Vol. 21: 173–186, 2002 | CLIMATE RESEARCH
Clim Res | Published June 14

Comparison of two potato simulation models under climate change. I. Model calibration and sensitivity analyses

Joost Wolf*

Group Plant Production Systems, Department of Plant Sciences, Wageningen University, PO Box 430, 6700 AK Wageningen, The Netherlands

ABSTRACT: To analyse the effects of climate change on potato growth and production, both a simple growth model, POTATOS, and a comprehensive model, NPOTATO, were applied. Both models were calibrated and tested against results from experiments and variety trials in The Netherlands. The sensitivity of model results to different values of weather variables was determined. The comparison of the results from both models indicated the sort of conditions in which model results differed and may become less reliable. The average tuber yield level and the inter-annual yield variation in potato experiments were predicted well by NPOTATO, whereas POTATOS sometimes calculated yields that were too high. The fit between yields observed in variety trials on clay soils and simulated yields from both models was quite good over the last 4 yr of the period 1974–1988. However, in almost all earlier years a considerably lower yield occurred in the trials than was calculated. This yield difference might be caused by factors that were not described by the models (e.g. a change in management). Irrigated tuber yield from both models considerably increased with increases in both solar radiation and atmospheric CO_2, and it had its optimum at the present temperatures in Wageningen, The Netherlands. Water-limited yield from both models had a slightly lower temperature optimum, considerably increased with increasing precipitation, atmospheric CO_2 and vapour pressure and decreased with increasing wind speed. The main differences between NPOTATO and POTATOS results were the higher evapo-transpiration and, hence, the stronger yield reduction by water limitation from NPOTATO, and with irrigation, the lower yields for present conditions and the weaker and stronger yield increases with increasing radiation and atmospheric CO_2, respectively, from NPOTATO compared with those from POTATOS.

KEY WORDS: Climate change · Model comparison · Potato · Sensitivity analyses · Simulation model

1. INTRODUCTION

Since agricultural production is greatly affected by climate, any changes in climate which may result from increasing concentrations of greenhouse gases in the atmosphere (Mearns 2000) could have dramatic consequences for agricultural yield potential. In this study the effects of climate change on the yield potential of potato have been analysed.

The relationship between climate, crop growth and yield is complicated, since a large number of climate, soil, management and crop characteristics are involved. In addition, crop growth mainly appears to respond to changing conditions in a non-linear way (Nonhebel 1994). For example, crop yields may decrease with an increase in temperature variability (i.e. temperatures more often outside of the optimum range for crop growth) or rainfall variability (i.e. longer dry spells), as shown by Semenov & Porter (1995) and

---

*Present address: Department of Soil and Land Use, ALTERRA Research Institute, Droevendaalse steeg 3, PO Box 47, 6700 AA Wageningen, The Netherlands.
E-mail: j.wolf@alterra.wag-ur.nl

Semenov et al. (1996). As a consequence, the effects of climate change on crop yield cannot be described in terms of simple and average relationships between the two. In the last 2 decades methods have been developed for calculating yield levels of crops under well-specified conditions. These methods are based on the application of crop growth simulation models, combining knowledge about crop characteristics and their interactions with the environment.

In this way, the effects of climate change in the USA on the yields of a large number of main crops, such as wheat, maize, soya bean and alfalfa, and the efficacy of management responses to climate change have been examined (Wilks 1988, Adams et al. 1990, Cooter 1990, Curry et al. 1990, 1995, Easterling et al. 1992a,b, Sinclair & Rawlins 1993). For potato production in the USA, only Rosenzweig et al. (1996) investigated the impacts of climate change. Although effects of climate change on the yields of a number of crops, such as wheat (Wolf 1993, Nonhebel 1996, Semenov et al. 1996), maize (Wolf & Van Diepen 1994, 1995) and grapevines (Bindi et al. 1996, Bindi & Fibbi 2000), have been analysed for Europe, impacts on potato production have been studied only for Scotland (Peiris et al. 1996) and for England and Wales (Davies et al. 1997).

Potato is the only important tuber crop in the EU. Almost 2% of the arable land area in the EU is used for potato production. This potato area is almost 4% of the land area used for all cereal crops in the EU but the tuber production (in fresh weight) is as large as 20% of the total grain production of cereal crops in the EU (FAO [Food and Agriculture Organization of the United Nations] statistical data bases[1]). Within a recent EU-project (CLIVARA), the effects of climate change and climatic variability on the growth and yield of 4 crop species (e.g. potato) in Europe were analysed (Downing et al. 2000). The climate change impacts on potato were studied at the site and regional scales (i.e. the present study and Wolf 2000a,b), the national scale (Great Britain: Butterfield et al. 2000; Finland: Carter et al. 2000; Hungary: Harnos et al. 2000; Denmark: Olesen et al. 2000) and the European scale (Harrison et al. 2000).

A detailed potato model, NPOTATO, developed within the CLIVARA project, was applied within this climate change impact study under European conditions. This model was first calibrated and tested against results from potato trials. Subsequently, the sensitivity of tuber production of potato to separately changed weather variables was determined. These analyses were also done with a more simplified model, POTATOS. Both models were also applied to analyse the possible effects of climate change, change in climatic variability and change in crop management in response to climate change on tuber production of potato at a number of sites in Europe (Wolf 2002 this issue).

2. METHODOLOGY

NPOTATO contains more elaborate descriptions of crop growth, assimilate allocation, leaf area expansion, phenology, senescence of crop organs, water balance, sink limitation, stress effects on assimilate production and allocation and on senescence than POTATOS. A schematic of both models and their main differences is shown in Fig. 1. The main characteristics of both models and their input data requirements are described in the following.

2.1. POTATOS

The growth simulations with POTATOS are conducted from crop emergence to maturity and are carried out in time steps of 1 d. POTATOS can simulate both potato growth under optimal nutrient and water supply (i.e. with irrigation), taking into account the climatic conditions, and growth without irrigation, also considering the amount of available soil water. More information on the basic concepts of POTATOS and a number of applications of this model are given by Spitters (1990), Kooman (1995) and Kooman & Spitters (1995).

2.1.1. Crop growth

Daily growth is computed as radiation interception multiplied by a specified radiation use efficiency (RUE). The radiation interception is calculated from incoming radiation and the fractional radiation interception (FINT). FINT is determined by leaf area expansion after crop emergence and senescence of leaves near maturity. RUE is corrected for sub-optimal temperatures and soil water contents and for a change in atmospheric CO_2 concentration. Optimum day temperatures are between 16 and 24°C (Kooman 1995), and outside of this range RUE is reduced linearly with temperature. If the available soil water in the root zone becomes limiting for crop transpiration, RUE and thus crop growth are reduced proportionally to the reduction in transpiration.

2.1.2. Crop phenology and assimilate allocation

The initial increase in FINT, the date of tuber initiation, and the decrease in FINT by canopy senescence

---

[1] FAOSTAT database collections on food balances, land use and irrigated areas (http://apps.fao.org)

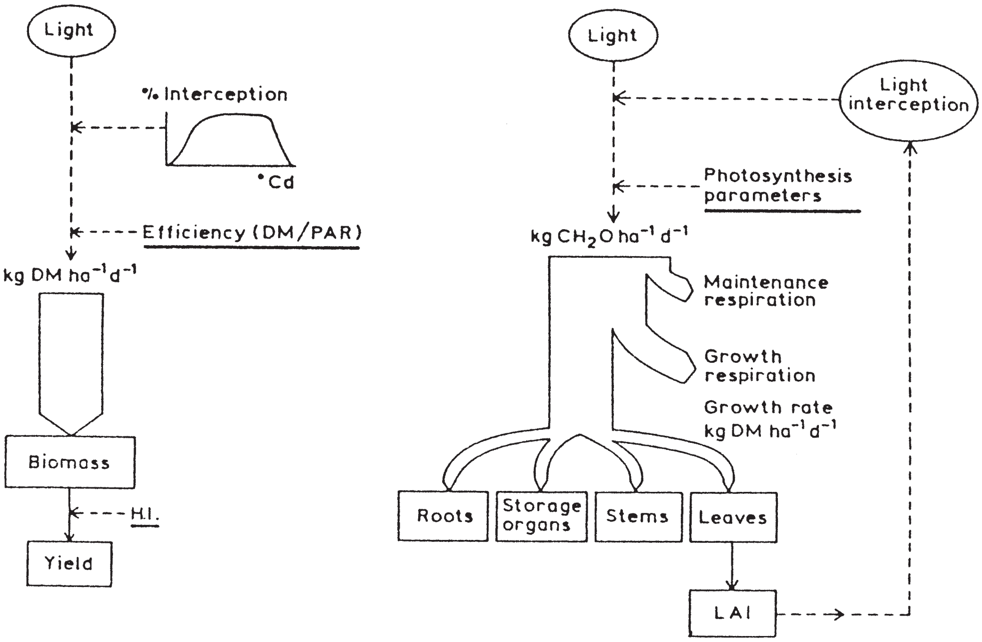

Fig. 1. Schematic of the calculation of crop growth. Left: POTATOS model based on light interception, light use efficiency and harvest index. Right: NPOTATO model based on the light profile within the canopy, photosynthesis and respiration characteristics, and dry matter partitioning; LAI: leaf area index. Source: Spitters (1990)

are all determined by variety-specific temperature sum requirements (°C d) from crop emergence (Spitters 1990, Kooman & Spitters 1995), and the last two may be determined by day length too (Kooman 1995). A fraction of total biomass that increases with thermal time (°C d) from tuber initiation is allocated to the tubers. However, dry matter partitioning among plant organs and leaf weight increase and leaf area expansion are not explicitly calculated in POTATOS.

Late varieties in POTATOS differ from the early ones by the increased temperature sum requirement to initiate tuber filling, by a reduced increase in tuber fraction against thermal time, and by an increased temperature sum requirement for final canopy senescence (Spitters 1987). In this way the late varieties start tuber filling at a later date and are able to maintain foliage and produce biomass over a longer period. This results in a larger final biomass but in a lower fraction of biomass in the tubers.

2.1.3. Water balance

The available amount of soil water in the root zone is calculated from the water balance, which includes precipitation, irrigation, losses by runoff, soil evaporation, crop transpiration, and leaching from the root zone. Potential rates of soil evaporation and crop transpiration are calculated using the Penman approach (Frère & Popov 1979). The actual transpiration rate is calculated from its potential rate by correction for the degree of radiation interception by the crop and the available soil water content in the root zone (Supit et al. 1994). The actual evaporation rate is calculated from its potential rate by correction for the degree of radiation interception by the soil and the time since it last rained (Ritchie 1972).

2.1.4. Direct effects of increased atmospheric CO_2

Doubling of the ambient atmospheric CO_2 concentration results in observed biomass increases of 20 to 30% for potato (Dijkstra et al. 1995, Miglietta et al. 1998, Schapendonk et al. 2000). This CO_2 effect may vary depending on the degree of sink limitation and the resulting down-regulation of the CO_2 assimilation between nil and about 40% increase in biomass (Sage et al. 1989, Wheeler et al. 1991, Van de Geijn & Dijkstra 1995). Sink limitation is strongest at high radiation levels, a long day length, which results in retarded tuber filling, and low soil temperatures. In POTATOS, RUE increases by 20% with a doubling of ambient CO_2, assuming a small sink limitation, and FINT does not change with CO_2 enrichment, as observed in a large number of potato experiments under elevated CO_2 within the EU-CHIP project (Wolf 2000c). The potential transpiration is reduced by 5% for a doubling of ambient CO_2, representing a large decrease in stomatal conductance, which is largely nullified by micrometeorological feedback (Goudriaan & Unsworth 1990, Morison 1993).

2.2. NPOTATO

The simulation of potato growth and water and nitrogen dynamics is carried out from planting to maturity in time steps of 1 d. NPOTATO comprises submodels that simulate crop growth, phenological development, nitrogen uptake by the crop, soil nitrogen dynamics and soil moisture dynamics. The principles of the original model for winter wheat, NWHEAT, and its application for analysing soil nitrogen supply and nitrogen uptake by the crop during the growth period and for improvement of nitrogen application methods, were discussed by Groot & De Willigen (1991) and Groot & Spiertz (1991). A complete description of NWHEAT was given by Groot (1987, 1993). NPOTATO differs mainly from NWHEAT with respect to crop phenology and dry matter allocation, based largely on the work by Kooman (1995) and Spitters (1990).

2.2.1. Crop growth

Simulation of crop growth is done in the way described by Spitters et al. (1989); this approach is, for example, applied in the SUCROS model (Van Laar et al. 1997). Gross assimilation of the canopy is calculated as a function of the leaf area index, the radiation distribution in the canopy and the photosynthesis-light response curve of individual leaves. The maximum of this response curve increases with increasing nitrogen content in the leaves (Van Keulen & Seligman 1987) and with increasing atmospheric CO_2, and it is reduced for sub-optimal temperatures. Maintenance requirements, calculated as a function of crop weight and chemical composition (Penning de Vries 1975), are subtracted from daily gross assimilation. The remaining assimilates are allocated to the different crop organs. If the available soil water in the rooted soil layers becomes limiting for crop transpiration, the assimilate production is reduced proportionally to the reduction in transpiration.

2.2.2. Crop phenology and assimilate allocation

The rate of phenological development is mainly determined by the ambient temperatures, and this relationship is cultivar-specific. Between emergence and tuber initiation the effect of day length is also important (Kooman 1995), and NPOTATO accounts for this effect, resulting in an advanced tuber initiation under short days. The allocation of available assimilates to the different crop organs changes over time and depends on the phenological development of the crop.

After tuber initiation, the fraction of assimilates allocated to the tubers increases with the rate of potential tuber growth and with increasing water stress or nitrogen shortage (Kabat et al. 1995), resulting in a larger final harvest index. Hence, the reduction of tuber yields by these stresses is smaller than the corresponding decrease in biomass production. Temperatures that are low or high compared to the small optimal range (16 to 22°C) for tuber growth (Kooman 1995) have an opposite effect, resulting in a smaller harvest index. At the end of the crop growth period, vegetative plant organs die rapidly and a considerable part of their carbon and nitrogen is translocated to the tubers. Late potato varieties differ from the early ones by both the increased temperature sum requirement to initiate tuber filling and the increased life span of the leaves (Spitters 1987).

2.2.3. Water balance

The soil is treated as a multi-layered system. For each layer, changes in soil water content are the result of infiltration, soil evaporation, crop transpiration, and downward movement to the lower layer. If precipitation occurs, the first layer is filled to field capacity. Excess water drains to the next layer, which is also filled to maximum field capacity. This procedure is repeated for the deeper layers as long as there is excess water. Upward movement of water, for example, by capillary rise from ground water, is not calculated by the model.

Potential soil evaporation is calculated using the Penman approach (Frère & Popov 1979) and potential crop transpiration by the Penman or Penman-Monteith approach (Smith 1992). The actual transpiration rate is calculated from its potential rate by correction for the degree of radiation interception by the canopy and the available soil water content in the rooted soil layers (Supit et al. 1994). The actual evaporation is calculated from its potential rate by correction for the degree of radiation interception by the soil and the soil moisture content in the top layer (Van Keulen 1975).

2.2.4. Nitrogen uptake

Crop nitrogen demand is based on the concept of nitrogen deficiency (i.e. the degree that actual nitrogen concentrations in crop organs are below their maximum possible values). The actual nitrogen uptake proceeds according to crop demand as long as the amount of mineral nitrogen in the soil is not limiting. This amount of mineral nitrogen depends on fertilizer nitrogen application, nitrogen in rainfall, decomposition of old (humus) and fresh organic matter (crop residues), crop nitrogen uptake and downward movement of nitrogen by leaching. After the start of tuber filling, crop nitrogen is translocated from the canopy to the tubers. Limiting nitrogen supply results in lower leaf nitrogen concentration and photosynthetic capacity.

2.2.5. Direct effects of increased atmospheric CO_2

Effects of CO_2 enrichment were incorporated in the model by increasing the maximum value and the initial angle of the photosynthesis-light response curve of single leaves, by increasing the thickness of leaves, and by decreasing the stomatal conductance. These changes in model parameters were based on experimental results for potato under CO_2 enrichment by Sage et al. (1989), Dijkstra et al. (1995) and Schapendonk et al. (2000) and on more general studies on the responses of photosynthesis and transpiration to CO_2 enrichment by Goudriaan (1990), Goudriaan & Unsworth (1990) and Morison (1993).

2.3. Data requirements for both models

For application of both models, data that specify crop growth, phenological development and assimilate allocation are required. For POTATOS, these data were mainly based on work by Spitters (1990). For NPOTATO, data that determine phenological development, assimilation and respiration processes, dry matter allocation to and death rate of plant organs, and the temperature sensitivity of various growth processes were mainly based on studies by Spitters (1990), Kooman (1995) and Boons-Prins et al. (1993).

Daily minimum and maximum air temperatures, atmospheric CO_2 concentration and solar radiation are required for both models to calculate CO_2 assimilation rates and crop growth (Goudriaan & Van Laar 1978). To calculate the components of the water balance, daily precipitation, wind speed and vapour pressure are also required. Historical or generated sets of daily weather data over a period of about 30 yr were used.

To calculate the soil water balance, the soil physical characteristics must be known. For POTATOS, these are maximum rooted soil depth, soil moisture characteristics such as soil porosity and volumetric moisture contents at field capacity and wilting point for the rooted soil, and the fraction of precipitation lost by surface runoff. For NPOTATO, the required characteristics are the texture class for each soil layer, maximum rooted soil depth and soil moisture characteristics for each texture class. To calculate organic matter decomposition and nitrogen mineralisation with NPOTATO, initial amounts of old and fresh organic matter, their relative decomposition rates and carbon and nitrogen contents must be known. To calculate the amount of soil mineral nitrogen, the initial amount of mineral nitrogen in each layer and the inputs of nitrogen in precipitation and fertilizer applications are also required. The limited soil information for POTATOS can be derived from the European soil map (King et al. 1995), but the detailed information for NPOTATO requires field trials with elaborate soil sampling and analyses.

3. RESULTS

Both models were calibrated and tested against results from a number of potato experiments and variety trials in The Netherlands. For analysis of the possible effects of climate change, the sensitivity of modelled tuber production of potato to separately changed values of weather variables was determined.

3.1. Model calibration and validation

Results from potato experiments at Varsseveld, The Netherlands, and from variety trials on both clay and sandy soils were compared with simulated results from both models.

3.1.1. Experiments at Varsseveld

Field experiments with a number of potato varieties were carried out on sandy soils with a high organic matter content at Varsseveld. Data on biomass production, assimilate distribution between crop organs, leaf area, and crop husbandry and dates of planting, emergence and harvest were available, but no soil physical and weather data. Hence, maximum available soil water was estimated based on qualitative soil information and historical weather data from Wageningen (50 km west of Varsseveld) were used. No irrigation was applied and nutrient supply was presumed to be sufficient to prevent nutrient limitation of crop growth. The trials were carried out in the years 1968, 1969, 1971, 1972 and 1973. Further information about these trials can be found in Caesar et al. (1981) and Gmelig

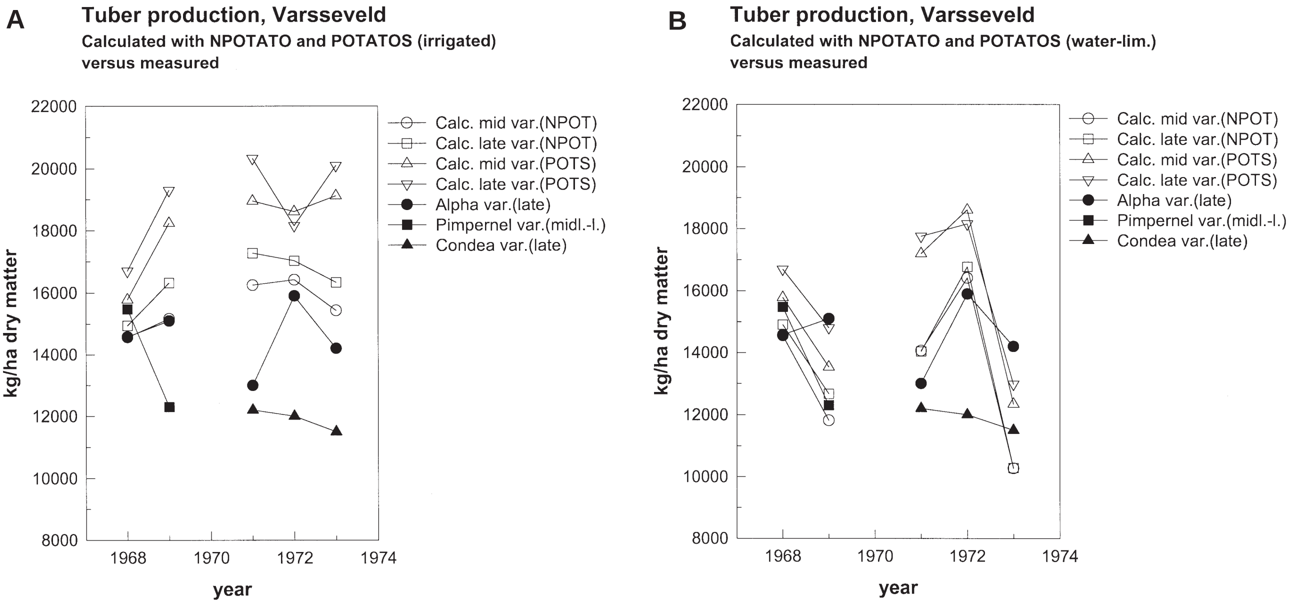

Fig. 2. Tuber yields of potato calculated (Calc.) with NPOTATO (NPOT) and POTATOS (POTS) (both with RUE = 3.0) for mid and late varieties at Varsseveld (A) with and (B) without irrigation and actual tuber yields for different varieties

Meyling & Bodlaender (1981). A large part of the dataset is given by Boons-Prins et al. (1993).

Observed tuber yields for different varieties during the 5 years were compared with yields calculated with both models for both mid and late varieties and with and without irrigation (Fig. 2). The difference between the simulated and observed yields was considerable for irrigated production, in particular for POTATOS. This indicated that tuber yields were limited by water supply. The difference between simulated tuber production without irrigation and observed yield data was small, particularly for NPOTATO. The average tuber yield and the inter-annual variation in tuber yield were predicted well by NPOTATO, but the water-limited yields from POTATOS were sometimes too high.

3.1.2. Variety trials

Trials with a large number of potato varieties have been conducted over many years in different parts of The Netherlands. Information on measured tuber yield, potato variety, location and soil type are available from these trials. The cultivated varieties has changed over time, and hence, only the average of the yields of all varieties cultivated at a given location could be compared with the simulated yields. The only exception was the Bintje variety, which was grown on different soils and locations over a period of more than 20 yr.

Observed tuber yields on clay soils at Dronten in the central polders of The Netherlands were compared with simulated yields from both models for the same location (Fig. 3). This showed that average yield and inter-annual yield variation of the average of all varieties were almost identical to average yield and yield variation of the Bintje variety. It also showed that water supply was not limiting production in the trials, as can be seen in the results for the relatively dry years 1975, 1976, 1983 and 1986 (Fig. 3B: in these years simulated yields without irrigation were lower than the yields under irrigated conditions, whereas such a yield reduction did not occur in the trial). Hence, simulations with irrigation were used for comparison with the trial results. The fit between observed and simulated yields with irrigation from both models was good over the last 4 yr. However, in almost all years before 1985 a considerably lower yield occurred in the trials than was calculated with both models for an irrigated crop. The inter-annual yield variation simulated with NPOTATO for both irrigated and water-limited production was essentially similar to that simulated with POTATOS. Note that POTATOS used a lower value for RUE than NPOTATO. This was due to the simple calculation method for radiation interception in POTATOS, which sometimes resulted in overestimated interception values.

Observed tuber yields on sandy soils at Wageningen were compared with simulated yields from the 2 models for the same location (Fig. 4). These results also showed that average yield and inter-annual yield variation of the average of all varieties were almost identical to average yield and yield variation of the Bintje

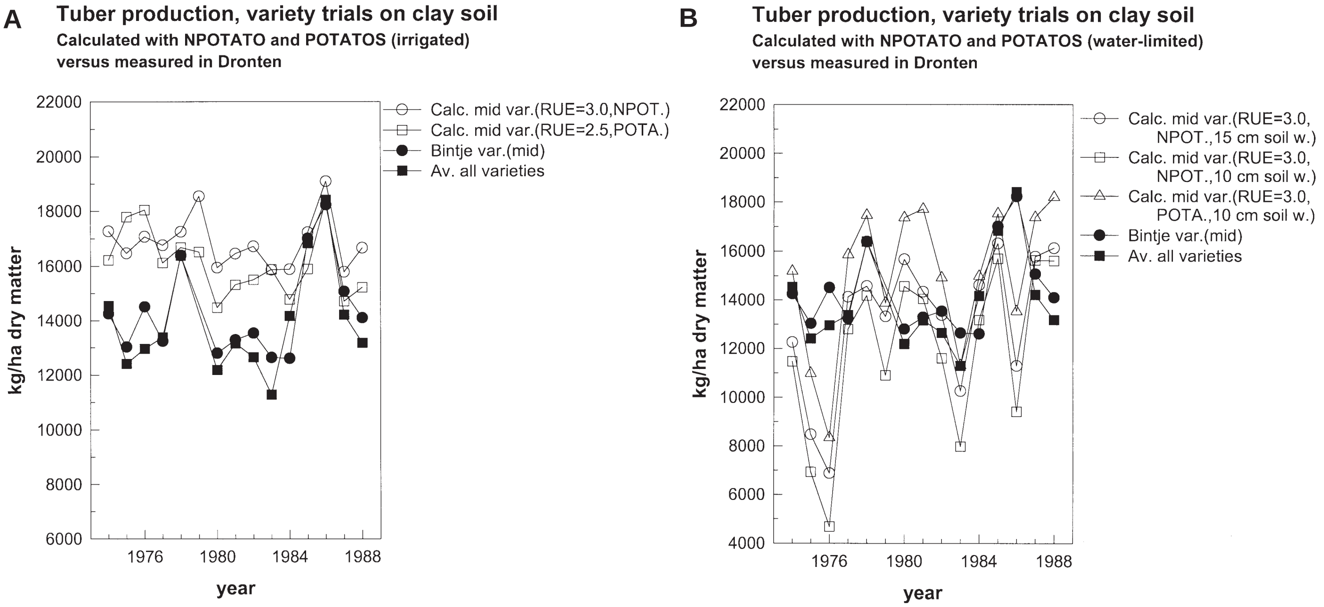

Fig. 3. Tuber yields of potato calculated (Calc.) with NPOTATO (NPOT.) and POTATOS (POTA.) for mid variety at Dronten (A) with and (B) without irrigation, for different values of the radiation use efficiency (RUE) and available soil water (soil w.), and actual tuber yields of the Bintje variety and average yields of all potato varieties in field trials on clay soil

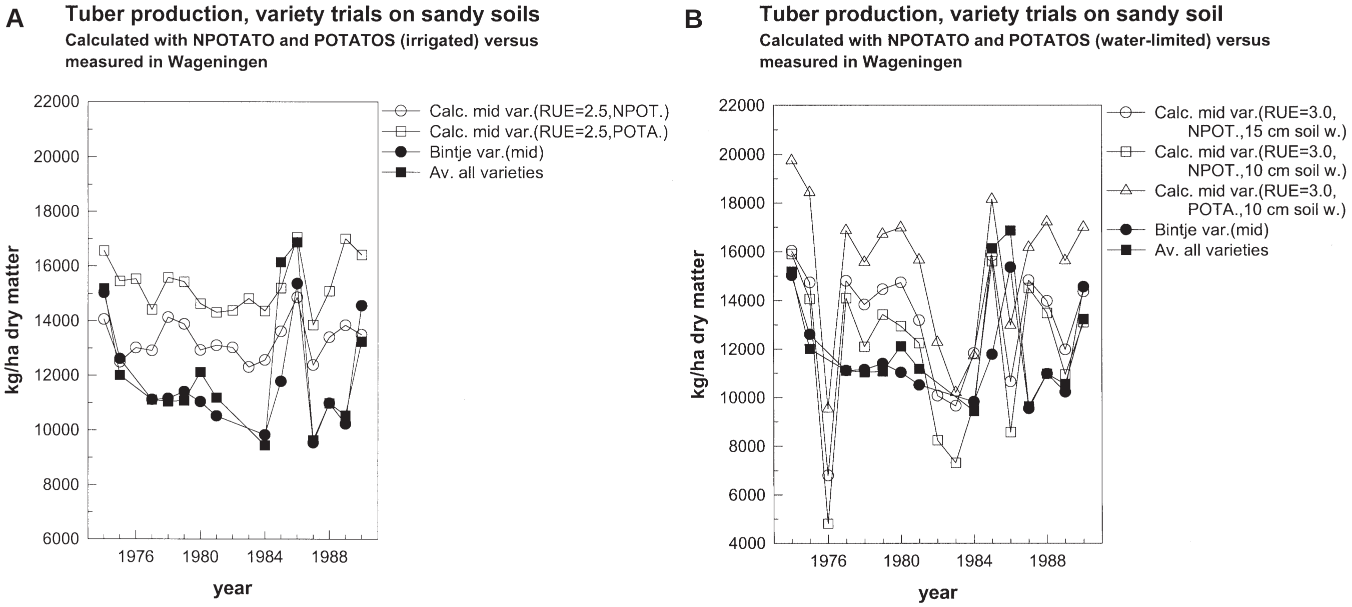

Fig. 4. Tuber yields of potato calculated (Calc.) with NPOTATO (NPOT.) and POTATOS (POTA.) for mid variety at Wageningen (A) with and (B) without irrigation, and for different values of RUE and available soil water (soil w.), and actual tuber yields of the Bintje variety and average yields of all potato varieties in field trials on sandy soil

variety. Water supply probably did not limit yield on the sandy soil (see Fig. 4B, year 1986), and hence, simulations with irrigation were used for comparison with the trial results. Even with an RUE of 2.5 (g dry matter MJ^{-1} PAR [photosynthetically active radiation]), simulated yields from both models corresponded with observed yields in only a few years (Fig. 4A). This indicated that the simulated yield level can be attained on sandy soils. However, unknown factors resulted in a lower observed mean yield level and a larger yield variability on sandy soils than on clay soils (Fig. 3) and in a larger difference between simulated and measured yields. The inter-annual yield variation simulated with NPOTATO for irrigated and water-limited production at Wageningen (Fig. 4) was similar to that simulated with POTATOS. As both models used an identical value for RUE, the average yield level was higher for POTATOS due to overestimated radiation interception than for NPOTATO.

3.2. Sensitivity analyses

For both irrigated and water-limited potato production in Wageningen the sensitivity of model results to systematic changes in climate were analysed. The main characteristics of the climate in Wageningen during the growth period of potato (from end of May to half September) are the following: mean minimum and maximum temperatures of respectively about 10 and 20°C; daily mean irradiation of 12 to 18 MJ m^{-2} (decreasing from June to September); and a monthly mean rainfall of about 75 mm. Growth simulations were conducted with both NPOTATO and POTATOS over a time period of 20 yr (1970–1989) for a historical climate dataset from Wageningen. Weather variables in this dataset were adjusted independently, in a stepwise manner, in order to gauge the sensitivity of model results to changing values of each variable. Sensitivity to changes in the following variables were analysed: temperature, atmospheric CO_2 concentration, rainfall, solar radiation, vapour pressure and wind speed. Values for each output variable are the mean result of 20 yr of growth simulations.

The optimum temperature for irrigated total biomass and tuber production was encompassed by present conditions in Wageningen for both models, and it was slightly lower than present temperatures for water-limited production (Fig. 5A,B). Temperature rise caused an accelerated death of leaves and, thus, advanced the end of growth. In addition, more days with a reduced assimilation rate and tuber growth rate occurred at high temperatures. This resulted in a lower biomass and tuber production. A decrease in temperature also caused lower yields, partly because there were more days with a reduced assimilation and growth rate at low temperatures and partly because of the reduced length of the growing season. The sensitivity of total biomass and tuber yields to temperature change from both models was almost identical. The main differences were the higher irrigated yields at optimum temperature (because of overestimated radiation interception), the stronger increase in yield to its optimum due to temperature change, and the weaker yield reduction for water-limited production (due to lower evapo-transpiration; Fig. 5D) from POTATOS, in comparison to NPOTATO.

The coefficient of variation (CV) of the tuber yields, which indicates the degree of inter-annual yield variation, was lowest when the crop was irrigated and increased with both increases and decreases in temperature (Fig. 5C). This indicated that yield variability increased if temperatures were too low and limited the length of the growing season and if temperatures were too high and caused advanced leaf death and were sub-optimal for assimilation and tuber growth. For water-limited production CV values were higher (i.e. indication of yield sensitivity to water shortage), particularly for NPOTATO due to the higher evapo-transpiration (Fig. 5D), but the CV was practically not sensitive to temperature. Cumulative evapo-transpiration had a maximum close to that for the present temperature regime, which was due mainly to the length of the effective growth period. In NPOTATO evapo-transpiration was calculated with the Penman-Monteith method (Smith 1992), which gave higher evapo-transpiration values than the Penman approach (Frère & Popov 1979) in POTATOS. In the subsequent applications of POTATOS (Wolf 2002) a factor has been incorporated to correct for the lower Penman estimate.

Tuber production considerably increased with the amount of precipitation when no irrigation was applied (Fig. 6). The amount of soil water available to a potato crop is rather limited, owing to its relatively shallow rooting depth (i.e. 50 cm). This explains the strong sensitivity of potato production to precipitation. Note that in the variety trials at Wageningen, water supply did not limit the potato yields (see above). This was probably due to high groundwater levels and the resulting capillary rise, which were not taken into account in these sensitivity analyses. Irrigated tuber production considerably increased with the amount of radiation and atmospheric CO_2 concentration as long as atmospheric CO_2 was less than twice the ambient CO_2 concentration. For water-limited production the yield sensitivity to radiation was smaller than that for irrigated production (i.e. moderate yield increase from POTATOS and no yield change from NPOTATO) as a result of increasing water limitation with increasing radiation. The vapour pressure deficit and, thus, evapo-transpiration were reduced with increasing vapour pressure. This resulted in fewer growth days with water stress and, thus, in a higher tuber yield, but only if no irrigation water was applied. The opposite occurred with increasing wind speed, i.e. evapotranspiration increased, which reduced tuber yields. The sensitivity of tuber production to these weather variables and atmospheric CO_2 concentration was almost the same for NPOTATO and POTATOS. The main differences between NPOTATO and POTATOS results were the higher irrigated yields and the smaller yield reduction for water-limited production from POTATOS. Other differences were the smaller yield

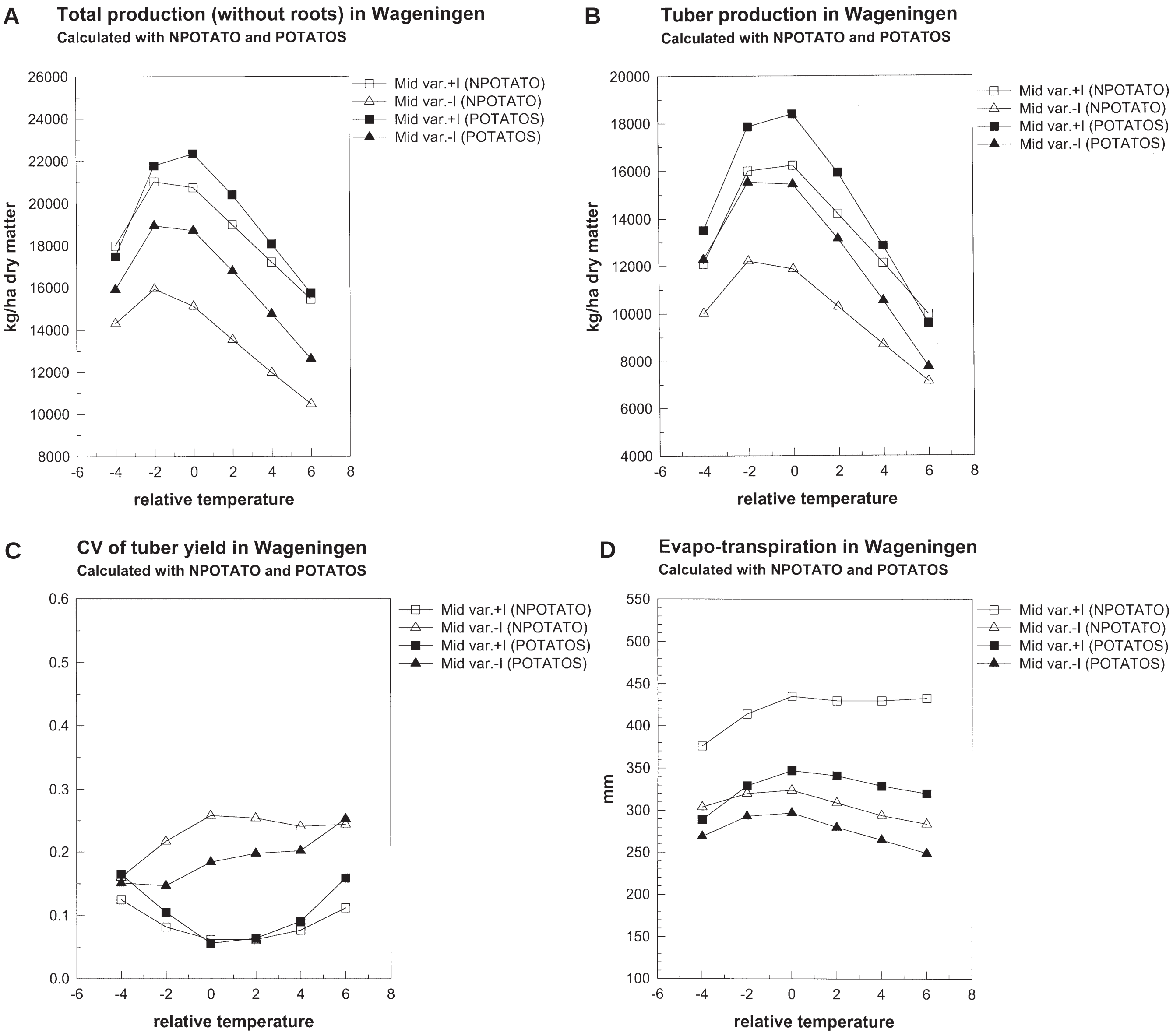

Fig. 5. Sensitivity to change in temperature of (A) total biomass (without roots) production, (B) tuber production, (C) coefficient of variation (CV) of tuber yield, and (D) cumulative evapo-transpiration from planting for irrigated (+I) and water-limited (–I) potato (mid variety) in Wageningen, as simulated with NPOTATO and POTATOS (both with RUE = 3.0). Results were established for 20 yr (1970–1989) of historical weather data of which temperature values were changed as indicated

increase with increasing solar radiation for NPOTATO (due to the curvi-linear photosynthesis-light response relationship) and the larger curvi-linear yield increase with increasing CO_2 concentration for NPOTATO compared with the linear increase for POTATOS.

4. DISCUSSION AND CONCLUSIONS

To analyse the effects of climate change on potato growth and production, 2 different potato models were used. The POTATOS model had a limited degree of detail in the description of growth processes. Hence, the number of model relations that needed to be tested, the number of parameters that needed calibration to site-specific conditions, and the required data base of inputs were more limited than in the NPOTATO model. In addition, the results from such a simple model are often more stable than those from a more comprehensive model. These model characteristics are an advantage in regional-scale studies (Boote et al. 1996). Hence, POTATOS has been applied in

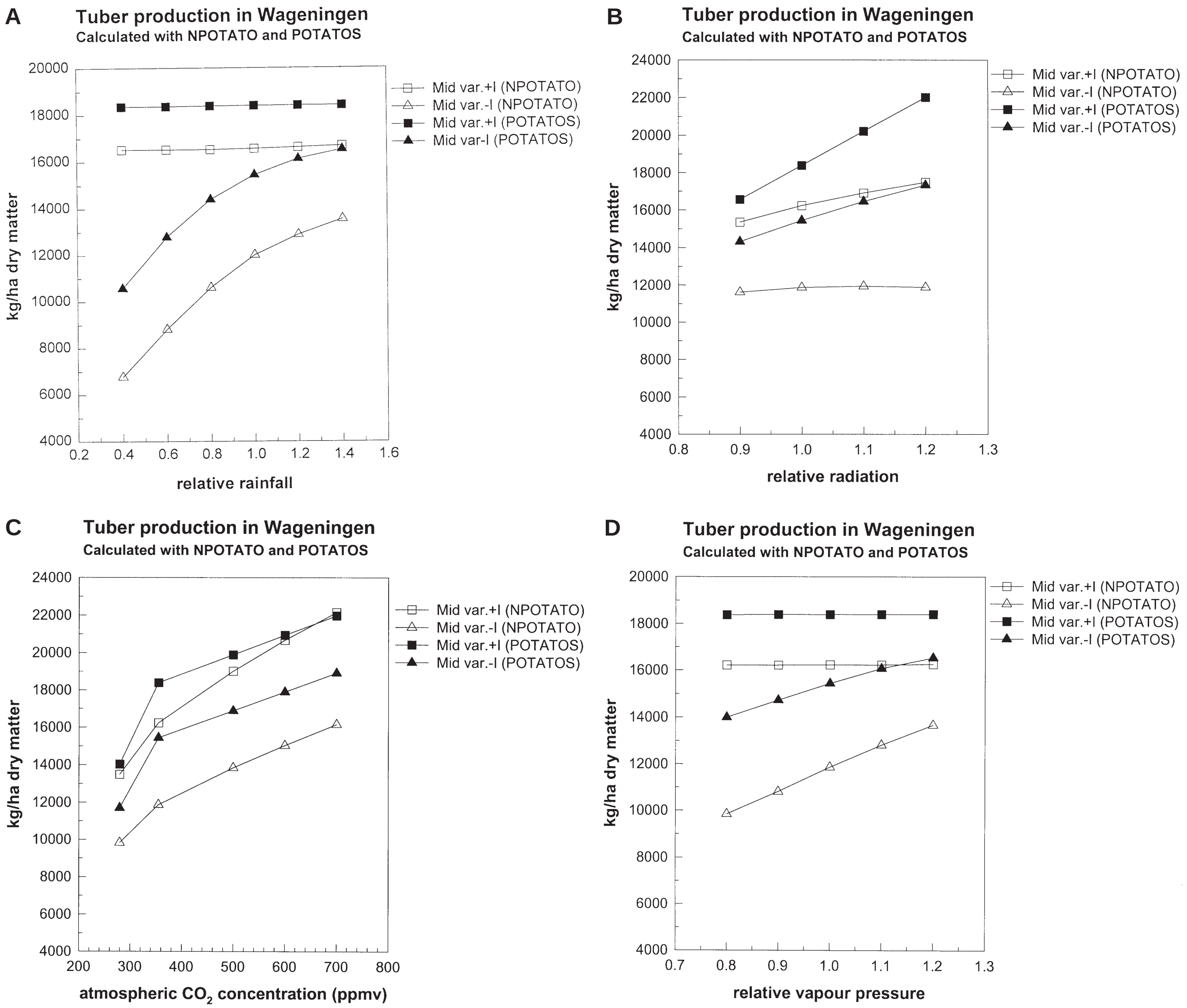

Fig. 6. Sensitivity to changes in (A) precipitation, (B) solar radiation, (C) atmospheric CO$_2$ concentration, and (D) vapour pressure of irrigated (+I) and water-limited (–I) tuber production of potato (mid variety) in Wageningen, as simulated with NPOTATO and POTATOS (both with RUE = 3.0). Results were established for 20 yr (1970–1989) of historical weather data for which values for 1 weather variable were changed as indicated

national- and European-scale studies on climate change impacts on potato (Carter et al. 2000, Harrison et al. 2000, Olesen et al. 2000). On the other hand in a more detailed model, such as NPOTATO, the growth processes, the responses of these processes to changes in environmental conditions, and the interactions between these responses are described in a more mechanistic and more realistic way. The comparison of the results from the 2 models indicated the differences in their model approaches and the sort of environmental conditions in which the model results differed and may become less reliable.

Results from both POTATOS and NPOTATO were compared with results from potato experiments at Varsseveld. The average tuber yield level and the inter-annual variation in tuber yield were predicted well by NPOTATO. Tuber yields from POTATOS were sometimes too high, caused by overestimation of the radiation interception (intercepted radiation fraction calculated as a function of thermal time) and perhaps also by a lack of sink limitation. The inter-annual variation in observed tuber yields was different between crop varieties. This indicated that this inter-annual yield variation was not only caused by weather effects on crop growth, but also by other factors (e.g. pests, diseases, premature leaf death, and losses due to poor harvesting conditions) that were not incorporated in the models.

Observed yields from variety trials on clay soils in The Netherlands were compared with simulated yields from both models for the period 1974–1988. The fit between observed and simulated yields with irrigation from both models was good over the last 4 yr. However, in almost all the earlier years a considerably lower yield occurred in the trials than was calculated with the 2 models. As information on these trials was limited, it was not possible to determine why the earlier yields were relatively low. The yield difference might be caused by factors that were not described by the model (e.g. change in crop management and protection or in nutrient supply). These results correspond well with the conclusions from modelling studies for winter wheat and potatoes in Denmark (Olesen et al. 2000) and for winter wheat in the UK (Landau et al. 1998) that, first, crop growth model simulations could explain only to a limited extent the inter-annual yield variation from the inter-annual variation in weather conditions and, second, for most crop species in the EU a clear technology trend (i.e. yield increase over time [FAO statistical data bases] due to improved crop varieties and crop management) was observed.

Observed yields from variety trials on sandy soils in The Netherlands were compared with simulated yields from the 2 models. Simulated yields corresponded well with observed yields in only a few years. This indicated that the simulated yield can be attained on the sandy soils. However, the observed mean yield level was lower and the yield variability larger than those on a clay soil, and the difference between simulated yields from both models and observed yields was larger than on a clay soil. These low yields on sandy soils compared with those on clay soils could not be explained but might result from a more problematic control of pests and diseases and/or a less favourable soil rootability and nutrient availability. In Denmark, mean crop yields in counties with sandy soils were lower than those in counties with loamy soils; this yield difference could also not be explained (Olesen et al. 2000).

The inter-annual yield variations simulated with NPOTATO for irrigated and water-limited production in the variety trials on both clay and sandy soils were essentially similar to those simulated with POTATOS. If both models applied an identical value for radiation use efficiency, the average yield from POTATOS was higher, mainly due to overestimated radiation interception.

The sensitivity of tuber production to systematic changes in climate was calculated with both potato models for Wageningen. These climate effects that were largely determined by the model approaches, were already discussed in the sensitivity analyses (Section 3.2). Hence, mainly the conclusions of these analyses are given here. Irrigated tuber production from both models considerably increased with increases in both solar radiation and atmospheric CO_2 concentration and had its optimum at present temperatures in Wageningen. The main differences between NPOTATO and POTATOS results for irrigated production were the lower yields for present conditions, the weaker and stronger increases with increasing radiation and atmospheric CO_2 concentration, respectively, and the higher evapo-transpiration from NPOTATO compared with those from POTATOS. Water-limited production from both models had a slightly lower temperature optimum than present temperatures, considerably increased with increases in amount of precipitation, atmospheric CO_2 concentration, and vapour pressure, and decreased with an increase in wind speed. The main differences between NPOTATO and POTATOS results for water-limited production were the stronger yield reduction by water limitation from NPOTATO (due to its higher evapo-transpiration), which resulted in a higher CV of tuber yield, and the nil yield change with increasing radiation from NPOTATO compared with the moderate yield increase from POTATOS.

Comparable model analyses of the sensitivity of potato production to climate change have been performed for both Scotland (Peiris et al. 1996) and different states in the USA (Rosenzweig et al. 1996). In the cooler climate in Scotland (than in Wageningen) temperature rise gave higher tuber yields because of the increased length of the growing season, whereas in the warmer climates in the USA, especially in the more southern states, temperature rise had a strongly negative effect on tuber yields. These results correspond well with the sensitivity of tuber production to temperature in NPOTATO and POTATOS, which model calculated maximum tuber yields at the present temperatures in The Netherlands.

Acknowledgements. The author is grateful to all colleagues within the EU-project CLIVARA (see Downing et al. 2000) for the good collaboration and in particular to Elaine Barrow (Climatic Research Unit, University of East Anglia, UK) for providing the climate change scenarios. This work was funded by the Commission of the European Communities' Environment Programme (contract ENV4-CT95-0154).

LITERATURE CITED

Adams RM, Rosenzweig C, Peart RM, Ritchie JT and 6 others (1990) Global climate change and US agriculture. Nature 345:219–223

Bindi M, Fibbi L (2000) Modelling climate change impacts at the site scale on grape vine. In: Downing TE, Harrison PA, Butterfield RE, Lonsdale KG (eds) Climate change, climatic variability and agriculture in Europe: an integrated assessment. Research report no. 21, Environmental Change Institute, University of Oxford, p 117–134

Bindi M, Fibbi L, Gozzini B, Orlandini S, Miglietta F (1996) Modelling the impacts of future climate scenarios on yield and yield variability of grapevine. Clim Res 7:213–224

Boons-Prins ER, De Koning GHJ, Van Diepen CA, Penning De Vries FWT (1993) Crop-specific simulation parameters for yield forecasting across the European Community. Simulation Reports AB-TPE, no. 32, AB-DLO, Wageningen

Boote KJ, Jones JW, Pickering NB (1996) Potential uses and limitations of crop models. Agron J 88:704–716

Butterfield RE, Harrison PA, Orr JL, Gawith MJ, Lonsdale KG (2000) Modelling climate change impacts on wheat, potato and grapevine in Great Britain. In: Downing TE, Harrison PA, Butterfield RE, Lonsdale KG (eds) Climate change, climatic variability and agriculture in Europe: an integrated assessment. Research report no. 21, Environmental Change Institute, University of Oxford, p 265–287

Caesar K, Bodlaender KBA, Hunicken C , Roer L, Umaerus M (1981) Growth of four potato varieties under different ecological conditions. Report of a working group of the section physiology of the European Association for Potato Research, Berlin

Carter TR, Saarikko RA, Joukainen SKH (2000) Modelling climate change impacts on wheat and potato in Finland. In: Downing TE, Harrison PA, Butterfield RE, Lonsdale KG (eds) Climate change, climatic variability and agriculture in Europe: an integrated assessment. Research report no. 21, Environmental Change Institute, University of Oxford, p 289–312

Cooter EJ (1990) The impact of climate change on continuous corn production in the southern U.S.A. Clim Change 16: 53–82

Curry RB, Peart RM, Jones JW, Boote KJ, Allen LH (1990) Response of crop yield to predicted changes in climate and atmospheric CO_2 using simulation. Trans Am Soc Agron Eng 33:1383–1390

Curry RB, Jones JW, Boote KJ, Peart RM, Allen LH, Pickering NB (1995) Response of soybean to predicted climate change in the USA. In: Climate change and agriculture: analysis of potential international impacts. ASA special publication number 59, American Society of Agronomy, Madison, p 163–182

Davies A, Jenkins T, Pike A, Shao J, Carson I, Pollock CJ, Parry ML (1997) Modelling the predicted geographic and economic response of UK cropping systems to climate change scenarios: the case of potatoes. Ann Appl Biol 130: 167–178

Dijkstra P, Schapendonk AHCM, Van de Geijn SC, Visser A, Rozema J (1995) Interactions between atmospheric CO_2 concentration, temperature and environmental factors with respect to photosynthesis, assimilate distribution and development rhythm of three agricultural crops. Nota 9, AB-DLO Institute, Wageningen, Free University, Amsterdam

Downing TE, Harrison PA, Butterfield RE, Lonsdale KG (eds) (2000) Climate change, climatic variability and agriculture in Europe: an integrated assessment. Research report no. 21, Environmental Change Institute, University of Oxford

Easterling WE, McKenney MS, Rosenberg NJ, Lemon KM (1992a) Simulations of crop response to climate change: effects with present technology and no adjustments (the 'dumb farmer' scenario). Agric For Meteorol 59:53–73

Easterling WE, Rosenberg NJ, Lemon KM, McKenney MS (1992b) Simulations of crop responses to climate change: effects with present technology and currently available adjustment (the 'smart farmer' scenario). Agric For Meteorol 59:75–102

Frère M, Popov GF (1979) Agrometeorological crop monitoring and forecasting. FAO Plant Production and Protection Paper 17, FAO, Rome

Gmelig Meyling HD, Bodlaender KBA (1981) Varietal differences in growth, development and tuber production of potatoes. Neth J Agric Sci 29:113–127

Goudriaan J (1990) Primary productivity and CO_2. In: Goudriaan J, Van Keulen H, Van Laar HH (eds) The greenhouse effect and primary productivity in European agro-ecosystems. Pudoc, Wageningen, p 23–25

Goudriaan J, Unsworth MH (1990) Implications of increasing carbon dioxide and climate change for agricultural productivity and water resources. In: Kimball BA, Rosenberg NJ, Allen LH, Heichel GH, Stuber CW, Kissel DE (eds) Impact of carbon dioxide, trace gases, and climate change on global agriculture. ASA Special Publication no. 53, American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, Madison, p 111–130

Goudriaan J, Van Laar HH (1978) Calculation of daily totals of the gross CO_2 assimilation of leaf canopies. Neth J Agric Sci 26:373–382

Groot JJR (1987) Simulation of nitrogen balance in a system of winter wheat and soil. Simulation Reports CABO-TT no. 13, DLO Research Institute for Agrobiology and Soil Fertility and Department of Theoretical Production Ecology, Wageningen Agricultural University

Groot JJR (1993) NWHEAT: nitrogen balance in a system of winter wheat and soil. In: Engel T, Klöcking B, Priesack E, Schaaf T (eds) Simulationsmodelle zur Stickstoffdynamik, Analyse und Vergleich. Agrarinformatik, Band 25. Ulmer, Stuttgart, p 397–411

Groot JJR, De Willigen P (1991) Simulation of the nitrogen balance in the soil and a winter wheat crop. Fertil Res 27: 261–272

Groot JJR, Spiertz JHJ (1991) The role of nitrogen in yield formation and achievement of quality standards in cereals. In: Porter JR, Lawlor DW (eds) Plant growth: interactions with nutrition and environment. Society for experimental biology seminar series, Cambridge University Press, Cambridge, p 227–247

Harnos, Z, Bussay A, Harnos N (2000) Modelling climate change impacts on wheat and potato in Hungary. In: Downing TE, Harrison PA, Butterfield RE, Lonsdale KG (eds) Climate change, climatic variability and agriculture in Europe: an integrated assessment. Research report no. 21, Environmental Change Institute, University of Oxford, p 349–364

Harrison PA, Butterfield RE, Orr JL (2000) Modelling climate change impacts on wheat, potato and grapevine in Europe. In: Downing TE, Harrison PA, Butterfield RE, Lonsdale KG (eds) Climate change, climatic variability and agriculture in Europe: an integrated assessment. Research report no. 21. Environmental Change Institute, University of Oxford, p 367–390

Kabat P, Marshall B, Van den Broek BJ (1995) Comparison of simulation results and evaluation of parameterization schemes. In: Kabat P, Marshall B, Van den Broek BJ, Vos J, Van Keulen H (eds) Modelling and parameterization of the soil-plant-atmosphere system. A comparison of potato growth models. Wageningen Press, Wageningen, p 439–501

King D, Le Bas C, Daroussin J, Thomasson AJ, Jones RJA (1995) The EU map of soil water available for plants. In: King D, Jones RJA, Thomasson AJ (eds) European land information systems for agro-environmental monitoring, EUR 16232, Agriculture series, European Commission, Luxembourg, p 131–141

Kooman PL (1995) Yielding ability of potato crops as influenced by temperature and daylength. PhD thesis, Wageningen Agricultural University

Kooman PL, Spitters CJT (1995) Coherent set of models to simulate potato growth. In: Kabat P, Marshall B, Van den Broek BJ, Vos J, Van Keulen H (eds) Modelling and parameterization of the soil-plant-atmosphere system. A comparison of potato growth models. Wageningen Press, Wageningen, p 253–274

Landau S, Mitchell RAC, Barnett V, Colls JJ, Craigon J, Moore KL, Payne RW (1998) Testing winter wheat simulation models' predictions against observed UK grain yields. Agric For Meteorol 89:85–99

Mearns LO (2000) Climatic change and variability. In: Reddy KR, Hodges HF (eds) Climate change and global crop productivity. CABI Publishing, Wallingford, p 7–35

Miglietta F, Magliulo V, Bindi M, Cerio L, Vaccari FP, Loduca V, Peressotti A (1998) Free air CO_2 enrichment of potato (solanum tuberosum L.): development, growth and yield. Global Change Biol 4:163–172

Morison JIL (1993) Response of plants to CO_2 under water limited conditions. Vegetatio 104/105:193–209

Nonhebel S (1994) The effects of use of average instead of daily weather data in crop growth simulation models. Agric Syst 44:377–396

Nonhebel S (1996) Effects of temperature rise and increase in CO_2 concentration on simulated wheat yields in Europe. Clim Change 34:73–90

Olesen JE, Jensen T, Bøcher PK (2000) Modelling climate change impacts on wheat and potato in Denmark. In: Downing TE, Harrison PA, Butterfield RE, Lonsdale KG (eds) Climate change, climatic variability and agriculture in Europe: an integrated assessment. Research report no. 21, Environmental Change Institute, University of Oxford, p 313–332

Peiris DR, Crawford JW, Grashoff C, Jefferies RA, Porter JR, Marshall B (1996) A simulation study of crop growth and development under climate change. Agric For Meteorol 79:271–287

Penning de Vries FWT (1975) The cost of maintenance processes in plant cells. Ann Bot 39:77–92

Ritchie JT (1972) Model for predicting evaporation from a row crop with incomplete cover. Water Resour Res 8: 1204–1212

Rosenzweig C, Phillips J, Goldberg R, Carroll J, Hodges T (1996) Potential impacts of climate change on citrus and potato production in the US. Agric Syst 52:455–479

Sage RF, Sharkey TD, Seemann JR (1989) Acclimation of photosynthesis to elevated CO_2 in five C3 species. Plant Physiol 89:590–596

Schapendonk AHCM, Van Oijen M, Dijkstra P, Pot CS, Jordi WJRM, Stoopen GM (2000) Effects of elevated CO_2 concentration on photosynthetic acclimation and productivity of two potato cultivars grown in open-top chambers. Aust J Plant Physiol 27:1119–1130

Semenov MA, Porter JR (1995) Climatic variability and the modelling of crop yields. Agric For Meteorol 73:265–283

Semenov MA, Wolf J, Evans LG, Eckersten H, Iglesias A (1996) Comparison of wheat simulation models. II. Application of climate change scenarios. Clim Res 7: 271–281

Sinclair TR, Rawlins SL (1993) Inter-seasonal variation in soybean and maize yields under global environmental change. Agron J 85:406–409

Smith M (1992) Report of expert consultation on revision of FAO methodologies for crop water requirements. FAO, Land and Water Development Division, Rome

Spitters CJT (1987) An analysis of variation in yield among potato cultivars in terms of light absorption, light utilization and dry matter partitioning. Acta Horticult 214: 71–84

Spitters CJT (1990) Crop growth models: their usefulness and limitations. Acta Horticult 267:349–368

Spitters CJT, Van Keulen H, Van Kraalingen DWG (1989) A simple and universal growth simulator: SUCROS87. In: Rabbinge R, Ward SA,Van Laar HH (eds) Simulation and systems management in crop production. Simulation Monographs, Pudoc, Wageningen, p 147–181

Supit I, Hooijer AA, Van Diepen CA (eds) (1994) System description of the WOFOST 6.0 crop simulation model implemented in CGMS, Vol 1: Theory and algorithms. Joint Research Centre of the European Commission, EUR 15956, European Commission, Luxembourg

Van de Geijn SC, Dijkstra P (1995) Physiological effects of changes in atmospheric carbon dioxide concentration and temperature on growth and water relations of crop plants. In: Haverkort AJ, MacKerron DKL (eds) Potato ecology and modelling of crops under conditions limiting growth. Current issues in production ecology, Vol 3. Kluwer Academic Publishers, Dordrecht, p 89–99

Van Keulen H (1975) Simulation of water use and herbage growth in arid regions. Simulation Monographs, Pudoc, Wageningen

Van Keulen H, Seligman NG (1987) Simulation of water use, nitrogen nutrition and growth of a spring wheat crop. Simulation Monographs, Pudoc, Wageningen

Van Laar HH, Goudriaan J, Van Keulen H (eds) (1997) SUCROS97: Simulation of crop growth for potential and water-limited production situations as applied to spring wheat. Quantitative approaches in systems analysis No. 14, AB-DLO Research Institute & Graduate School for Production Ecology, Wageningen

Wheeler RM, Tibbitts TW, Fitzpatrick AH (1991) Carbon dioxide effects on potato growth under different photoperiods and irradiance. Crop Sci 31:1209–1213

Wilks DS (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

Wolf J (1993) Effects of climate change on wheat production potential in the European Community. Eur J Agron 2: 281–292

Wolf J (2000a) Modelling climate change impacts at the site scale on potato. In: Downing TE, Harrison PA, Butterfield RE, Lonsdale KG (eds) Climate change, climatic variability and agriculture in Europe: an integrated assessment. Research report no. 21, Environmental Change Institute, University of Oxford, p 135–154

Wolf J (2000b) Modelling climate change impacts on potato in central England. In: Downing TE, Harrison PA, Butterfield RE, Lonsdale KG (eds) Climate change, climatic variability and agriculture in Europe: an integrated assessment. Research report no. 21, Environmental Change Institute, University of Oxford, p 239–261

Wolf J (2000c) Analysis of the responses of potato cv. Bintje to elevated CO_2 and O_3 and assessment of future potato yields in Europe. In: De Temmerman L, Vandermeiren K, Hacour A (eds) Final report of EU-project CHIP (Changing climate and potential impacts on potato yield and quality). Veterinary and Agrochemical Research Centre, Tervuren, p 221–271

Wolf J (2002) Comparison of two potato simulation models under climate change. II. Application of climate change scenarios. Clim Res 21:187–198

Wolf J, Van Diepen CA (1994) Effects of climate change on silage maize production potential in the European Community. Agric For Meteorol 71:33–60

Wolf J, Van Diepen CA (1995) Effects of climate change on grain maize yield potential in the European Community. Clim Change 29:299–331

Editorial responsibility: Gerd Esser,
Gießen, Germany

Submitted: June 11, 2001; Accepted: October 18, 2001
Proofs received from author(s): May 17, 2002