Expanding the Production and Use of Cool Season Food Legumes

A global perspective of peristent constraints and of opportunities and strategies for further increasing the productivity and use of pea, lentil, faba bean, chickpea and grasspea in different farming systems

Proceedings of the Second International Food Legume Research Conference on pea, lentil, faba bean, chickpea, and grasspea, Cairo, Egypt, 12–16 April 1992

Edited by

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Kluwer Academic Publishers
Dordrecht / Boston / London

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Abstract

A simulation study was done with a well-tested and validated model for crop growth and production of faba bean to evaluate the consequences of some aspects of climate change on yield and yield variability. The model used was a version of SUCROS87, including a water balance.

For three locations differing in climate (Tel Hadya, Syria; Migda, Israel; Wageningen, Netherlands) at least 8 years with detailed weather data were used to simulate the consequences of temperature rise and increase of atmospheric CO_2 (based on assessments of the Intergovernmental Panel on Climate Change [IPCC]), separately and combined. It appears that temperature rise causes a decrease in seed yield of rain-fed crops in Wageningen and Migda, due to a shortening of the growing season. At Tel Hadya, seed yield of rain-fed crops increases, due to an accelerated start of the reproductive phase and consequently an "escape" from water shortage later in the season. For fully irrigated crops, temperature rise causes, at all locations, a decrease of seed yield which is greatest at Migda and smallest at Tel Hadya. CO_2-enrichment causes, in all situations, an increase in growth and production of faba bean, which compensates for the decrease from temperature rise. The effects are not completely additive at all locations. Yield increases due to CO_2-enrichment are much higher than the yield decrease due to temperature rise. At Wageningen, Tel Hadya, and Migda the positive net effect of a CO_2 concentration to 460 ppm and a temperature increase of 1.7°C was respectively, 12, 68, and 28% for rain-fed crops and 5, 16, and 13% for fully irrigated crops. Fully irrigated crops show remarkably smaller yield variability than rain-fed crops in all these assessments. In rain-fed crops, the variation in yield over the years remains the same or is somewhat reduced due to reduced sensitivity to water shortage. Thus the net effects on productivity and stability due to the scenarios used for global climate change are at all locations positive. Other effects, such as, for example, morphological effects, may overrule these physiological effects. Such effects are not taken into account in this simulation study.

F.J. Muehlbauer and W.J. Kaiser (eds.), Expanding the Production and Use of Cool Season Food Legumes, 159–174.

Introduction

The increasing presence of atmospheric trace gases such as CO_2, CH_4, and N_2O due mainly to human activity, directly or indirectly, may influence the earth's climate by transmitting incoming solar radiation, while partly blocking outgoing terrestial black body radiation. The increased "greenhouse" effect may cause temperature rise. This may affect the functioning of various agro-ecosystems in general and faba bean production more specifically.

Different processes are influenced by the various factors that are affected by climate change. CO_2-increase affects the stomatal conductance and increases photosynthesis rate (Lemon, 1983; Cure and Acock, 1986) and water use efficiency (Gifford, 1979; Sionit *et al.*, 1980). Temperature rise may increase developmental rate of the crop, and adversely effect crop production. Evaluation of the effects which work in contrary directions with direct qualitative or quantitative methods is difficult. Crop growth simulation models may be used for such an evaluation as the causal relations between rate variables and forcing variables is present in such models. The consequences of CO_2-increase and temperature rise may be evaluated with these models.

Climate change may have strong effects on faba bean production, as this crop is very sensitive to water shortage and has high yield variability when grown in the present climate (Dantuma *et al.*, 1983; Grashoff, 1990a, 1990b). A feasibility study of effects of climate change on growth and production of faba bean is described.

Consistent Climate Change Assessments

With respect to simulation of the future climate, the same procedure as described in Nonhebel (1993) was used. Based on the Report of Working Group I to the Intergovernmental Panel on Climate Change (IPCC) (Houghton *et al.*, 1990) two scenarios were considered: for the year 2030 with a CO_2 concentration of 460 ppm and a temperature of 1.7°C above the present level, and for the year 2080 with a CO_2 concentration of 700 ppm and a temperature rise of 3°C. The changes in precipitation as estimated by the General Circulation Models (GCMs) are low (<10%) in comparison with the present inter-annual variability in precipitation, and were not taken into account.

Model Description

The simplified structure of the model[1] is shown in Figure 1.

Simulation of crop growth under potential growth situations is done with a

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[1] A complete, documented listing of the simulation model and a quantification of the parameters and functions specific for faba bean are available from the authors.

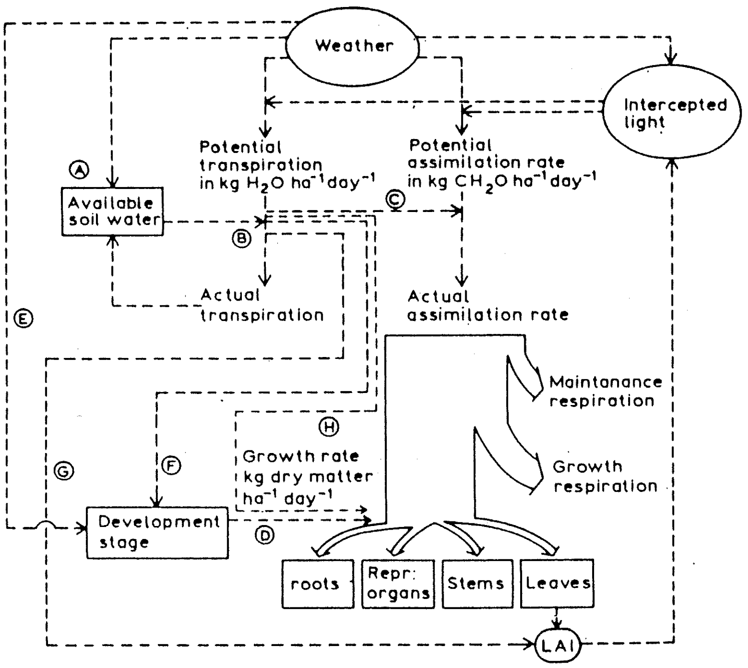

Figure 1. Schematic representation of faba bean growth. Effects of TRAN/TRP: on rate of photosynthesis (C); on developmental rate (F); on death rate of leaves and other plant organs (G); on dry matter partitioning (H). NB: the scheme provides an overview, not a relation diagram.

general crop growth simulator (Spitters *et al.*, 1989; Penning de Vries *et al.*, 1989). The developmental stage of the crop is simulated through integration of the rate of development, which is influenced by temperature. Assimilation rate is calculated from the incident amount of photosynthetically active radiation (PAR), the fraction of PAR intercepted by the canopy, and the photosynthesis/light response curve of individual leaves. The total amount of carbohydrates available for growth is calculated from the assimilation rate, the reallocation and redistribution of dry matter, and losses due to respiration of the plant organs ("maintenance respiration"). Dry matter growth of the plant organs is determined by the total net carbohydrate production, the fraction of carbohydrates allocated to the plant organs and the values for conversion of carbohydrates into dry matter ("growth respiration"). The fraction of carbohydrates allocated to the organs is affected by the developmental stage of the crop (cf. Van Heemst, 1986). Leaf area growth is calculated from the dry matter allocated to the leaves and the specific leaf weight, as influenced by the developmental stage of the crop.

The parameters and functions specific for faba bean were mainly derived from experiments with faba bean in The Netherlands (Grashoff, 1990a,b). The parameters for growth respiration were calculated from analysis of chemical composition of plant organs, using equations of Vertregt and Penning de Vries (1987).

Detailed measurements of maintenance respiration were not available, so commonly used coefficients for different plant organs that depend on their chemical composition were applied (Penning de Vries *et al.*, 1989; Spitters *et al.*, 1989). For leaves and stems, allowance was made for the decrease of these coefficients with plant development, by relating them to the nitrogen content of these organs, according to an approach described by Kropff (1989).

Soil Water Balance

A water balance model for a free draining soil profile is included, according to Van Keulen (1975, 1986) and Jansen and Gosseye (1986). The daily change in soil water content is calculated from rainfall (and irrigation), crop transpiration, and soil evaporation percolation in ten soil layers of 10 cm. Percolation is calculated as the amount of water in excess of field capacity, which drains to the next soil layer. Potential transpiration and evaporation are calculated from incoming radiation, air humidity, wind speed, and properties of the transpiring cq. evaporating surfaces (e.g., roughness, emissivity, reflectance, resistance for vapor transport), using the Penman/Monteith equation (Monteith, 1965). Soil evaporation is reduced when the upper layer of the soil dries out. The model does not calculate capillary rise, however the relative contribution of each soil layer to the total evaporation is calculated following a mimic procedure (Van Keulen, 1975). In this concept, the relative contribution of each soil layer to the total evaporation decreases exponentially with the depth of the layer. The relative contribution of each soil layer to the total transpiration is based on the rooted length in each layer and the maximum water uptake per rooted length.

Crop-Water Relations

When the soil dries out, stomata close and transpiration falls below its potential value. The ratio between actual and potential transpiration (TRAN/TRP) is supposed to decrease linearly with soil water content from unity at a critical water content, to zero at wilting point (Feddes *et al.*, 1978). According to Doorenbos and Kassam (1979) and Driessen (1986), the critical soil water content at which water uptake is reduced, is typical for a group of species. This critical content is also affected by TRP and the leaf area index (LAI) and in this way, the rate of water uptake at a certain soil water content depends on the actual leaf area of the crop and on the evaporative demand. Based on the sensitivity of faba bean to water shortage, the crop belongs to the group with a rather "weak" extracting capacity, like clover and carrot (Driessen, 1986). The ratio TRAN/TRP linearly affects the actual assimilation rate (Figure 1), assuming a constant water use efficiency. From a physiological point of view, the ratio TRAN/TRP indicates the water availability to the crop.

Two other crop-water relations were included in the simulation model. First, water shortage accelerates the development of the faba bean crop. With water shortage, pod development begins earlier in the season and maturity also is reached earlier (Grashoff, 1990a). This accelerating effect was modelled by multiplying the developmental rate of the crop by a factor proportional to 1/(TRAN/TRP) (Grashoff and Stokkers, 1992). Second, a mild water shortage results in an increase of the relative part of assimilates which flows towards the reproductive organs (Grashoff, 1990a,b; Grashoff and Verkerke, 1991). This is included in the following way. The total daily assimilation decreases *linearly* with decreasing TRAN/TRP, but the daily relative part of assimilates which flows to vegetative organs decreases *exponentially* with decreasing TRAN/TRP. Hence, as water shortage results in a decrease of the ratio TRAN/TRP, an increasing part of assimilates cannot be incorporated in vegetative organs. This part is used for the developing pods and seeds (Grashoff and Stokkers, 1992).

Input Data

The input variables for the model are standard data of daily solar radiation, temperature, rainfall, air humidity, and wind speed; date of crop emergence and values of crop dry matter and leaf area index at emergence; rootable depth; some characteristics of soil water retention, such as total pore space, volumetric soil water content at field capacity, at wilting point, and at air-dry soil; and reflection coefficient for total radiation of the soil, average clod height, and extinction coefficient for soil evaporation.

Model Calibration, Validation, and Testing

The crop growth model was calibrated with a series of field experiments with varying water supply patterns in The Netherlands in 1977, 1980–1982, and 1988. Then, the reliability of the model was tested in a comparison of simulated yields with measured yields. For this test, we used a data set consisting of faba bean yields collected over a 14-year period (1975–1988) at one experimental farm at Wageningen, The Netherlands. Secondly, we used a data set which was collected over a two-year period (1985, 1986) at nine locations of the so-called "EC-Joint Faba Bean Trials" (Roskilde in Denmark, Dundee, Nottingham, and Cambridge in the United Kingdom, Wageningen in The Netherlands, Gottingen and Hohenheim in Germany, Vienna in Austria, and Dijon in France). For both data sets, the average seed yields over the years and/or locations and the standard deviation (used as a measure of variability) were simulated correctly. Moreover, linear regressions of measured versus simulated yields fitted through the origin, had slopes of almost one and accounted for up to 80% of the yield variation (Grashoff and Stokkers, 1992). An example of the model performance for the Wageningen data set 1975–1988 is presented in Figure 2. The model was tested also for autumn-sown faba bean under Mediterranean climate conditions, using weather conditions for Giza (Egypt) and with three levels of irrigation (Kropff and Schippers, 1986). The simulated seed yields varied between 2 t ha^{-1} (rain-fed) to 7 t ha^{-1} (fully irrigated). These yields are realistic when compared with results of field trials (Nassib *et al.*, 1984; Zahran, 1982). However, an evaluation of the model results in comparison with detailed data sets from field experiments in the Mediterranean region was not yet possible.

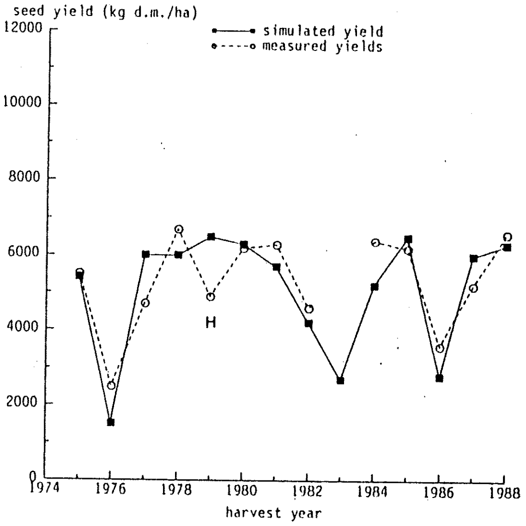

Figure 2. Simulated and measured seed yields at Wageningen 1975–1988. H = hail damage.

Robustness of the Model

In the above sections, some details about the reliability of the model were given. Besides this, with small changes of model parameters and/or input, simulation models should give consistent results. This is called the *robustness* of the model. Like all the models, derived from the SUCROS-stem, the faba bean model contains many negative feed-backs, which prevents the model from being hypersensitive to small changes in input. A point of attention is the effect of environmental factors on specific leaf weight (SLW), which is not yet included in the model. Lieth *et al.* (1986) found an increase in SLW of 9% with a doubling of the CO_2 concentration in soybean.

Adaptations of the Model for the Feasibility Study on Climatic Change

For the present study on the effects of climatic change, adaptations to the model had to be made for increased CO_2 concentration and increased temperatures as follows:

The Effect of Increased CO_2 Concentration

The effect of higher CO_2 levels on leaf photosynthesis was simulated according to Goudriaan and Unsworth (1990). The initial light use efficiency (EFF) and the maximum rate of photosynthesis (AMAX) are affected by the CO_2 concentration. At an average temperature of 20°C, a doubling of the CO_2 concentration results in an increase of EFF by 15% and a doubling of AMAX. A higher CO_2 concentration also can affect stomatal resistance and consequently transpiration. Based on Goudriaan and Unsworth (1990) it is assumed that faba bean follows the most common response for C3 plants. This means that the ratio of intracellular to external CO_2 concentration is stabilized. With a doubling of external CO_2 concentration, the stomatal aperture is reduced very little, combined with a strong response of assimilation. Typically in C3 plants transpiration will be reduced by 10 to 20% and assimilation stimulated by 40%. By consequence, the water use efficiency (WUE) is considerably stimulated.

The Effect of Increased Temperature

This effect was simulated by adding the estimated temperature rise to the daily input data on minimum and maximum temperature. The vapor pressure was adjusted in such a way that the relative humidity of the air was kept at the original value (Nonhebel, 1993).

Simulation Runs

For each of the scenarios 2030 and 2080, two conditions were distinguished: "rain-fed" crops and "fully irrigated" crops (which means no water shortage during the whole growing season). For rain-fed crops, the following simulation runs were made: one with the present weather situation, one run with the temperature rise only, one with the increased CO_2 concentration only, and one with both effects combined. Next, the same runs were made for fully irrigated crops. Other weather variables (radiation, windspeed) were not changed.

Historic Weather Data as Basis for the Feasibility Study

As input for the following simulation studies, weather and soil data sets for three locations were used. Set 1: 14 years (1975–1988) for Wageningen, Netherlands (Meteorological Station of the Agricultural University) combined with a clay soil data set for the experimental farm "De Bouwing" of the Centre for Agrobiological Research (CABO-DLO), Wageningen. Set 2: 8 years (1979/80–1985/86, 1989/90) for Tel Hadya, Syria (Meteorological Station of ICARDA) combined with an estimated soil data set for the heavy clay soil of the ICARDA Experimental Farm at Tel Hadya (Harmsen *et al.*,1983; Penning de Vries *et al.*, 1989). Set 3: 13 years (1962/63, 1963/64, 1965/66, 1966/67, 1969/70–1973/74, 1976/77–1979/80) for Migda, Israel (Gilat Meteorological Station) combined with a sandy soil data set for the Migda Experimental Farm (Van Keulen and Seligman, 1987).

All simulation runs were started at crop emergence, with the soil assumed to be at field capacity. For Wageningen, measured dates of emergence were used as input. On average, the date of emergence of the spring-sown crops in Wageningen is day 125 (5 May). As measured dates were not available for Tel Hadya and Migda, an estimated and fixed date of emergence for these autumn-sown crops was used: day 330 (26 November) in all the runs. This agrees with earlier simulation studies made by Kropff and Schippers (1986).

Results of the Feasibility Study

Effects of Temperature Rise and CO_2-Enrichment on Average Yields

Temperature Rise

Table 1 presents the general results of the simulation runs. In fully irrigated crops, a temperature increase of 3°C resulted in a general decrease of average seed yield at all locations. The strongest reduction was found in Migda (23%), the smallest in Tel Hadya (17%). This general reduction is mainly due to the fact that higher temperatures cause a 15 to 25 day shortening of the growing season. In rain-fed crops, the effect is more complicated: at Wageningen and Migda, seed yield was reduced 25 and 21%, respectively, but at Tel Hadya, seed yield increased 29%. This is due to the fact that the present temperature in Tel Hadya during the phase of vegetative growth of the crop (in autumn/winter) is about 5°C lower than in the same period at Migda and up to 8°C lower than at the comparable period for spring-sown crops at Wageningen (Figure 3). Due to this low temperature, pod filling starts much later at Tel Hadya than at Wageningen and Migda (Figure 3). Due to rapidly developing water shortage, the period of pod filling is short. Temperature increases of 1.7 and 3.0°C enhance the start of pod filling by 15 and 30 days, respectively. Consequently, the total period of pod filling will be longer than in the present situation, which causes an increase of

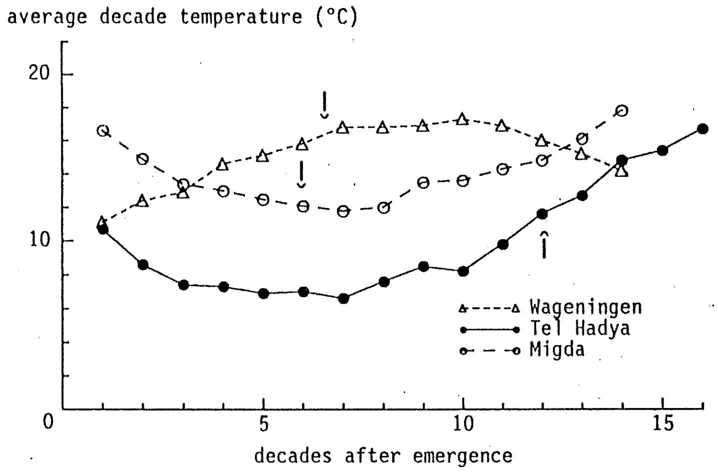

Figure 3. Comparison of present temperatures after crop emergence at Wageningen, Tel Hadya, and Migda. The arrows (↑; ↓) in the Figure indicate the start of pod filling. NB: in the figure, "decade" is used for a 10-day period.

seed yields. However, the physiological parameters and functions used in the model are derived from experimental data of the cultivar Minica, one of the most productive West European cultivars and may be different for cultivars used in the Mediterranean region.

CO_2-Enrichment

Increased CO_2 enhanced average seed yields of the fully irrigated crops at Wageningen, Tel Hadya, and Migda by 48, 54, and 72%, respectively (Table 1). In these simulations, the total transpiration of the crops was reduced by 10% to 20%. This agrees with results of Goudriaan and Unsworth (1990). The increase in assimilation, with a concomitant decrease in transpiration, resulted in a large increase of water use efficiency (WUE). This explains why the effects of CO_2 increase are greater in the rain-fed crops: at Tel Hadya and Migda the rain-fed yields were more than doubled (Table 1) while at Wageningen, a 61% yield increase was found.

Combined Effects of Warming and CO_2

When temperature and CO_2 increase were included together in the simulations, a completely consistent increase of average yields of rain-fed and fully irrigated crops resulted. At Wageningen, Tel Hadya, and Migda the increase was 12, 68, and 28%, respectively, for rain-fed crops and 5, 16, and 13%, respectively, for fully irrigated crops in scenario 2030. In scenario 2080, the increments at these locations were 31, 164, and 72%, respectively, for rain-fed crops and 18, 38, and

Table 1. Average seed yields (y) in t ha^{-1}, absolute standard deviation (s) in t ha^{-1} and relative standard deviation s (%) in %, for standard simulations, simulations with temperature rise (T + 1.7 and T + 3.0), simulations with increased CO_2 concentration (C460 and C700), and simulations with temperature rise and CO_2-increase combined in two scenarios for 2030 and 2080 (Sc 2030 and Sc 2080). All simulations are presented for rain-fed and fully irrigated crops

Locations and	rain-fed			fully irrigated		
	y	s	s(%)	y	s	s(%)
De Bouwing						
'standard sim'	5.1	1.6	32	6.1	0.5	9
T +1.7	4.4	1.4	32	5.2	0.3	7
T +3.0	3.8	1.2	32	4.7	0.3	5
C 460	6.4	1.8	28	7.4	0.7	9
C 700	8.2	2.0	24	9.0	0.8	9
Sc 2030	5.7	1.7	29	6.4	0.4	7
Sc 2080	6.7	1.5	22	7.2	0.4	6
Tel Hadya						
'standard sim'	2.8	1.1	41	6.9	0.8	11
T +1.7	3.5	1.3	37	6.4	0.4	7
T +3.0	3.6	1.2	32	5.7	0.3	6
C 460	3.6	1.5	43	8.5	1.1	12
C 700	6.2	2.5	40	10.6	1.5	14
Sc 2030	4.7	1.7	35	8.0	0.6	8
Sc 2080	7.4	1.6	22	9.5	0.6	6
Migda						
'standard sim'	3.9	1.5	39	6.4	0.6	9
T +1.7	3.5	1.5	42	5.2	0.6	12
T +3.0	3.1	1.3	41	4.3	0.6	14
C 460	5.4	2.1	40	8.4	0.6	7
C 700	7.9	2.8	36	11.0	0.7	7
Sc 2030	5.0	2.0	41	7.2	0.7	10
Sc 2080	6.7	2.4	35	8.5	0.9	11

33%, respectively, for fully irrigated crops. The negative effect of temperature rise is more than compensated by the positive effect of CO_2 increase, both for the 2030 and for the 2080 scenario (Table 1). The net effect of temperature and CO_2 agrees almost completely with the addition of the separate effects (Table 1).

Effects of Temperature Rise and CO_2-Enrichment on Stability in Yield Responses

As indicators for yield stability, the absolute standard deviation and the relative standard deviation of the simulated yield series are used. The relative standard deviation is defined as the absolute standard deviation, expressed as a percentage of the average yield. Stable yields require both an absolute and a relative standard deviation that are small.

Effects of Climate Change on Stability of Rain-Fed Crops

With temperature rise, the absolute standard deviations decrease with about 0.3 t ha^{-1} (at Wageningen and Migda) or stay the same (at Tel Hadya) (Table 1). At Tel Hadya, this unchanged absolute standard deviation and the increased average yield result in a clear decrease of 9% in the relative standard deviation (Table 1). At Wageningen and Migda, the combination of decreased average yields and decreased absolute standard deviations results in almost unchanged relative standard deviations. The effect of increased temperature for individual years at Wageningen is illustrated in Figure 4. It clearly shows that temperature rise reduces yields in the "high-yielding years" (the years with adequate precipitation). The reduction is due to a shortening of the growing season. In the "low yielding years" (the years without adequate precipitation) the negative effect is smaller. In those years, a part of the negative effect is compensated by an earlier start of pod filling and a consequent escape from water shortage later in the season. In a year such as 1976, the net effect of temperature rise will be positive. Figure 4 shows that the stabilizing effect of temperature rise is a stabilization in the "wrong direction" as it reduces the larger yields.

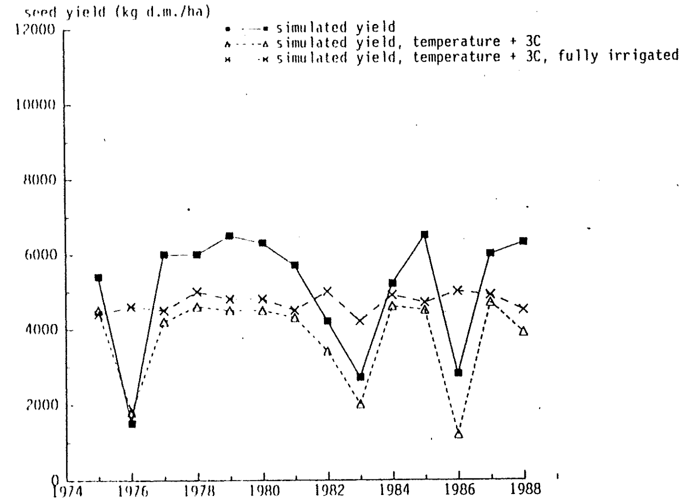

Figure 4. Simulated seed yields at Wageningen with 1) present weather, 2) with a temperature rise of 3.0°C and a rain-fed situation, 3) with a temperature rise of 3°C and a fully irrigated situation.

With CO_2-increase, the absolute standard deviations increase (with 0.4–1.4 t ha^{-1}) at all locations. At Wageningen and Migda, this increase is smaller than the increase in average yields. Thus, the relative standard deviations decrease about 9% at these locations. At Tel Hadya, the relative standard deviation remains unchanged (Table 1). The effect of increased CO_2 for the individual years at Wageningen is illustrated in Figure 5. The large positive effect on seed yield is present even in drier years such as 1976, 1983, and 1986. This is due to the increased water use efficiency with CO_2 increase. Figure 5 shows that, in the present situation, the yields at Wageningen vary from 1.5 t ha^{-1}–6.5 t ha^{-1}. With CO_2 increase, seed yields vary from 2.5–10.5 t ha^{-1}, which means a range of 8 t ha^{-1}. Figure 5 shows that, although the relative standard deviation decreases with CO_2-increase (Table 1), the absolute variation in seed yields increases.

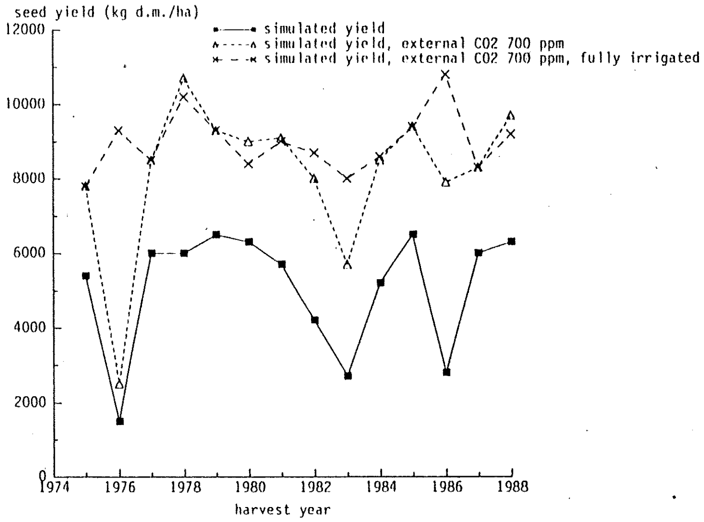

Figure 5. Simulated seed yields at Wageningen with 1) present weather, 2) with a CO_2-increase to 700 ppm and a rain-fed situation, 3) with a CO_2-increase to 700 ppm and a fully irrigated situation.

The combination of temperature and CO_2-increase results in an increase (0.5–0.9 t ha^{-1}) of absolute standard deviations at Tel Hadya and Migda, but not at Wageningen. The average yields show a larger increase at all locations, and consequently the relative standard deviations decreased 4 to 19% at all the locations. From Table 1 it follows that at Wageningen and Migda, the combined effect of temperature and CO_2 on the standard deviations is the addition of the separate effects. This does not hold for Tel Hadya. At that location, the combined effect on absolute standard deviation is smaller than the added separate effects. In contrast, the combined effect on relative standard deviation is much larger than the added separate effects.

In general, the explored climate changes in Table 1 stabilize relative variations in seed yields. It is uncertain if this can be seen as a real stabilizing effect. Figure 6 illustrates this for the individual years at Wageningen: although the relative standard deviation is reduced, the relatively small yields in dry years e.g., 1976, will remain in the rain-fed crops. In the present situation, yields vary from 1.5–6.5 t ha^{-1}, which is a range of 5 t ha^{-1}. In the 2080 simulation, the yields of the rain-fed crops vary from 3.0–8.5 t ha^{-1}, which is a range of 5.5 t ha^{-1} (Figure 6). This small increase in yield range and the increase in absolute standard deviation indicate that absolute yield variability slightly increases under rain-fed conditions; however, the relative standard deviation decreases.

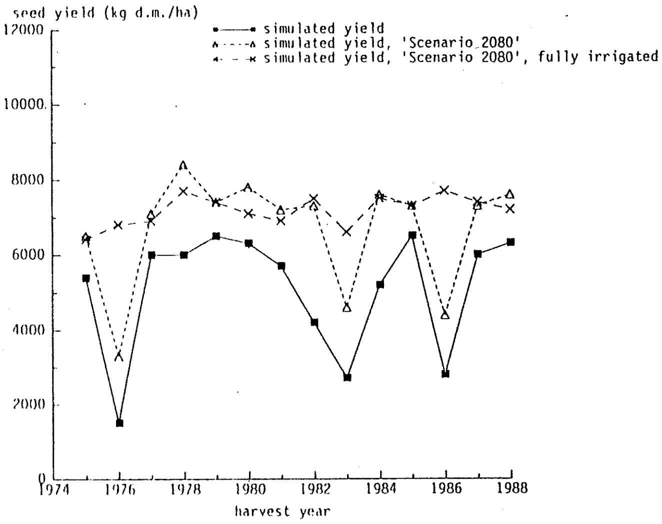

Figure 6. Simulated seed yields at Wageningen with 1) present weather, 2) with a scenario 2080 and a rain-fed situation 3) with scenario 2080 and a fully irrigated situation.

Effects of Climate Change on Stability of Fully Irrigated Crops

The effects of temperature and CO_2 on yield variation in fully irrigated crops are of minor importance. In these crops, the separate effects of temperature rise, increase of CO_2, and the combination result only in minor increases or decreases of absolute and relative standard deviations (Table 1). In fact, the most important factor is the stabilizing effect of irrigation itself. Over all the simulations for fully irrigated crops, the absolute standard deviations (0.3 to 1.5 t ha^{-1}) are much lower than for the rain-fed crops (1.1 to 2.8 t ha^{-1}). Also the relative standard deviations (9 to 14%) are much lower than for the rain-fed crops (22 to 43%) (Table 1). This shows the general stabilizing effect of enhanced water supply on faba bean yields and is in agreement with earlier experimental and simulation studies (Grashoff, 1990a,b; Grashoff and Verkerke, 1991; Grashoff and Stokkers, 1992). Apparently, this stabilizing effect of water supply remains very large in the assessments dealing with climate change.

The stabilizing effect of irrigation in the changed climate is illustrated in Figure 6 for the individual years at Wageningen. On one hand, it shows that yields of fully irrigated crops in dry years (e.g., 1976 and 1986) will be much higher than those of rain-fed crops, due to the higher availability of water. On the other hand, it shows that yields of fully irrigated crops will be slightly lower than those of the rain-fed crops in years such as 1978, 1980, 1981, and 1988. This is due to the fact that faba bean needs a mild water shortage during flowering for optimum dry matter partitioning and optimum seed yields (Grashoff and Stokkers, 1992). In years with such a pattern of precipitation, this effect will stay with climate change and may be even slightly stronger than in the present situation. Apparently, full irrigation is a strong stabilizing factor as it increases the lower yields, but decreases the "peak yields" in other years, which is not efficient. These peak yields can be obtained if irrigation is applied in such a way that a mild water shortage is allowed during flowering and no water shortage after flowering (Grashoff and Stokkers, 1992).

Concluding Remarks

The assessed effects on average yield and yield variability are in the same order of magnitude as presented by Nonhebel (1993), who studied the combined climate effects for spring wheat with the scenarios for 2030 and 2080. Jansen (1990) studied the combined climate effects on potential rice production in Asia. He found increments in average potential seed yields of 0 to 10% for comparable scenarios as used in this paper.

The simulation results presented in this paper are the results of a survey of the sensitivity of the crop/weather system to changes in temperature and CO_2 concentration. CO_2-increase and temperature rise are regarded as the most important aspects of climate change. This paper shows that the direct CO_2 effect on assimilation and thus on crop production is substantial and thus essential in assessments of crop production under climate change. When only the temperature effects were studied, it is concluded that the climate change induced by the greenhouse gases would result in a yield decline in most cases. However, the combined effect of temperature rise on development and of CO_2-increase on assimilation is resulting in a yield increase on all sites. This shows that simulation models which include a synthesis of the most important physiological processes on crop growth are a valuable tool to explore the possible effects of climate changes on crop growth, yields and yield stability. It emphasizes also, the need for validation of these models with experiments of crop growth under increased atmospheric CO_2 concentrations. In this validation, two aspects have to be considered. Firstly, the positive effect of CO_2-increase on AMAX (maximum rate of photosynthesis), which we used, is a maximum possible effect (J. Goudriaan, pers. comm.). Measured positive effects on AMAX and thus on photosynthesis may be smaller. Secondly, attention has to be paid to the possible effects of CO_2-increase on morphological characters such as specific leaf weight (SLW). These effects are neglected in the present study. Usually SLW increases with CO_2-increase, which results in a slower increase of LAI. This effect is small in experiments with comparable crops such as soybean (Lieth *et al.*, 1986). However, when CO_2-experiments with faba bean show smaller positive effects on AMAX and important increments of SLW, this will result in a tendency towards smaller positive effects of CO_2-increase on crop growth than assessed in this paper.

Climate change may also affect other weather variables such as global radiation, precipitation, vapor pressure, and wind speed. Based on the IPCC reports, it is assumed in this paper that changes in radiation, relative humidity, precipitation, and wind speed are of minor importance in comparison with the effects of CO_2-increase and temperature rise. However, precipitation has a strong regional character, and when the GCMs are able to give reliable assessments with respect to possible changes in (regional) precipitation in the future (Houghton *et al.*, 1990), a detailed analysis is needed. As soon as these studies might assess major changes in precipitation, radiation, or windspeed in individual regions, the results can be included in the presented type of crop growth models to continue the study of regional aspects of climate change on crop growth and yields. Once more, this emphasizes the usefulness of these types of models in assessments of future yields.

From this paper the following conclusions are drawn. In the first place, the positive effect of CO_2-increase on average yields of faba bean more than compensates for the negative effect of temperature rise. Based on these effects, a general increase of future average seed yields is assessed. Secondly, the effects of climate change on yield variability are not completely equal at all locations, but for both scenarios, 2030 and 2080, the relative variability shows a tendency to decrease. Nevertheless, in the scenarios for 2030 and 2080, faba bean remains relatively sensitive to water shortage, and irrigation will remain the most effective factor in stabilizing yields.

Acknowledgements

The authors wish to thank Dr. Ir. J. Goudriaan (TPE-LUW) and Dr. Ir. A. J. Haverkort (CABO-DLO) for helpful criticism of the manuscript.

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