

The Effect of Climate Change on Agricultural and Horticultural Potential in Europe

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Effects of climate change on wheat and maize production potential in the EC.

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5 Effects of climate change on wheat and maize production potential in the EC

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Summary

- Crop 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 climate variables was tested. Subsequent analyses were made using climate change scenarios with and without the direct effects of increased CO₂. The impact of climate change on crop management (irrigation and cultivar type) was also assessed.
- Water-limited production of winter wheat increased with increasing vapour pressure, rainfall and atmospheric CO₂ and decreased with increasing wind-speed, temperature (except for southern Europe) and solar radiation. Potential production of grain maize increased with increasing solar radiation, and with rising temperature increased in northern Europe, remained the same in central Europe and decreased in southern Europe. Water-limited production of silage maize increased with increasing CO₂, rainfall and vapour pressure, increased with rising temperature and increasing solar radiation in northern Europe, and decreased with increasing windspeed and temperature in central and southern Europe.
- For composite scenarios potential production of winter wheat increased in northern Europe, remained unchanged in central Europe until 2050 and decreased in southern Europe. Water-limited production decreased at most locations. Average water-limited winter wheat production in the EC decreased by about 230 kg/ha dry matter by 2050. With the direct effect of increasing CO₂, both potential and water-limited winter wheat production increased, with an increase in average water-limited production in the EC of about 1960 kg/ha dry matter by 2050.
- Potential production of grain maize increased in northern Europe, remained unchanged in central Europe until 2050 and decreased in southern Europe for composite scenarios. In central Europe there was a small decrease in water-limited production with the direct effect of increasing CO₂ and a strong decrease without it. Water-limited production in southern Europe is dependent on irrigation, both in the present and with the scenarios. Potential production of silage maize increased in northern Europe and decreased in central and southern Europe. In central Europe water-limited production of silage maize was unchanged with increasing CO₂ and climate change. In northern Europe water-limited production of silage maize increased, with relatively constant but low production in southern Europe.
- Potential production of winter wheat decreased for individual GCM scenarios by varying amounts. Largest decreases were for the UKMO-L scenario and in the western EC for the GFDL scenario. There were smaller decreases for the GFDL scenario in other parts of the EC and the smallest overall decreases occurred for the GISS scenario. Average water-limited production of winter wheat in the EC increased by 90 kg/ha dry matter for the GISS scenario and decreased by 670 and 960 kg/ha for the GFDL and UKMO-L scenarios. With the direct effect of CO₂, potential production of winter wheat increased strongly for the GISS scenario, increased for the GFDL scenario, with the exception of western Europe where a decrease was found, and decreased for the UKMO-L scenario. Water-limited production increased at most locations. This effect was greatest for the GISS scenario and smallest for the UKMO-L scenario. The GFDL and UKMO-L scenarios showed decreased grain production in the western EC. Average water-limited production of winter wheat for the EC increased by 1310, 2300 and 1040 kg/ha dry matter for the GFDL, GISS and UKMO-L scenarios.
- Potential production of grain maize increased in northern Europe for individual GCM scenarios and decreased in central and southern Europe. Water-limited production of silage maize remained unchanged for the GISS scenario, except in northern Europe where it increased. Moderate and strong production decreases were calculated for the UKMO-L and GFDL scenarios except in southern Europe, where production remained unchanged.
- Composite scenarios showed that highest potential grain production of winter wheat will be attained by varieties with a relatively long period of grain filling. For present weather conditions and composite scenarios highest water-limited grain production will be attained by varieties with an early start of grain filling. Average irrigation requirements to attain potential wheat production in the EC remained about constant for the 2050 scenario. Irrigation requirements increased with climate change in northern Europe and decreased in southern Europe. With increasing CO₂ and climate change, irrigation requirements in northern Europe remained unchanged and decreased further in southern Europe.

5.1 Introduction

Since agricultural production is greatly affected by climate, any climate changes which result from increasing concentrations of greenhouse gases in the atmosphere may have dramatic consequences for agricultural production potential. In this part of the project, potential production of grain crops was calculated with three different models. Two of these are crop growth simulation models (AFRCWHEAT2 model, Semenov *et al.*, Chapter 6; WOFOST model, this chapter) and the third is a statistical model for regional production forecasting (Couvreur and Tranchefort, Chapter 7). Production results for wheat calculated with the three models are compared in Chapter 8. In this chapter the effects of climate change on the production of winter wheat, grain and silage maize in the EC and the implications for crop management are 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, straightforward 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 interaction with the environment.

In order to analyse the effects of climate change on crop production potential in the EC, the production of winter wheat, grain and silage maize for 20 locations, covering the main agro-climatic conditions in the EC, was calculated for current climate and changed climatic conditions, using climate change scenarios. Next the direct effect of increasing atmospheric CO₂ concentrations was incorporated in the production calculations for the changed climate. The sensitivity of crop production to separately changed weather variables and the impact of changed crop management on crop production were also determined.

5.2 Methodology

5.2.1 The WOFOST model

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 be applied easily to a large number of combinations of different weather data, soil characteristics and crop species. The principles underlying it have been discussed in detail by van

Keulen and Wolf (1986), the implementation and structure have been described by van Diepen *et al.* (1988) and van Diepen *et al.* (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).

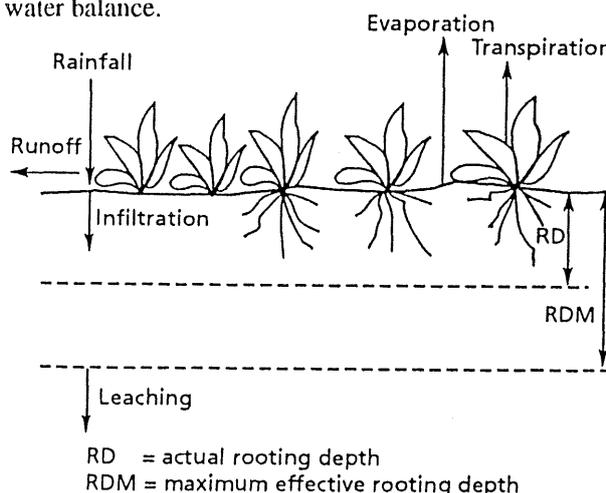
In the model, the growth of a crop was simulated from emergence (for winter wheat from January 1) to maturity on the basis of physiological processes as determined by the crop's response to environmental conditions. The simulation was carried out in time steps of one day. The major processes considered were CO₂ assimilation, respiration, partitioning of assimilates to various plant organs, transpiration and phenological development.

Two levels of crop production were calculated:

- potential production, determined by crop characteristics, temperature and solar radiation, and realised in situations where the supply of water and plant nutrients, and crop management, are optimum;
- water-limited production, determined by crop characteristics, temperature, solar radiation and water availability, dictated by rainfall pattern and soil physical properties, and realised in situations where the supply of plant nutrients and crop management are optimum.

Soil moisture content in the root zone follows from quantification of the water balance (Figure 5.1) including rainfall, surface runoff, soil surface evaporation, crop transpiration and leaching from the root zone. If the soil 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:

Figure 5.1 Schematic representation of the terms of the water balance.



in a dry soil due to water shortage, in a wet soil due to oxygen shortage.

Crop data for winter wheat

In order to apply the model, data specifying crop growth and phenological development were 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. Phenological development depends on temperature sums to anthesis, and from anthesis to maturity, that are specified for a given crop cultivar and that can be modified by the effects of day length.

For the most part a standard crop data set was used (van Heemst, 1988). The sowing of winter wheat occurs mainly from the end of September until November in northern Europe and in November or December in southern Europe (Thran and Broekhuizen, 1965). As the dormant winter period cannot be handled by the model, the simulation was started on January 1. Data from field experiments in the Netherlands and the UK (Alblas *et al.*, 1987; Darwinkel, 1985; Green and Ivins, 1985; Green, Paulson and Ivins, 1985; Groot, 1987; PAGV, 1987; Porter *et al.*, 1987) were used to assess the rate of phenological development that determines the dates of anthesis and maturity, the level of production, and the partitioning of assimilates to the plant organs that determines the grain/straw ratio.

The crop data obtained for wheat varieties in the Netherlands and the UK were used for all locations in the EC. Information on production levels and grain/straw ratios from variety trials in other countries (France, Italy and Spain) indicates that this assumption was quite realistic. The rate of phenological development was calculated with temperature sums from January 1 to anthesis and from anthesis to maturity. This method yields dates of anthesis and maturity that correspond quite well with the real dates given for all regions in Europe by Thran and Broekhuizen (1965).

The direct effect of increasing atmospheric CO₂ concentrations on the CO₂ assimilation and growth of the wheat crop was incorporated in the model as follows:

- maximum and initial angle of the CO₂ assimilation – light response curve of single leaves increases with increasing CO₂ concentration and maximum is shifted to higher temperatures;
- increase in thickness of leaves;
- limited decrease in transpiration rate.

The changes in model parameters that reflected these changes in plant behaviour at increasing CO₂ concentrations are summarised in Table 5.1. These parameter adaptations were based on studies by Allan *et al.*, 1990, Goudriaan *et al.* (1984), Goudriaan *et al.* (1985),

Table 5.1 Changes in specific leaf area (SLA), in initial angle (EFF) and in maximum (AMAX) of the CO₂ assimilation-light response curve and in the reduction factor for potential transpiration (RTRA) for adaptation of the wheat model to equivalent doubling of the atmospheric CO₂ concentration.

Atmospheric CO ₂ concentration	SLA (m ² leaf / kg leaf)	EFF (kg/ha/h / J/m ² /s)	AMAX (kg/ha/h)	RTRA (-)
353	20.0	0.450	40.0	1.000
560	17.7	0.506	63.5	0.933

Goudriaan (1990), Goudriaan and Unsworth (1990), Goudriaan and de Ruiter (1983) and Idso (1990), and on literature surveys on crop responses to CO₂ doubling by Cure (1985), Cure and Acock (1986), and Kimball (1983).

Crop data for grain and silage maize

For the most part the standard crop data set for maize was used (van Heemst, 1988). The sowing date was set at day 120 (April 30) for all locations except Seville, for which it was set at day 70 (March 11). The emergence date was determined by the temperature sum required from sowing to emergence. In southern Europe sowing can be shifted to an earlier or a later date depending on the crop rotation, but on average sowing occurs at about the same date as in northern Europe (Bignon, 1990), except for southern Spain. Four maize varieties were used in the calculations, ranging between a variety for northern and central Europe with a relatively low temperature sum required for crop development, and a variety with a high temperature sum for the extreme south of Europe. The crop data used for grain maize were different from those for silage maize in two respects:

- grain maize requires a higher temperature sum for the grains to ripen;
- grain production is sensitive to drought during flower initiation and tasseling/silking (Shaw, 1977; Bloc *et al.*, 1978). If severe drought stress occurs during that stage, the calculated maximum for grain production is reduced, but not that for total production.

The effect of increased atmospheric CO₂ concentration is different for maize: doubled CO₂ has no effect on the CO₂ assimilation rate but results in a reduction of the potential transpiration rate by about a quarter.

Weather data

In order to calculate CO₂ assimilation rates, daily minimum and maximum air temperatures and solar radiation are required (Goudriaan and van Laar, 1978). In order to calculate the components of the water balance, data on daily rainfall, windspeed and vapour pressure are also required. For example, the calcula-



Figure 5.2 Sets of historical weather data, used for calculating wheat production potential in the EC, were available for the following meteorological stations: Kinloss and Nottingham in the UK, 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 for the arable land area around that station, as roughly indicated (exclusive areas of sea, wetlands, mountains etc.)

tions of the potential rates of evaporation and transpiration that are done 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 5.2) except Greece (for which no sets of daily weather data were available), were provided by the Environmental Change Unit, University of Oxford, UK. For most stations the sets of historical weather data covered a period of 20 years (1966–1985). They were used to calculate the average and the standard deviation of wheat grain production in the EC in current climate and changed climate conditions, according to various scenarios, as well as the sensitivity to separately changed weather variables and the impact of changes in crop management.

Soil physical data

In order to calculate the soil water balance, the soil's infiltration, retention and transport properties must be known. Soils are physically defined by:

- soil moisture characteristics, notably soil porosity and volumetric moisture contents at field capacity and wilting point, respectively;
- effective soil depth;
- maximum infiltration rate or surface runoff fraction;
- the hydraulic conductivity of the subsoil.

For each meteorological station, the main soil types that occur on arable land areas within a radius of 100–150 km around the station 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, quantitative terms for use in the simulation model could be obtained: fraction of precipitation lost by surface runoff, maximum effectively 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% were left out, being too steep for arable farming.

For winter wheat the initial amount of soil moisture in the maximum rooted soil profile is required for the start of the crop growth simulation (at January 1). This amount was calculated for each location from average water losses by evapo-transpiration, and average replenishment by precipitation during summer and autumn. For maize the initial amount of soil moisture was recalculated for the date of emergence.

Certain soil characteristics such as gravelliness, stoniness, shallow rocks etc., may set limitations to the intensification and mechanisation of arable farming. These limitations were not taken into account in this analysis. Other simplifications applied were the assumptions that in all soil types the ground water table is at such a depth that it does not influence the water

balance, and that excess water may drain rapidly to the subsoil or to artificial drainage systems, so that growth reduction due to oxygen shortage does not occur.

5.2.2 Model validation

Potential grain production levels were calculated for weather data from Wageningen and de Bilt (about 40 km west of Wageningen), the Netherlands over the period 1980–1988. Going back in time from 1980, grain production from field trials appeared to decrease rapidly over time as a result of less optimum crop management and less productive crop varieties. Therefore these production data could not be used for comparisons with calculated grain production. Calculated potential grain production was compared with actual results from variety trials (Figure 5.3) that were carried out in the period 1980–1988 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 (i.e. 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 actually found in the variety trials. In years with high solar radiation during grain filling, actual grain production was relatively high. In those years losses by diseases mainly associated with ripening (fungi such as mildew) were limited, hence, calculated and actual grain production levels were comparable.

In years with high rainfall and low solar radiation during grain filling, the opposite applied. The levels of

both calculated and actual grain production were relatively low. But grain production levels in variety trials were found to be 10–20% lower than the calculated ones, which has to be explained by the high 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.

5.3 Winter wheat

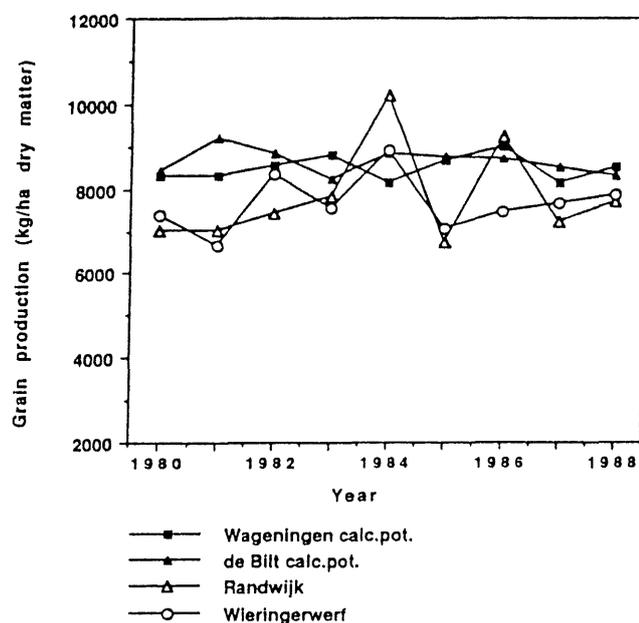
5.3.1 Baseline

Potential and water-limited grain production levels were calculated for 20 locations in the EC and for the main soil types of each location. Potential production is about 9000 kg/ha dry matter in grains. For locations where the amount of solar radiation is high (low) during grain filling and the average temperature is relatively low (high), resulting in a long (short) period of grain filling, higher (lower) grain productions are calculated. This explains the relatively high production in Lisbon and Porto and the relatively low production in Milan and Madrid (Table 5.2).

Table 5.2 Relation between duration of grain filling period (days) and the average potential grain production for winter wheat (kg/ha dry matter).

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

Figure 5.3 Potential grain production of winter wheat calculated for Wageningen and de Bilt, Netherlands and actual grain production of variety trials on clay soils in the Netherlands

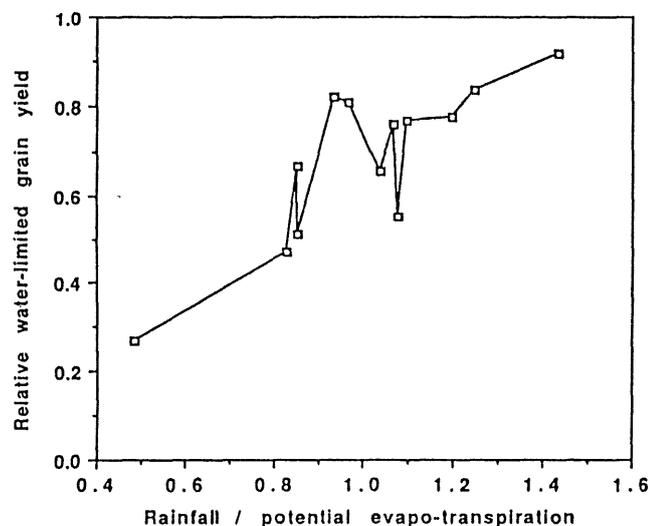


Water-limited grain production varied widely between locations and also between cultivated soil types. Highest production was found at locations with a relatively high ratio between precipitation and potential evapo-transpiration (Figure 5.4) and a high amount of available soil moisture. If the amount of available soil moisture decreased, e.g. sandy, gravelly and/or shallow soils compared to deep, loamy or clay soils, water-limited grain production could decrease greatly, as shown in Table 5.3 for Kinloss and Lisbon.

Simultaneously with an increasing risk of drought stress and thus lower average grain production, the standard deviation (SD) of the production and the coefficient of variation ($CV = SD/average$) appeared to increase in most situations, particularly compared to those of the potential production.

The CV is a good indicator of production variability and the risk of relatively low production. Climate change may cause changes in the CV, as will be shown in the scenario analyses. Calculated increases or decreases in the CV indicate that the agricultural risks in future may increase or decrease.

Figure 5.4 Water-limited grain production of winter wheat as fraction of the potential grain production on 13 locations in the EC, in relation to the ratio between precipitation and potential evapo-transpiration during the growth period. Production calculated for average soil characteristics per location and for historical weather data over a period of 20 years (1966–1985).



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

5.3.2 Sensitivity analyses

The weather variables that determine crop production directly are atmospheric CO₂ concentration, solar radiation and temperature; those that affect the water balance and hence the length of drought periods and the degree of drought stress are rainfall, windspeed, vapour pressure and again solar radiation, temperature and atmospheric CO₂. These variables were changed separately to

various extents, in order to obtain the sensitivity of crop production to changing values for each variable.

A sensitivity analysis for winter wheat was carried out for three locations covering the main differences in climate in the EC: Kinloss in the UK, Orleans in France, and Brindisi in Italy. For each location the calculations were done for historical weather data over a period of 20 years, with the data for each variable being varied separately. For unchanged weather data, water-limited production appeared to be reduced much more by drought stress in Brindisi than in Kinloss and Orleans (Table 5.4).

Table 5.4 Average potential and water-limited grain production (kg/ha dry matter) of winter wheat on three locations in the EC. Production has been established for average soil characteristics per location and for historical unchanged weather data over a period of 20 years (1966–1985).

	Kinloss	Orleans	Brindisi
Potential production	8740	9630	9370
Water-limited production	5680	6510	4510

Vapour pressure

- Potential production is not influenced by the water balance and thus not by a change in vapour pressure.
- Water-limited production increases greatly with increasing vapour pressure (Figure 5.5), as an increase in vapour pressure results in a decrease in vapour pressure deficit of the air and thus in less evapo-transpiration.

Rainfall

- Potential production is not influenced by the amount of rainfall.
- Water-limited production increases greatly with the amount of rainfall (Figure 5.5).

Windspeed

- Potential production does not depend on the water balance and hence is not influenced by the windspeed.

Table 5.3 Relation between average values, standard deviations and coefficients of variation of potential and water-limited grain production of winter wheat (kg/ha dry matter) and the amount of available soil moisture (cm).

Location	Available soil moisture	Potential production			Water-limited production		
		Average	SD	CV	Average	SD	CV
Kinloss	6.6	8740	830	0.09	4490	2700	0.60
"	16.0	8740	830	0.09	7510	1540	0.21
Lisbon	6.0	10420	630	0.06	4780	2570	0.54
"	8.2	10420	630	0.06	5740	2490	0.43
"	16.0	10420	630	0.06	9080	1500	0.17

- Water-limited production decreases greatly at increasing windspeed (Figure 5.5), as an increase in windspeed results in an increase in evapo-transpiration.

Radiation

- Potential production increases moderately to greatly (greatest effect in Kinloss) at increasing solar radiation (Figure 5.6), as an increase in radiation results in a higher rate of the CO₂ assimilation process.
- Water-limited production decreases moderately at increasing radiation, as an increase in radiation results in higher rates of crop transpiration and evaporation from the soil surface. Apparently, the effect of water shortage on crop production is greater than the positive effect of increasing radiation on CO₂ assimilation

Temperature

- Potential production decreases moderately and greatly at rising temperatures in Orleans and Brindisi respectively (Figure 5.6), as a result of the concurrently decreasing duration of grain filling. In Kinloss actual temperatures are so low that a rise in temperature may have a positive effect on production by advancing the starting date of grain filling. Only with a rise in temperature of 3°C and more does potential production in Kinloss decrease.
- Water-limited production decreases greatly at rising temperatures in Kinloss and Orleans, due both to the decreasing period of grain filling and to the increasing vapour pressure deficit of the air. For Brindisi this relation is not found. Here rising temperatures advance the period of grain filling to such an extent that the amount of rainfall during grain filling and hence grain production become higher.

CO₂ concentration

- Potential production increases greatly at increasing atmospheric CO₂ concentration (Figure 5.6), as a result of the changes in CO₂ assimilation-light response curve of single leaves at increasing atmospheric CO₂ concentration (Table 5.1).
- Water-limited production increases greatly with increasing atmospheric CO₂ concentration and relatively more greatly than the potential production. This is due to both the increasing CO₂ assimilation rate and the decreasing transpiration rate at a higher CO₂ concentration.

Table 5.5 summarises the sensitivity of grain production of winter wheat to changing values for the different weather variables.

Figure 5.5 Sensitivity to changes in vapour pressure, amount of rainfall and windspeed of the average water-limited grain production of winter wheat cultivated in Kinloss, UK, Orleans, France and Brindisi, Italy. Production has been established for the average soil characteristics per location and for historical weather data over a period of 20 years (1966–1985) of which values have been varied as indicated.

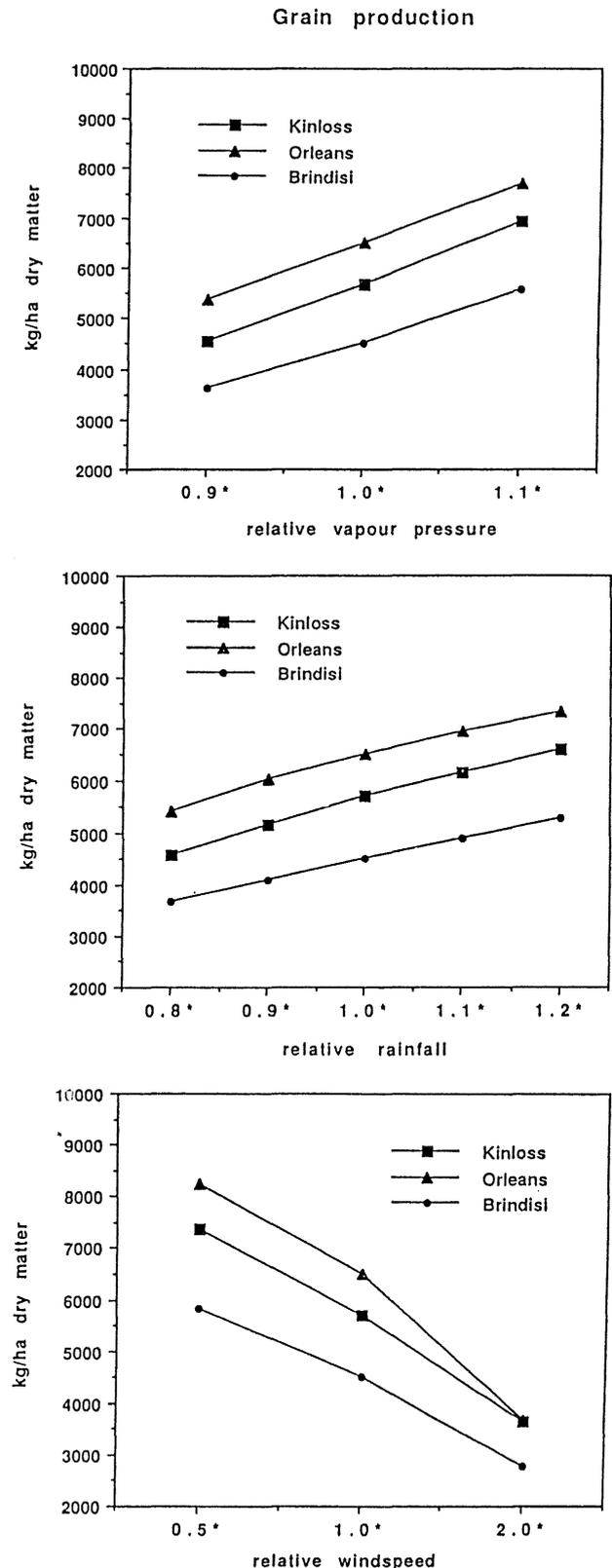


Figure 5.6 Sensitivity to changes in radiation, daily air temperature and atmospheric CO₂ concentration of the average potential (Pot.) and water-limited (Wat.) grain production of winter wheat cultivated in Kinloss, UK, Orleans, France and Brindisi, Italy. Production has been established for the average soil characteristics per location and for historical weather data over a period of 20 years (1966–1985) of which values have been varied as indicated.

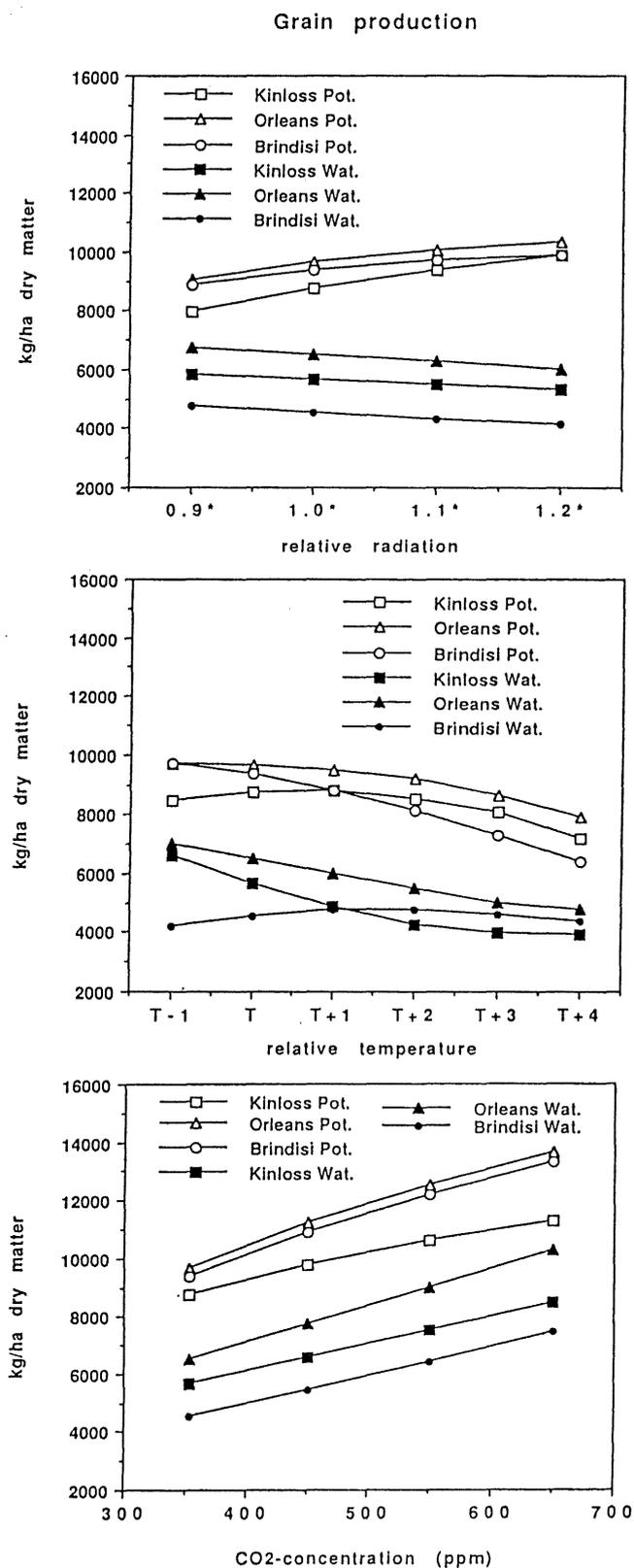


Table 5.5 Sensitivity of potential (POT) and water-limited (WAT) grain production of winter wheat in Kinloss, UK, Orleans, France, and Brindisi, Italy to increasing values for atmospheric CO₂ concentration (C), temperature (T), rainfall (R), solar radiation (S), windspeed (W) and vapour pressure (V)¹.

	C	T	R	S	W	V
POT	++	—, 0 ²	0	+, ++	0	0
WAT	++	—, + ³	++	—	—	++

¹ 0, +, ++ : no, moderate, major increase in grain production; —, —: moderate, major decrease in grain production.
² Temperature effect varies from almost zero in Kinloss to strongly negative in Brindisi.
³ Temperature effect varies from strongly negative in Kinloss and Orleans to slightly positive in Brindisi.

5.3.3 Scenario analyses without direct CO₂ effect

Composite time-dependent scenarios

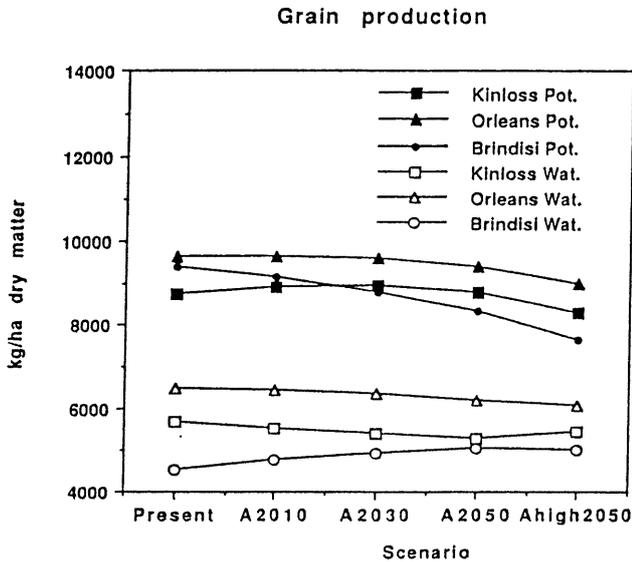
Potential and water-limited grain production of winter wheat were calculated for historical climate data that were changed on the basis of composite scenario A for the years 2010, 2030 and 2050, and composite scenario A High for the year 2050. These changes, as supplied by Barrow (Chapter 2), were specified per day for 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 applied.

Potential production levels in northern Europe, eg. in Kinloss, UK, increase over time according to the calculated results for the different scenarios (Figure 5.7). This is due to rising temperatures in the future which advance the period of grain filling, hence taking place at longer days and a higher solar elevation. Only for scenario A High 2050, with the greatest change in climate, does the rise in temperature become so high and the vegetative growth period so short that the leaf area and hence interception of solar radiation limit grain production. The result is a decrease in potential production.

Potential production levels in southern Europe, eg. in Brindisi, Italy, decrease over time on most locations (Figure 5.7), because rising temperatures in the future advance the period of grain filling, which then takes place during a time of the year with shorter days and a lower solar elevation.

Water-limited production decreases over time at most locations, probably because rising temperatures result in larger water losses by soil evaporation and crop transpiration. But these decreases in production are limited (Figures 5.7 and 5.8). Weather conditions during the period of grain filling are influenced not only by the

Figure 5.7 Average potential (Pot.) and water-limited (Wat.) grain production of winter wheat cultivated at current and future climate conditions in Kinloss, UK, Orleans, France and Brindisi, Italy (direct effect of increasing atmospheric CO₂ in future not taken into account). Production has been established for the average soil characteristics per location and for historical weather data over a period of 20 years (1966–1985), and for historical weather data that were changed on the basis of composite scenario A for the years 2010, 2030 and 2050, and composite scenario A Ihigh for the year 2050.



changes according to the scenarios, but also to a considerable extent by the shift in time of the grain-filling period. For example, for locations with dry summers such as Brindisi and Pescara, water-limited production is calculated to increase over time (Figures 5.7 and 5.8). The period of grain filling is advanced to such an extent that the amount of rainfall during grain filling becomes higher and results in higher grain production.

The standard deviation and CV of potential grain production change over time to a limited extent, both upwards and downwards (Table 5.6). The standard deviation and CV of water-limited grain production decrease over time, probably because of the advancing and shortening of the period of grain filling, but remain much larger than those for potential grain production.

Individual GCM scenarios

Potential and water-limited grain production of winter wheat were calculated for historical weather data that were changed on the basis of output from three general circulation models, ie. the GFDL, the GISS and the UKMO-L models respectively for an equilibrium situation at doubled atmospheric CO₂. These changes, as supplied by Barrow (Chapter 2), were specified per day over a period of one year for each weather variable, and were location specific.

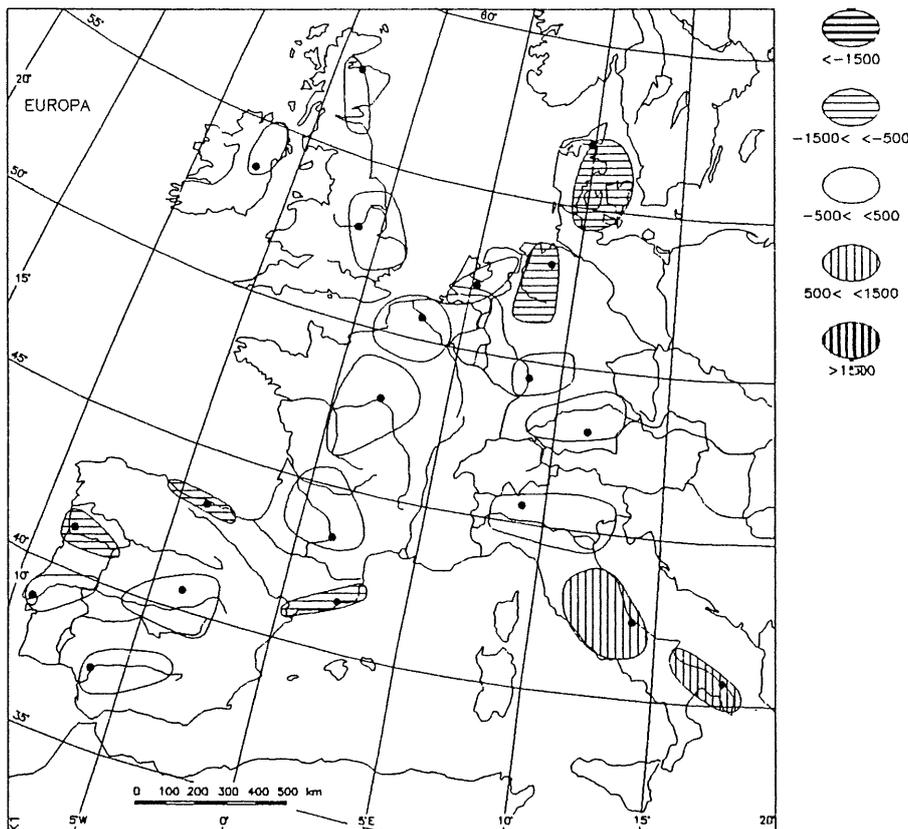


Figure 5.8 Changes in water-limited grain production (kg/ha dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of composite scenario A for the year 2050 (direct effect of increasing atmospheric CO₂ not taken into account).

Table 5.6 Standard deviation (SD) and coefficient of variation (CV) of potential (POT) and water-limited (WAT) grain production (kg/ha dry matter) of winter wheat, established for average soil characteristics per location and for historical weather data over a period of twenty years (1966–1985) that were changed on the basis of composite scenario A for years 2010, 2030 and 2050 and composite scenario A High for the year 2050.

Location		Historical weather		Scenario							
				A2010		A2030		A2050		AHi2050	
		SD	CV	SD	CV	SD	CV	SD	CV	SD	CV
Brindisi	POT	610	0.07	610	0.07	650	0.07	710	0.09	730	0.10
"	WAT	2440	0.54	2490	0.53	2450	0.50	2350	0.47	2160	0.43
Kinloss	POT	830	0.09	810	0.09	810	0.09	920	0.10	970	0.12
"	WAT	2360	0.42	2310	0.42	2100	0.39	1750	0.33	1500	0.28
Orleans	POT	1040	0.11	950	0.10	800	0.08	760	0.08	810	0.09
"	WAT	2680	0.41	2710	0.42	2660	0.42	2520	0.41	2420	0.40

Table 5.7 Average values (AV), standard deviations (SD) and coefficients of variation (CV) of potential (POT) and water-limited (WAT) grain production (kg/ha dry matter) of winter wheat, established for historical weather data that were changed on the basis of output from GFDL, GISS and UKMO-L models for an equilibrium situation at doubled atmospheric CO₂ (direct effect of doubled CO₂ not taken into account).

Location		Historical weather		Scenario					
				GFDL		GISS		UKMO-L	
		POT	WAT	POT	WAT	POT	WAT	POT	WAT
Brindisi	AV	9370	4510	6080	5340	5970	5440	5380	4820
"	SD	610	2440	720	1140	630	910	660	890
"	CV	0.07	0.54	0.12	0.21	0.11	0.17	0.12	0.18
Kinloss	AV	8740	5680	3110	3110	7680	6990	6540	5670
"	SD	830	2360	990	990	940	920	1040	1070
"	CV	0.09	0.42	0.32	0.32	0.12	0.13	0.16	0.19
Orleans	AV	9630	6510	7850	6940	8380	5520	6620	6020
"	SD	1040	2680	730	1260	750	2670	630	940
"	CV	0.11	0.41	0.09	0.18	0.09	0.48	0.10	0.16

Potential grain production decreases at almost all locations for the changed weather data (Table 5.7). This is mainly due to the higher temperatures which result in an advanced and often shorter period of grain filling, and sometimes also in a short vegetative growth period and thus a small leaf area that limits interception of solar radiation and hence CO₂ assimilation and grain production (Table 5.7: Kinloss, GFDL scenario). Particularly in southern Europe, advanced grain filling takes place at a lower solar elevation and shorter days. Consequently, the available amount of radiation becomes less, which causes lower grain production. Comparing the output from the three models, the lowest production is generally derived for the UKMO-L scenario, which often gives the highest temperature increase, or for the GFDL scenario, which gives slightly lower 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 often the lowest. For that scenario grain production is higher than for the other two scenarios, but generally lower than that for unchanged historical weather data.

Changes in temperature and radiation on the basis of the scenarios influence water-limited grain production in the same way as they influence potential grain production (Table 5.7). In addition, water losses by evapotranspiration are found to be potentially highest for the GFDL scenario and particularly in Spain and Portugal, probably due to large increases in windspeed. Also the amount of rainfall is often highest for the GFDL scenario. Higher temperatures as based on the scenarios may result in advanced and shorter periods of grain filling and often in less water shortage during grain filling. The interaction between such changes in the different weather variables is very complex; besides, the changes vary considerably between locations and over the year. Hence, simple and straightforward explanations of their effects on grain production cannot be derived.

The GFDL scenario gives major decreases in water-limited grain production in the UK, Ireland, northern Spain and northern Germany that can be explained in the same way as the decrease in potential production: the effect of higher temperatures and a lower amount of

radiation (Figure 5.9). The major decrease in water-limited production in Lisbon and Seville is due to the decrease in potential production and the higher water losses by evapo-transpiration, while the moderate to major increase in central and southern Italy is probably

due to relatively higher amounts of rainfall during grain filling. The GISS scenario gives moderate decreases in production for Ireland, northern Germany, northern and central France, northern Spain and northern Portugal (Figure 5.10) and mainly moderate increases for

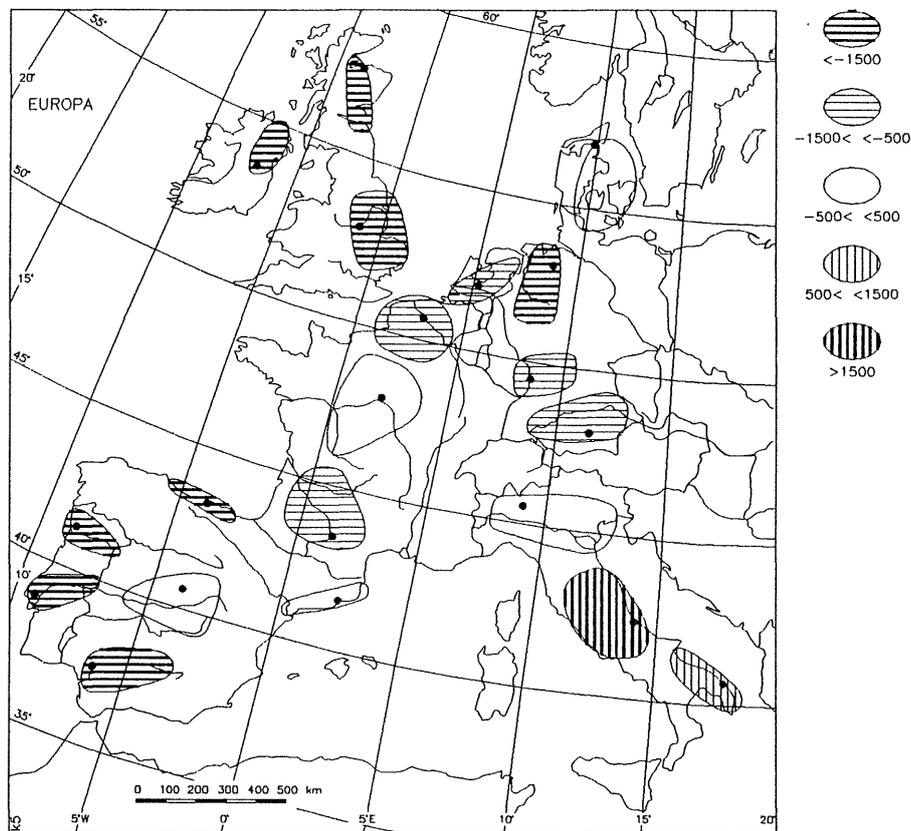


Figure 5.9 Changes in water-limited grain production (kg/ha dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of output from the GFDL model for an equilibrium situation at doubled atmospheric CO₂ (direct effect of doubled CO₂ not taken into account).

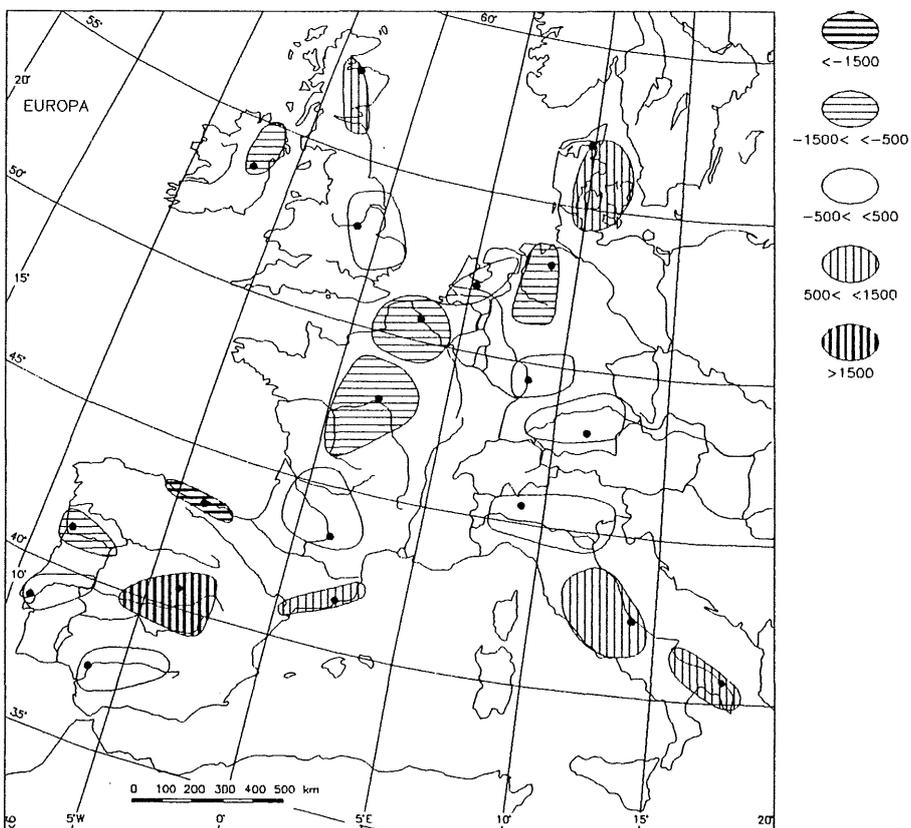


Figure 5.10 Changes in water-limited grain production (kg/ha dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of output from the GISS model for an equilibrium situation at doubled atmospheric CO₂ (direct effect of doubled CO₂ not taken into account).

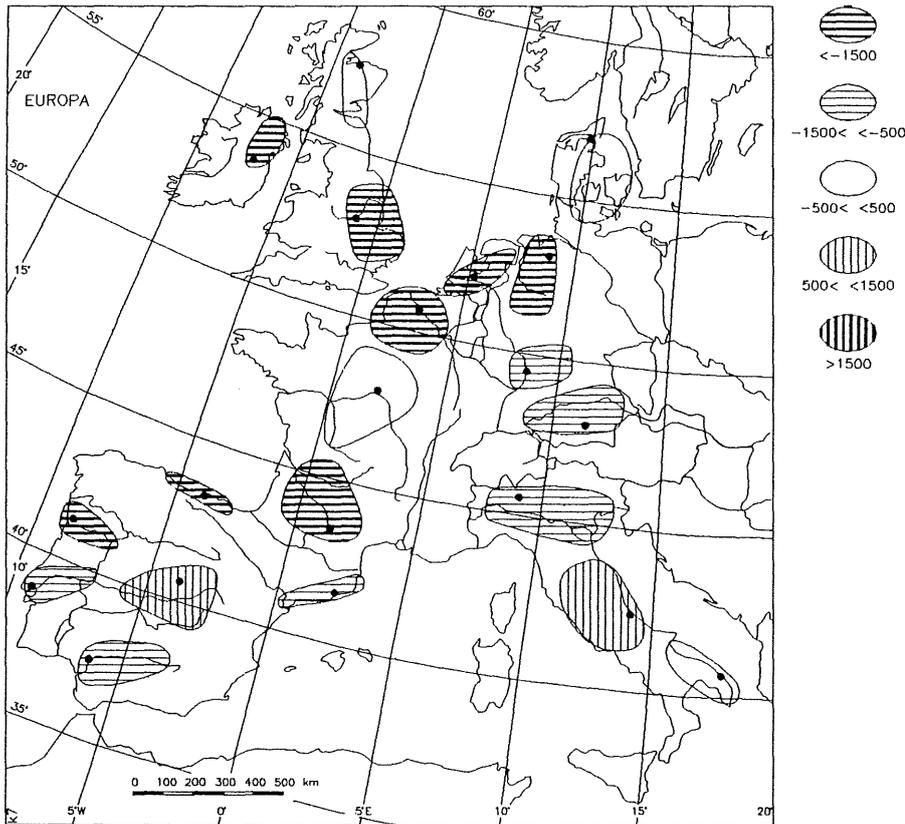


Figure 5.11 Changes in water-limited grain production (kg/ha dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of output from the UKMO-L model for an equilibrium situation at doubled atmospheric CO₂ (direct effect of doubled CO₂ not taken into account).

Scotland, Denmark, central and eastern Spain and central and southern Italy. The UKMO-L scenario (highest temperature increase) gives major decreases in production for Ireland, England, northern Germany, northern and southern France, northern Spain and northern Portugal (Figure 5.11), and moderate decreases for central and southern Germany, northern Italy, eastern and southern Spain and central Portugal.

The standard deviation of potential grain production differs among the three scenarios and between historical climate and the scenarios, but the differences are negligible (Table 5.7). The CV decreases slightly in Orleans and increases slightly in Kinloss and Brindisi. The only exception is the GFDL scenario for Kinloss, where the average production decreases greatly, and consequently the CV shows a major increase. The standard deviations and coefficients of variation of water-limited grain production for the scenarios are generally lower than those for historical climate. This is caused by the smaller differences between potential and water-limited grain production that are calculated for the scenarios. Potential grain production is reduced, mainly due to a higher temperature for the scenarios, and water-limited grain production remains the same or becomes higher, mainly due to advanced periods of grain filling. Hence, if water shortage affects grain production less, the standard deviation and CV of water-limited grain production decrease. Only the GISS scenario for Orleans results in more water shortage and thus a higher CV.

5.3.4 Scenario analyses with direct CO₂ 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 the composite scenarios. In these calculations the direct effect of increasing atmospheric CO₂ concentrations was taken into account. Increasing CO₂ results mainly in a higher CO₂ assimilation rate and thus a higher crop production level, and in a somewhat lower transpiration rate. Calculations were carried out for weather data on the basis of composite scenario A for the years 2010, 2030 and 2050, and composite scenario A High for the year 2050, and for CO₂ concentrations projected for the same scenarios and years (Barrow, Chapter 2).

Potential production levels increase greatly over time at all locations, mainly due to the increasing CO₂ concentration (Figures 5.7 and 5.12).

Water-limited production increases greatly over time at all locations, mainly due to the increasing CO₂ concentration (Figures 5.7 and 5.12). For scenario A High for year 2050, with the greatest increase in temperature, the increase in production is generally somewhat less than that for scenario A for the same year. The relatively lowest increases in production were calculated for Denmark, northern Germany and Spain (Figure 5.13).

Figure 5.12 Average potential (Pot.) and water-limited (Wat.) grain production of winter wheat cultivated at current and future climate conditions in Kinloss, UK, Orleans, France and Brindisi, Italy, taking into account the direct effect of increasing atmospheric CO₂ in future. Production has been established for the average soil characteristics per location and for historical weather data over a period of 20 years (1966–1985), and for historical weather data that were changed on the basis of composite scenario A for the years 2010, 2030 and 2050, and composite scenario A High for the year 2050.

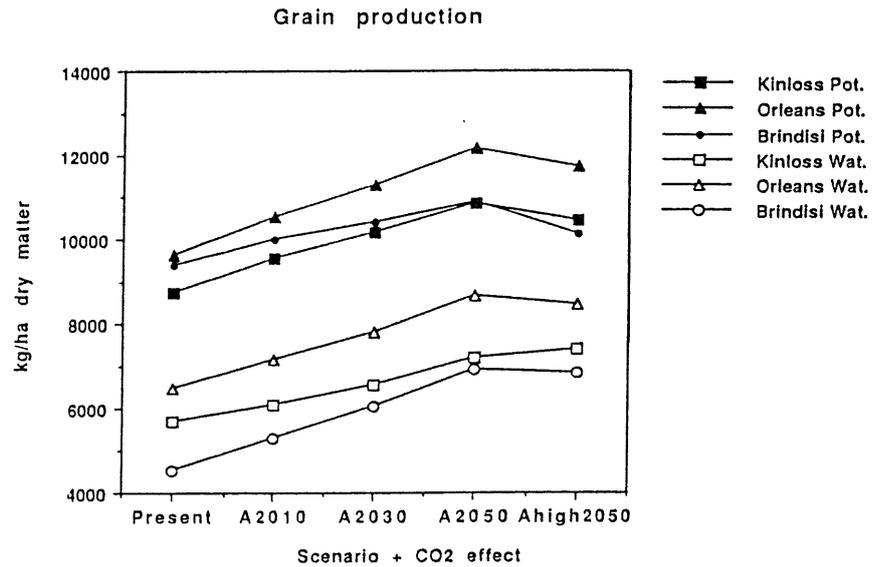
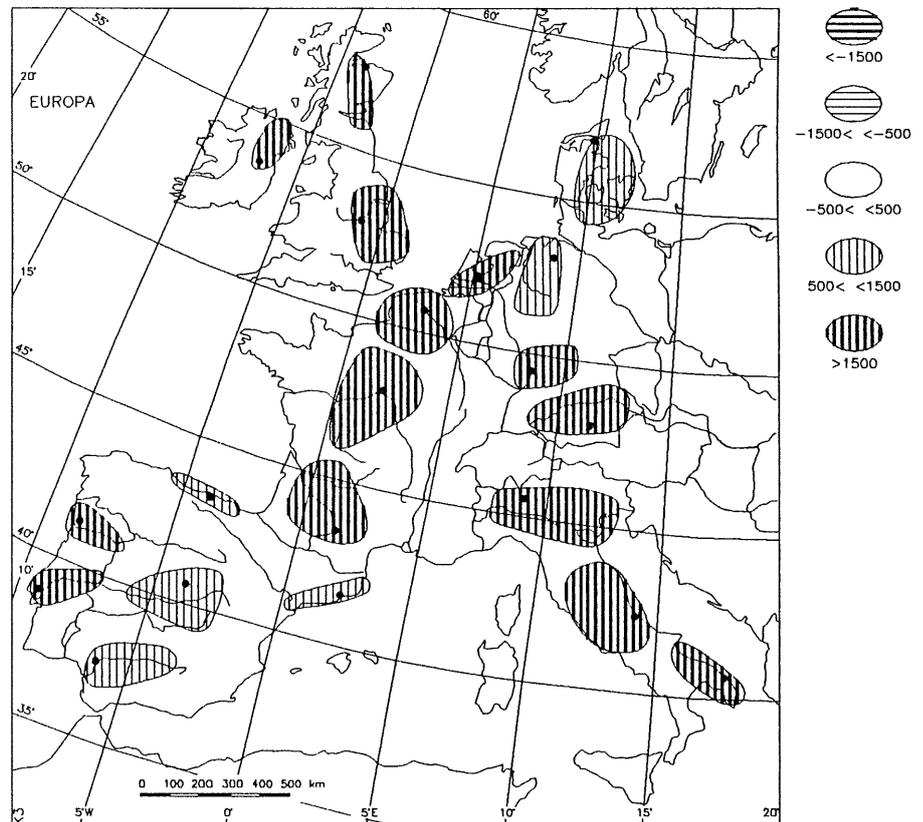


Figure 5.13 Changes in water-limited grain production (kg/ha dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of the composite scenario A for the year 2050 and the direct effect of increasing atmospheric CO₂ is taken into account.



Individual GCM scenarios

Potential and water-limited grain production levels of winter wheat were calculated for historical weather data that were changed on the basis of output from three general circulation models, i.e. the GFDL, the GISS and the UKMO-L model, respectively for an equilibrium situation at equivalent doubling of atmospheric CO₂ concentration. In these calculations the direct effect of increasing CO₂ concentration (from 353 to 560 ppm) is taken into account.

Increasing CO₂ results in a higher CO₂ assimilation rate and thus in higher potential grain production, in comparison to those calculated for the same GCM scenarios without direct CO₂ effect (Tables 5.7 and 5.8). The change in climate (mainly a rise in temperature and, for the GFDL scenario, also a decrease in radiation) alone generally causes a decrease in potential grain production compared to that for historical climate (Table 5.7). Hence, if the effect of the climate change scenario is largest, potential production will decrease, and if the direct effect of atmospheric CO₂ is largest,

potential production will increase (Table 5.8). The highest potential grain production is derived generally for the GISS scenario due to the smallest temperature rise, and the lowest generally for the UKMO-L scenario, and for the GFDL scenario only on locations where radiation becomes limiting (Kinloss).

In the same way as described for the individual GCM scenarios without direct CO₂ effect, water-limited grain production is determined by the level of potential production and the change in and interaction of weather variables. This complexity prevents straightforward explanations of the effects on grain production of the climate change scenarios (Table 5.8). The GFDL scenario gives major decreases in water-limited grain production for Ireland, Scotland and northern Spain, due to

an earlier start in spring (low radiation) at the higher temperatures and a reduction of the amount of radiation according to the scenario (Figure 5.14). Moderate production decreases are calculated for England, Portugal and southern Spain and constant production for northern Germany and the Netherlands. At the other locations major increases in water-limited grain production are found as a result of the direct CO₂ effect. The GISS scenario gives major increases in water-limited grain production for most locations (Figure 5.15). Also for the UKMO-L scenario, water-limited grain production increases at most locations. Exceptions are decreases in northern Spain, Ireland and England and constant production in the Netherlands and the northern parts of Portugal, France and Germany (Figure 5.16).

Table 5.8 Average potential (POT) and water-limited (WAT) grain production (kg/ha dry matter) of winter wheat, established for historical weather data that were changed on the basis of output from GFDL, GISS and UKMO-L models for an equilibrium situation at doubled atmospheric CO₂. Direct effect of doubled CO₂ is taken into account.

Location	Historical weather		Scenario					
			GFDL		GISS		UKMO-L	
	POT	WAT	POT	WAT	POT	WAT	POT	WAT
Brindisi	9370	4510	9420	8580	9210	8620	8530	7830
Kinloss	8740	5680	4180	4180	10530	10160	9310	8630
Orleans	9630	6510	11740	10830	12360	9050	9970	9410

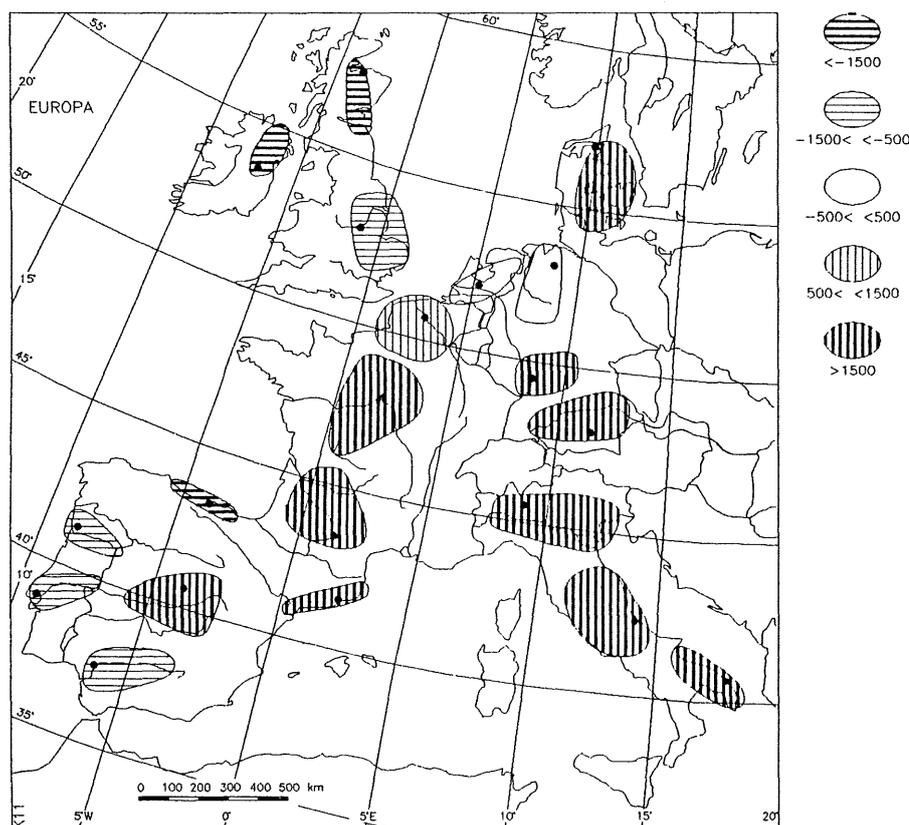


Figure 5.14 Changes in water-limited grain production (kg/ha dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of output from the GFDL model for an equilibrium situation at doubled atmospheric CO₂ and the direct effect of doubled CO₂ is taken into account.

Figure 5.15 Changes in water-limited grain production (kg/ha dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of output from the GISS model for an equilibrium situation at doubled atmospheric CO₂ and the direct effect of doubled CO₂ is taken into account.

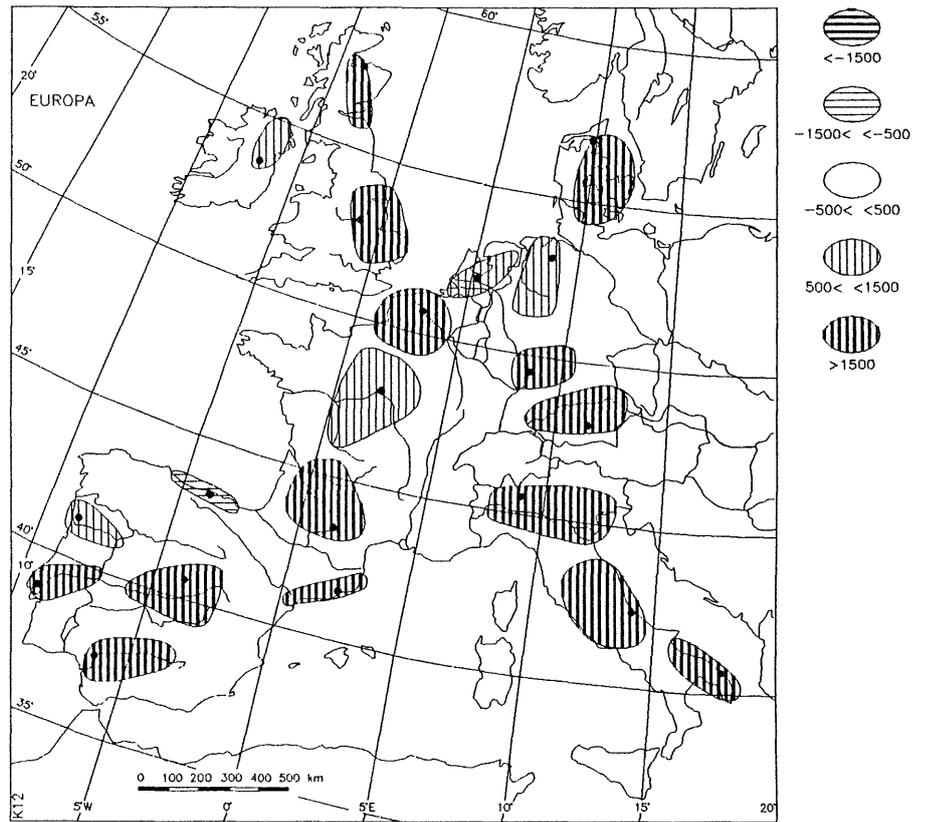
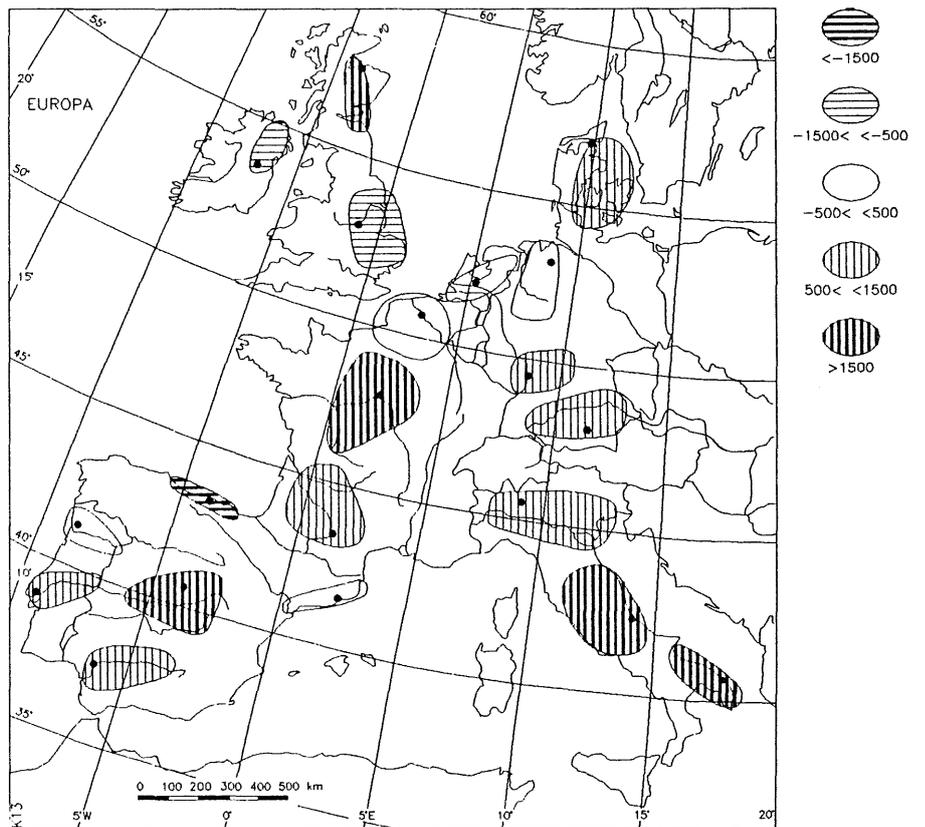


Figure 5.16 Changes in water-limited grain production (kg/ha dry matter) of winter wheat in the main arable land areas in the EC if the weather is changed on the basis of output from the UKMO-L model for an equilibrium situation at doubled atmospheric CO₂ and the direct effect of doubled CO₂ is taken into account.



5.3.5 Management analyses

Crop temperature sums

The interactions between the temperature sums required for crop development and the effects of climate change and increasing atmospheric CO₂ concentration were determined for three locations covering the main differences in climate in the EC, i.e. Kinloss in Scotland, Orleans in France and Brindisi in Italy. It was assumed that, compared to the main wheat varieties grown at the moment, plant breeding might be able to produce varieties needing 10% higher or 10% lower temperature sums (°C days) for crop development from January 1 to anthesis and from anthesis to the end of grain filling. Varieties developed for climate change should probably be changed not only with respect to their temperature sum requirements but also with respect to their photoperiod sensitivity, as the start of crop growth in spring will occur at an earlier date and thus when days are shorter. But the effect of day length was not taken into account in these model calculations.

For the average wheat variety grown at the moment, and for these artificially constructed wheat varieties, average grain production was calculated for historical weather data, for historical weather data changed on the basis of the composite scenario A for the year 2050, both without and with the direct effect of increased

atmospheric CO₂ concentration, and for historical weather data changed on the basis of the composite scenario A High for the year 2050 with direct CO₂ effect (Table 5.9).

A longer (shorter) period of grain filling appears to result in a slightly higher (lower) grain production (Table 5.9), except where drought stress occurs at the end of the grain-filling period (eg. water-limited production in Brindisi), and this effect on production becomes almost nil. An earlier (later) start of grain filling results in higher (lower) grain production, particularly where drought stress occurs at the end of the grain-filling period. This does not occur, however, in a situation with both irrigation (potential production) and relatively higher temperatures in the future (according to the climate scenarios), because then the short duration of the vegetative growth period and the resulting small leaf area become limiting for grain production.

For both potential and water-limited production optimum temperature sums from January 1 to anthesis and from anthesis to the end of grain filling were derived for the three locations and for both historical and scenario weather data. The resulting optimum temperature sums are summarised in Table 5.10.

From these results it can be concluded that the highest potential production for a changed climate will be

Table 5.9 Sensitivity to temperature sums (°C days) for crop development from 1 January to anthesis (T-anth) and from anthesis to the end of grain filling (T-ripe) of the average potential (POT) and water-limited (WAT) grain production (kg/ha dry matter) of winter wheat for historical weather data and scenario weather data from Orleans, France, without and with direct CO₂ effect.

T-anth	T-ripe	Hist.		Scenario					
		Weather		A2050		A2050 + CO ₂		A High 2050 + CO ₂	
		POT	WAT	POT	WAT	POT	WAT	POT	WAT
100%	100%	9630	6510	9400	6220	12170	8640	11720	8450
90%	100%	9860	7710	9270	7210	12110	9820	11450	9540
100%	90%	9230	6330	8990	6050	11640	8390	11200	8200
90%	90%	9400	7460	8810	6950	11510	9460	10860	9180
110%	100%	8860	5110	8950	4990	11540	7110	11360	7060
100%	110%	9950	6640	9710	6340	12560	8820	12110	8630
110%	110%	9130	5200	9190	5070	11860	7210	11680	7170

Table 5.10 Optimum temperature sums from January 1 to anthesis (T-anth) and from anthesis to the end of grain filling (T-ripe) for Kinloss in Scotland, Orleans in France, Brindisi in Italy and for both historical and scenario weather data.

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

¹ Only in Brindisi, Italy.

² Only in Orleans, France.

attained with wheat varieties that need higher temperature sums for grain filling and hence have a longer period of grain filling, and that the highest water-limited production in projected future and also current conditions will be attained with wheat varieties that need lower temperature sums until anthesis and hence have an early start of grain filling.

Comparing the effects on grain production of varying crop temperature sums, changes in climate according to the scenarios, and increasing atmospheric CO₂ concentrations (Table 5.9), it is increasing CO₂ which appears to have the largest positive effect on both potential and water-limited production of winter wheat.

Irrigation requirements

The amount of irrigation water required to prevent drought stress during the growth period of winter wheat, and to attain the potential level of grain production in the EC, was calculated. Conveyance and application losses are not included in the amount, as they are widely variable and dependent on local conditions (management, the irrigation system, etc.). The calculations were done for historical weather data, for historical weather data that were changed on the basis of the composite scenario A for the year 2050, both without and with direct effect of increased atmospheric CO₂ concentration, and for historical weather data that were changed on the basis of composite scenario A High for the year 2050 with direct CO₂ effect (Table 5.11).

Table 5.11 Required average amounts of irrigation water (cm) for attaining the potential level of grain production for winter wheat at six locations in the EC, both for historical weather data and for scenario weather data without and with direct CO₂ effect.

Location	Hist. weather	Scen. A 2050	Scen. A 2050 + CO ₂	Scen. 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

Climate changes according to scenario A 2050 result in higher irrigation requirements in northern Europe, but lower irrigation requirements in southern Europe (Table 5.11). According to the scenario temperatures become higher, so the beginning of crop growth in spring is shifted to an earlier date, particularly in northern Europe and to a more limited extent in southern Europe. Moreover, grain filling ends earlier. Therefore, a rise in temperature appears to result in a shifted and constant or sometimes even longer period of 'effective' growth in northern Europe, and in a shorter period in

southern Europe. This explains the higher water use and irrigation requirements in northern Europe and the lower ones in southern Europe as a result of the changes in climate.

Increasing atmospheric CO₂ concentrations result in more efficient water use. This effect of CO₂ roughly counteracts the higher water use and irrigation requirements in northern Europe as result of the climate changes, and causes a larger decrease in the irrigation water required in southern Europe.

Nutrient requirements

Large increases in wheat grain production are calculated for climate change conditions, mainly due to increasing atmospheric CO₂ concentrations. Such production increases, however, can only be attained if the nutrient supply does not limit production. For example, the dry matter production of wheat in pot experiments was found to increase to 145%, if the atmospheric CO₂ concentration was doubled and the nutrient supply was sufficient (Goudriaan and de Ruiter, 1983). Production increased to 117% if the nitrogen supply was deficient, and remained 100% if the phosphorus supply was deficient. As discussed by van Kraalingen (1990), increases in dry matter production resulting from doubled atmospheric CO₂ concentration but with a deficient supply of nitrogen and/or phosphorus, might result in large amounts of vegetative plant material but lower grain yields. Hence, the increases in grain production at doubled CO₂ concentration will only be realised if the amounts of fertiliser nutrients applied are simultaneously adapted to the higher production.

5.3.6 Interpretation of scenario and management analyses for the EC

The effects of climate change on winter wheat production appear to differ widely for the different regions of Europe but also for the different scenarios (Figures 5.9, 5.10 and 5.11). In order to obtain an overall picture, changes in water-limited grain production due to climate change as calculated per location were multiplied by the relative wheat area in the EC (Eurostat, 1990) represented by that location. Note that a certain degree of inaccuracy is unavoidable in such a rough approach.

Grain production of winter wheat in the EC appears to decrease with climate change, as derived from the different scenarios. Composite scenarios A 2050 and A High 2050 result in average decreases in grain production of 170 and 290 kg/ha dry matter, respectively, for the EC as a whole. The GFDL and UKMO-L scenarios show average decreases in grain production of 670 and 960 kg/ha dry matter, respectively. Only the GISS scenario, which gives a relatively small temperature rise, shows an average grain production increase of 90 kg/ha

dry matter in the EC. The GFDL scenario gives a large decrease in grain production, as a result of the higher temperature rise and partly also as a result of decreased solar radiation in winter and spring, mainly in the western part of the EC (Figure 5.9: UK, Ireland and northern Spain). The UKMO-L scenario gives the largest temperature rise and thus the largest decrease in production.

If not only the climate change scenarios but also the direct effect of increasing atmospheric CO₂ concentrations are taken into account, grain production of winter wheat in the EC appears to increase in the future. For the EC as a whole, average increases in grain production were calculated of 2040 and 1890 kg/ha dry matter respectively for composite scenarios A 2050 and A High 2050, and of 1310, 2300 and 1040 kg/ha dry matter respectively for the GFDL, GISS and UKMO-L scenarios. The GISS scenario gives the greatest increase in production as a result of increasing CO₂ and a relatively limited increase in temperature. For the GFDL and the UKMO-L scenarios the increases in production due to increasing CO₂ are limited by the greater increase in temperature, and for the GFDL scenario by the decrease in solar radiation in winter and spring (Figure 5.14: Scotland, Ireland and northern Spain).

Increasing atmospheric CO₂ concentration appears to cause a large increase in wheat grain production in the EC. This direct CO₂ effect is much larger than the decrease in grain production that is calculated on the basis of the climate change scenarios alone. For the individual scenarios, the direct effect of equivalent doubling of CO₂ results in average increases in grain production between 1980 and 2210 kg/ha dry matter.

In order to achieve an overall picture of the effects of climate change on the irrigation requirements for potential winter wheat production in the EC, changes in irri-

gation requirements due to climate change as calculated per location were multiplied by the relative wheat area in the EC represented by that location. The result shows about the same average irrigation requirements (ie. a decrease of 0.3 cm) in the EC, if the climate is changed on the basis of composite scenario A 2050. If the direct effect of increasing atmospheric CO₂ is also taken account and the climate is changed on the basis of composite scenarios A 2050 and A High 2050, average irrigation requirements decrease by 1.6 and 2.1 cm respectively compared to those in current climate.

5.4 Grain and silage maize

Identical sensitivity, scenario and management analyses as described above for winter wheat, were carried out for maize. The information given here is mainly restricted to results from the scenario analyses. Some additional information is given on the sensitivity to changes in weather variables, and on the differences between the approach and data base for winter wheat and those for grain and silage maize, mainly to allow explanation of the results from the scenario analyses. Complete information on the results from the analyses for grain and silage maize can be found in the report mentioned at the end of this chapter.

5.4.1 Sensitivity analyses

Table 5.12 summarises the sensitivity of grain maize and silage maize production to changing values for the different weather variables. Potential production of grain and silage maize increases with increasing solar radiation and also with a rise in temperature if current temperatures are relatively low (Kinloss, Scotland). In Brindisi, Italy, however, a rise in temperature results in a shorter growing period and hence lower production.

Table 5.12 Sensitivity of potential (POT) and water-limited (WAT) production of grain maize (GR) and silage maize (SIL) in Kinloss, UK (KIN), Orleans, France (ORL), and Brindisi, Italy (BRI) to increasing values for atmospheric CO₂ concentration (C), temperature (T), rainfall (R), solar radiation (S), windspeed (W) and vapour pressure (V)¹.

	C			T			R		
	KIN	ORL	BRI	KIN	ORL	BRI	KIN	ORL	BRI
GR POT	0	0	0	++	0	—	0	0	0
GR WAT	0	++	0	++	—	0	0	++	0
SIL POT	0	0	0	++	—	—	0	0	0
SIL WAT	0	++	+	++	—	-	0	++	0
	S			W			V		
	KIN	ORL	BRI	KIN	ORL	BRI	KIN	ORL	BRI
GR POT	+	++	+	0	0	0	0	0	0
GR WAT	0	-	0	-	—	0	0	++	0
SIL POT	++	++	++	0	0	0	0	0	0
SIL WAT	++	0	0	-	—	-	0	++	0

¹ 0, +, ++ : no, moderate, major increase in production; -, — : moderate, major decrease in production.

Water-limited production of grain and silage maize, influenced by temperature in about the same way as the potential production, increases with increasing atmospheric CO₂ concentration, vapour pressure and rainfall, and decreases with increasing windspeed. These changes in water-limited production are sometimes restricted by the low values for current temperatures (Kinloss) or amounts of rainfall (Brindisi).

5.4.2 Scenario analyses

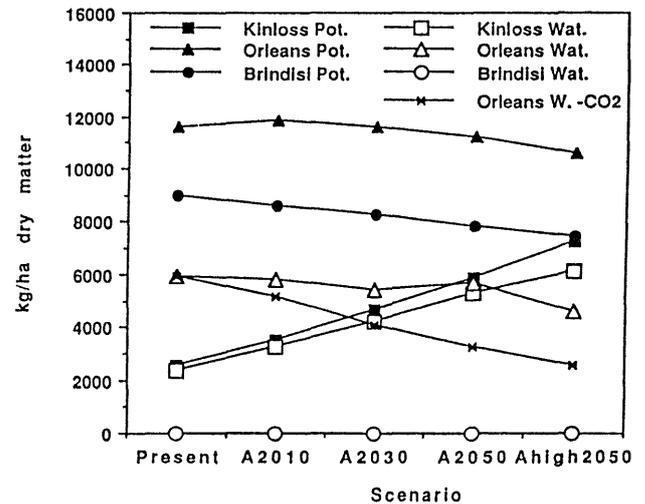
Grain maize

For the composite scenarios, it is calculated that potential production in Orleans will remain roughly the same (Figure 5.17) up to year 2050, when production goes down, particularly for scenario A High with its stronger increase in temperature. In Kinloss, a temperature rise over time results in a higher assimilation rate and longer growth period and hence increasing grain production. However, in the year 2050 grain production is not yet possible (except possibly for scenario A High), as the production level is still too low (ie. an indication of incomplete grain ripening). In locations in southern Europe such as Brindisi, grain production decreases over time as a result of a gradual decrease in the growth period.

Water-limited production in Orleans is about half the potential production and decreases over time, as a result of a limited increase in periods with drought stress and a shorter growth period. If the direct effect of atmospheric CO₂ on crop growth is not taken into account, water-limited production decreases over time much more rapidly (Figure 5.17). As presented above, increasing CO₂ results in a major reduction of the crop transpiration rate and this explains the difference in production. In Kinloss the water-limited production increases over time, being mainly limited by the temperature. In Brindisi the water-limited production is zero and depends completely on the application of irrigation water. As the water supply in summer appears to be strongly limiting for the production of grain maize in central Europe and particularly in southern Europe, only the results for the potential production of grain maize in the EC will be presented in the following.

For composite scenario A 2050, major production increases were found in the UK, Ireland, Denmark and southern Germany (Figure 5.18), areas which are unsuitable or of limited suitability for grain maize production at the moment. From the production levels it can be derived that in the year 2050 only Kinloss and Mullingar will not yet be suitable for grain maize production. Moderate increases in production were calculated for northern France, Netherlands and northern Germany, areas where grain maize production is just possible at present. Moderate to major decreases in

Figure 5.17 Average potential (Pot.) and water-limited (Wat.) grain production of maize cultivated at current and future climate conditions in Kinloss, UK, Orleans, France and Brindisi, Italy, taking into account the direct effect of increasing atmospheric CO₂ in future (for Orleans also without this CO₂ effect). Production has been established for the average soil characteristics per location and for historical weather data over a period of 20 years (1966–1985), and for historical weather data that were changed on the basis of composite scenario A for the years 2010, 2030 and 2050, and composite scenario A High for the year 2050.



grain production were calculated for southern Europe, as a result of the rising temperatures that cause a shorter growth period. This can probably be largely prevented by growing maize varieties with higher temperature sum requirements.

The GFDL scenario gives major decreases in grain production for almost all locations in the EC except the UK, Ireland and Denmark, for which major production increases were calculated, and the Netherlands and northern Germany, for which grain production was calculated to remain about the same (Figure 5.19). Then grain maize can be grown at all locations in the EC. The GISS scenario gives almost the same change in grain production (Figure 5.20) as the GFDL scenario, but as the temperature rise on the basis of this scenario is slightly less, the calculated decreases in grain production are generally smaller and the increases are generally larger. According to the UKMO-L scenario the temperature rise in the summer is almost identical to that for the GFDL scenario; consequently, the resulting changes in grain production (Figure 5.21) are almost identical for both scenarios.

Silage maize

For the composite scenarios, potential total production in Orleans is calculated to decrease slowly over time (Figure 5.22). For scenario A High with its higher temperature rise, total production decreases more rapidly. In Kinloss, the rise in temperature over time results in a

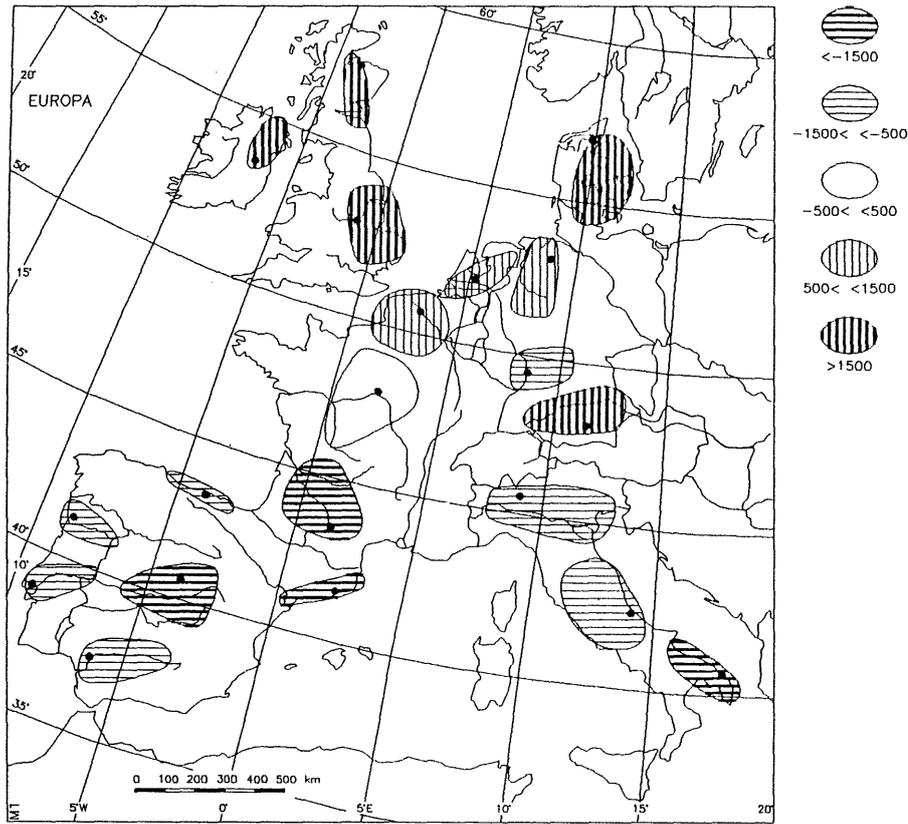


Figure 5.18 Changes in potential grain production (kg/ha dry matter) of maize in the main arable land areas in the EC if the weather is changed on the basis of the composite scenario A for the year 2050.

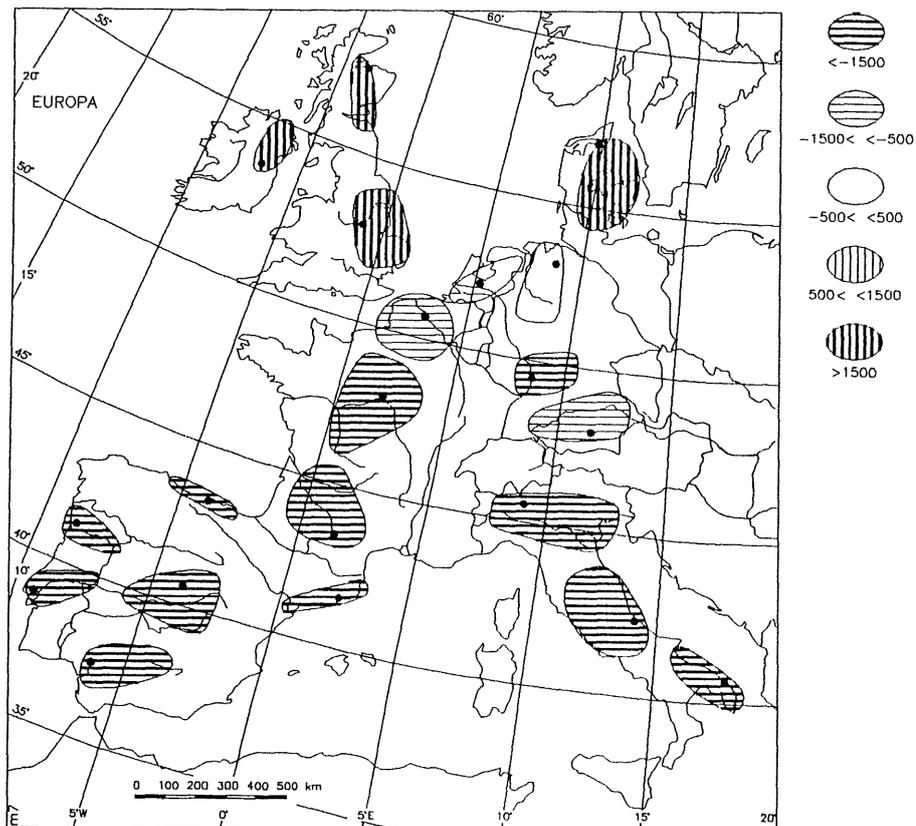


Figure 5.19 Changes in potential grain production (kg/ha dry matter) of maize in the main arable land areas in the EC if the weather is changed on the basis of output from the GFDL model for an equilibrium situation at doubled atmospheric CO₂.

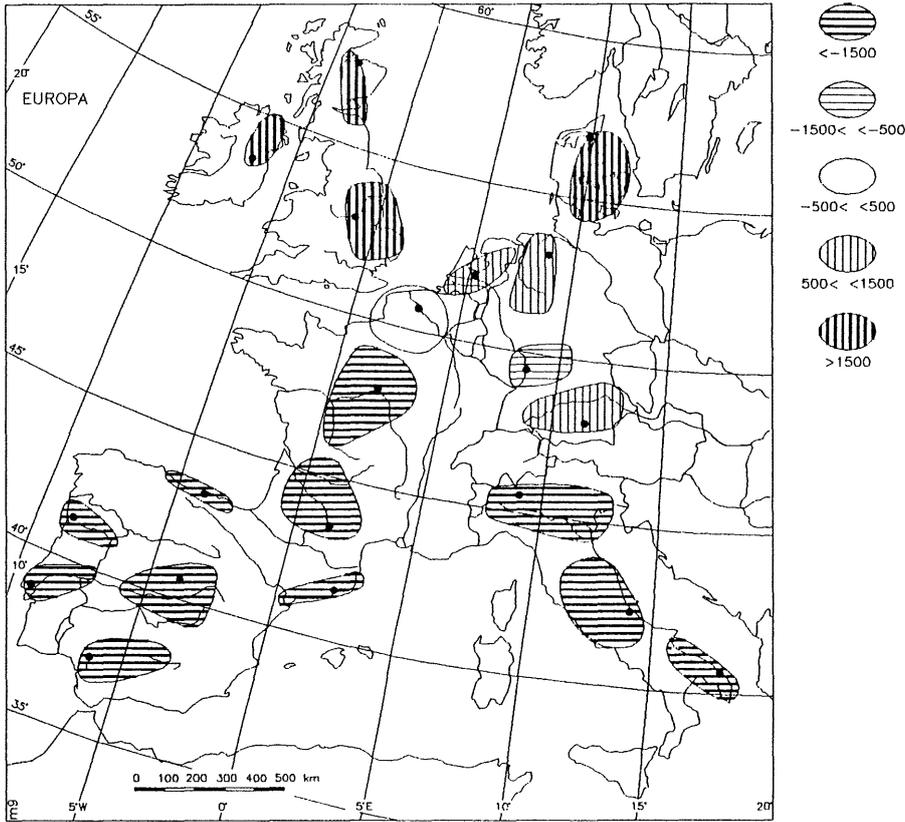


Figure 5.20 Changes in potential grain production (kg/ha dry matter) of maize in the main arable land areas in the EC if the weather is changed on the basis of output from the GISS model for an equilibrium situation at doubled atmospheric CO₂.

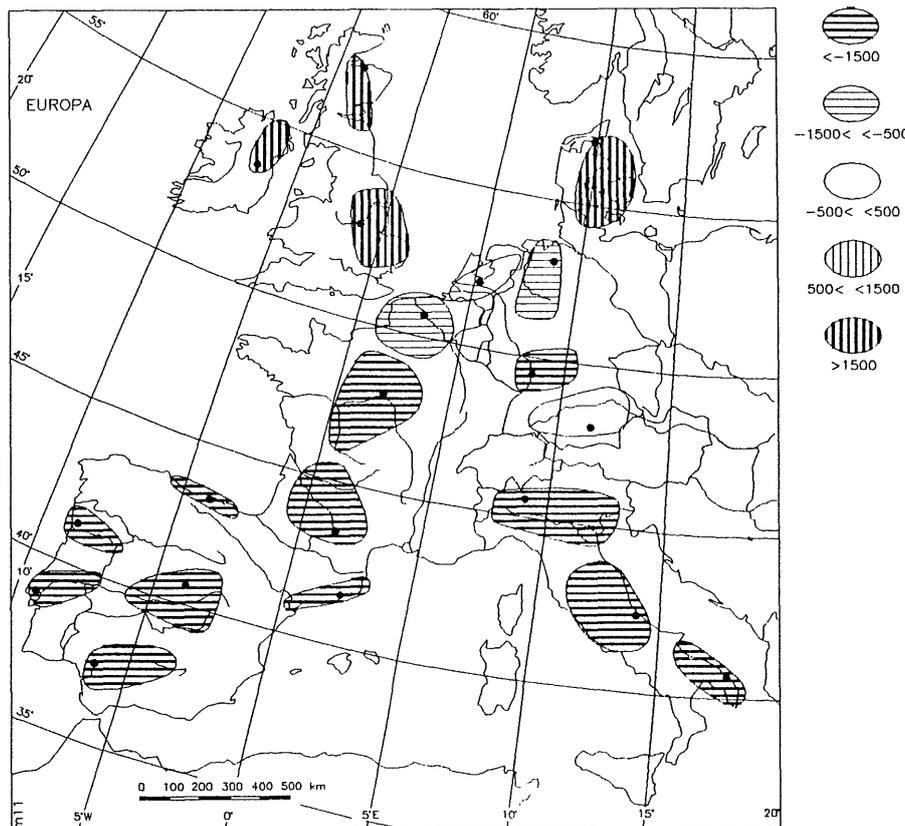
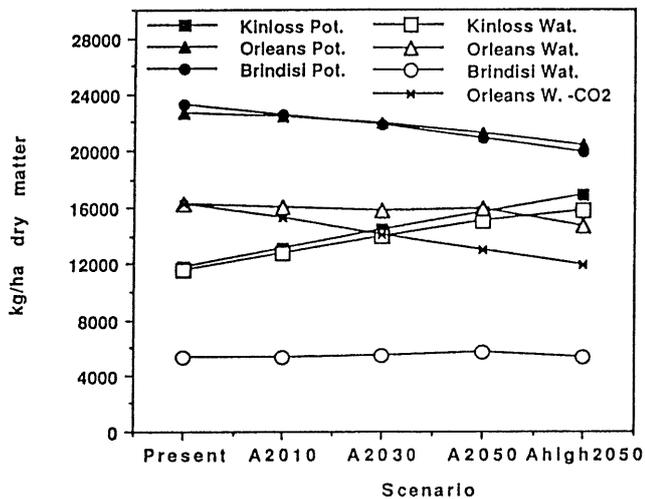


Figure 5.21 Changes in potential grain production (kg/ha dry matter) of maize in the main arable land areas in the EC if the weather is changed on the basis of output from the UKMO-L model for an equilibrium situation at doubled atmospheric CO₂.

Figure 5.22 Average potential (Pot.) and water-limited (Wat.) total production of silage maize cultivated at current and future climate conditions in Kinloss, UK, Orleans, France and Brindisi, Italy, taking into account the direct effect of increasing atmospheric CO₂ in future (for Orleans also without this CO₂ effect). Production has been established for the average soil characteristics per location and for historical weather data over a period of 20 years (1966–1985), and for historical weather data that were changed on the basis of composite scenario A for the years 2010, 2030 and 2050, and composite scenario A High for the year 2050.



longer growth period and higher assimilation rate and hence a major increase in production. From the year 2050, production of silage maize is high enough to become of interest, particularly if scenario A High applies. In locations in southern Europe such as Brindisi, production decreases over time as a result of the gradual decrease in growth period.

Water-limited production in Orleans is about 70% of the potential production and gradually decreases over time, as a result of a limited increase in periods with drought stress and a shorter growth period. If the direct effect of atmospheric CO₂ on crop transpiration is not taken into account, water-limited production decreases much more rapidly (Figure 5.22). In Kinloss water-limited production rises over time, being mainly limited by the temperature. In Brindisi the water-limited production is about a quarter of the potential production and remains almost constant over time. Although the water supply in summer may be strongly limiting for the production of silage maize, particularly in southern Europe, it is assumed that irrigation water may be applied only in limited amounts on this fodder crop; hence, only results for water-limited production of silage maize in the EC will be presented in the following.

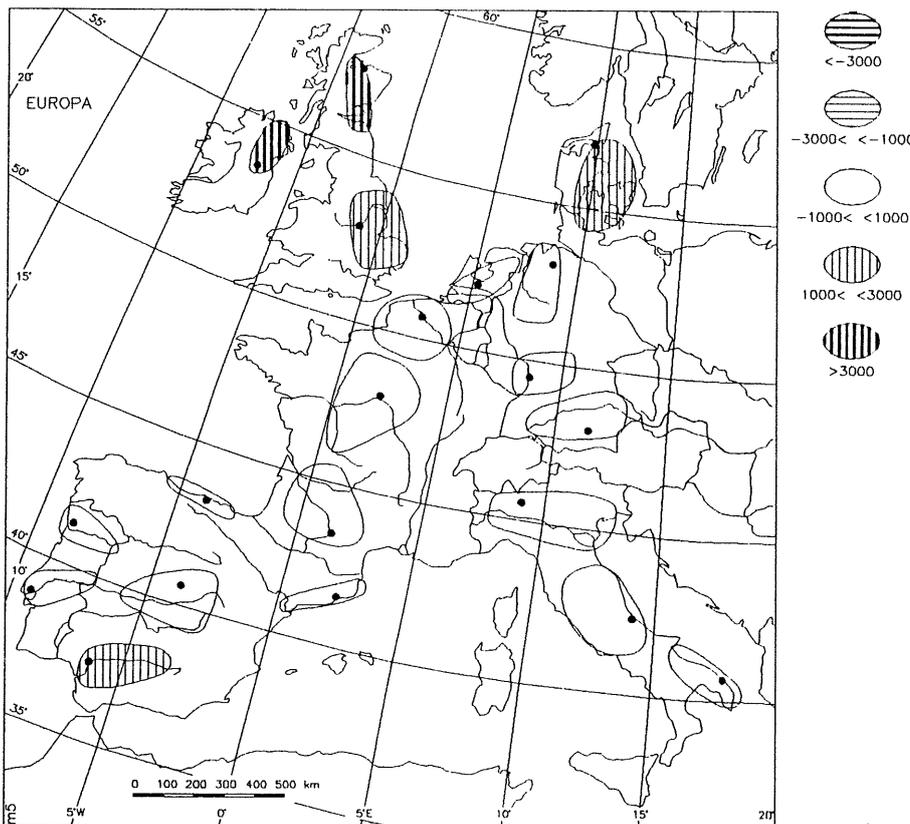


Figure 5.23 Changes in water-limited total production (kg/ha dry matter) of silage maize in the main arable land areas in the EC if the weather is changed on the basis of the composite scenario A for the year 2050 and the direct effect of increasing atmospheric CO₂ is taken into account.

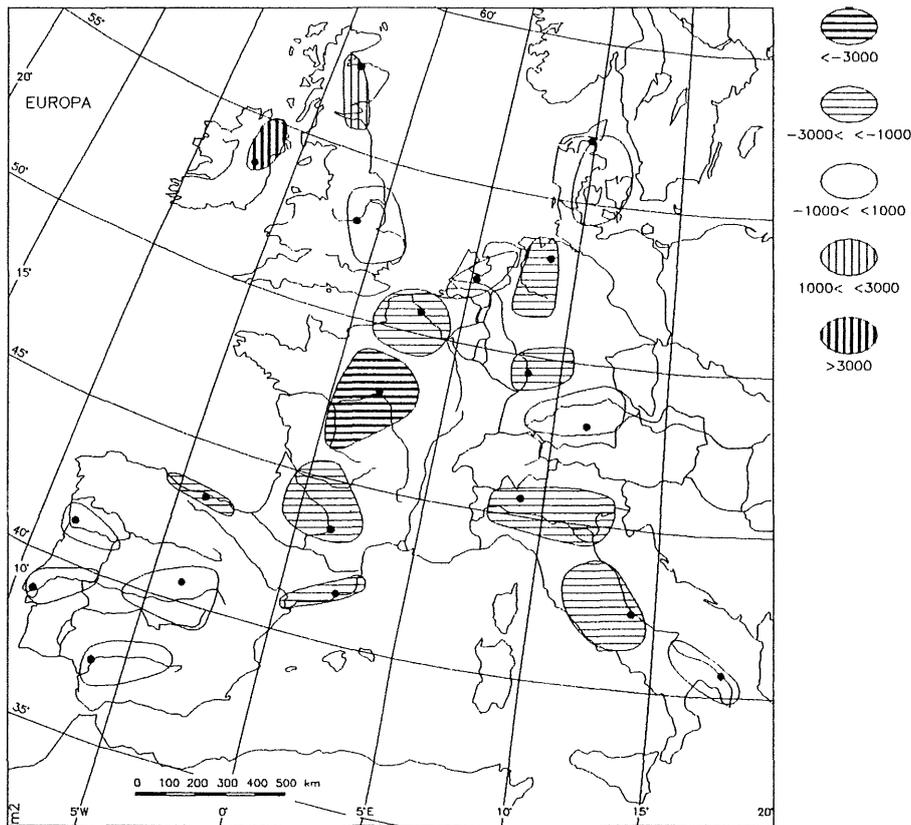


Figure 5.24 Changes in water-limited total production (kg/ha dry matter) of silage maize in the main arable land areas in the EC if the weather is changed on the basis of the composite scenario A for the year 2050 (direct effect of increasing atmospheric CO_2 not taken into account).

For composite scenario A 2050, large production increases are found for Ireland and Scotland, which are unsuitable at present, and moderate production increases for England and Denmark (Figure 5.23). According to the production levels in year 2050, silage maize can be grown at all locations in the EC except for Kinloss, where this is only possible if scenario A High applies. At almost all other locations in the EC the silage maize production remains the same. Although there is a shorter growth period at the higher temperature, a potential decrease in production appears to be counteracted by less drought stress, as a result of a lower crop transpiration rate at increasing atmospheric CO_2 . If the direct effect of CO_2 on crop transpiration is not taken into account, a decrease in production is calculated for most locations in the EC (Figure 5.24), except for northern Europe. On most locations in southern Europe the water-limited production is calculated to be very low, i.e. equal to or less than 40% of the potential production, so growing silage maize in southern Europe generally requires irrigation.

The GFDL scenario gives constant production for Scotland and a moderate increase for Ireland because of rising temperatures, major decreases in production for central Europe, as a result of shorter growth periods at the higher temperatures, and sometimes more drought stress because of less rainfall, and approximately constant production for southern Europe (Figure 5.25). In southern Europe water-limited production at present is low, being mainly determined by the limited water

supply. Rising temperatures will therefore reduce the growth period and production only to a limited extent. In all locations in the EC silage maize can be grown then. According to the GISS scenario, the production of silage maize at most locations in the EC will remain the same, i.e. the effect of a shorter growth period will be counteracted by less drought stress (Figure 5.26). Only in northern Europe will rising temperatures result in moderate to major increases in production. The temperature rise according to the UKMO-L scenario is almost identical to that for the GFDL scenario, but with less drought stress as a result of more rainfall. Hence, for most locations moderate decreases in production are calculated, except for major increases in production in Ireland and Scotland and fairly constant production in southern Europe (Figure 5.27).

5.5 Conclusions

Increasing concentrations of greenhouse gases in the atmosphere may cause climate change. Using various climate change scenarios, such changes appear to yield considerably different changes in production for the different scenarios, both for each location and for the EC as a whole. For example, the average grain production of winter wheat in the EC at equivalent doubling of atmospheric CO_2 may remain roughly constant or may decrease by about 1000 kg/ha dry matter, depending on the scenario.

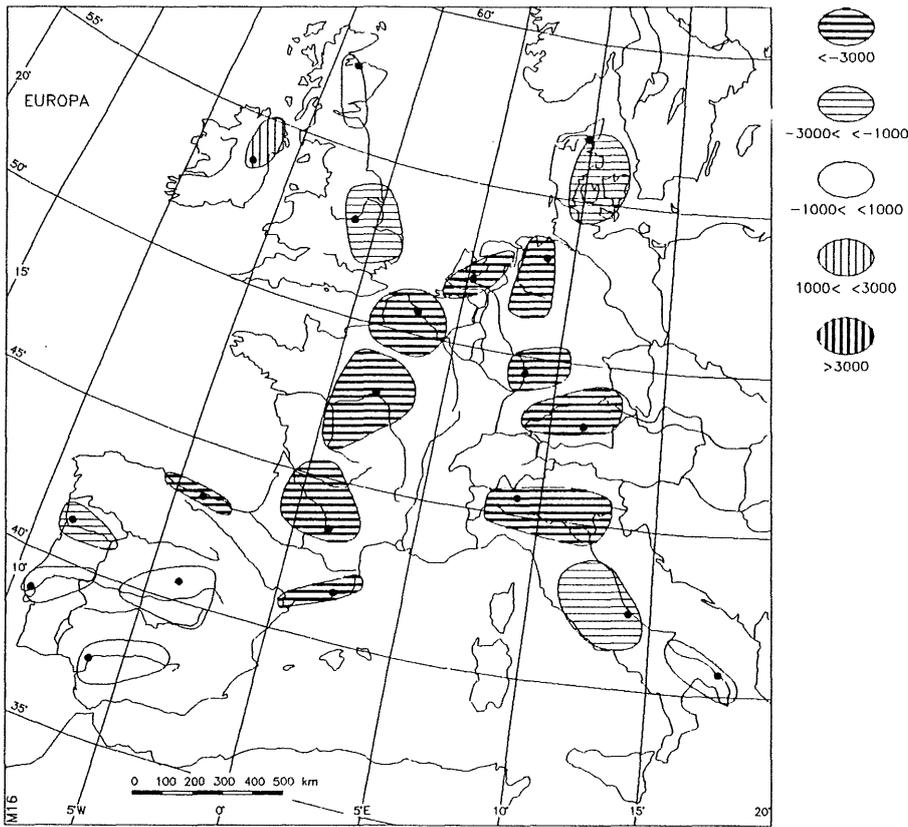


Figure 5.25 Changes in water-limited total production (kg/ha dry matter) of silage maize in the main arable land areas in the EC if the weather is changed on the basis of output from the GFDL model for an equilibrium situation at doubled atmospheric CO₂ and the direct effect of doubled CO₂ is taken into account.

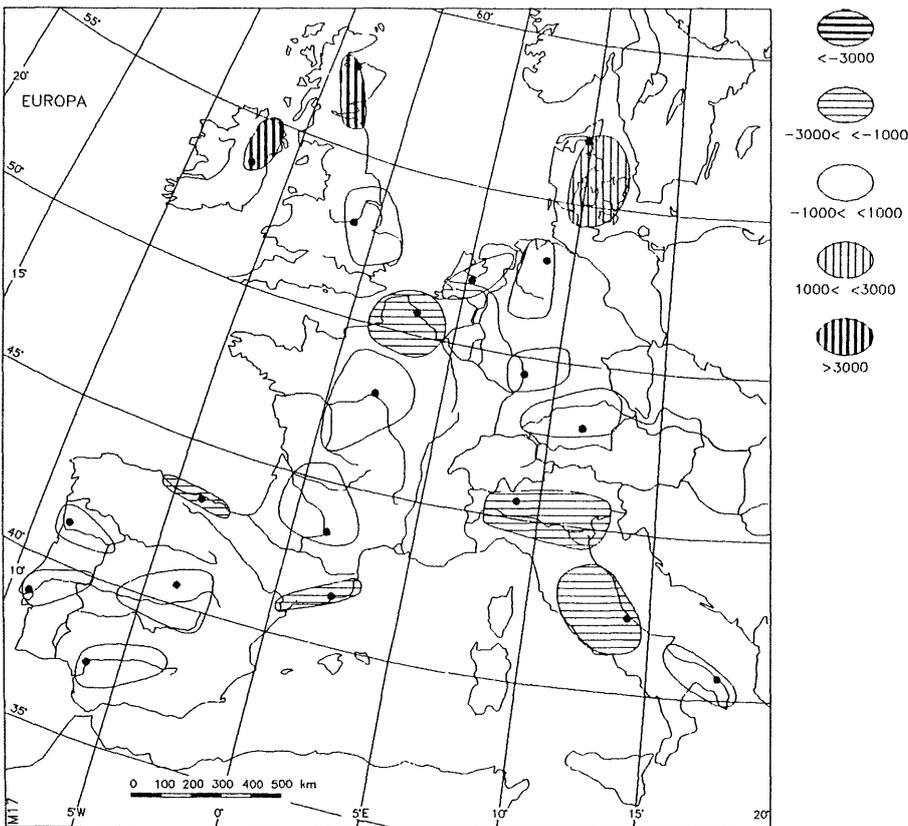


Figure 5.26 Changes in water-limited total production (kg/ha dry matter) of silage maize in the main arable land areas in the EC if the weather is changed on the basis of output from the GISS model for an equilibrium situation at doubled atmospheric CO₂ and the direct effect of doubled CO₂ is taken into account.

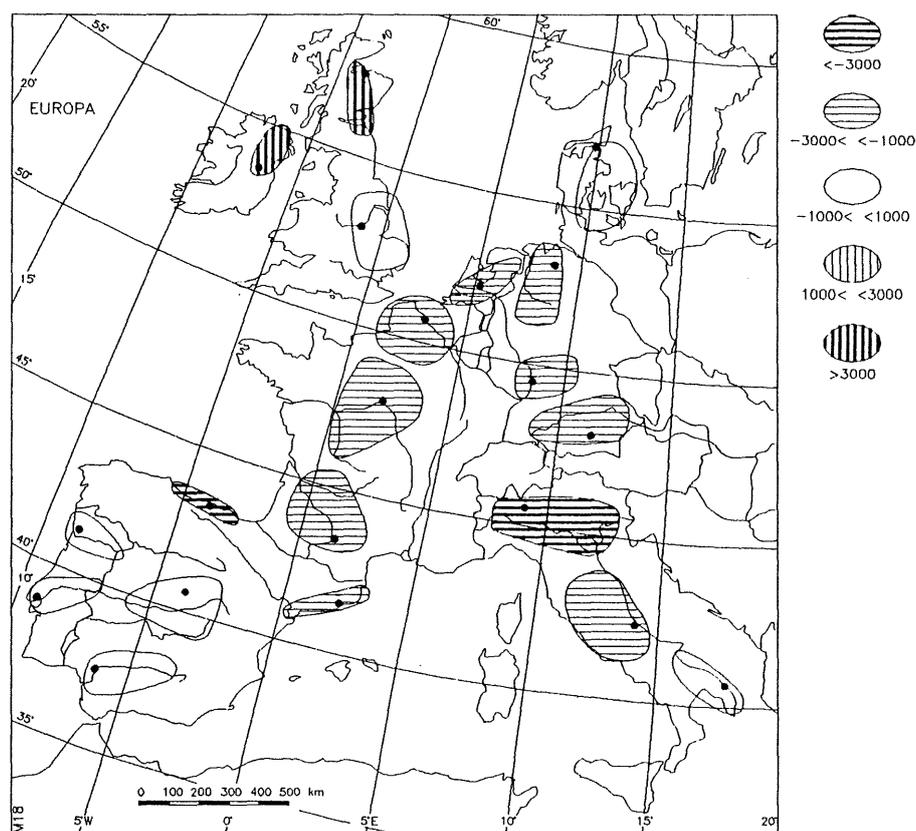


Figure 5.27 Changes in water-limited total production (kg/ha dry matter) of silage maize in the main arable land areas in the EC if the weather is changed on the basis of output from the UKMO-L model for an equilibrium situation at doubled atmospheric CO_2 and the direct effect of doubled CO_2 is taken into account.

The direct effect of increasing atmospheric CO_2 on wheat grain production appears to be much greater than the effects of climate change which may result from greenhouse gases such as CO_2 . Moreover, the direct effect of CO_2 on production is more certain, whereas the effect through climate change is widely variable depending on the scenario, and is not yet established as fact. If both effects are taken into account, the average grain production of winter wheat in the EC may increase by 1100–2300 kg/ha dry matter at equivalent doubling of CO_2 . However, such production increases will only be achieved completely if applications of fertiliser nutrients are adapted to the higher production levels.

Grain production of winter wheat is calculated to increase greatly with increasing vapour pressure, rainfall and atmospheric CO_2 concentration, to decrease greatly with increasing windspeed and temperature (except for southern Europe, where there is a slight increase with rising temperature) and to decrease moderately with increasing solar radiation.

With climate change highest potential production will generally be attained with wheat varieties that have higher temperature sum requirements for grain filling and hence have a longer period of grain filling. If drought occurs at the end of the grain filling period, wheat varieties with lower temperature sum requirements to anthesis and hence an early start of grain

filling may yield higher grain production, in both current and future climatic conditions.

The average irrigation requirements for attaining the potential level of wheat production in the EC remain fairly constant, if the climate is changed on the basis of the composite scenario for the year 2050. But at locations in northern Europe the irrigation requirements increase with changing climate, and in southern Europe they decrease. If the direct effect of increasing atmospheric CO_2 concentrations is also taken into account, this counteracts the higher irrigation requirements in northern Europe due to climate change, causes a greater decrease in irrigation requirements in southern Europe and causes a decrease in average irrigation requirements for the E.C.

For almost all arable land areas in the EC, climate change as based on the different scenarios appear to yield an equal or lower CV of wheat grain production compared to that at current climate. A considerable decrease in the CV of grain production can be attained by reducing the risk of a drought period by applying irrigation water.

The potential production of grain maize is calculated to increase moderately to greatly with increasing solar radiation, and with rising temperatures to increase greatly in northern Europe, remain constant in central Europe and decrease greatly in southern Europe. Water-limited production of silage maize is calculated to

remain constant in northern Europe and to increase moderately and greatly in southern and central Europe, respectively, with an increasing CO₂ concentration; to increase greatly in northern Europe and to decrease moderately and greatly in southern and central Europe, respectively, with rising temperatures; to increase mainly in central Europe with increasing rainfall and vapour pressure; to increase mainly in northern Europe with increasing radiation; and to decrease with increasing windspeed.

According to the composite scenarios, in the year 2050 in northern Europe the area suitable for the production of grain maize becomes larger, and the level of grain production increases. In southern Europe in 2050 grain production decreases, but this effect can largely be prevented by growing other maize varieties. For the individual scenarios at equivalent doubling of CO₂, increases in grain production for northern Europe and decreases for central and southern Europe were calculated. In the year 2050 the production of silage maize is about the same as that at present. Production increases were calculated only for areas in northern Europe, which are marginal at present. For the individual scenarios at equivalent doubling of CO₂, the production of silage maize at most locations in the EC remains about the same according to the GISS scenario, and decreases moderately according to the UKMO-L scenario, and decreases greatly according to the GFDL scenario. For the marginal areas in northern Europe (too cold) and southern Europe (too dry), a zero to major increase in production and a zero to moderate decrease in production, respectively, were calculated.

This article is based on two detailed reports on the effects of climate change on wheat production potential and maize production potential in the EC. These reports can be obtained from the Department of Theoretical Production Ecology, Wageningen Agricultural University, P.O. Box 430, 6700 AK Wageningen, Netherlands.

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