EFFECTS OF CHANGES IN TEMPERATURE AND CO_2 CONCENTRATION ON SIMULATED SPRING WHEAT YIELDS IN THE NETHERLANDS

SANDERINE NONHEBEL
Department of Theoretical Production Ecology, Agricultural University, POB 430, 6700 AK Wageningen, The Netherlands

Abstract. A crop growth simulation model based on SUCROS87 was constructed to study the effects of temperature rise and increase of the atmospheric CO_2 concentration on spring wheat yields in The Netherlands. The model simulated potential production (limited by crop characteristics, temperature and radiation but without any stress from water or nutrient shortages or pests, diseases and weeds) and water-limited production in which growth is also limited by water shortage. The model was validated for the present climatic conditions. When daily weather data from a nearby station were used, the model was well able to simulate yields obtained in field experiments.

Effects of several combinations of temperature rise and atmospheric CO_2 concentration on simulated yields were studied. A temperature rise resulted in a reduction in simulated yield due to shortening of the growing period. Large variations existed in the magnitude of this reduction. Increases in atmospheric CO_2 concentration led to yield increases due to higher assimilation rates and to increase of the water use efficiency. Combination of temperature rise and higher CO_2 concentration resulted in small yield increases in years in which water was not limiting growth and large yield increases in dry years.

Change of variety or of sowing date could not reduce the negative effects of temperature rise on simulated yields.

Introduction

Increasing atmospheric CO_2 concentration can affect agricultural production in two ways. On the one hand a higher CO_2 concentration has a stimulating effect on photosynthesis (Lemon, 1983; Cure and Acock, 1986) and leads to improved water use efficiency of crops (direct effect, Goudriaan and van Laar, 1978; Gifford, 1979; Sionit *et al.*, 1980). On the other hand, being a greenhouse gas, increasing CO_2 can induce climatic change (indirect effect).

In the last decade a large body of research was done on the effects of increasing CO_2 concentration on crop production, varying from indoor CO_2 enrichment experiments with individual plants (Kimball, 1983; Acock and Allen, 1985) to modelling the effects of climatic change on crop production in various parts of the world (Rosenzweig, 1985; Parry and Carter, 1989). A very limited number of studies exists in which the combined effects of increased CO_2 concentration and climatic change on crop production are investigated.

Experimental analyses of the combined effects of climatic change and CO_2 concentration on crop growth is very difficult under field conditions. Moreover the

Climatic Change **24:** 311–329, 1993.

annual variability of the climate is such that long time series are required for reliable results. In such cases the use of simulation models can be helpful. In simulation models knowledge of causal relations at process level can be integrated to examine the overall effect on, for instance, crop growth and yield. An adequate description of processes affected by weather and/or CO_2 concentration is vital for reliable simulation results.

A rather sophisticated crop growth model is needed to simulate the direct effects of CO_2 on leaf photosynthesis and stomatal conductance. This type of model requires detailed, site-specific information (e.g. daily weather data) to simulate crop growth. These data are only available from a small number of sites, which limits the number of simulation runs. Jansen (1990) studied the combined effect of CO_2 concentration rise and climatic change on rice production in Asia and Adams *et al.* (1990) the effect on production of wheat, maize and soybean in the United States. In both studies only the effects on average yields were discussed. In here the combined effect of temperature rise and increase of CO_2 concentration on wheat yields in Western Europe is investigated.

This simulation experiment was done with a crop growth simulation model for spring wheat. Wheat is an important crop and is grown all over Europe. The spring wheat version was used because simulation results with this model were better than the results with the winter wheat version. The spring wheat model is well able to simulate crop production as observed in the field. It is therefore likely that most important relations between weather and crop production are well quantified. This makes the model a proper tool for studying the effects of climatic change on crop yields.

In this paper the effects of several combinations of temperature rise and CO_2 concentration on simulated yields for only one site in The Netherlands are described. Effects for other sites in Europe will be discussed in a forthcoming paper. It is emphasized to validate the model for present climatic conditions. Because it is likely that agricultural practices will change when the climate changes, attention is paid to effects of other sowing dates or varieties on simulated yields.

Present Climate and Agricultural Practices

The average air temperature in The Netherlands is 1 °C in January increasing to 17 °C in July and August (Können, 1983). The daylength at the longest day is 17 h. Precipitation is distributed homogeneously over the year with an average of 60–70 mm month^{-1}. Total annual precipitation may vary from 400 up to 1200 mm (Buishand and Velds, 1980). Evapotranspiration requirements for a spring wheat crop are about 300–400 mm season^{-1} (Buishand and Velds, 1980; Feddes, 1987). In most years water is not a major limiting factor.

In The Netherlands spring wheat is sown in March, anthesis is around June 21st and harvest takes place at the end of August – beginning of September (Broekhuizen, 1969). Average grain yields are 4–6 ton ha^{-1} (de Jong, 1986). Early sowing is favorable for high yields (Spiertz *et al.*, 1971). When sowing is delayed till after April 1st, strong yield decline is observed (Alblas *et al.*, 1987).

Crop Growth Simulation Model

As starting point, a spring wheat version of SUCROS87 (Simple and Universal CROp Simulation model) was used (Spitters *et al.*, 1989). The centre of this model is the calculation of canopy photosynthesis and respiration based on processes at organ level. The model operates with a time interval of one day, but allows for the diurnal course of radiation. Daily dry matter production is distributed to plant organs as a function of the developmental stage. Numerical integration in time gives the time course of dry matter of various organs. The simulation covers the period from crop emergence to maturity. The model has been developed for simulation of crop growth and development at field level in present climatic conditions. For simulation of the effect of climate change and increase of the CO_2 concentration on crop production some adaptations to the original model were necessary.

Adaptations to the Model

The simulation period was extended to include crop emergence. This was done to enlarge the validation possibilities: sowing date is given in most field data sets rather than emergence date. Crop emergence was simulated according to Porter (1987), i.e. only a function of air temperature. This assumption is only valid in conditions in which soil moisture does not limit germination. The simulation of development rate between crop emergence and heading in the original model was replaced by the Miglietta routine (Miglietta, 1991) which gave a better description of the development rate of wheat cultivars in various climates. Development of the crop is determined by rate of leaf appearance which is temperature dependent and the total number of leaves induced which is a function of daylength and the daylength sensitivity of the variety grown. Daylength sensitivity is related to the latitude of origin of the variety (Miglietta, 1991). Development of the crop between heading and maturity was assumed to be a function of air temperature only (van Keulen and Seligman, 1987). The distribution of assimilates is dependent on development stage of the crop, as described by functions derived by van Keulen and Seligman (1987). A sink limitation based on Spiertz and van Keulen (1980) was incorporated in the model; the number of grains formed is a function of the total aboveground biomass at anthesis.

The effect of CO_2 concentration on leaf photosynthesis was simulated according to Goudriaan *et al.* (1985): both initial light use efficiency (EFF) and the maximum rate of leaf photosynthesis at light saturation (AMAX) are affected by CO_2 concentration. At an average temperature of 20 °C doubling of the CO_2 concentration results in an increase of EFF by 15% and a doubling of AMAX.

For simulation of potential soil evaporation and crop transpiration the Penman-

Monteith equation (Monteith, 1965) was used, with intercepted radiation, air temperature and vapor pressure deficit as driving factors. Canopy, boundary layer and aerodynamic resistance (the latter two depending on wind speed and crop structure; Goudriaan, 1977) co-determine the transpiration rate. Canopy resistance was calculated from the average photosynthetic rate per unit leaf area and the gradient between ambient and internal CO_2 concentration (Goudriaan, 1977). The latter is linearly related to the ambient CO_2 concentration (Goudriaan *et al.*, 1985). At a fixed assimilation rate per unit leaf area, doubling of CO_2 concentration leads to doubling of the canopy resistance. However, because a higher CO_2 concentration also stimulates assimilation per unit leaf area, canopy resistance is less than doubled.

The effects of higher CO_2 levels on specific leaf area and dry matter distribution as found in CO_2 enrichment experiments (Acock and Allen, 1985; Cure and Acock, 1986) were not taken into account in this study. However, this crop growth model can be used to simulate the influence of these effects on crop production.

A soil water balance based on van Keulen and Seligman (1987) was used. The soil is treated as a 10-layered system. When precipitation occurs, the first soil layer is filled till field capacity and all excess water entering the layer drains to the next layer. Run off is not taken into account. Soil moisture losses occur by drainage below the potential rooting zone, by crop transpiration from the rooted soil layers and by soil evaporation, mainly from the top layer. When water shortage occurs, assimilation rate is reduced by the ratio between actual transpiration (depending on the available amount of water in the profile) and potential transpiration (de Wit, 1958). Other processes are not affected by water shortage.

The model requires as input: daily weather data on minimum and maximum air temperature (°C), total global radiation (MJ m^{-2} d^{-1}), early morning vapor pressure (mb), total precipitation (mm) and average wind speed at 10 m (m s^{-1}). Ambient CO_2 concentration (ppm), sowing date of the crop and latitude of origin of the spring wheat variety used, available water holding capacity of the various layers of the soil, thickness of these layers and soil moisture at sowing date are also required.

The model simulates potential production (limited by crop characteristics, temperature and radiation but without any stress from water or nutrient shortages or pests, diseases and weeds) and water-limited production in which growth is also limited by water shortage (de Wit and Penning de Vries, 1982). This implies that the simulated yield is always higher than the one observed in the field, because even very well managed crops will suffer from some growth limitations during the growing season.

For simulation of crop production in The Netherlands some simplifications were introduced. The depth of the soil profile was set at 1 m based on data from Groenendijk (1989) and depths of the various soil layers were set at 2, 8, 10, 10, 10, 10, 10, 10, 10 and 20 cm (from the soil surface downward). Since no detailed data on the soils were available, it was assumed that at sowing date the profile was at field capacity and that the profile was homogenous.

Validation of the Simulation Results

The model requires daily weather data, so validation of the model for various seasonal weather patterns requires daily data over many years. Daily data are very difficult and/or very expensive to attain and hence not available from every weather station. Daily data on global radiation are especially scarce, since global radiation is only recorded at a limited number of meteorological stations (Duivenvoorden, 1986). The longest available set of daily data that includes global radiation was collected at Wageningen for 1954–1987 (Figure 1). Other meteorological stations in The Netherlands started recording global radiation only in the late nineteen sixties.

The model simulates highest yield obtainable under given weather and soil conditions. For validation of simulation results data on crops free from nutrient shortage, pests, diseases and weeds are required.

Field data from very well managed spring wheat crops, grown in more or less the same area over more than 30 y, are also scarce, especially because during the last 10 y the growing area under spring wheat declined (de Jong, 1986). Only one set of data longer than 30 y could be constructed. Data were derived from spring wheat variety trials conducted on an experimental farm in Emmercompascuum (Figure 1) from 1954 till 1987. In each year data from the highest yielding variety were used. The crops were grown on a sandy soil reclaimed from peat. The water

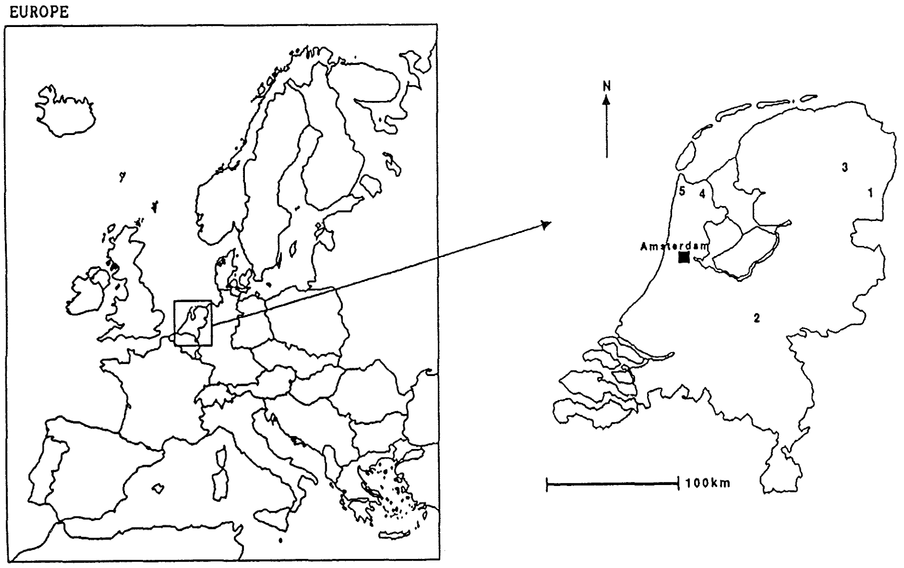

Fig. 1. Location of sites mentioned in text; 1: Emmercompascuum, 2: Wageningen, 3: Eelde, 4: Wieringermeer, 5: De Kooy.

holding capacity of this soil was estimated at 200 mm m^{-1} based on Groenendijk (1989).

Simulation runs were made with the spring wheat model using sowing date in the field experiment in Emmercompascuum and the weather data from Wageningen as input. Although distance between field experiment and the site from which meteorological data were obtained was too large for reliable validation of the simulation results, the simulated and observed yields were compared (Figure 2). This was done since both sets were unique with respect to the length of the period over which data were available. The differences in climate between the sites were very small but large differences in daily weather occurred.

Up to 1975 simulated yields (grains, dry matter) were much higher than observed yields. From 1975 to 1987 the model gave a reasonable simulation of the yields obtained in the field in various years (Figure 2). From 1975 onwards the yield levels in the field experiment increased, in some years up to the potential levels simulated by the model. The explanation of this yield increase can be found in the changed management of the crop. In 1975 the use of biocides against ripening diseases and aphids was introduced in this experiment and so was an additional nitrogen application. This change in agricultural practices resulted in an increase in yield, since negative effects of nutrient shortage and pests and diseases on crop yield were reduced. This implies that, for validation of the simulation results, data

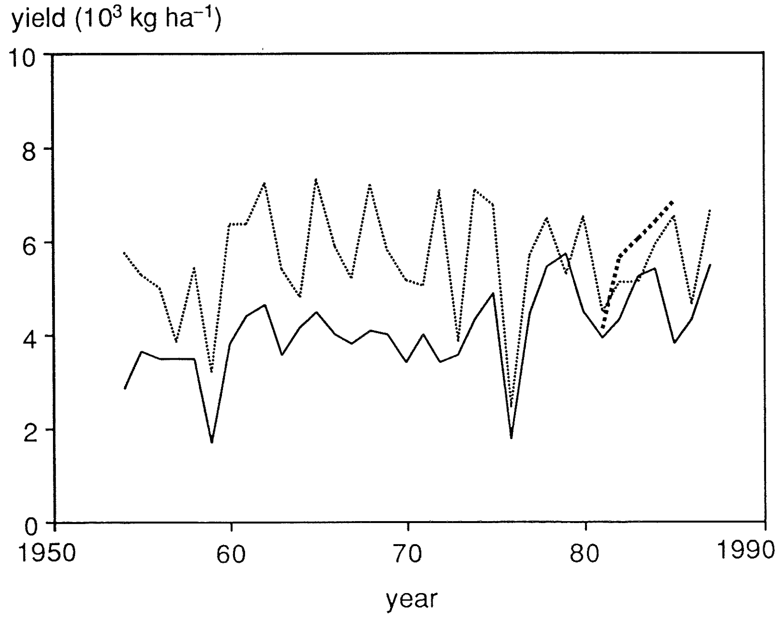

Fig. 2. Spring wheat yields (grains, dry matter) in field experiments in Emmercompascuum (——), simulated yields with weather data from Wageningen 1954–1987) (.......) and with weather data from Eelde 1981–1985 (----).

are required from field experiments conducted in the last 15 y (up to 1975 most crops were grown under suboptimal conditions).

For 5 y (1981–1985) daily weather data from Eelde (Figure 1) were available. The simulation results with these data used as input are also shown in Figure 2. Use of weather data from Eelde as input resulted in generally small differences from the simulated yield using the Wageningen weather data (Figure 2). In all years, simulated yields were higher than observed, which was to be expected since even well managed crops are not completely free from pests and diseases.

Also data from variety trials conducted in 1976–1985 in the north-western part of the country (Wieringermeer) were available. Here the crops were grown on a marine clay soil, with an estimated available water holding capacity of 350 mm m^{-1} (Groenendijk, 1989). Due to the large water holding capacity of this soil, growth is seldom limited by water. In this region weather is strongly influenced by the sea. Temperatures in spring and summer are lower than in the centre of the country and radiation levels are higher. This difference in climate comes to expression in the (simulated) yields. When weather data from Wageningen were used as input, simulated yields were lower than observed yields. However, when data from weather station de Kooy (Figure 1) were used, simulated yields were higher than observed yields (Figure 3). From these results it can be concluded that when daily weather data from a nearby weather data are used the model is well able to simulate yield

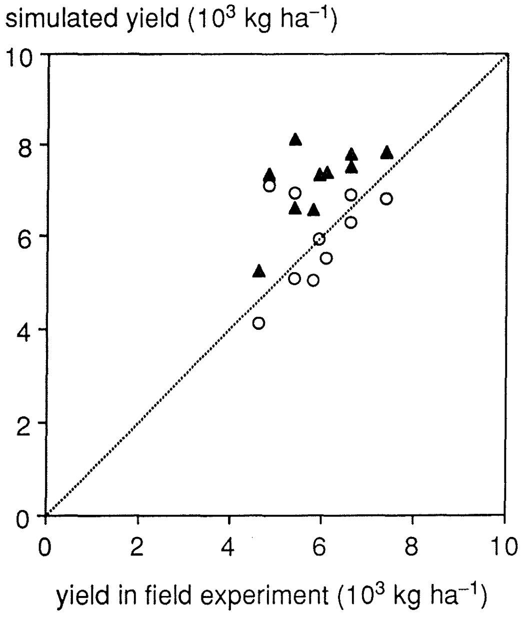

Fig. 3. Comparison between spring wheat yields in field experiments in Wieringermeer (1976–1985) and simulated yield using weather data from Wageningen (O) and weather data from de Kooy (▲).

observed in a field experiment. The inter-annual variability of the yield is simulated reasonably well. But yield levels are generally higher than observed.

Growing Conditions and Simulated Yield

Present Situation

As mentioned above, spring wheat yield is favored by early sowing. For this reason sowing date in the field experiment was used as input variable in validation studies. When the effect of various weather conditions on simulated yields is studied, effects of different sowing dates on yields must be eliminated. Therefore new simulation runs were made using the 34 y of weather data from Wageningen and a constant sowing date of March 11, the average sowing date in the experiments in Emmercompascuum. Two production levels were distinguished: potential and water-limited (de Wit and Penning de Vries, 1982). For water-limited production, available water holding capacity as estimated for the soil in Emmercompascuum was used. This type of soil has a low available water holding capacity, so that soil moisture is depleted relatively soon, and large differences between potential and water-limited production can be expected. The potential production was simulated through assuming an optimal water supply: the assimilation rate was never reduced due to water shortage.

The results of these runs are shown in Figure 4. Potential yield (grains, dry matter) varied from 6–9 ton ha^{-1} and water-limited yield from 2–9 ton ha^{-1}.

In potential circumstances a strong sink limitation occurred during the grain filling period in all years. The size of the sink is determined by the biomass produced during vegetative period (Spiertz and van Keulen, 1980), therefore growing conditions during this period have a large effect on final simulated yield. Low temperatures and high radiation levels during the vegetative period favored grain yield.

Water-limited yield was much lower than the potential one in only 5 out of 34 y (1957, 1959, 1973, 1976 and 1986, Figure 4). In these years precipitation during the growing season was low (less than 250 mm), resulting in water shortage at the end of the growing season. Since grains are filled during the last weeks of the growing season, limitation of growth during this period has a large effect on the final yield.

Simulation of Future Climate

The Report of Working Group I to the Intergovernmental Panel on Climate Change (IPCC) (Houghton *et al.*, 1990) was used as point of departure. Depending on the General Circulation Model (GCM) used, a doubling of the equivalent CO_2 concentration increases the global mean surface air temperature by 1.9–5.2 °C (Cubash and Cess, 1990). Indications exist that large local deviations from this global mean can be expected (Mitchell *et al.*, 1990). So it is rather likely that the

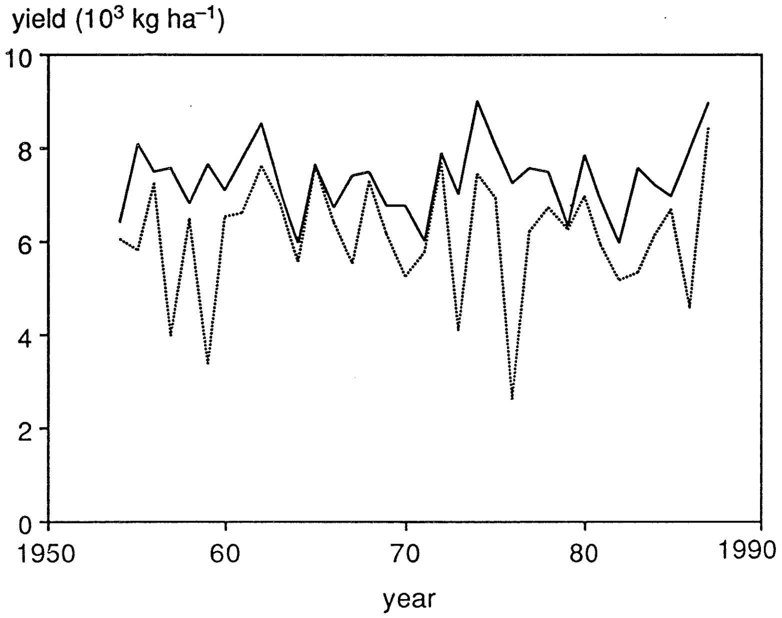

Fig. 4. Simulated potential (——) and water-limited yield (.......) of a spring wheat crop using weather data from Wageningen 1954–1987.

temperature rise during the growing season of crops will deviate from the global mean. However, the confidence in the regional estimates for temperature rise is low (Houghton *et al.*, 1990). Therefore it was decided to study the effects of the global mean temperature rise on crop growth.

A CO_2 induced climatic change will also affect other weather variables than the air temperature. The present GCM's do not give reliable estimates for changes in other variables, and they are not considered here.

For simulation of the future weather, the data set with 34 y of Wageningen weather was used as basis. The expected temperature rise was added to daily minimum and maximum temperature. Vapor pressure was adjusted in such way that relative humidity of the air was kept constant. The other weather variables in the set (global radiation, precipitation and wind speed) were not changed.

The effects of temperature rise on simulated yields were studied for all 34 growing seasons.

For each scenario three runs were made; one with temperature rise only, one with increased CO_2 concentration and one with both temperature rise and a higher CO_2 level. The present atmospheric CO_2 concentration was assumed to be 350 ppm.

IPCC Business-As-Usual-Scenario was used to determine future atmospheric CO_2 concentration. And for the associated temperature rise the so called 'best estimate' was used. The temperature rise given in the IPCC report is above the pre-industrial levels (1800). This temperature rise is adjusted to the nineteen fifty level because the data used as baseline start in 1954.

Two main scenarios were considered: for the year 2030 a CO_2 concentration of 460 ppm and a temperature rise of 1.7 °C and for the year 2080 a CO_2 concentration of 700 ppm and a temperature rise of 3 °C. Both scenarios were chosen to enable comparison with other impact studies. Under the Business-As-Usual-Scenario the *equivalent* CO_2 concentration is expected to reach the 700 ppm level in 2030 (atmospheric CO_2 concentration 460 ppm). Most climate models give data for the equilibrium response to doubled CO_2 concentration and many impact studies were done for this climatic change (Rosenzweig, 1985; Santer, 1985; Wilks, 1988; Cooter, 1990). In 2080 the atmospheric CO_2 concentration is expected to reach the 700 ppm level and most research on the direct effects of CO_2 on crops has been done for the 650–700 ppm level (Cure and Acock, 1986).

Scenario 2080

Potential Production

Figure 5 shows the simulated yield with increased temperature, doubled CO_2 concentration and the combination of both, versus simulated yield with the original weather data set (the latter is also shown in Figure 4). The effect of a temperature

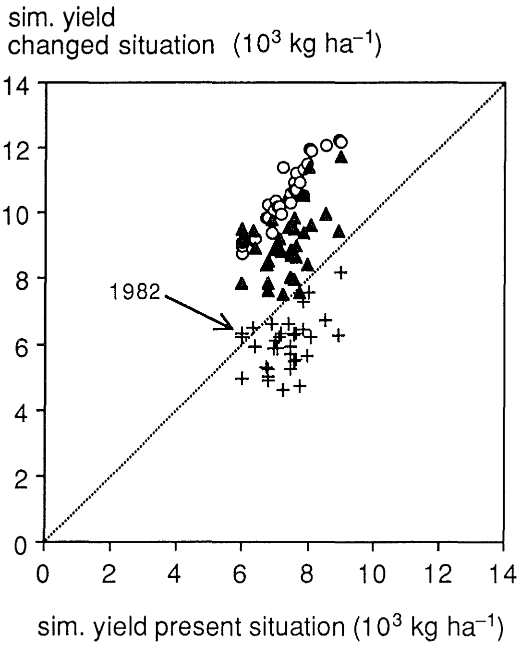

Fig. 5. The effect of scenario 2080 on simulated potential spring wheat yields in comparison with yields simulated for the present situation. Temperature rise of 3 °C and present CO_2 concentration (+); CO_2 concentration of 700 ppm and present weather (O); temperature rise of 3 °C and CO_2 concentration of 700 ppm (▲).

rise on simulated yield shows large variations: in some years a 3 °C temperature rise had no effect on the simulated yield, whereas in others a decline of 2 ton ha^{-1} was found. Many crop growth processes are affected by temperature. In the model rise in temperature leads to increase of many rates (maintenance respiration rate, assimilation rate, death rate of the leaves, etc.). These effects act in different directions and some are compensating each other. However the effect of temperature on development rate of the crop is overruling all other effects.

In the model air temperature is used to determine timing and duration of the growing period of the crop. A temperature rise of 3 °C results in a shortening of the growing period by 15–20 days (= 15%). The simulated decline in yield is caused by this reduction (in a shorter growing period less radiation is intercepted and thus less biomass is produced). The temperature rise affected both vegetative period and grain filling period. Besides shortening the growing period, this period occurs 7–10 days earlier in season, due to earlier crop emergence (rate of crop emergence is temperature dependent). Hence weather conditions (radiation levels etc.) during crop growth are different. This shift is the explanation for the large variation in the effects of a rise in temperature on simulated yields in various years. In 1982, for instance, there was a period with very low radiation levels just before flowering of the crop (simulated with the original weather data). An increase in temperature resulted in earlier flowering that year, causing the period with low radiation to coincide with the grain filling period. Because the production in this period is determined by the size of the sink, the effect of low radiation levels was small. In fact the temperature rise even resulted in a small yield increase (Figure 5).

The effect of a 700 ppm CO_2 concentration on the simulated yield was more uniform than the temperature effect. In general a yield increase of 40–50% was obtained (Figure 5). This yield increase is caused by an increase in assimilation rate during both vegetative and grain filling periods.

The effect of the combination of high temperatures and doubled CO_2 concentration on simulated yields varied considerably (Figure 5). However, the increase in yield due to doubling CO_2 concentration was nearly the same for the present and future temperature regimes (about 2 ton ha^{-1}).

Water-Limited Period

The effect of changes in temperature and CO_2 concentration on simulated water-limited yield and total biomass produced during the growing season are shown in Figures 6 and 7. Simulated water-limited yields in the present situation are also shown in Figure 4. Dry years can be recognized in Figure 6 as the low yielding ones in the lower left hand corner of the graph. In dry years simulated yields were only 2–4 ton ha^{-1}. In low yielding (= dry) years the effect of temperature rise on simulated yield was very small. In the high yielding (= wet) years a yield decline was observed. Due to this difference in effect in dry and wet years, temperature rise resulted in a decline in yield variability. Yield varied from 2 to 9 ton ha^{-1} under

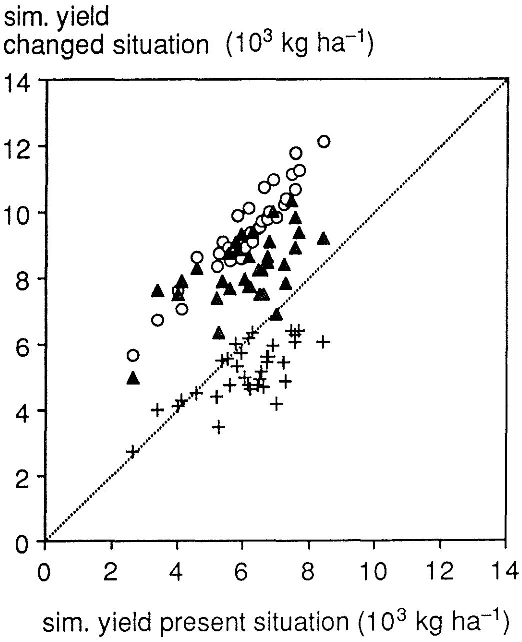

Fig. 6. The effect of scenario 2080 on simulated water-limited spring wheat yields in comparison with yields simulated for the present situation. Temperature rise of 3 °C and present CO_2 concentration (+); CO_2 concentration of 700 ppm and present weather (○); temperature rise of 3 °C and CO_2 concentration of 700 ppm (▲).

present conditions but only varied from 2 to 6 ton ha^{-1} after a temperature rise of 3 °C.

The effect of higher temperatures on yields in low yielding years can be explained as follows: a shorter vegetative period implies a lower biomass production but also a reduction in the amount of water used in this period. In the following grain filling period more water is available and reduction of the yield due to water shortage is therefore smaller, resulting in a small yield increase at higher temperatures. In high yielding years (with no water shortage) the effect is the same as for potential production: reduction of yield as a result of the shorter growing season.

Higher temperatures always reduced total biomass (Figure 7). In dry years increase in production during grain filling period (due to less water shortage) was counterbalanced by decreased production during the shortened vegetative period.

The effect of a higher CO_2 concentration on simulated water-limited yield was especially large in dry years: a yield increase of nearly 100% was simulated. In years with no water shortage the increase was 60% (Figure 6). Higher CO_2 concentration stimulates water-limited production by increasing the assimilation rate and by reducing transpiration via increase of the canopy resistance. In all years, simulated total transpiration per season was reduced by 10%. In dry years this reduction increased the amount of water available during the grain filling period, reducing the

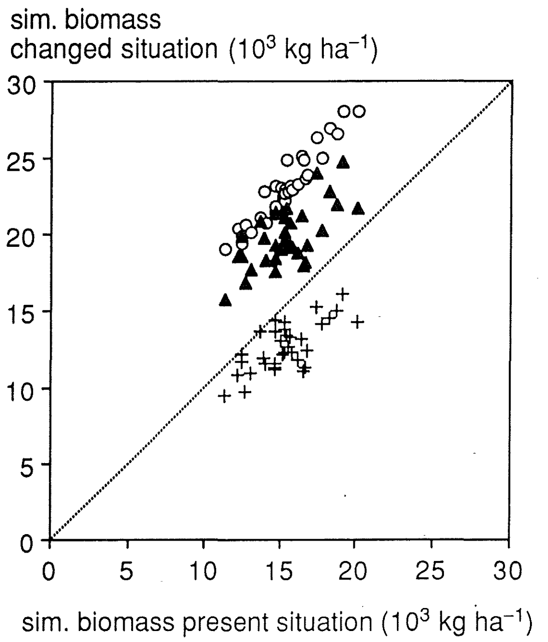

Fig. 7. The effect of scenario 2080 on simulated water-limited total biomass in comparison with simulation results for the present situation. Temperature rise of 3 °C and present CO_2 concentration (+); CO_2 concentration of 700 ppm and present weather (○); temperature rise of 3 °C and CO_2 concentration of 700 ppm (▲).

water shortage and increasing the yield. Reduction of total transpiration by 10% is less than expected on the basis of the increase of canopy resistance. The increase of biomass as a result of the higher assimilation rates at higher CO_2 concentrations increases water requirements which counteracts the effects of increase of the canopy resistance.

The effect of higher CO_2 levels on total biomass, a 45% increase, was smaller than the effect on yield (Figure 7). At this site water shortage only occurs at the end of the growing season, so for most of the season no shortage exists and CO_2 only affects biomass production via the assimilation rate.

As with potential production, the effect of a doubled CO_2 concentration was the same for both temperature regimes (Figure 6). This causes large yield increases in dry years because both high temperatures and high CO_2 concentration reduce water shortage during grain filling period.

Simulated effects of doubled CO_2 concentration on water-limited production (decrease of transpiration by 10%, increase biomass by 40% and increase in yield in dry circumstances up to 100%) are of the same order of magnitude as the effects found in the literature (Gifford, 1979; Sionit *et al.*, 1980; Kimball and Idso, 1983; Cure and Acock, 1986; Goudriaan and Unsworth, 1990).

Use of Other Varieties and Sowing Dates

The effects of temperature rise on simulated yields are primarily caused by shortening and shifting the growing period (the period between crop emergence and maturing). Both sensitivity of the variety to daylength and sowing date influence timing and duration of the growing period. By changing variety and sowing date in the model it was tried to restore the original growing period despite the higher temperature. When temperature was increased by 3 °C a combination of 10 days later sowing and a variety from higher latitudes (Miglietta, 1991) was required to obtain the original emergence and maturing dates. The effect of use of this new variety and sowing date on simulated water-limited yield is shown in Figure 8. In almost all years, yields decreased in comparison with both the present situation (present weather, variety and sowing date) *and* with the temperature +3 °C situation (temperature increase of 3 °C, present variety and sowing date). Sowing date and variety only affect the vegetative period. By restoring the original growing period the vegetative period is stretched, but duration of the grain filling period is unchanged. This longer vegetative period results in the use of more water in this period and water shortage during the grain filling period is exacerbated resulting in a yield decline. Total biomass from the new variety did reach original levels, which is sensible since

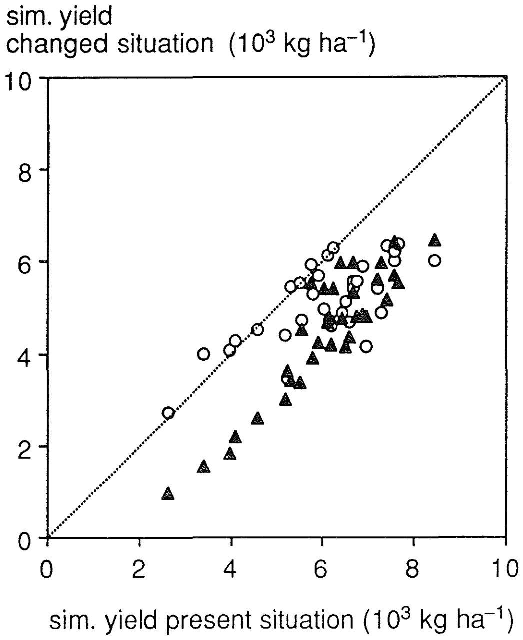

Fig. 8. The effect of changed agricultural practices on simulated water-limited crop yields in comparison with simulated yield for present circumstances. Temperature rise of 3 °C, present sowing date (March 11) and variety (○), temperature rise of 3 °C, sowing at March 21 and northern variety (▲).

the crop is growing during the same period. Only use of a postulated variety with a longer grain filling period could restore the original yield levels. However, the sparse information available suggests there is little variation among wheat varieties in duration of the grain filling period (van Keulen and Seligman, 1987; Wiegand and Cuellar, 1981). Often wheat crops ripen due to water and/or nutrient shortage occurring at the end of the growing period and not as the result of reaching physiological maturity. So the effects of, for instance, temperature on development have to be determined on crops grown under optimal conditions (no water shortage!). This type of experiment is lacking.

Effects of Other Scenarios

The effect of the 2030 scenario (temperature rise of 1.7 °C, 460 ppm CO_2) on simulated water-limited yield is shown in Figure 9. Effects were similar to those of the 2080 scenario, only the deviation from the present yield was smaller. Yields varied from 2–7 ton ha^{-1} when a temperature rise was introduced. The CO_2 effect was similar for both temperature regimes and yields increased most from changes in temperature and CO_2 concentration in dry years.

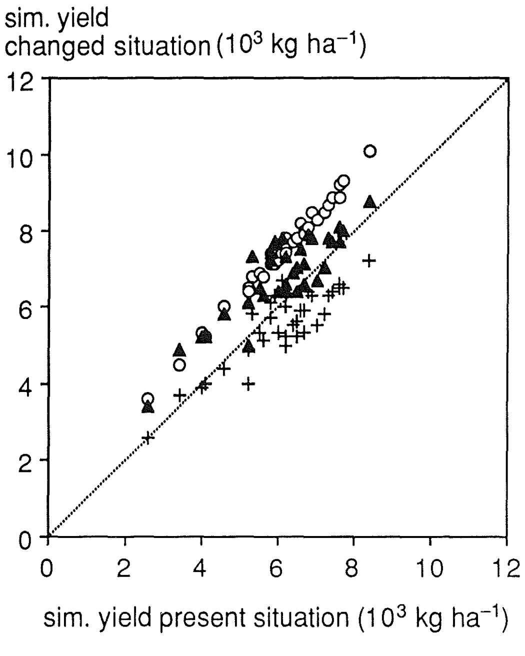

Fig. 9. The effect of scenario 2030 on water-limited spring wheat yields in comparison with yields simulated for the present situation. Temperature rise of 1.7 °C and present CO_2 concentration (+); CO_2 concentration of 460 ppm and present weather (O); temperature rise of 1.7 °C and CO_2 concentration of 460 ppm (▲).

When instead of the 'best estimate', the 'highest estimate' for the temperature increase for 2080 was used (= temperature increase of 5 °C; Houghton *et al.*, 1990), the CO_2 effect no longer compensated for the temperature effect in all cases (Figure 10). In wet years a yield decline was simulated for this scenario, while in dry years this scenario resulted in a yield increase.

For the scenarios 2030 and 2080 the effect of CO_2 was similar for all temperature regimes: the CO_2 and temperature effects hardly interfered. Therefore it is relatively simple to infer assessments on the effect of other combinations of temperature and CO_2 concentrations on simulated yields. The combination of a temperature rise of 3 °C and 460 ppm CO_2 will lead to a yield decline in most years, since yield increase due to this higher CO_2 concentration is 1 ton ha^{-1} (Figure 9) and the yield decline due to the higher temperatures is 2 ton ha^{-1} (Figure 6).

Concluding Remarks

Because the model used in this study can simulate the effect of various weather conditions on spring wheat yields, it is a useful tool for studying possible effects of climate change on crop yields. However, it was also shown that the model required daily weather data for reliable simulation results. Of course, these data are not available for the future climate. The simulation results presented in this paper

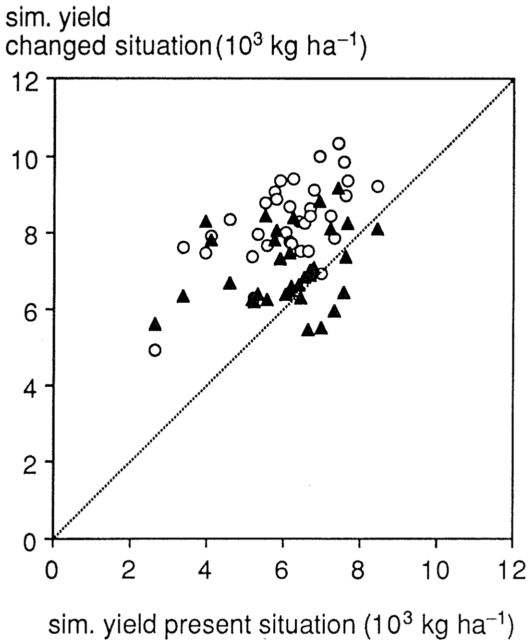

Fig. 10. Comparison between simulated water-limited yield with the original weather data and simulated yield at 700 ppm CO_2 in combination with a temperature rise of 3 °C (○) and of 5 °C (▲).

should therefore not be regarded as estimates for future yields. They are the results of a survey to the sensitivity of the system to changes in temperature and CO_2 concentration. Because it is reasonable to assume that climatic change will also affect other weather variables like radiation etc., climatic effects on yields could be far different from the effects simulated here.

Temperature rise causes a decline in yield in most years, but large differences in the magnitude of this decline are found. Use of a long time series of weather data as basis is important to obtain a reliable picture of the possible effects. Higher CO_2 concentrations lead to an increase in simulated crop yields.

In the scenarios used, the positive effects of higher atmospheric CO_2 concentrations on crop yields compensate the negative effects of temperature rise. An important feature found is that both higher temperatures and higher CO_2 concentrations reduce the inter-annual yield variability.

Use of other sowing dates and/or different varieties can not reduce the negative effects of temperature rise on simulated crop yields.

In this paper climatic change effects are only studied for one site. It is realistic to assume that effects can be different in other locations in other climates. In a forthcoming paper the methods developed in here are used to assess effects of climatic change on wheat yield in 12 other sites in Western Europe. Special attention is paid to effects of climatic change on inter-annual yield variability.

Acknowledgements

This work was partly funded by the Ministry of Housing, Physical Planning and Environment (VROM) of the Dutch government and partly by the Commission of the European Communities (EV4C-0019-NL). Weather data from Wageningen were obtained from the Department of Meteorology of the Agricultural University Wageningen. I thank C. T. de Wit, J. Goudriaan and H. van Keulen for discussion and two anonymous reviewers for very useful commentary.

References

Acock, B. and Allen, L. H., Jr.: 1985, 'Crop Responses to Elevated Carbon Dioxide Concentrations', in Strain, B. R. and Cure, J. D. (eds.), *Direct Effects of Increasing Carbon Dioxide on Vegetation*, United States Department of Energy DOE/ER-0238, pp. 53–98.

Adams, R. M., Rosenzweig, C., Peart, R. M., Ritchie, J. T., McCarl, B. A., Glyer, J. D., Curry, R. B., Jones, J. W., Booth, K. J., and Hartwell Allen, L., Jr.: 1990, 'Global Climate Change and U.S. Agriculture', *Nature* **345**, 219–223.

Alblas, J., Boekel, P., and van der Beek, M. A.: 1987, 'Gewaseisen', in *Themadag "Werkbaarheid en Tijdigheid"*, Proefstation voor de Akkerbouw en de Groenteteelt in de Vollegrond, Lelystad, The Netherlands (in Dutch), pp. 1–20.

Broekhuizen, S.: 1969, *Atlas of the Cereal-Growing Areas in Europe*, Pudoc, Wageningen, The Netherlands, 160 pp.

Buishand, T. A. and Velds, C. A.: 1980, *Neerslag en Verdamping*, KNMI, de Bilt, The Netherlands (in Dutch), 206 pp.

Cooter, E. L.: 1990, 'The Impact of Climate Change on Continuous Corn Production in the Southern U.S.A.', *Clim. Change* **15**, 53–82.

Cubash, U. and Cess, R. D.: 1990, 'Processes and Modelling', in Houghton, J. T., Jenkins, G. J., and Ephraums, J. J. (eds.), *Climate Change, The IPCC Scientific Assessment*, Cambridge University Press, Cambridge U.K., pp. 69–91.

Cure, J. D. and Acock, B.: 1986, 'Crop Responses to Carbon Dioxide Doubling: A Literature Survey', *Agric. Forest Meteor.* **38**, 127–145.

Duivenvoorden, J. C. M.: 1986, *Inventarisatie Meteo-Stations. Klimatologische Gegevens van Nederlandse Stations No. 26*, KNMI 150-26, De Bilt, The Netherlands (in Dutch).

Feddes, R. A.: 1987, 'Crop Factors in Relation to Makkink Reference-Crop Evapotranspiration', in Hooghart, J. C. (ed.), *Evaporation and Weather*, Proceedings and Information/TNO Committee on Hydrological Research: No. 39, The Netherlands, pp. 33–46.

Gifford, R. M.: 1979, 'Growth and Yield of Carbon Dioxide-Enriched Wheat under Water-Limited Conditions', *Austral. J. Plant Physiol.* **6**, 367–378.

Goudriaan, J.: 1977, *Crop Micrometeorology: A Simulation Study*, PUDOC, Wageningen, The Netherlands, 250 pp.

Goudriaan, J. and van Laar, H. H.: 1978, 'Relations between Leaf Resistance, CO_2-Concentration and CO_2 Assimilation in Maize, Beans, Lalang Grass and Sunflower', *Photosynthetica* **12**, 241–249.

Goudriaan, J. and Unsworth, M. H.: 1990, 'Implications of Increasing Carbon Dioxide and Climate Change for Agricultural Productivity and Water Resources', in *Impact of Carbon Dioxide, Trace Gases, and Climate Change on Global Agriculture*, ASA special publication no. 53. American Society of Agronomy, Madison U.S.A., pp. 111–129.

Goudriaan, J., van Laar, H. H., van Keulen, H., and Louwerse, W.: 1985, 'Photosynthesis CO_2 and Plant Production', in Day, W. and Atkin, R. K. (eds.), *Wheat Growth and Modelling*, NATO ASI Series, Series A Life Sciences Vol. 86, Plenum Press, New York, pp. 107–122.

Groenendijk, H.: 1989, 'Estimation of the Waterholding-Capacity of Soils in Europe, The Compilation of a Soil Dataset', *Simulation Report CABO-TT* nr. **19**, Wageningen, The Netherlands, 24 pp.

Houghton, J. T., Jenkins, G. J., and Ephraums, J. J.: 1990, *Climate Change, The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, U.K., 365 pp.

Jansen, D. M.: 1990, 'Potential Rice Yields in Future Weather Conditions in Different Parts of Asia', *Neth. J. Agri. Sci.* **38**, 661–680.

de Jong, J. A.: 1986, *De Teelt van Granen*, De Jong, Drachten, The Netherlands (in Dutch), 208 pp.

van Keulen, H. and Seligman, N. G.: 1987, *Simulation of Water Use, Nitrogen Nutrition and Growth of a Spring Wheat Crop*, Simulation Monographs, Pudoc Wageningen, The Netherlands, 310 pp.

Kimball, B. A.: 1983, 'Carbon Dioxide and Agricultural Yield: An Assemblage and Analysis of 430 Prior Observations', *Agron. J.* **75**, 779–788.

Kimball, B. A. and Idso, S. B.: 1983, 'Increasing Atmospheric CO_2: Effects on Crop Yield, Water Use and Climate', *Agricult. Water Managem.* **7**, 55–72.

Können, G. P.: 1983, *Het Weer in Nederland*, Thieme, Zutphen, The Netherlands (in Dutch), 144 pp.

Lemon, E. R.: 1983, *CO_2 and Plants, The Response of Plants to Rising Levels of Atmospheric Carbon Dioxide*, Westview Press, Boulder, Colorado.

Miglietta, F.: 1991, 'Simulation of Wheat Ontogenesis: II. Predicting Dates of Ear Emergence and Main Stem Final Leaf Number', *Clim. Res.* **2**, 151–160.

Mitchell, J. F. B., Mannebe, S., Tokioka, T., and Meleshko, V.: 1990, 'Equilibrium Climate Change', in Houghton, J. T., Jenkins, G. J., and Ephraums, J. J. (eds.), *Climate Change, The IPCC Scientific Assessment*, Cambridge University Press, Cambridge, U.K., pp. 131–172.

Monteith, J. L.: 1965, 'Evaporation and Environment', *Proc. Symp. Soc. Exp. Biol.* **19**, 205–234.

Parry, M. L. and Carter, T. R.: 1989, 'An Assessment of Effects of Climate Change on Agriculture', *Clim. Change* **15**, 95–116.

Porter, J. R.: 1987, 'Modelling Crop Development in Wheat', *Span* **30**, 19–22.

Rosenzweig, C.: 1985, 'Potential CO_2-Induced Climate Effects on North American Wheat-Producing Regions', *Clim. Change* **7**, 367–389.

Santer, B.: 1985, 'The Use of General Circulation Models in Climate Impact Analysis, A Preliminary Study of the Impacts of a CO_2 Induced Climatic Change on West European Agriculture', *Clim. Change* **7**, 71–93.

Sionit, N., Hellmers, H., and Strain, B. R.: 1980, 'Growth and Yield of Wheat under CO_2-Enrichment and Water Stress', *Crop Sci.* **20**, 456–458.

Spiertz, J. H. J. and van Keulen, H.: 1980, 'Effect of Nitrogen and Water Supply on Growth and Grain Yield of Wheat', *Proceedings of 3rd International Wheat Conference*, Madrid, Spain, 1980, pp. 595–610.

Spiertz, J. H. J., ten Hag, B. A., and Kupers, L. P. J.: 1971, 'Relation between Green Area Duration and Grain Yield in Some Varieties of Spring Wheat', *Neth. J. Agric. Sci.* **19**, 211–222.

Spitters, C. J. T., van Kraalingen, D. W. G., van Keulen, H.: 1989, 'A Simple and Universal Crop Growth Simulator: SUCROS 87', in Rabbinge, R., Ward, S. A., and van Laar, H. H. (eds.), *Simulation and Systems Management in Crop Protection*, Simulation Monographs, Pudoc, Wageningen, The Netherlands, pp. 145–181.

Wiegand, C. L. and Cuellar, J. A.: 1981, 'Duration of Grain Filling and Kernel Weight of Wheat as Affected by Temperature', *Crop Sci.* **21**, 95–101.

Wilks, D. S.: 1988, 'Estimating the Consequences of CO_2-Induced Climatic Change on North American Grain Agriculture Using General Circulation Model Information', *Clim. Change* **13**, 19–42.

de Wit, C. T.: 1958, 'Transpiration and Crop Yields', *Agricult. Res. Papers* **64.6**, Pudoc, Wageningen, 88 pp.

de Wit, C. T. and Penning de Vries, F. W. T.: 1982, 'La Synthèse et la Simulation des Systèmes de Production Primaire', in Penning de Vries, F. W. T. and Djitèye, M. A. (eds.), *La Productivité des Pâturages Sahélien*, Agricultural Research Reports 918 Pudoc, Wageningen, The Netherlands, pp. 23–25.

(Received 24 October, 1990; in revised form 16 March, 1993)