKMO-L (low resolution) models. These changes, as described by Barrow (1993), were specified per day over a period of one year for each weather variable and were location-specific.

Potential grain production decreased at almost all locations for the changed weather data (Table 3), mainly due to higher temperatures. The lowest production level was generally calculated for the UKMO-L scenario, which tends to give the largest temperature increase, or for the GFDL scenario, which gives slightly smaller temperature increases but often combined with a decrease in the amount of radiation in winter and/or spring. The temperature increase given in the GISS scenario is generally the smallest. For the latter scenario the level of grain production was higher than for the other two scenarios, but generally lower than that for unchanged historical weather data.

Changes in temperature and radiation based on the scenarios influenced water-limited grain production in the same way as they influenced potential grain production (Table 3). The interaction between these changes and changes in the other weather variables is

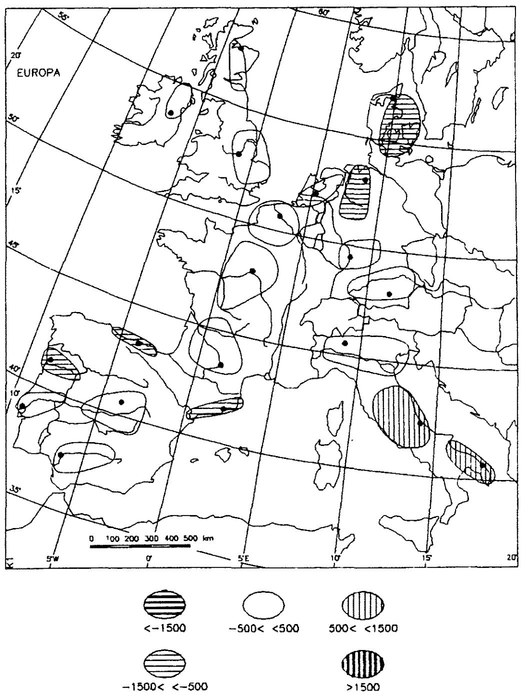


Figure 4. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of composite scenario A for the year 2050. Direct effect of increasing atmospheric CO_2 was not taken into account.*

Table 3. *Average potential (POT) and water-limited (WAT) grain production (kg ha⁻¹ dry matter) of winter wheat established for historical weather data that were changed on the basis of GFDL, GISS and UKMO-L equilibrium 2 × CO_2 scenarios, with and without the direct effect of increased CO_2 (353 ppm → 560 ppm).*

Location	Historical weather	Scenario					
		GFDL		GISS		UKMO-L	
		− CO_2	+ CO_2	− CO_2	+ CO_2	− CO_2	+ CO_2
Brindisi POT	9370	6080	8360	5970	8180	5380	7530
Brindisi WAT	4510	5340	7350	5440	7410	4820	6690
Kinloss POT	8740	3110	3840	7680	9620	6540	8430
Kinloss WAT	5680	3110	3840	6990	8950	5670	7510
Orleans POT	9630	7850	10510	8380	11100	6620	8910
Orleans WAT	6510	6940	9350	5520	7700	6020	8120

very complex. In addition, the changes varied considerably among locations and over the year. Hence, simple and straightforward explanations of their effects on grain production cannot be derived. The GFDL scenario gave major decreases in water-limited grain production in the UK, Ireland, northern Spain, Portugal and northern Germany that can mainly be explained in the same way as the decrease in potential production via the higher temperatures and the lower level of radiation, while the moderate to major increase in central and southern Italy was probably due to relatively larger amounts of rainfall during the advanced period of grain-filling (Figure 5). The GISS scenario (smallest temperature increase) gave moderate decreases in production for Ireland, northern Germany, northern and central France, northern Spain and northern Portugal (Figure 6) and mainly moderate increases for Scotland, Denmark, central and eastern Spain and central and southern Italy. The UKMO-L scenario (highest temperature increase) gave major decreases in production for Ireland, England, northern Germany, northern and southern France, northern Spain and northern Portugal (Figure 7), and moderate decreases for central and southern Germany, northern Italy, eastern and southern Spain and central Portugal.

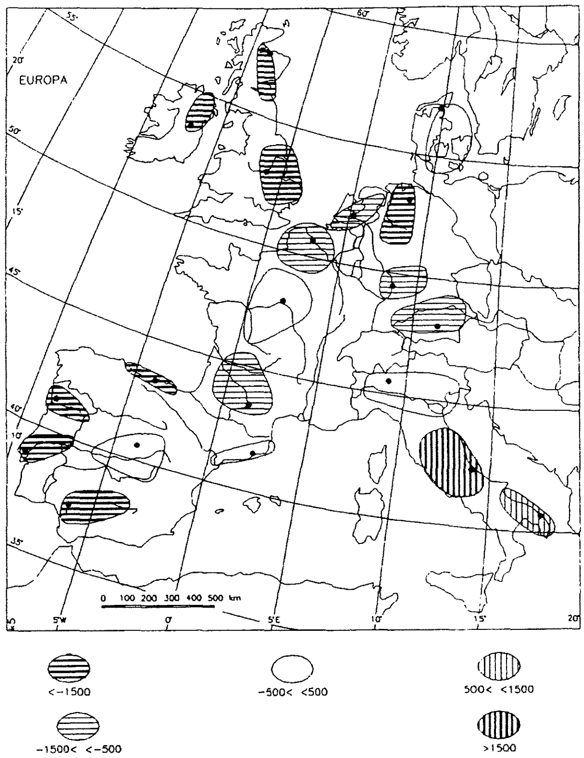


Figure 5. *Changes in water-limited grain production (kg ha⁻¹ dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of the GFDL equilibrium 2 × CO_2 scenario. Direct effect of increased CO_2 was not taken into account.*

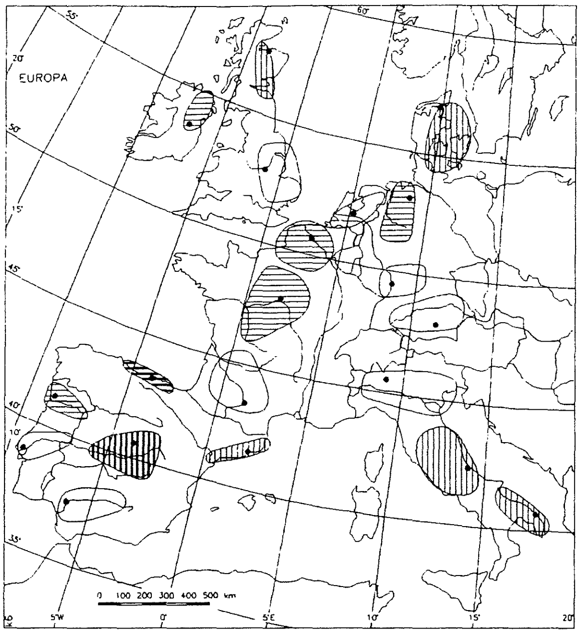
Scenario analyses with direct CO_2 effect

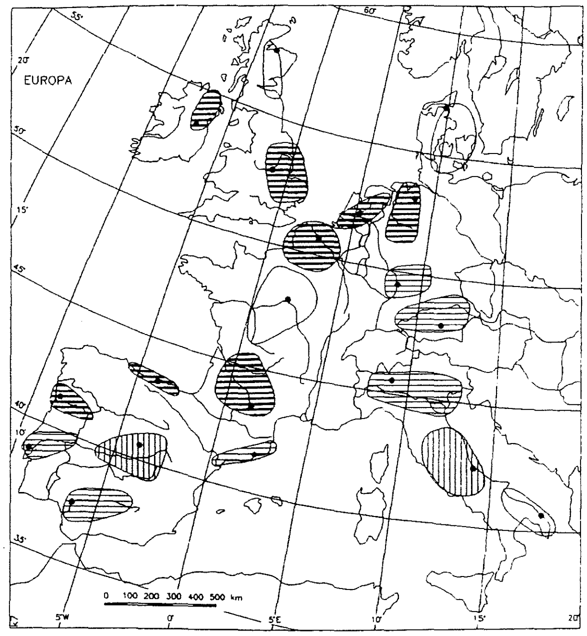
Composite time-dependent scenarios

In these analyses the direct effect of increasing atmospheric CO_2, which results mainly in a higher CO_2 assimilation rate and thus larger crop production and in a somewhat lower transpiration rate, was taken into account. Potential production levels increased greatly over time at all locations, mainly due to increasing CO_2 (Figures 3 and 8). For water-limited production the same applied. For scenario A High for year 2050, which shows the largest increase in temperature, the increase in production was generally somewhat less than that for scenario A for the same year. The smallest relative increases in production were calculated for Denmark, northern Germany and Spain (Figure 9).

Individual GCM approach

In these analyses the effects of the GFDL, GISS and UKMO-L scenarios of climate change and of





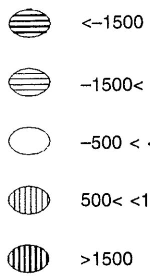


Figure 6. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of the GISS equilibrium $2 \times CO_2$ scenario. Direct effect of increased CO_2 was not taken into account.*

Figure 7. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of the UKMO-L equilibrium $2 \times CO_2$ scenario. Direct effect of increased CO_2 was not taken into account.*

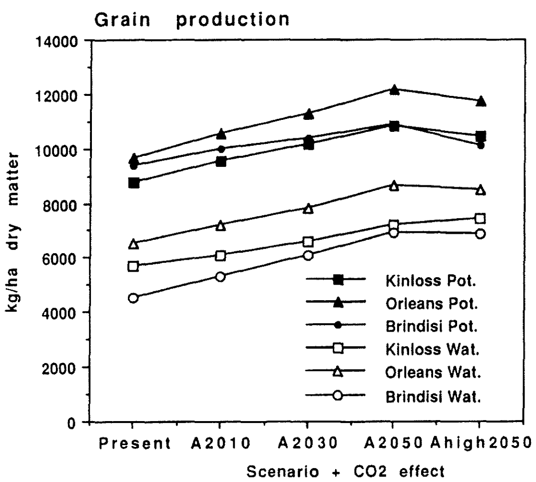


Figure 8. *Average potential (Pot.) and water-limited (Wat.) grain production of winter wheat cultivated at current and future weather conditions in Kinloss, UK; Orleans, France; and Brindisi, Italy, taking into account the direct effect of increasing atmospheric CO_2 in future. Production has been established for historical weather data over a period of 20 years (1966-85), for composite scenario A for the years 2010, 2030 and 2050, and for composite scenario A High for the year 2050.*

increasing CO_2 concentration (from 353 to 560 ppm) were taken into account. Increasing CO_2 resulted in an increase in potential grain production while the change in climate alone generally caused a decrease compared to production under the historical climate (Table 3). Hence, if the effect of the climate change scenario is larger, potential production will decrease, and if the direct effect of atmospheric CO_2 is larger, potential production will increase. The largest potential grain production was calculated generally for the GISS scenario which gives the smallest temperature rise and the smallest, generally, for the UKMO-L scenario and the GFDL scenario only at locations where radiation became limiting (e.g. Kinloss).

The GFDL scenario gave major decreases in water-limited grain production for Ireland, Scotland and northern Spain, due to an earlier start in spring (low radiation level) as a result of higher temperatures, and a reduced amount of solar radiation according to the scenario (Figure 10). Moderate production decreases were calculated for England, Portugal and southern Spain with constant productions for northern Germany and the Netherlands. At the other locations major increases in water-limited grain production were found as a result of the direct CO_2 effect. The GISS scenario gave major increases in water-limited grain pro-

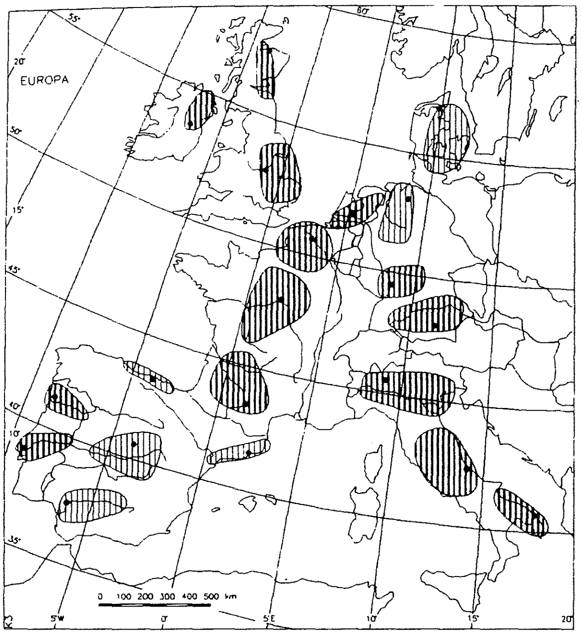
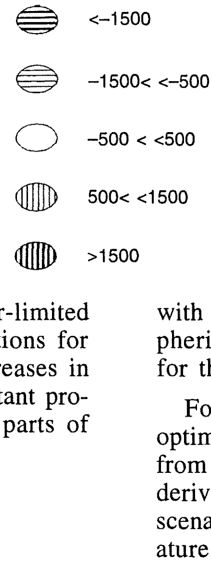


Figure 9. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather was changed on the basis of the composite scenario A for the year 2050 and the direct effect of increased atmospheric CO_2 was taken into account.*



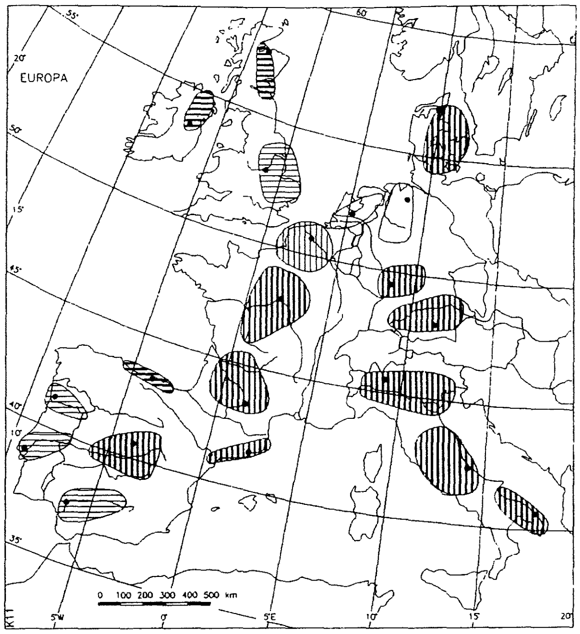


Figure 10. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather was changed on the basis of the GFDL equilibrium 2 × CO_2 scenario and the direct effect of increased CO_2 was taken into account.*

duction for most locations (Figure 11). Water-limited grain production also increased at most locations for the UKMO-L scenario. Exceptions were decreases in northern Spain, Ireland and England and constant production in the Netherlands and the northern parts of Portugal, France and Germany (Figure 12).

Management analyses

Crop temperature sums

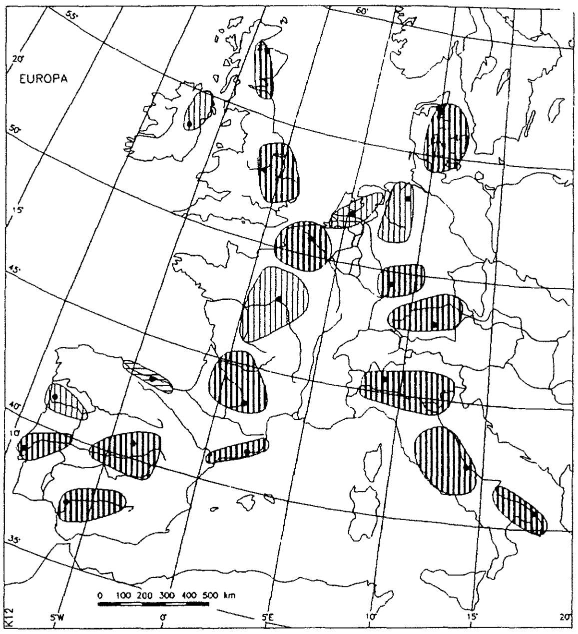
The interactions between the temperature sum required for crop development and the effects of climate change and increasing atmospheric CO_2 were determined for the locations Kinloss, Orleans and Brindisi. It was assumed that, compared to the main wheat varieties grown at present, plant breeding might be able to produce varieties requiring 10 per cent greater or 10 per cent smaller temperature sums (°C days) for crop development until anthesis and from anthesis to the end-of-grain filling. For the average wheat variety grown at present and for these artificially constructed wheat varieties, average grain production was calculated for historical weather data, for the composite scenario A for the year 2050, both with and without the direct effect of increased atmospheric CO_2, and for the composite scenario A High for the year 2050 with the direct CO_2 effect.

For both potential and water-limited production optimum temperature sums until anthesis (T-anth) and from anthesis to the end-of-grain filling (T-ripe) were derived for the three locations for both historical and scenario weather data. The resulting optimum temperature sums are summarized in Table 4.

From these results it can be concluded that the largest potential production in changed climate, particularly that on the basis of scenario A High, will be attained with wheat varieties that need increased temperature sums for grain filling and hence have a longer period of grain filling. The largest water-limited production under projected future and also current conditions will be attained with wheat varieties that need smaller temperature sums until anthesis and hence have an early start to grain filling.

Irrigation requirements

The amount of irrigation water required to prevent drought stress during the growth of winter wheat and to attain the potential level of grain production in the



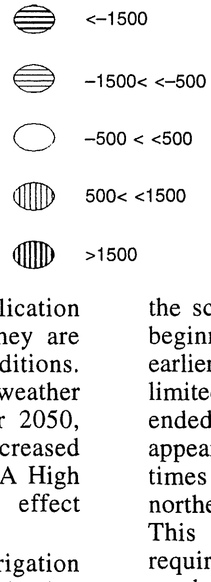


Figure 11. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather was changed on the basis of the GISS equilibrium 2 × CO_2 scenario and the direct effect of increased CO_2 was taken into account.*

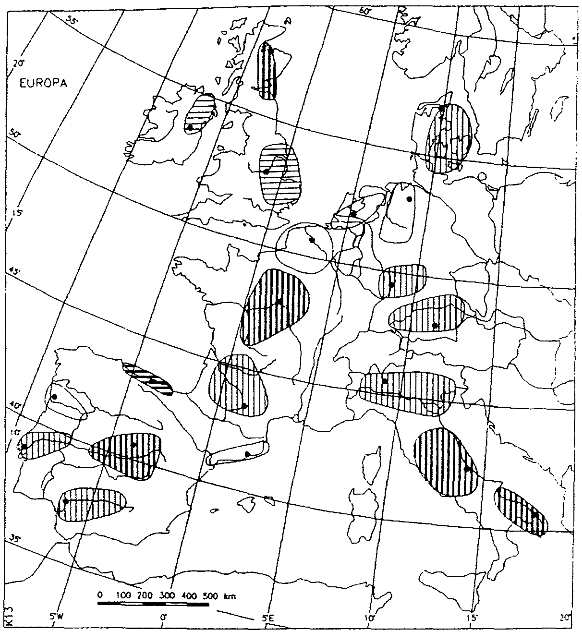


Figure 12. *Changes in water-limited grain production (kg ha^{-1} dry matter) of winter wheat in the main arable land areas in the EC if the weather was changed on the basis of the UKMO-L equilibrium 2 × CO_2 scenario and the direct effect of increased CO_2 was taken into account.*

EC, was calculated. Conveyance and application losses are not included in the amount, as they are widely variable and dependent on local conditions. The calculations were made using historical weather data, the composite scenario A for the year 2050, both with and without the direct effect of increased atmospheric CO_2, and the composite scenario A High for the year 2050 with the direct CO_2 effect (Table 5).

Scenario A 2050 resulted in larger irrigation requirements in northern EC, but in smaller irrigation requirements in southern EC (Table 5). According to the scenario, temperatures will become higher so the beginning of crop growth in spring was shifted to an earlier date, particularly in northern EC and to a more limited extent in southern EC. Moreover, grain filling ended earlier. Therefore, a rise in temperature appeared to result in a shifted and constant, or sometimes even longer, period of 'effective' growth in northern EC and in a shorter period in southern EC. This explains the larger water use and irrigation requirements in northern EC and the smaller ones in southern EC. Increasing atmospheric CO_2 resulted in more efficient water use. This effect of CO_2 roughly

Table 4. *Optimum crop temperature sums (as a percentage of average temperature sums for present varieties) until anthesis (T-anth) and from anthesis to the end of grain filling (T-ripe) for Kinloss in Scotland, Orleans in France and Brindisi in Italy for historical and scenario weather data.*

Weather	Potential production T-anth & T-ripe[1]	Water-limited production T-anth & T-ripe[1]
Historical weather	100 % & 110 %, 90 % & 100 %	90 % & 100 %, 90 % & 90 %
Scenario A2050	100 % & 110 %, 100 % & 100 %, 110 % & 110 %[2]	90 % & 100 %, 90 % & 90 %
Scenario A2050 + CO_2 effect	100 % & 110 %, 100 % & 100 %, 110 % & 110 %[2]	90 % & 100 %, 90 % & 90 %
Scenario A High 2050 + CO_2 effect	100 % & 110 %, 110 % & 110 %, 100 % & 100 %[3]	90 % & 100 %, 90 % & 90 %

[1] Best temperature sums indicated first (starting from the left side), followed by second best sums.
[2] Only in Brindisi, Italy.
[3] Only in Orleans, France.

counteracted the increased water use and irrigation requirements in northern EC which resulted from climate change, and which caused a larger decrease in the irrigation water required in southern EC.

CONCLUSIONS

Sensitivity analyses showed that water-limited grain production of winter wheat increased greatly with increasing vapour pressure, rainfall and atmospheric CO_2 concentration, decreased greatly with increasing windspeed, and decreased moderately with increasing solar radiation and temperature, except for southern EC where there was a slight increase with rising temperature.

Increasing concentration of greenhouse gases in the atmosphere may cause changes in climate. Various climate change scenarios appeared to yield considerably different changes in production both for each location and for the EC as a whole. For example, for the equilibrium $2 \times CO_2$ scenarios (without a direct effect of CO_2), the average grain production of winter wheat in the EC remained roughly constant for the GISS scenario but decreased by about 1 000 kg ha^{-1} dry matter for the UKMO-L scenario.

The direct effect of increasing atmospheric CO_2 on wheat grain production appeared to be much greater than the effect of climate change. Moreover, the direct effect of CO_2 on production is more certain, whereas the effect of climate change is widely variable depending on the scenario and not yet established as fact. If both effects are taken into account, the average grain production of winter wheat in the EC increases by 1 000 kg ha^{-1} dry matter or more for the equilibrium $2 \times CO_2$ scenarios.

With climate change the highest level of potential production will generally be attained with wheat varieties that have larger temperature sum requirements for grain filling and hence a longer period of grain filling. If drought occurs at the end of the grain filling period, wheat varieties with smaller temperature sum requirements until anthesis, and hence an early start to grain filling, may yield the largest grain production, in both a current and a changed climate.

Irrigation requirements for attaining the potential level of wheat production increased at locations in northern EC with the climate changed on the basis of the composite scenario for the year 2050, and in southern EC they decreased. When the direct effect of increasing atmospheric CO_2 was also taken into account, this counteracted the increased irrigation requirements in northern EC and caused a larger decrease in required irrigation water in southern EC.

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Table 5. *Required average amounts of irrigation water (cm) for attaining the potential level of grain production for winter wheat at six locations in the EC for historical weather data and for scenario weather data with and without direct CO_2 effect.*

Location	Historical weather	Scenario A 2050	Scenario A 2050 + CO_2	Scenario A High 2050 + CO_2
Ålborg	14.4	18.0	16.2	16.3
Brindisi	15.7	13.1	12.1	10.8
Kinloss	8.7	11.3	9.7	9.5
Madrid	27.0	25.3	23.4	23.7
Mannheim	8.9	9.0	7.1	6.7
Orleans	14.5	14.8	12.9	12.6

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