EFFECTS OF CLIMATE CHANGE ON GRAIN MAIZE YIELD POTENTIAL IN THE EUROPEAN COMMUNITY *

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Abstract. Grain maize yield in the main arable areas of the European Community (E.C.) 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 (sowing date, irrigation and cultivar type) in a changed climate was also assessed. Scenario climate change generally results in larger grain yields for the northern E.C., similar or slightly smaller yields for the central E.C. and considerably smaller yields for the southern E.C. The various climate change scenarios used appear to give considerably different changes in grain yield, both for each location and for the E.C. as a whole. Management analyses show that for both current and scenario climates the largest grain yield will be attained by varieties with an early start of grain filling, that average irrigation requirements to attain potential grain yield in the E.C. will increase with climate change but will decrease with both increased CO_2 and climate change, and that sowing at both current and scenarios climate should occur as early as possible.

1. Introduction

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

Grain maize is at present grown in the central and southern E.C. up to its northern thermal limit. About 85% of the total grain maize acreage in the E.C. is found in France, Italy and Spain. The total E.C. grain maize acreage has increased slightly (about 5%) over the last 20 years, mainly because of increasing acreages in Spain, Germany and Greece. The average level of grain maize yields has increased rapidly, for example over a ten-year period (1979–1988) from 5220 to 7320 kg/ha in France, from 6620 to 7550 kg/ha in Italy and from 4850 to 6430 kg/ha in Spain. Maize is also grown for silage for animal feeding. As silage maize is harvested

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before grain maturity, the growth cycle of such maize requires smaller temperature sums. This explains why silage maize production occurs mainly in the northern and central E.C. countries, where animal production is of importance. The distribution of varieties depends on the temperature sums during the growth cycle of the maize crop. Early varieties are grown in the central E.C.and late varieties in the southern E.C. In the southern E.C. maize is often sown as a second crop after a forage or winter grain crop (Bignon, 1990). This is impossible in the central E.C. because temperature sums are too small during the growing season. More information on current production areas of grain maize, yield levels, maize varieties used, crop physiology, sowing dates and crop management can be found in an overview on grain maize production in the E.C. by Bignon (1990).

Expansion of grain maize production to the northern E.C. might occur in the future should temperatures rise. Using minimum temperature sums required for physiological ripening of grain maize, a northern limit to grain production in the E.C. has been calculated and mapped by Carter *et al.* (1991), Kenny and Harrison (1992), and Kenny *et al.* (1993a) for current and scenario climate conditions. Future climate conditions according to different scenarios indicated a significant expansion of the northern thermal limit of suitability for grain maize production. In the southern E.C. the main climatic constraint to grain maize production is lack of water. Therefore, high yield levels of grain maize in the southern E.C. can only be attained if sufficient irrigation water can be supplied, particularly if maize follows a winter crop. In a Europe-wide study the effects of water shortage on current and future grain maize production have been analysed with a water balance model (Kenny and Harrison, 1992; Kenny *et al.*, 1993a).

The relationship between climate, crop growth and yield is complicated since a large number of climate, soil, landscape, management and crop characteristics are involved. In addition, crop growth mainly appears to respond to changing conditions in a non-linear way (Nonhebel, 1994). For example, this non-linearity may lead to a lower maize yield, both in situations where the average temperature rises and where the average temperature remains similar but its variability increases (Semenov *et al.*, 1993b). As a consequence, the effects of climate change on crop yield 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 yield 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. In this way the effects of climate change in the U.S. on the yields of a large number of crops, such as wheat, maize, soybean and alfalfa, and the efficacy of management responses to climate change have been calculated and examined (Adams *et al.*, 1990; Cooter, 1990; Easterling *et al.*, 1992a,b; Wilks, 1988). For E.C. agriculture only the effects of climate change on the yields of spring wheat (Nonhebel, 1993) and winter wheat (Semenov *et al.*, 1993a; Wolf, 1993) have been analysed.

Prior to evaluation of the effects of climate change, the sensitivity of grain maize yields was determined for weather variables changing independently. To analyse the effects of climate change on the yield potential of grain maize in the E.C. 20 locations, representative of the main agro-climate conditions in the E.C., were chosen. The yield 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 yield calculations for changed climate. The impact of changes in crop management was also determined.

2. Methodology

2.1. MODEL DESCRIPTION

A dynamic crop growth model WOFOST, developed for calculating agricultural yield 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 yield has been discussed by Van Diepen *et al.* (1987) and Wolf and Van Diepen (1991).

The model simulates crop growth from sowing date 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 yield are calculated. Firstly the potential yield, which is determined by crop characteristics, temperature and solar radiation and which can be realized in situations where the supply of water and plant nutrients, and crop management are optimum. Secondly the water-limited yield, which is determined by crop characteristics, temperature, solar radiation and water availability (dictated by precipitation pattern and soil physical properties), and which can be realized in situations where the supply of plant nutrients and crop management are optimum. This means that a number of factors that limit or reduce yields, such as nutrient supply or infestation by pests and diseases, are not taken into account in the calculations.

Available soil moisture in the root zone follows from quantification of the water balance including precipitation, 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 because of water shortage, in a wet soil because of oxygen shortage.

Grain yield of maize is particularly sensitive to drought during flower initiation, tasseling and silking. If severe drought occurs during these phenological stages, the number of grains and hence the maximum grain yield are reduced. Based on data from the literature (Bloc *et al.*, 1978; Claassen and Shaw, 1970; Denmead and Shaw, 1960; Shaw, 1977) a maximum level for the final grain yield has been included in the standard model version. This maximum level decreases if the number of days with drought stress during the sensitive stages increases, and it becomes zero if the average transpiration rate during this period is less than or equal to half the average potential transpiration rate.

The model takes into account the direct effect of increasing atmospheric CO_2 on the growth and transpiration of the crop. For C4 plants such as maize and other tall tropical grasses such as millet, sorghum and sugar cane, the photosynthetic response to CO_2 is only very steep for atmospheric CO_2 concentrations well below the current level. In the present and also the future range of atmospheric CO_2 concentrations (e.g., 300 to 1000 μmol/mol), the rate of CO_2 assimilation practically does not change at increasing CO_2, even under high light intensities (Goudriaan and Unsworth, 1990). But, concurrently, the transpiration rate of the maize crop strongly decreases. Literature reviews by Cure (1985) and Cure and Acock (1986) indicated a decrease in stomatal conductance by 40% and a decrease in transpiration by 28% for maize at doubled atmospheric CO_2 and high light conditions. The reduction of the transpiration by maize at doubled CO_2 was calculated in a study with a stratified micrometeorological model (Goudriaan, 1977; Chen, 1984). If the stomatal conductance at doubled CO_2 was reduced by 45%, this resulted in a reduction of the transpiration by 26% if both the effects of increasing leaf temperature and decreasing air humidity in the canopy were taken into account (Goudriaan and Unsworth, 1990). As this micrometeorological feedback was not included in the method applied for calculating the rate of transpiration (i.e., Penman formula), calculated transpiration rates were reduced by an overall factor. This reduction factor increased with increasing CO_2 and was set at 26% for a doubled CO_2 concentration.

2.2. 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). Data from the literature and field experiments (Alblas *et al.*, 1987; Bignon, 1990; Bloc *et al.*, 1978; Derieux and Bonhomme, 1982; Efdé, 1990; Sibma, 1987)

TABLE I

Temperature sums (°C × days) for phenological development from emergence to silking (T-silk) and from silking to ripening[1] (T-ripe) for the grain maize varieties used in the model calculations. Data collected from information from Bignon (1990), Bloc *et al.* (1978, 1984), and Derieux and Bonhomme (1982)[2].

Maize variety	T-silk	T-ripe
Very early	695	775
Early	775	825
Late	855	880
Very late	935	930

[1] Model calculations are stopped at ripening which corresponds with the moment that the moisture content in the grains is 35 to 40%. In southern Europe maize crops often remain in the field for longer periods to allow further drying of grains.
[2] Sum of temperatures above a base temperature of 6 °C.

were used to assess the rate of phenological development that determines the dates of silking and maturity, the partitioning of assimilates to the plant organs that determines the grain/straw ratio, and the effective growth duration that determines the yield level.

Sowing of grain maize should occur as early as possible to attain a high grain yield because of the limited duration of the growing season. Advancement of sowing, however, is limited in the northern and central E.C. by the warming of the soil in spring, which mainly depends on the course of air temperature in spring and the soil moisture content. Actual dates of sowing in Germany, the Netherlands and northern France are generally the end of April or the beginning of May (Alblas *et al.*, 1987; Bignon, 1990). For the model calculations sowing was set at day 120 (April 30) at all locations in the northern and central E.C. Two to three weeks later crop emergence occurs. In the southern E.C. sowing can be shifted to an earlier or a later date than day 120 because of the longer growing season. In practice mainly the crop rotation appears to determine the sowing date. For example in central and southern Italy, sowing of maize after a fodder crop is postponed to between early May and early June (Bignon, 1990). As in most areas of the southern E.C. sowing appears to occur on average at the end of April or the beginning of May (Bignon, 1990), the sowing date used in the model calculations was also set at day 120, except Seville (southern Spain). Here the sowing date is set at day 70 which appears to be more appropriate, in connection with the prevention of red spider attacks (Bignon, 1990).

Four maize varieties were used for the yield calculations of grain maize in the E.C. They differed only with respect to their rate of phenological development, as determined by temperature sums (Table I). Although photoperiod sensitivity may

Fig. 1. Sets of historical weather data used for calculating the grain maize yield potential in the E.C., 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 Seville 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 (excluding areas of sea, wetlands, mountains, etc.).

also influence the development rate, in the calculations it was assumed that the maize varieties used were well adapted to regional conditions and hence development rates could be based on temperature sums alone. For locations in the northern and central E.C. very early and early varieties were used in the calculations and for locations in the southern and extremely southern E.C., late and very late varieties. If the climate changes, in reality the varieties grown may also change. In this analysis, however, the varieties used remain identical in a changed climate.

In order to calculate CO_2 assimilation rates, daily minimum and maximum air temperatures, and solar radiation are required (Goudriaan and Van Laar, 1978). To calculate the components of the water balance, data on daily precipitation, windspeed, vapour pressure, and atmospheric CO_2 concentration 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 E.C. 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 (1966–1985) except for Barcelona, Madrid, Lisbon, Santander and Seville (for which weather data for the time periods 1976–1988, 1975–1989, 1970–1989, 1975–1989 and 1975–1987, respectively have been used).

In order to calculate the 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 depth to bedrock, 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 effectively rooted soil depth ($\leq$ 100 cm for maize) and available volumetric moisture content in the soil. Areas with a slope gradient of more than 15% were left out as they are too steep for arable farming. For all soil types the groundwater table was assumed to be at such a depth that it does not influence the water balance and that excess water may drain rapidly to the subsoil, so that growth reduction due to oxygen shortage does not occur.

2.3. MODEL VALIDATION

Potential grain yields were calculated for weather data from Wageningen, the Netherlands and Toulouse, France over the periods 1983–1990 and 1985–1986, respectively. The calculated yield was compared with actual results from variety trials (Figure 2) that were carried out in the same years and at the same locations. Maize growth at both locations has probably not suffered from water shortage during the summer because of a relatively high groundwater level in Wageningen and irrigation in Toulouse. Hence, these field results are comparable with the calculated potential yields.

The comparison showed that the calculated average grain yield and the variation in grain yield over time are nearly the same as those actually found in the variety

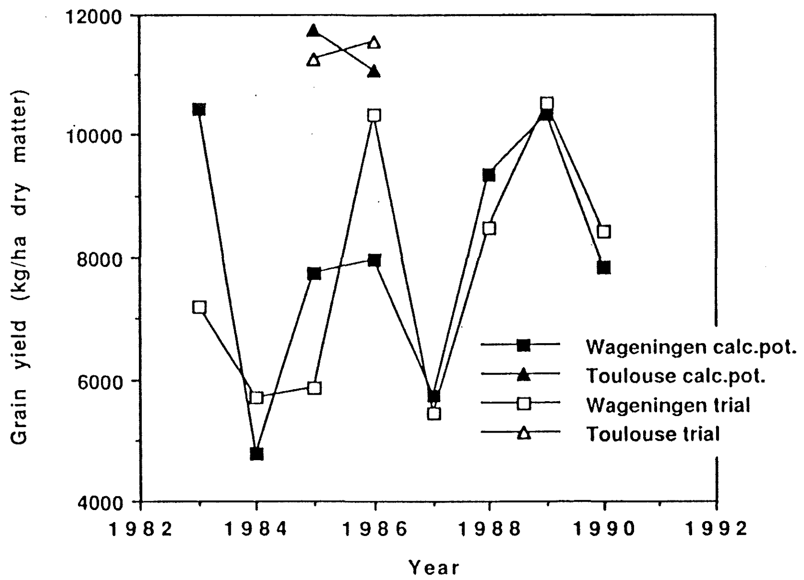

Fig. 2. Potential grain yield of maize calculated for Wageningen, Netherlands, and Toulouse, France, and actual grain yield from variety trials at the same locations.

trials. However, for unknown reasons the correspondence between calculated and actual yields in Wageningen is much less during the first years of the variety trials than during the later years. As the grain maize variety trials in Wageningen started in 1980, crop management during the first years was perhaps less optimum and reduced the yield level attained. In years with a relatively high cumulative temperature sum during the growing season in Wageningen, both calculated and actual levels of grain yield appeared to be relatively high. Hence, the variation in cumulative temperature sum was the main cause of the large annual variation in grain yield in Wageningen, which is a result of the fact that Wageningen is on the northern margin of the area where grain maize production is currently possible.

3. Results

3.1. BASELINE

Potential yield is about 10 000 kg/ha dry matter in grains if temperatures in summer are not too low. Higher grain yield levels are calculated for locations where the level of solar radiation is high during grain filling and the average temperature is relatively low, which results in a long period of grain filling. On the other hand, lower yield levels are calculated for locations with higher temperatures and less solar radiation. This explains the relatively large yields in Orleans and Porto and the relatively small yields in Brindisi and Madrid (Table II). If identical maize varieties were used at these locations, the differences in the periods of grain filling and in

TABLE II

Duration of the period of grain filling (days) and the average potential grain yield for maize (kg/ha dry matter).

Location, Maize variety	Period of grain filling	Grain yield
Brindisi, very late	51	8990
Madrid, late	49	9610
Orleans, very early	64	11630
Porto, early	61	13260

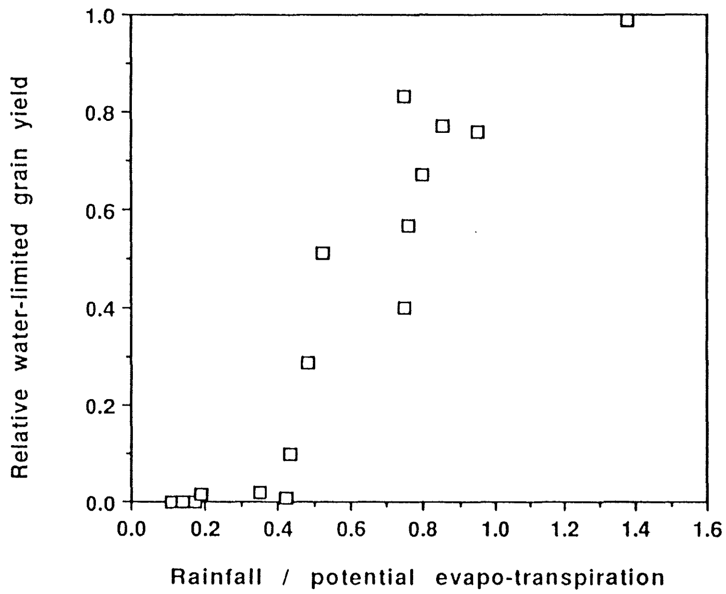

Fig. 3. Water-limited grain yield of maize as fraction of the potential grain yield at 16 locations in the E.C. in relation to the ratio between precipitation and potential evapo-transpiration during the growth period. Yields calculated for average soil characteristics per location and for historical weather data over a period of 20 years (1966–1985).

grain yields would have been even larger. According to the calculated yield levels, grain maize cannot be grown at present in Kinloss, U.K., and Mullingar, Ireland. Neither can it probably be grown during most years in Nottingham, England and Ålborg, Denmark, because of too low temperatures for the grains to reach maturity.

Water-limited grain yield varied widely among locations and also among cultivated soil types. The largest yields were found at locations with a relatively large ratio between precipitation and potential evapo-transpiration (Figure 3) and a large amount of available soil moisture. A lower amount of available soil moisture (e.g., sandy, gravelly and/or shallow soils instead of deep, loamy or clay soils) often

TABLE III

Average values (AV), standard deviations (SD) and coefficients of variation (CV) of potential and water-limited grain yields of maize (kg/ha dry matter) and the amount of available soil moisture (cm).

Location	Available soil moisture	Potential yield AV	Potential yield SD	Potential yield CV	Water-limited yield AV	Water-limited yield SD	Water-limited yield CV
Bremen	6.0	9540	1720	0.18	5420	2910	0.54
...	11.7	9540	1720	0.18	7770	2360	0.30
...	16.0	9540	1720	0.18	8450	2030	0.24
Milan	3.4	10030	890	0.09	550	1060	1.93
...	11.2	10030	890	0.09	4680	3120	0.67
...	16.0	10030	890	0.09	6420	3200	0.50

results in a much lower water-limited grain yield, as shown in Table III for Bremen, Germany, and Milan, Italy. Simultaneously with an increasing risk of drought stress and thus lower average grain yield, the standard deviation (SD) of the yield generally appears to increase, particularly compared to that of the potential production. Hence, the coefficient of variation (CV = SD/Average) increases in situations with an increasing risk of drought stress and it decreases strongly with increasing irrigation.

The coefficient of variation is a good indicator of yield variability and the risk of a relatively low yield. Climate changes may cause changes in the coefficient of variation, as will be shown in the scenario analyses. Increases or decreases in the coefficient of variation indicate that the agricultural risks may either increase or decrease in the future.

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

3.2. SENSITIVITY ANALYSES

The weather variables that determine crop yield directly are solar radiation and temperature. Those that affect the water balance, and hence the duration and degree of drought stress, are precipitation, windspeed, vapour pressure and again, solar radiation and temperature. The atmospheric CO_2 concentration also affects crop yield. These variables were adjusted independently, in a stepwise manner, in order to gauge the sensitivity of crop yield to changing values of each variable.

TABLE IV

Average potential and water-limited grain yields (kg/ha dry matter) of maize at three locations in the E.C. Yields were established for average soil characteristics per location and for historical unchanged weather data over a period of 20 years (1966–1985).

	Location, Maize variety		
	Kinloss, very early	Orleans, very early	Brindisi, very late
Potential yield	2530	11630	8990
Water-limited yield	2330	5910	20

TABLE V

Sensitivity of potential (POT) and water-limited (WAT) grain yields of maize in Kinloss, U.K. (KIN), Orleans, France (ORL), and Brindisi, Italy (BRI) to increasing values for atmospheric CO_2 concentration (C), temperature (T), precipitation (P), solar radiation (S), windspeed (W) and vapour pressure (V) (expressed in relative change in grain yield per unit change in temperature (°C) or per relative change in one of the other weather variables) and changes in grain yield (as a percentage of yield at current climate) at these locations for specified changes in weather variables.

Sensitivity	C			T			P		
	KIN	ORL	BRI	KIN	ORL	BRI	KIN	ORL	BRI
POT	0.0	0.0	0.0	+0.710	+0.000	−0.063	0.0	0.0	0.0
WAT	+0.109	+0.816	0.0	+0.378	−0.199	0.0	+0.215	+1.374	0.0
	S			W			V		
POT	+0.787	+0.527	+0.447	0.0	0.0	0.0	0.0	0.0	0.0
WAT	+0.419	−0.806	0.0	−0.200	−0.644	0.0	+0.573	+2.795	0.0

Changes	C (353 → 550μmol/mol)			T (+3 °C)			P (+30%)		
	KIN	ORL	BRI	KIN	ORL	BRI	KIN	ORL	BRI
POT	0%	0%	0%	+213%	0%	−19%	0%	0%	0%
WAT	+6%	+46%	0%	+113%	−60%	0%	+6%	+41%	0%
	S (+10%)			W (+30%)			V (+10%)		
POT	+8%	+5%	+4%	0%	0%	0%	0%	0%	0%
WAT	+4%	−8%	0%	−6%	−19%	0%	+6%	+28%	0%

Sensitivity analyses were carried out for three locations representative of the main differences in climate in the E.C.: Kinloss in the U.K. (cool temperate), Orleans in France (continental), and Brindisi in Italy (Mediterranean). Calculations were made for each location using historical weather data for a period of 20 years, with the data for each variable being varied independently. For unchanged weather data, the potential yield in Kinloss appears to be very low. This can be explained from the low rate of CO_2 assimilation at the low temperatures in summer (Table IV). Water-limited yield in Orleans is relatively low and in Brindisi nil, which indicates that in most situations irrigation water is required to attain high yields.

Table V summarises the sensitivity of potential and water-limited grain yields to changing values of each weather variable. It should be noted that results for Kinloss are strongly influenced by the current temperatures being too low for grain maize production. Potential grain yield increases with increasing solar radiation (via higher CO_2 assimilation rate), and increases with rising temperatures in Kinloss (via higher CO_2 assimilation rate), remains the same in Orleans and decreases in Brindisi (via shorter growth period). Potential yield is not influenced by the water balance and is thus insensitive to changes in windspeed, vapour pressure, precipitation and atmospheric CO_2 concentration.

The water-limited yield in Orleans increases with increasing atmospheric CO_2 and vapour pressure (because of more efficient water use) and with higher precipitation (due to the increased water supply). It decreases with increasing solar radiation and windspeed (less efficient water use) and with rising temperature (shorter growth period). In Kinloss the water supply is not often a yield limiting factor. This explains the much smaller, positive effects of increasing atmospheric CO_2, vapour pressure and precipitation and the smaller negative effects of increasing windspeed. Increasing solar radiation causes a higher leaf assimilation rate but also a higher rate of evapo-transpiration. If water supply is strongly limiting for the yield level (e.g., Orleans), increasing radiation will result in a lower yield. But for a situation without water limitation (e.g., Kinloss) yield increases were calculated. In Brindisi the amount of precipitation is so low that the resulting water-limited yield is nil. Therefore, a relative increase in precipitation or a decrease in evapo-transpiration from increasing vapour pressure, decreasing windspeed, etc., has no effect on the water-limited yield in Brindisi. As, in reality, the various weather variables do not change to the same extent, sensitivities of potential and water-limited grain yields are also given for specified changes in weather variables (Table V). This indicates the degree of changes in yield that might be expected for a changed climate.

3.3. SCENARIO ANALYSES WITHOUT DIRECT CO_2 EFFECT

3.3.1. *Composite Time-Dependent Scenarios*

Average potential and water-limited grain yield levels of maize and the standard deviations of the yields were calculated for historical weather data that were changed on the basis of composite scenario A (based on the business-as-usual IPCC (Intergovernmental Panel on Climate Change) emission scenario of Houghton *et al.* (1990)) for the years 2010, 2030 and 2050, and composite scenario A High (high estimate of climate change for scenario A) for the year 2050. The composite

TABLE VI

Mean annual temperature changes (°C) and mean annual precipitation changes (%) associated with six scenarios of climate change (Source: Kenny *et al.*, 1993b).

	Composite scenario A			Equilibrium 2 × CO_2 scenario[1]		
	year 2010	2030	2050	GISS	GFDL	UKMO-L
Temperature (°C)						
Northwest Europe	0.5 – 1	1 – 2	1 – 3	2 – 6	4 – 14	3 – 9
Northeast Europe	0.5 – 1	1 – 2	1 – 4	2 – 8	2 – 14	3 – 13
Southeast Europe	0.5 – 1	1 – 1.5	1 – 3	2 – 6	2 – 8	3 – 13
Southwest Europe	0 – 1	0.5 – 1.5	1 – 3	2 – 6	2 – 8	3 – 9
Precipitation (%)						
Northwest Europe	0 – +4	0 – +8	0 – +12	−40 – +80	−25 – +75	0 – +90
Northeast Europe	0 – +4	0 – +8	0 – +12	−40 – +120	−50 – +75	−60 – +90
Southeast Europe	−4 – +4	−12 – +8	−18 – +12	−40 – +120	−50 – +75	−60 – +90
Southwest Europe	−4 – +4	−12 – +8	−18 – +12	−80 – +80	−75 – +50	−60 – +30

[1] GISS: Goddard Institute for Space Studies; GFDL: Geophysical Fluid Dynamics Laboratory; UKMO-L: UK Meteorological Office, Low resolution.

TABLE VII

Average values (AV), standard deviations (SD) and coefficients of variation (CV) of potential (POT) and water-limited (WAT) grain yields (kg/ha dry matter) of maize established for historical weather data and the same weather data changed on the basis of composite scenario A for years 2010, 2030 and 2050 and composite scenario A High for the year 2050 (direct effect of increased CO_2 not taken into account).

Location		Historical weather		Scenario							
				A2010		A2030		A2050		AHi2050	
		POT	WAT	POT	WAT	POT	WAT	POT	WAT	POT	WAT
Brindisi	AV	8990	20	8630	20	8260	10	7860	10	7450	10
...	SD	710	50	660	80	600	60	580	40	540	30
...	CV	0.08	2.50	0.08	4.00	0.07	6.00	0.07	4.00	0.07	3.00
Kinloss	AV	2530	2330	3520	3160	4630	3920	5850	4520	7240	4980
...	SD	1190	860	1240	840	1240	1000	1260	1550	1180	1910
...	CV	0.47	0.37	0.35	0.27	0.27	0.26	0.22	0.34	0.16	0.38
Orleans	AV	11630	5910	11860	5180	11590	4090	11190	3230	10570	2540
...	SD	1110	2230	800	2200	770	2020	680	1950	730	1770
...	CV	0.10	0.38	0.07	0.42	0.07	0.49	0.06	0.60	0.07	0.70

scenarios were based on the average standardized output (i.e., output corrected for differences in global-mean temperature change for a CO_2 doubling which ranged from 2.8 to 5.2 °C for the GCMs used) of seven equilibrium general circulation models (GCM). This output resulted in a regional pattern of climate change. By using estimates of global-mean warming for each IPCC emission scenario which were calculated with a simple climate model, the GCM-derived regional patterns could be scaled up to obtain the transient changes in climate. This method of composite scenario construction assumes that the spatial pattern of transient changes is similar to that of the equilibrium 2 × CO_2 GCM changes, although the magnitude of the changes is obviously different. More information on this method of scenario construction is given by Barrow (1993). Resulting changes in climate variables, of which mean values for different regions of Europe are given in Table VI, were supplied 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 no changes could be made for windspeed.

Potential yield in Orleans remain roughly the same (Table VII) up to the year 2050, when yields begin to decrease, particularly for scenario A High with its greater temperature rise. In the northern E.C., e.g., in Kinloss, U.K., temperature rise over time results in a higher assimilation rate and longer growth period, and hence a great increase in grain yield. However, in the year 2050 grain yield is still not possible, except maybe for scenario A High, as the yield level is still too low (i.e., an indication of incomplete grain ripening). In the southern E.C., e.g., in Brindisi, Italy, potential yield decreases over time, because rising temperatures cause a gradual decrease in growth duration.

Water-limited yield in Orleans is about half the potential yield and decreases greatly over time, as a result of an increase in periods with drought stress and a shorter growth period (Table VII). In Kinloss the water-limited yield increases over time, being mainly limited by the temperature. In Brindisi the water-limited yield is zero and depends completely on the use of irrigation water. As the water supply in summer appears to be a strong limitation on the yields of grain maize in the central E.C. and particularly in the southern E.C., mainly the results for the potential level of grain production in the E.C. are presented here. Water-limited production will be discussed mainly in the following section, where the direct effect of increasing CO_2 (reducing crop transpiration) is also taken into account.

Scenario A gives major increases in potential yield in the U.K., Ireland, Denmark, and southern Germany (Figure 4) for the year 2050, areas which are unsuitable or of limited suitability for grain maize production at present. From the yield level it can be derived that in the year 2050 only Kinloss, U.K., and Mullingar, Ireland, will still not be suitable for grain maize production. These results indicate that climate change will rapidly expand the northern margins of suitability for grain maize production in Europe, an expansion which has also been found by Kenny *et al.* (1993a). Moderate yield increases were calculated for northern France, the Netherlands and northern Germany, areas where grain maize production is just possible at present. Moderate to major decreases in grain yield were calculated for the southern E.C., as a result of rising temperatures that will cause a shorter

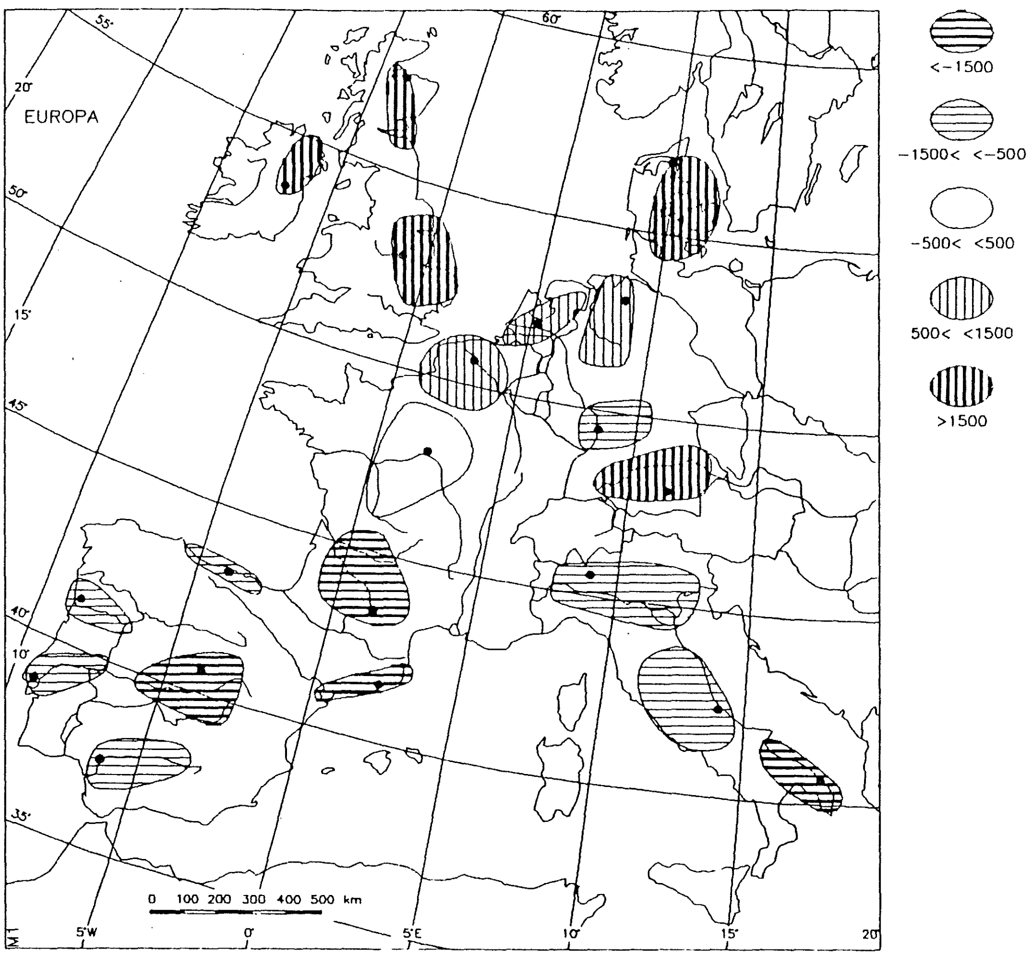

Fig. 4. Changes in potential grain yield (kg/ha dry matter) of maize in the main arable land areas in the E.C. if the weather is changed on the basis of composite scenario A for the year 2050.

growth period. This might be circumvented by growing maize varieties with higher temperature sum requirements.

SD of potential grain yield in Orleans and Brindisi decreases with time (Table VII). As average potential grain yield decreases with time too, the difference in CV between scenario and historical climate remains small. In Kinloss SD remains about constant with time. The major increase in average grain yield with time due to increasing temperatures here results in a major decrease in CV.

3.3.2. *Individual GCM Scenarios*

Average potential and water-limited grain yield levels of maize and the standard deviation of the yields were calculated for historical weather data that were changed on the basis of output from three equilibrium 2 × CO_2 general circulation models (GCMs), i.e., the GFDL (Geophysical Fluid Dynamics Laboratory), the GISS (Goddard Institute for Space Studies), and the UKMO-L (UK Meteorological Office, Low resolution) models. These changes, as described by Barrow (1993)

TABLE VIII

Average values (AV), standard deviations (SD) and coefficients of variation (CV) of potential (POT) and water-limited (WAT) grain yields (kg/ha dry matter) of maize established for historical weather data and the same weather data changed on the basis of the GFDL, GISS and UKMO-L equilibrium $2 \times CO_2$ scenarios (direct effect of increased CO_2 not taken into account).

Location		Historical weather		Scenario					
				GFDL		GISS		UKMO	
		POT	WAT	POT	WAT	POT	WAT	POT	WAT
Brindisi	AV	8990	20	6790	20	7450	20	6360	10
...	SD	710	50	510	70	540	60	470	50
...	CV	0.08	2.50	0.08	3.50	0.07	3.00	0.07	5.00
Kinloss	AV	2530	2330	7820	3550	8480	7090	8810	6180
...	SD	1190	860	630	2660	890	1890	700	2450
...	CV	0.47	0.37	0.08	0.75	0.10	0.27	0.08	0.40
Orleans	AV	11630	5910	8890	340	9530	3710	9440	3810
...	SD	1110	2230	92	210	700	2310	830	2420
...	CV	0.10	0.38	0.10	0.62	0.07	0.62	0.09	0.64

and given for different regions in Europe in Table VI, were specified per day over a period of one year for each weather variable and were location-specific.

Potential grain yield in Orleans and Brindisi decreases for the changed weather data (Table VIII). This is mainly caused by the higher temperatures which result in a shorter period of grain filling. This reduction in grain yield might be circumvented to some extent by growing maize varieties with higher temperature sum requirements. Comparing results for the three GCM scenarios, a lower potential yield level is generally calculated for the GFDL and UKMO-L scenarios, which tend to give greater temperature increases, than for the GISS scenario. At locations in the northern E.C. (e.g., Kinloss) the temperature rise as a result of the changed climate causes major increases in assimilation rate and in length of the growth period and hence, major increases in grain yield. Production of grain maize appears to become an option in the northern E.C. too.

The GFDL scenario gives major decreases in potential grain yield for almost all locations in the E.C. (Figure 5). Exceptions are the U.K., Ireland, and Denmark, for which major yield increases were calculated, and the Netherlands and northern Germany, for which grain yield was calculated to remain about the same. As the temperature rise on the basis of the GISS scenario is smaller, the decreases of grain yield calculated for this scenario are generally smaller and the increases generally greater than those calculated for the GFDL scenario (Figure 6). The temperature rise in summer based on the UKMO-L scenario is almost similar to that according to the GFDL scenario and, consequently, the resulting changes in grain yield (Figure 7) are almost similar for both scenarios.

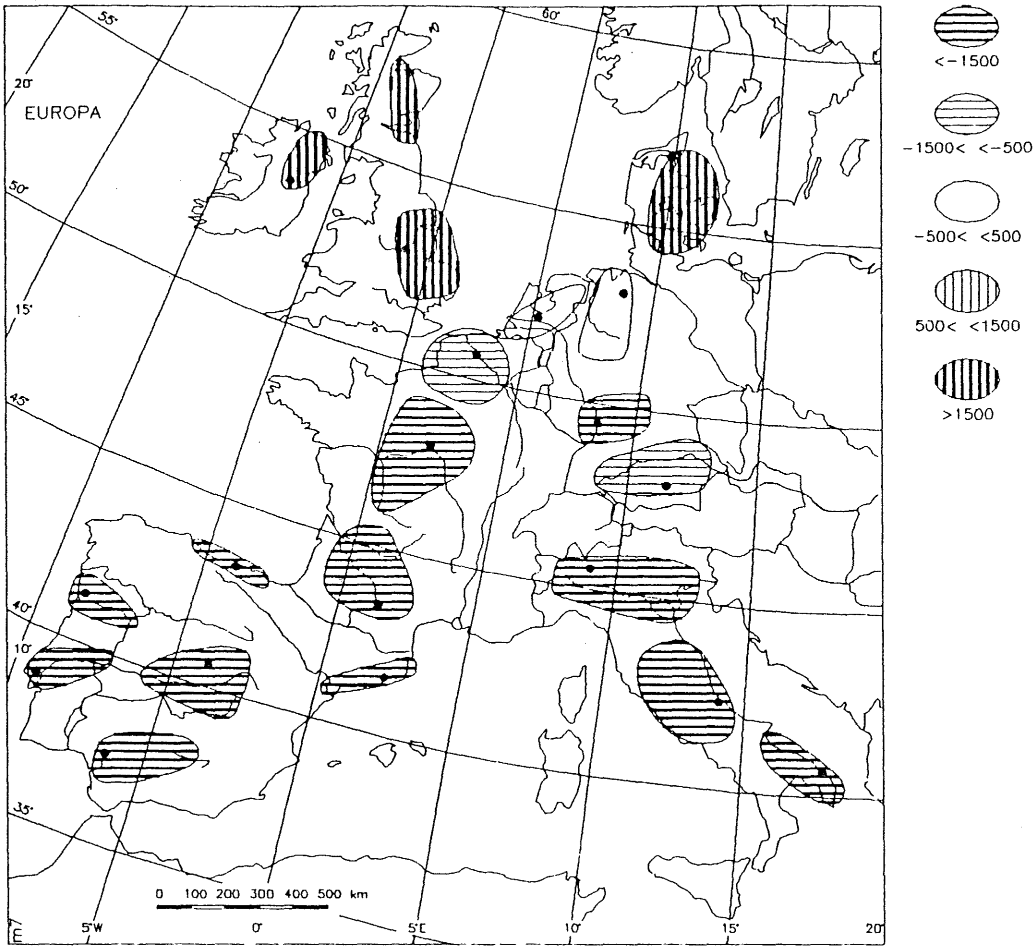

Fig. 5. Changes in potential grain yield (kg/ha dry matter) of maize in the main arable land areas in the E.C. if the weather is changed on the basis of the GFDL equilibrium 2 × CO_2 scenario.

SD of potential grain yield differs among the three scenarios to a limited extent and is lower than that for historical climate (Table VIII). Since the average potential grain yield decreases too as a result of scenario climate changes, differences in CV between both scenario and historical climate and between the three scenarios appear to be negligible. Only at Kinloss, U.K., is the CV much lower for scenario climate than for historical climate, since temperature rise on the basis of the scenario results in a much higher level of average grain yield.

3.4. SCENARIO ANALYSES WITH DIRECT CO_2 EFFECT

3.4.1. *Composite Time-Dependent Scenarios*

In these analyses the direct effect of increasing atmospheric CO_2 was taken into account. The CO_2 leaf assimilation rate of a maize crop does not increase with increasing atmospheric CO_2 and hence, the potential grain yield level remains the same. However, increasing CO_2 results in a lower transpiration rate and thus in a

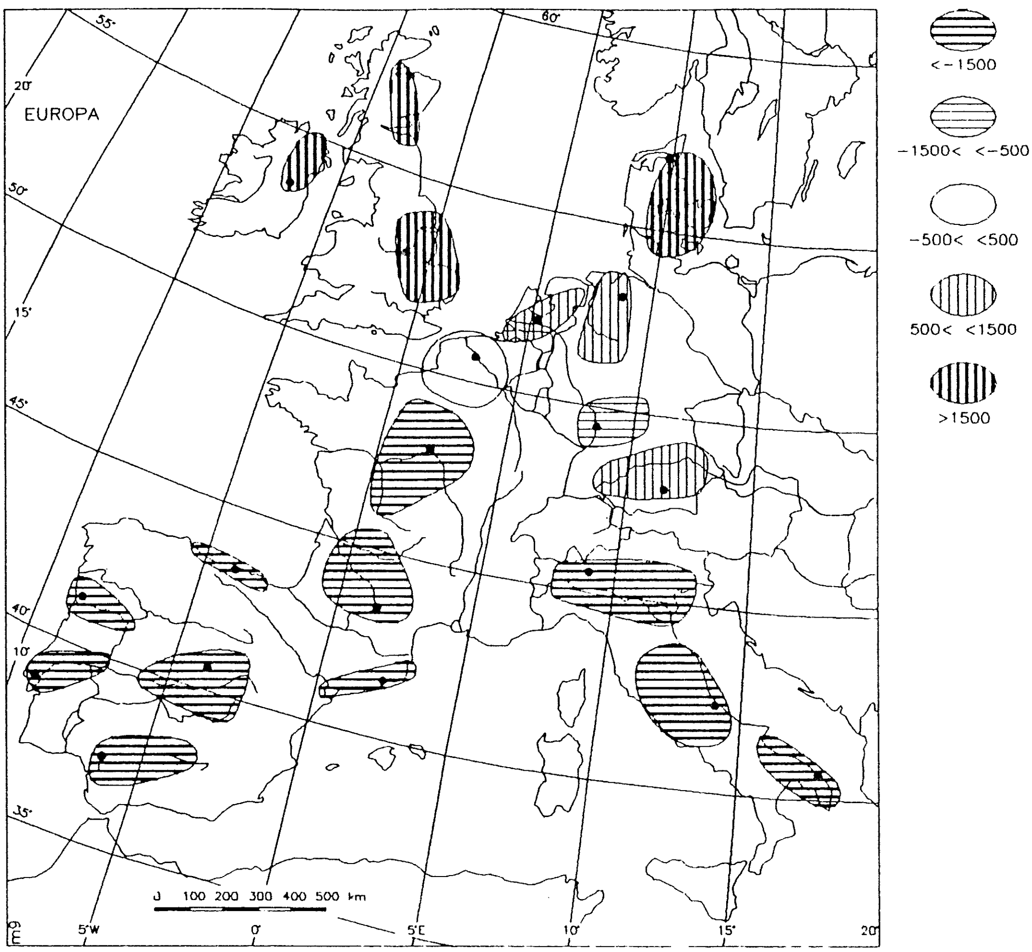

Fig. 6. Changes in potential grain yield (kg/ha dry matter) of maize in the main arable land areas in the E.C. if the weather is changed on the basis of the GISS equilibrium 2 × CO_2 scenario.

TABLE IX

Atmospheric CO_2 concentration (μmol/mol) projected for different emission scenarios and years (Barrow, 1993; Houghton *et al.*, 1990).

Scenario	Present	Year		
		2010	2030	2050
–	353			
A		400	458	539
A High				539

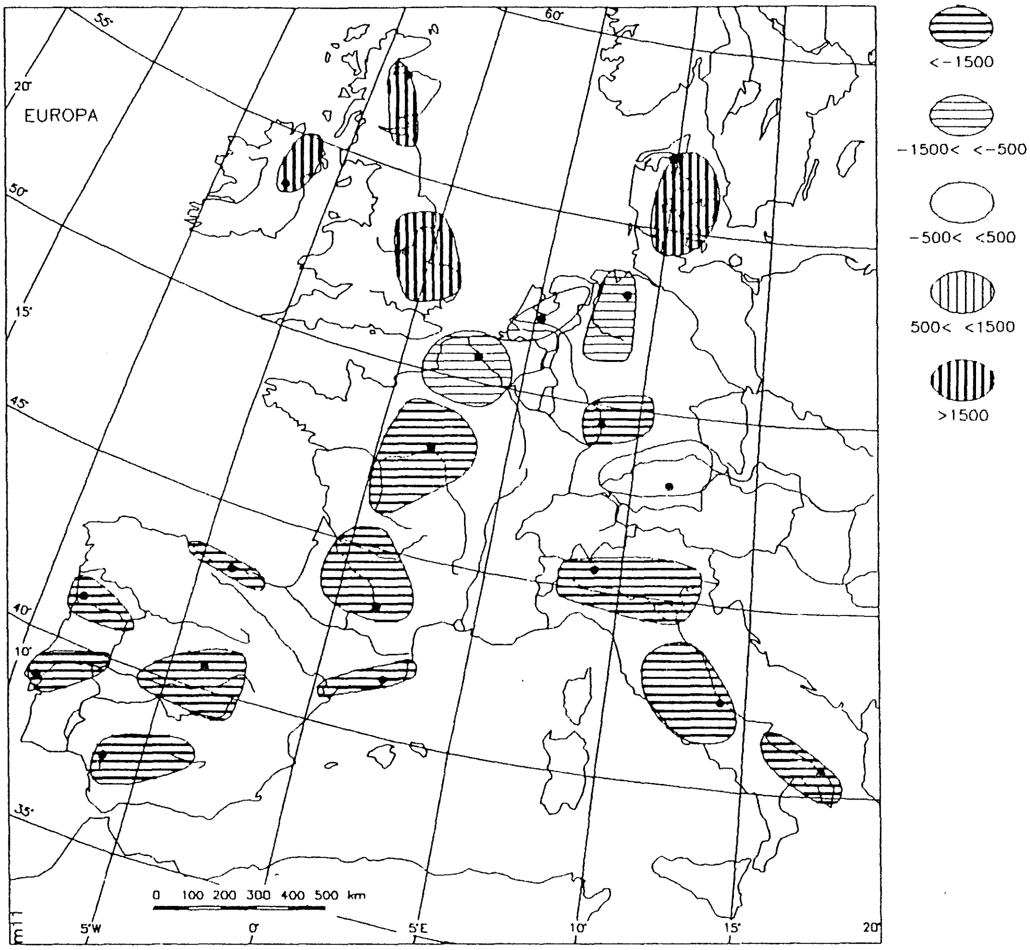

Fig. 7. Changes in potential grain yield (kg/ha dry matter) of maize in the main arable land areas in the E.C. if the weather is changed on the basis of the UKMO-L equilibrium 2 × CO_2 scenario.

higher water-limited grain yield. Consequently, only the water-limited yields differ from those without increased atmospheric CO_2 and these will be discussed here. Calculations were carried out for historical weather data changed on the basis of the composite scenarios A and A High and for CO_2 concentrations projected for the same scenarios and years (Table IX).

Changes in temperature based on the scenarios influence water-limited grain yields in the same way as they influence potential grain yields. In addition, both the amount of precipitation and the potential water losses by evapo-transpiration may change, depending on scenario-based changes in mainly windspeed, radiation and vapour pressure. The interaction between changes in the different weather variables is very complex and besides, the changes vary considerably among locations and over the year. Hence, simple and straightforward explanations of their effects on grain yield cannot be derived.

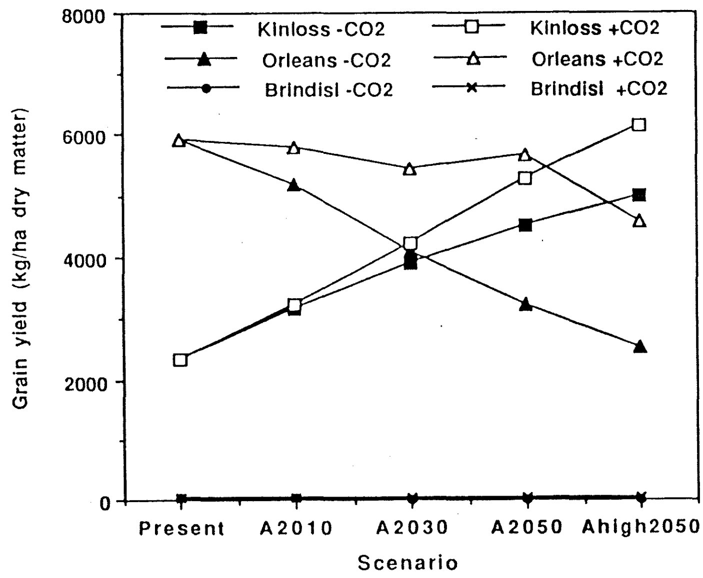

Fig. 8. Average water-limited grain yield of maize cultivated at current and at future climate conditions in Kinloss, U.K.; Orleans, France; and Brindisi, Italy, with (+CO_2) and without (−CO_2) the direct effect of increasing atmospheric CO_2 in future. Yield has been established for historical weather 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.

Water-limited yield in Orleans, France remains almost constant with time (Figure 8). If the direct effect of increasing atmospheric CO_2 on crop transpiration is not taken into account, a major yield decrease is found. Scenario A High gives for year 2050 a greater temperature rise, which causes a larger yield decrease. Actual temperatures in Kinloss, U.K., are a strong limitation on grain maize production. Hence, temperature rise as a result of scenario climate change results in a major yield increase, both with and without direct CO_2 effect (Figure 8). In Brindisi, Italy, water supply during the summer is so small that it prevents any yield of grain maize. For the other locations in the E.C. comparable changes in water-limited grain yield as a result of the scenario climate changes were calculated. Scenario A gives major increases in water-limited grain yield for the northern E.C. for year 2050, almost constant yields for the central E.C. and no production at all for the southern E.C. (Figure 9).

3.4.2. *Individual GCM Scenarios*

In these analyses the effects of the GFDL, GISS and UKMO-L equilibrium 2 × CO_2 scenarios and increased atmospheric CO_2 concentration (from 353 to 560 μmol/mol, i.e., equivalent CO_2 doubling) were taken into account. Only water-limited grain yields will be discussed here. Increased atmospheric CO_2 results in a higher water-limited yield, which can be explained from the lower transpiration rate and shortened periods with drought stress. This reduction in drought stress is clearly indicated by the increasing ratio between water-limited and potential yield with

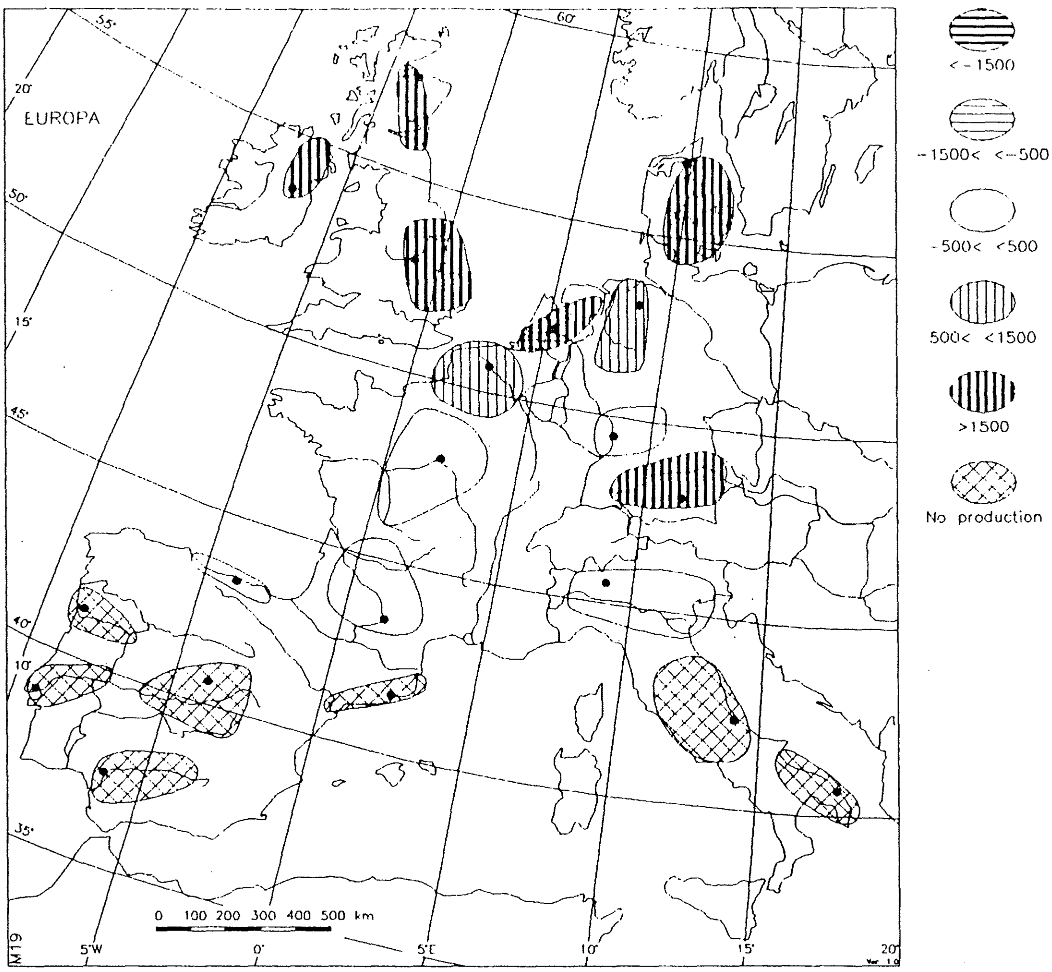

Fig. 9. Changes in water-limited grain yield (kg/ha dry matter) of maize in the main arable land areas in the E.C. if the weather is changed on the basis of the composite scenario A for the year 2050 and the direct effect of increased atmospheric CO_2 is taken into account (no production for scenario climate: < 2000 kg/ha).

increasing atmospheric CO_2 (Table X). In Kinloss, U.K., climate change according to GISS and UKMO-L scenarios results in major increases in water-limited yield, even at current atmospheric CO_2. For the GFDL scenario a much smaller yield increase was calculated, caused by the strongly limiting water supply. At current atmospheric CO_2 the yield increase for this scenario becomes even smaller because of the less efficient water use. In Orleans for the GISS and UKMO-L scenarios and increased atmospheric CO_2 the water-limited yield remains similar to that at historical weather. For the GFDL scenario yield becomes almost nil, because even at increased atmospheric CO_2 the water supply is strongly limiting. At current atmospheric CO_2 climate change according to the GISS and UKMO-L scenarios results in a major yield decrease. In Brindisi the water supply is so small that

TABLE X

Average potential (POT) and water-limited (WAT) grain yields (kg/ha dry matter) of maize established for historical weather data and the same weather data changed on the basis of the GFDL, GISS and UKMO-L equilibrium 2 × CO_2 scenarios. Direct effect of actual (353 μmol/mol) and increased atmospheric CO_2 concentrations (560 μmol/mol) is taken into account.

Location, CO_2 concentration		Historical weather	Scenario		
			GFDL	GISS	UKMO
Brindisi	POT	8990	6790	7450	6360
...	WAT CO_2 353	20	20	20	10
...	WAT CO_2 560		60	70	70
Kinloss	POT	2530	7820	8480	8810
...	WAT CO_2 353	2330	3550	7090	6180
...	WAT CO_2 560		4720	7970	7540
Orleans	POT	11630	8890	9530	9440
...	WAT CO_2 353	5910	340	3710	3810
...	WAT CO_2 560		790	6040	5740

TABLE XI

Average values (AV), standard deviations (SD) and coefficients of variation (CV) of water-limited grain yields (kg/ha dry matter) of maize in Orleans, France established for historical weather data (HIST) and the same weather data changed on the basis of composite scenario A for years 2010, 2030 and 2050, composite scenario A High for the year 2050, and GFDL, GISS and UKMO-L equilibrium 2 × CO_2 scenarios, with direct effect of increased CO_2.

	HIST	Composite scenarios				Individual scenarios		
		A2010	A2030	A2050	AHI2050	GFDL	GISS	UKMO
AV	5910	5780	5450	5660	4570	790	6040	5740
SD	2230	2420	2530	2790	2570	540	2590	2630
CV	0.38	0.42	0.46	0.49	0.56	0.68	0.43	0.46

no water-limited yield is possible at either historical climate or changed climate according to the three scenarios, nor even at increased atmospheric CO_2.

The GFDL scenario gives zero to major increases in water-limited grain yield for the northern E.C. (Figure 10). This is a result of the higher temperatures, which at present are too low for grain maize production. In England and Denmark this temperature rise causes a major increase in potential yield (Figure 5). The water-limited yield level at these locations, however, appears to remain the same because of increasing limitation of the water supply. For the Netherlands, Germany,

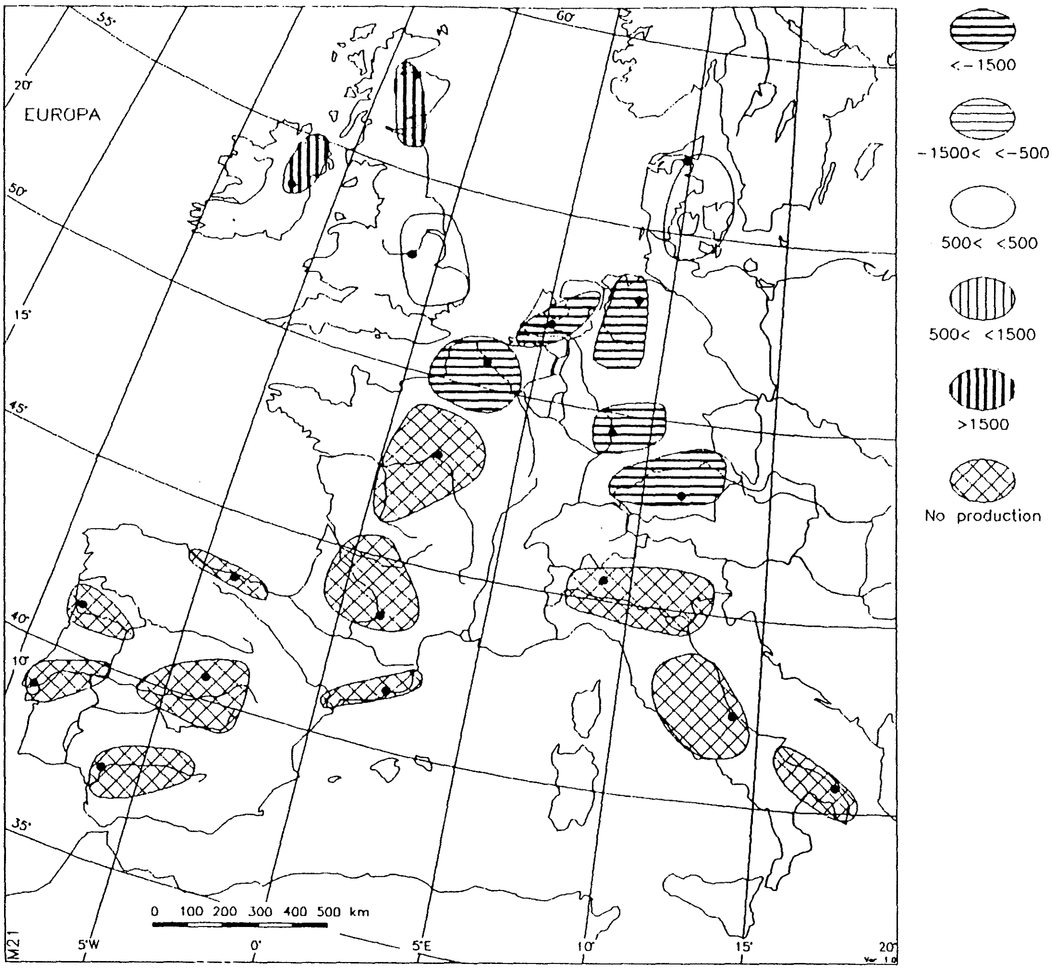

Fig. 10. Changes in water-limited grain yield (kg/ha dry matter) of maize in the main arable land areas in the E.C. if the weather is changed on the basis of the GFDL equilibrium 2 × CO_2 scenario and the direct effect of increased CO_2 (to 560 μmol/mol) is taken into account (no production for scenario climate: < 2000 kg/ha).

and northern France, which are on the border of the area where grain maize can be grown at present, major decreases in water-limited yields are calculated, also because of increasing water shortage. In the main parts of the central and southern E.C. water-limited yields appear to be negligible. This indicates that irrigation water is required to allow grain maize production in these areas. The GISS scenario gives major increases in grain yield for the northern E.C. (Figure 11), which are caused by a temperature rise that is high enough to allow grain maize production, even in Scotland. For the central E.C. zero to moderate yield increases are calculated. In the southern E.C. grain yields are negligible if no irrigation water can be supplied. This also applies to grain production in this area in the present climate. The UKMO-L scenario gives major yield increases for the northern E.C., moderate to zero

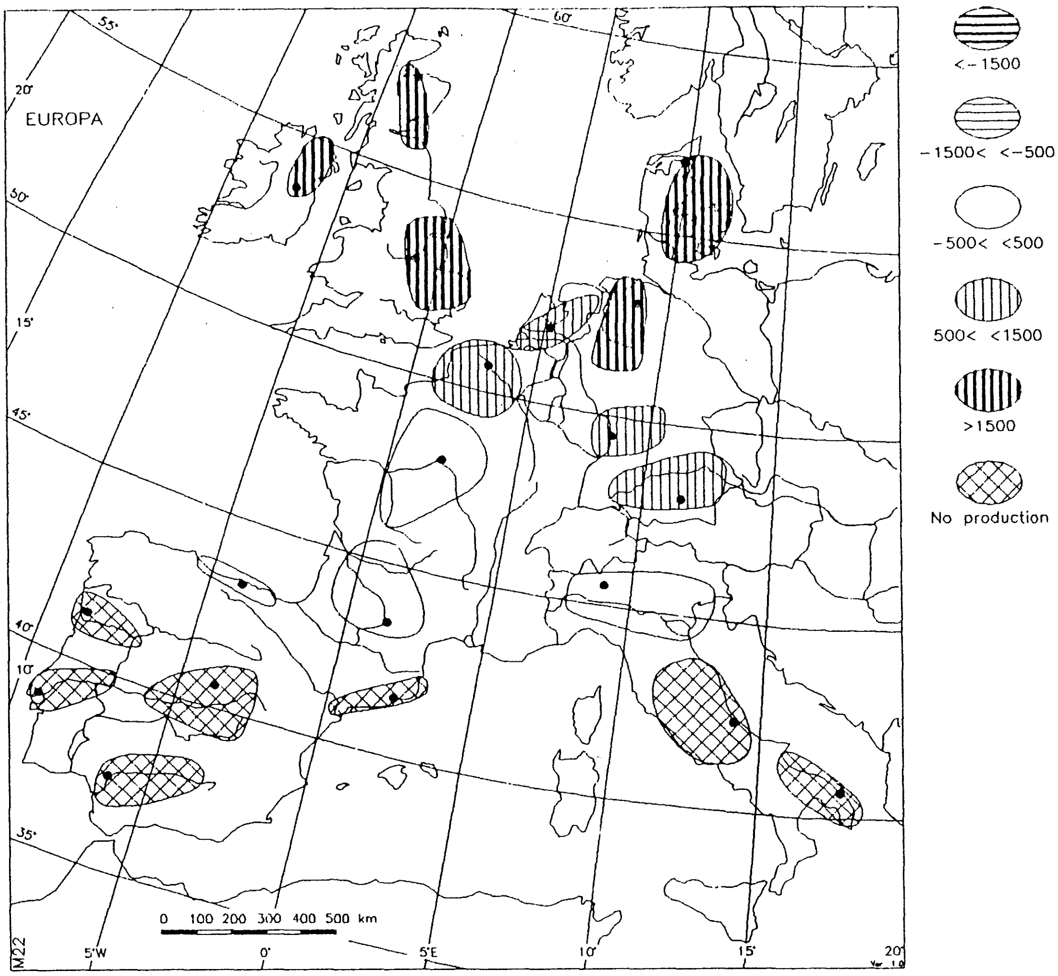

Fig. 11. Changes in water-limited grain yield (kg/ha dry matter) of maize in the main arable land areas in the E.C. if the weather is changed on the basis of the GISS equilibrium 2 × CO_2 scenario and the direct effect of increased CO_2 (to 560 μmol/mol) is taken into account (no production for scenario climate: < 2000 kg/ha).

decreases for the central E.C. and a negligible yield for the southern E.C. (Figure 12).

SD of water-limited grain yields in Orleans increases slightly for both the composite and the individual climate change scenarios (Table XI), except for the GFDL scenario with severe drought stress. As the average grain yield for the composite scenarios decreases slightly with time, this results in a moderate increase in CV. The average grain yield for the individual scenarios remains about similar to that for historical climate, which results in a slight increase in CV. These values calculated for CV appear to increase much less for scenario climate change than those given in Tables VII and VIII for a situation without direct effect of increased atmospheric CO_2. In this situation without increased CO_2 the much larger increase

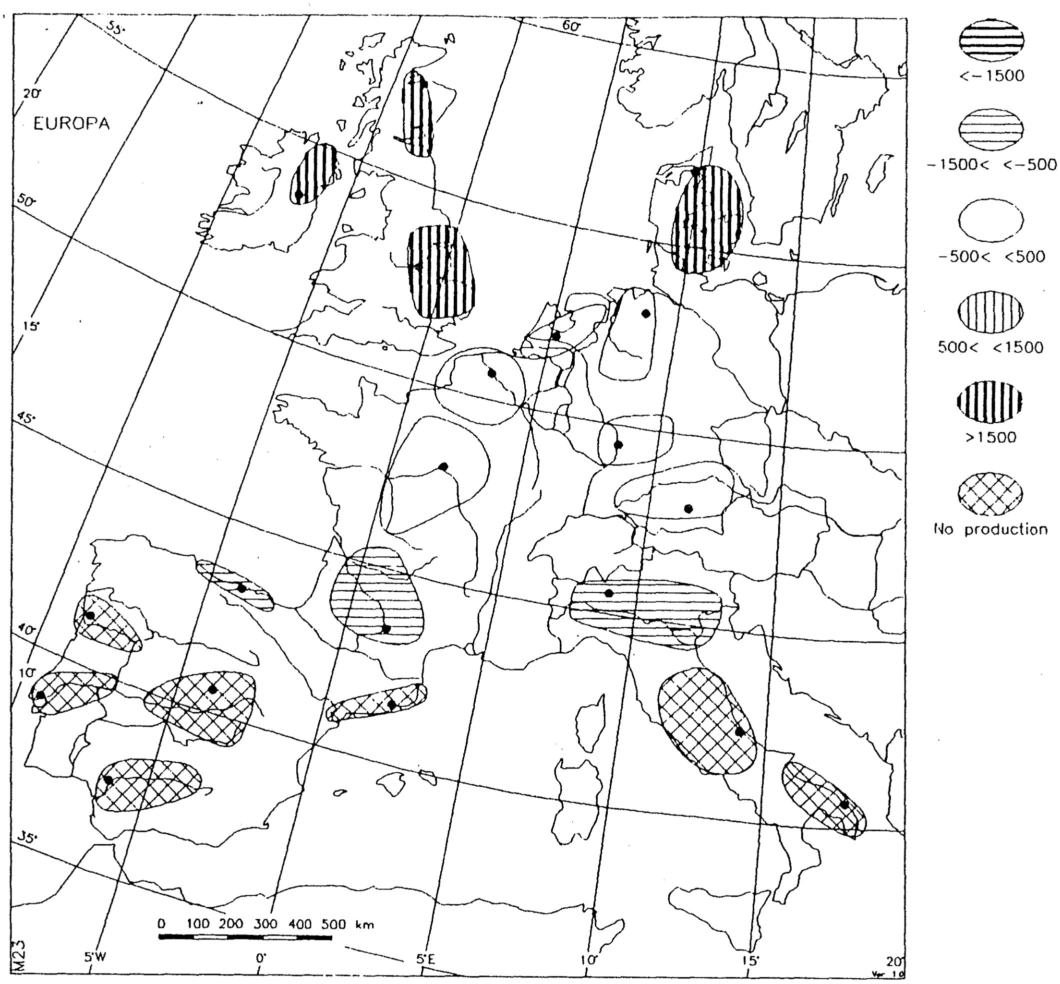

Fig. 12. Changes in water-limited grain yield (kg/ha dry matter) of maize in the main arable land areas in the E.C. if the weather is changed on the basis of the UKMO-L equilibrium 2 × CO_2 scenario and the direct effect of increased CO_2 (to 560 μmol/mol) is taken into account (no production for scenario climate: < 2000 kg/ha).

in CV can be explained from the major decrease in average grain yield, which is due to a strong increase in periods with drought stress.

3.5. MANAGEMENT ANALYSES

If climate changes, present crop management may be inadequate for the new climate conditions. A number of management responses and their potential usefulness in adapting to the adverse effects of climate change were evaluated. Firstly, grain yields were calculated with varieties that differ with respect to their temperature sum requirements for phenological development. Secondly, amounts of irrigation water required to attain the potential yield level were determined. Finally, the impact of changes in sowing date on the yield level were analysed.

TABLE XII

Crop temperature sums (as a percentage of average temperature sums for present varieties) from emergence to silking (T-silk) and from silking to ripening (T-ripe) that gave highest grain yields for Kinloss in U.K., Orleans in France, and Brindisi in Italy, both for historical and scenario weather data.

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

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

3.5.1. *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 three locations, i.e., Kinloss in U.K., Orleans in France, and Brindisi in Italy. It was assumed that, compared to the main maize varieties grown at present, plant breeding might be able to produce varieties requiring 10% greater or 10% smaller temperature sums (°C × days) from the date of emergence to silking and from silking to ripening. For the average maize variety grown at present and for these artificially constructed maize varieties, average grain yield 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. In Table XII the temperature sums from emergence to silking (T-silk) and from silking to ripening (T-ripe) that gave highest grain yields in these analyses for the three locations, are summarised for both potential and water-limited production.

It can be concluded from these results that the largest potential yield in both current and changed climate will be attained with maize varieties that need smaller temperature sums till silking and hence have an early start of grain filling, or that need greater temperature sums for grain filling and hence have a longer period of grain filling. The first option is mainly of interest in situations where the harvest index in the changed climate becomes too low or where temperatures are so low that they limit the growth duration of maize. Highest water-limited yields in projected future and also current climate conditions will be attained with maize varieties that

TABLE XIII

Required average amounts of irrigation water (mm) for attaining the potential level of grain yield for maize at six locations in the E.C., both 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, Denmark	73	122	78	90
Brindisi, Italy	382	400	326	330
Kinloss, U.K.	15	55	27	44
Madrid, Spain	459	464	376	376
Mannheim, Germany	92	109	66	66
Orleans, France	157	211	147	158

have an early start of grain filling. With these varieties the yield-reducing effect of drought at the end of the grain filling period occurs to a lesser extent.

3.5.2. *Irrigation Requirements*

The amount of irrigation water required to prevent drought stress during the growth period of grain maize and to attain the potential yield level in the E.C., was calculated. Conveyance and application losses are not included in the amount, since they vary widely and depend 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 XIII).

Climate change according to scenario A 2050 results in a major increase in irrigation requirements in the northern E.C., a moderate to major increase in the central E.C., and a nil to moderate increase in the southern E.C. (Table XIII). The temperature rise according to the scenario results in a longer effective growth duration for maize and thus more crop transpiration in the northern E.C. and in a shorter growth period (with almost similar evapo-transpiration but slightly less precipitation) in the southern E.C. Increasing atmospheric CO_2 results in more efficient water use. This effect of CO_2 roughly counteracts the higher water use and irrigation requirements in the northern E.C. which result from climate change, and causes moderate and major decreases of irrigation requirements in the central and southern E.C., respectively.

3.5.3. *Sowing Date*

The interactions between sowing date and the effects of climate change and increased atmospheric CO_2 were determined for Kinloss in U.K. and Orleans in France. For sowing dates varying between day 60 and 150, average grain yield

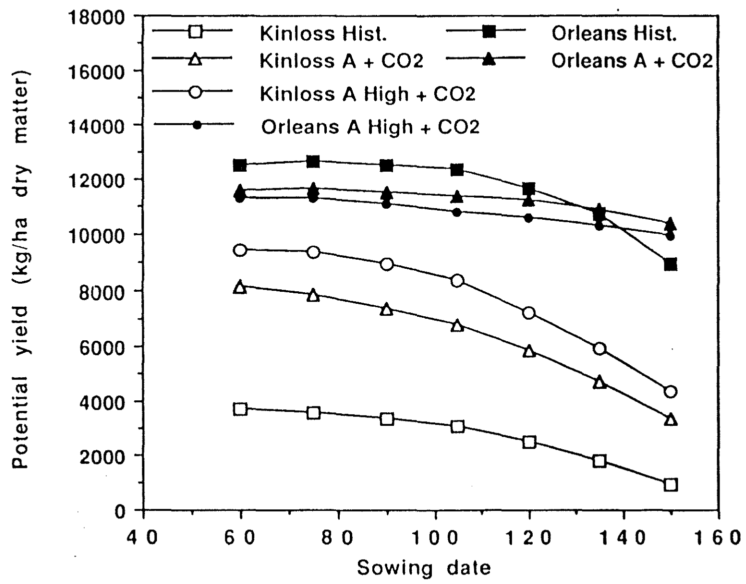

Fig. 13. Sensitivity to changes in sowing date of the average potential grain yield of maize cultivated in Kinloss, U.K., and Orleans, France. Yield has been established for historical weather data (Hist.), composite scenario A for the year 2050 with direct CO_2 effect (A + CO_2), and for composite scenario A High for the year 2050 with direct CO_2 effect (A High + CO_2).

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.

Potential yield decreases if sowing is shifted to a later date (Figure 13). For historical climate in Orleans sowing should not occur much later than day 105. In Kinloss highest yield was found at the earliest sowing date. This can be explained by the earlier start of grain filling and hence the longer duration of the grain filling period. In Orleans at changed climates according to scenarios A and A High for the year 2050, sowing should not occur much later than day 105 and day 90, respectively. Besides, the yield level at changed climate in Orleans appears to be lower because of the shorter grain filling period (at the higher temperatures). In Kinloss scenario climate change results in a higher yield level (higher assimilation rate at the higher temperatures), but the length of the growing season is rather short for grain maize and, consequently, highest yield is found at the earliest sowing date.

Water-limited yield also decreases if sowing is shifted to a later date (Figure 14). The effects discussed above for potential production also apply in this case. In addition, delayed sowing results in postponement of the growth period and therefore, in a generally lower amount of precipitation that is available for the crop. Hence, in Orleans sowing should occur as early as possible, both at historical and scenario climate, to limit the yield-reducing effects of drought during the grain filling period. For the scenario where the direct effect of increased CO_2 is

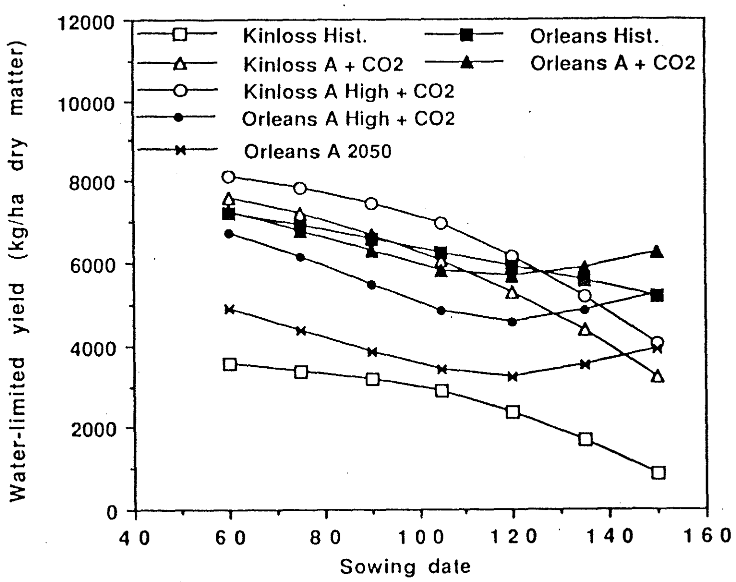

Fig. 14. Sensitivity to changes in sowing date of the average water-limited grain yield of maize cultivated in Kinloss, U.K., and Orleans, France. Yield has been established for historical weather data (Hist.), composite scenario A for the year 2050, both without (A) and with direct CO_2 effect (A + CO2), and for composite scenario A High for the year 2050 with direct CO_2 effect (A High + CO_2).

not taken into account, yield is about 2400 kg/ha lower as a result of the higher crop transpiration (Figure 14). For very late sowing dates in Orleans, small yield increases were calculated, which are caused by the shortening of the vegetative growth period that results in a slightly higher water supply during grain filling. In Kinloss a delay in sowing date, both for historical and scenario climate, results in a strong yield decrease, which is mainly determined by the decrease in grain filling duration.

A very early sowing date results in a long period between sowing and emergence. In such cases, plants may be severely affected by fungi and unfavourable growing conditions (e.g., frost and water-logging) during emergence and initial growth. In this way the positive effect of a very early sowing date may be undone completely. This applies in particular to conditions in Kinloss and elsewhere in the northern E.C.

4. Conclusions

Sensitivity analyses show that potential yield of grain maize increases with increasing solar radiation, and with rising temperatures increases in the northern E.C., remains similar in the central E.C. and decreases in the southern E.C., respectively. Water-limited grain yield appears to increase with increasing vapour pressure, atmospheric CO_2 concentration and precipitation, and to decrease with increasing windspeed, radiation (except for humid locations), and temperatures (except for the northern E.C.). In the southern E.C. the water supply is so low that water-limited yield, and hence the sensitivity to changes in weather variables, becomes nil.

Increasing concentrations of greenhouse gases in the atmosphere may cause changes in climate. Various climate change scenarios appear to yield considerably different changes in grain yield, both for each location and for the E.C. as a whole. For example, for the equilibrium $2 \times CO_2$ scenarios (without direct effect of CO_2), the average potential yield of grain maize in France (based on results from three locations in France) decreases by 1800 kg/ha dry matter for the GISS scenario, and 2600 and 2500 kg/ha for the GFDL and UKMO-L scenarios, respectively. The average water-limited yield in France decreases by 5200 kg/ha for the GFDL scenario, and 1500 and 1800 kg/ha for the GISS and UKMO-L scenarios, respectively.

The direct effect of increasing atmospheric CO_2 on water-limited grain maize yields appears to be considerable in comparison to the effects of climate change. Moreover, the direct effect of CO_2 is more certain, whereas the effect of climate change varies widely depending on the scenario and has not yet been established as fact. If both effects are taken into account, the average water-limited grain yield of maize in France may decrease by 4500 kg/ha dry matter for the GFDL scenario and by 400 kg/ha for the UKMO-L scenario, while it may increase by 200 kg/ha for the GISS scenario.

In both current and changed climate the highest level of potential grain yield will generally be attained with maize varieties that have smaller temperature sum requirements till silking and hence an early start of grain filling, or that have greater temperature sum requirements for grain filling and hence a longer period of grain filling. Largest water-limited grain yield in both current and changed climate conditions will be attained with maize varieties that have smaller temperature sum requirements till silking and hence an early start of grain filling.

Average irrigation requirements for attaining the potential level of grain maize yields in the E.C. increase if the climate is changed on the basis of the composite scenario for the year 2050. At locations in the northern E.C. irrigation requirements increase more and in the southern E.C less than the E.C. average. If the direct effect of increasing atmospheric CO_2 is also taken into account, average irrigation requirements in the E.C. decrease compared to those in current climate, with almost constant irrigation requirements at locations in the northern E.C. but a major decrease in the southern E.C.

The highest level of potential grain yield in the central E.C. will be attained if sowing does not occur much later than day 105 at current climate and if sowing does not occur much later than day 105 or 90 at changed climate on the basis of composite scenarios A and A High for the year 2050, respectively. In the northern E.C. the date of sowing should be as early as possible, since the length of the growing season is a strong limitation on the grain yield. For the highest level of water-limited grain yield, sowing should occur as early as possible, both for the historical and scenario climates, to limit the yield-reducing effects of drought during the grain filling period.

For almost all land areas in the E.C., changed climates, as based on the different composite and individual scenarios, appear to give a coefficient of variation (CV) of potential grain yields that is almost equal to that at current climate. For the different scenarios generally a much higher CV was calculated for water-limited yields without direct CO_2 effect and a slightly to moderately higher CV for water-limited yields with direct CO_2 effect. Irrigation can considerably decrease the CV by reducing the risk of drought stress.

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