The importance of weather data in crop growth simulation models and assessment of climatic change effects

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The importance of weather data in crop growth simulation models and assessment of climatic change effects

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Stellingen

1. Normaal weer bestaat inderdaad niet.
   Dit proefschrift

2. Data sets met weersgegevens over een groot aantal jaren dienen te zijn voorzien van een korte geschiedenis van het weerstation.

3. Automatische weerstations zijn niet nuttig.

4. In alle data sets met weersgegevens zitten storende fouten.

5. Veranderingen in het neerslagpatroon als gevolg van een klimaatverandering hebben een grotere invloed op de landbouwproduktie dan veranderingen in de luchttemperatuur.
   Dit proefschrift

6. Bij het gebruik van gewasgroei-simulatiemodellen in land-evaluatiestudies dient men zich te realiseren, dat een niet bestaande situatie gesimuleerd wordt. De simulatie-resultaten kunnen daarom niet worden vergeleken met waargenomen opbrengsten.

7. 'Carpoolen' bevordert de verkeersveiligheid.

8. Aangezien het niet op prijs wordt gesteld dat een promovendus (m/v) haar tijd besteedt aan andere zaken dan haar onderzoek, is het niet juist dat tenminste 6 'niet op het onderwerp van het proefschrift betrekking hebbende' stellingen een vereiste zijn om te promoveren.

9. Het getuigt van slecht personeelsbeleid, dat het overgrote deel van de tweede en derde geldstroom van universiteiten en onderzoeksinstellingen wordt gebruikt om AIO en OIO plaatsen te creëren.

10. Ook universiteiten en onderzoeksinstellingen hebben een hele trukendoos ontwikkeld, waarmee oneigenlijk gebruik gemaakt wordt van de sociale voorzieningen.

11. Als banken hun werkzaamheden zouden verrichten met een nauwkeurigheid die vergelijkbaar is met de nauwkeurigheid waarmee ze de luchttemperatuur op hun gebouwen weergeven, was er in Nederland nog op grote schaal sprake van ruilhandel.

Stellingen behorend bij het proefschrift van Sanderine Nonhebel:
'The importance of weather data in crop growth simulation models and the assessment of climatic change effects'.

Wageningen 12 Mei 1993.

Abstract

Yields of agricultural crops are largely determined by the weather conditions during the growing season. Weather data are therefore important input variables for crop growth simulation models. In practice, these data are accepted at their face value. This is not realistic. Like all measured values, are weather data subject to inaccuracies. Crop growth simulation models are sensitive to weather data used as input, so inaccuracies in weather data can affect the simulation results. The errors in weather data were estimated and their effects on the simulation results of a spring wheat crop growth simulation model were determined. Inaccuracies in weather data caused deviations in simulated yields of 10-15 %.

In most weather data sets missing values occur and since crop growth models require daily data the values of the missing data have to be estimated. Several methods to estimate missing values were discussed and their effects on simulation results were studied. Large differences in quality of the estimation methods were found. Some of them resulted in deviations in simulated yields up to 30 %.

Daily weather data are not always available and often average weather data are used instead. The effects of using average weather data on simulation results were studied for three sites in different climates. For all sites large deviations in simulation results were found.

The increasing CO_2 concentration is affecting agricultural production in two ways: via a climatic change and via effects on assimilation and transpiration rates. The spring wheat model was used to study the overall effects of higher CO_2 levels on wheat yields in Western Europe. A temperature rise of 3 °C resulted in a yield decline, doubled CO_2 concentration in a yield increase and the combination of both in a yield increase of about 2 ton ha^{-1}.

Keywords: wheat, crop growth simulation model, weather data, climatic data, climatic change, CO_2 concentration, greenhouse effect.

aan mijn ouders

'Een verstandig meisje trouwt niet met een genie, maar wordt er zelf een.'

Mevrouw Meermin
in: Vóór alles een dame (Renate Dorrestein, 1989).

Dankwoord

In oktober 1987 trad ik in dienst bij de vakgroep Theoretische Produktie Ecologie (TPE) als toegevoegd onderzoeker. Het project waarvoor ik aangesteld werd: 'Klimaatverandering en primaire produktie in Europa', werd gefinancierd door het ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieu (VROM). Eén van de onderdelen van het project was het organiseren van een workshop over de invloed van het broeikaseffect op de landbouwproduktie in West-Europa en het maken van de 'proceedings' van deze workshop. Een groot gedeelte van deze taken is door anderen van mij overgenomen, waardoor ik meer tijd aan het onderzoek kon besteden. Toen het VROM project was afgelopen, heb ik mijn onderzoek kunnen voortzetten als onderdeel van het door de EG gefinancierde project: 'Impacts of increasing CO_2 and climatic change on European agriculture'. Hierdoor was het voor mij mogelijk om genoeg materiaal te verzamelen voor het schrijven van een proefschrift. Nadat mijn aanstelling afgelopen was, heb ik als gastmedewerker gebruik mogen blijven maken van de faciliteiten van de vakgroep en was ik instaat dit proefschrift af te ronden. Ik ben erg dankbaar voor alle moeite die gedaan is, om mij instaat te stellen dit proefschrift te schrijven.

De aanstichter van dit alles is Kees de Wit die in 1988 zei: 'Als je hier toch al die tijd rond loopt, kun je net zo goed proberen er een promotie uit te slepen'. Mijn promotoren Kees de Wit en Jan Goudriaan hebben het leeuwendeel van de begeleiding voor hun rekening genomen. Zonder hen was dit boekje er waarschijnlijk niet gekomen en ik wil hen graag bedanken voor hun inspirerende en enthousiaste begeleiding en hun geduld.
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Gon van Laar, Herman van Keulen en Jan Goudriaan hebben destijds de organisatie van de workshop van me overgenomen en de proceedings samengesteld.
In een latere fase van het onderzoek heeft veel overleg plaats gevonden in het 'promotie team' van Kees de Wit bestaande uit: Martin Kropff, Daniël van Kraalingen, Kees Rappoldt, Gerrie van de Ven, Niek van Duivenbooden en Radha Raganathan. Deze bijeenkomsten waren bijzonder waardevol.
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Mijn ouders en mijn vrienden (m/v) wil ik graag bedanken voor hun belangstelling en Peter voor z'n steun 'vanaf de bank'.

Contents

Account

Except the General introduction, the chapters in this thesis have been written in the form of journal papers. They have been submitted to various journals

Chapter 2	Nonhebel, S. Inaccuracies in weather data and their effects on crop growth simulation results: I Air temperature. Submitted to Climate Research.
Chapter 3	Nonhebel, S. Inaccuracies in weather data and their effects on crop growth simulation results: II Global radiation. Submitted to Climate Research.
Chapter 4	Nonhebel, S. Inaccuracies in weather data and their effects on crop growth simulation results: III Water-limited production. Submitted to Climate Research.
Chapter 5	Nonhebel, S. The effects of use of average instead of daily weather data in crop growth simulation models. Accepted by Agricultural Systems.
Chapter 6	Nonhebel, S. Effects of changes in temperature and CO_2 concentration on simulated spring wheat yields in The Netherlands. Submitted to Climatic Change.
Chapter 7	Nonhebel, S. Effects of temperature rise and increase in CO_2 concentration on simulated wheat yields in Europe. Submitted to Climatic Change.

Chapter 1

General Introduction

Weather, as we observe it, is the situation of the lower part of the atmosphere. This situation can not be measured as a whole. The only way to quantify weather is to measure individual weather elements like air temperature or precipitation. Weather conditions have a large effect on society, but not all elements are of the same importance to various sections of the population. Sailors and fishermen are mainly interested in the wind speed and its direction, car drivers in the occurrence of frost and fog and ice cream sellers in air temperature and sunshine duration. Whether a weather element is recorded or not is determined by the interest of the person or institute carrying out (or paying for) the measurements and the availability of an instrument to do so.
Most instruments to measure weather elements were invented in the 17th and 18th centuries. The first practical thermometer was developed in 1641 and the first barometer in 1643 (Können 1983). However, an instrument to record global radiation was only developed in the nineteen twenties (Gulik 1927). In The Netherlands the first systematical measurements of air temperature were started in 1705. In England air temperature data were recorded as early as 1659. The oldest Dutch precipitation data go back to 1735 (Können 1983). In most countries, however, the systematical recordings of weather variables were only started in the beginning of the twentieth century.

An enormous variation in weather exists in space and time. Air temperature, for instance, declines with increasing height whereas wind speed increases. Further most elements show a course over the day and over the year. Hence, when weather data from various sites are to be compared, it is essential that these data are recorded according to a certain standard. One of the purposes of the World Meteorological Organization (WMO) is 'to promote the standardization of meteorological observations and to ensure the uniform publication of observations and statistics' (WMO 1983). The WMO formulates basic standards of instruments and observing practices. For instance, air temperature must be measured between 1.25 and 2.0 m height and the thermometer must be sheltered from radiation. Wind speed must be recorded at a height of 10 m.
This standardization also includes which variables are to be measured. Standard are air temperature (dry- and wet-bulb, maximum and minimum) and precipitation. The range can be extended with other elements, depending on the interest of the recording institute.
Information on the weather conditions improves when values of more elements are available. A maximum air temperature of 25 °C only indicates a warm day.

An air temperature of 25 °C in combination with high radiation and low relative humidity can be a nice sunny day. However, 25 °C in combination with low radiation levels and high relative humidity indicates to an oppressive unpleasant day.
An increase in the number of recordings per day also improves the description of weather conditions. A day with one shower of 10 mm in the evening is quite different from a day with 10 mm precipitation as permanent drizzle. Therefore at some meteorological stations weather data are recorded on an hourly (or even shorter) basis. The amount of data produced by these stations is huge. Daily data of the most frequently measured elements (minimum temperature, maximum temperature, sunshine hours, precipitation, relative humidity and wind speed) represent over 2000 data a year. When these variables are measured hourly it results in over 50000 data a year. One can imagine, that for most users, the logistical problems involved with handling such quantities of data do not counterbalance the benefits of a more detailed description of the weather situation.
It should be realized that weather data, even hourly data, do not give an exact description of the weather conditions. They only represent the values recorded by instruments on a moment at a particular site. The air temperature, measured at 1.25 m, gives not much information on temperature regime at soil surface. Ground frost, which can be an important weather phenomenon (frozen roads), is not recorded by this method.

Agricultural yields are strongly affected by the prevailing weather conditions during the growing season of the crop. Much research has been done on the effects of weather conditions on crop growth and yield. Up to 1960 it was tried to estimate yields from weather conditions by using statistical methods: e.g. average air temperature and precipitation in various months were related to the final yield. Woudenberg & Poelstra (1957) found the following relation between weather and spring wheat yield (Y, in quintals (= 100 kg ha^{-1}) in the northern part of The Netherlands:

$$Y = 24.81 - 0.06\ P_2 + 0.16\ S_5 - 0.02\ P_{5,II\text{-}III} \qquad (1.1)$$

in which P_2 is the total amount of precipitation in February (mm), S_5 is total sunshine hours in May (percentage of the maximum duration) and $P_{5,II,III}$ is total precipitation in the last twenty days of May (mm). It is striking that precipitation has a negative effect on crop yield in this relation. Woudenberg & Poelstra (1957) concluded that the forecasting quality of this relation was very poor. Comparable relations are derived for other crops in other climates by other research groups. In general, they arrive at similar conclusions.
Only when a crop is very susceptible to the occurrence of one element during a certain growth stage a relation can be found. For instance, the occurrence of

frost during flowering of fruit trees, when this happens the final fruit yields will certainly be very small.
Several explanations can be given why it is impossible to find a relation between, for instance, average air temperature in June and the final yield. In practice crop yield is not only determined by weather conditions. Effects as nutrient shortage, pests and diseases etc. can have a far larger effect on crop yield. Further, the yield of a crop is the result of all the weather conditions during its growth. Effects of a hot summer after a cold spring can be different from the effects of a hot summer after a warm spring. Another point is that weather elements are correlated: e.g. high temperatures occur often in combination with high radiation levels. This makes it impossible to determine whether the observed effect is caused by one variable or the other. Finally, crops grow under real weather conditions, which imply large variations from day to day. Therefore, monthly averages of weather variables do not give an appropriate description of the growing conditions of a crop. The effects of weather on crops must be studied on a far smaller time scale than of one month. The change from a monthly to a daily time scale leads to a 30-fold increase in the number of weather data required. The introduction of the computer in the early sixties made handling of these large amounts of data possible.

In the last decades, models have been developed in which crop growth is simulated in relation to observed weather conditions. These models integrate knowledge of the most important effects of weather on individual crop growth processes (e.g. global radiation on photosynthesis, air temperature on development). With these models it is possible to study the overall effect of weather on crop yield.
The final yield of a crop is determined by many factors: weather, crop variety, fertilizer supply, soil conditions, occurrence of pests and diseases etc. It is impossible to quantify all these effects on yield and, for most purposes, it is not necessary. In crop model research several production levels are therefore distinguished (de Wit & Penning de Vries 1982). In the potential production situation, the crop is optimally supplied with water and nutrients and free from pests, diseases and weeds. Crop growth is only determined by crop characteristics, temperature and radiation. In the water-limited situation, nutrients are in optimal supply and the crop is free of pests, diseases and weeds but yield is limited by the availability of water. In following production levels the effects of nutrient shortages are taken into account. Finally yield-reducing factors such as pests, diseases and weeds are distinguished (Rabbinge & de Wit 1989). Production under water-limited conditions can be influenced by irrigation. Production under nutrient limitation is affected by application of fertilizers. With use of pesticides, fungicides and herbicides the effect of pests and diseases and weeds on crop yields can be reduced.

The effect of certain weather conditions on crop production is different in various production levels. A dry summer can imply good growing conditions for a crop which is optimally supplied with water, but for a crop suffering from water shortage a dry summer can be disastrous. A humid rainy season can be beneficial for a crop previously affected by water shortage but the humidity will also favour the occurrence of some fungal pathogens in the crop.

Use of crop growth simulation models is increasing. They are used for various purposes from a tool to understand the observed phenomena in a field experiment to a method to quantify growing conditions in survey studies (Penning de Vries et al. 1989). Most crop growth models operate with a time interval of one day and require daily weather data as input (Whisler et al. 1986). Models are sensitive to these input data since weather data describe the conditions under which growth takes place. Other weather data (other site or other season) lead to other simulation results.
Weather data used as input for crop growth models are often accepted at their face value. Most users of weather data have never even visited a meteorological site and have no idea how meteorological data are obtained and what inaccuracies are involved. Storing of meteorological data in convenient data bases (which often also generate values for missing data) ensures that most users never see the original data with its unrealistic or missing values, so no feeling for quality of the data is developed. Weather data, however, are not error free nor do they give a precise description of the real weather conditions.

In this thesis the use of weather data in crop growth simulation models is studied. The inaccuracy in weather data is estimated and the effect of this inaccuracy on simulation results is determined. Various methods to estimate missing values are compared. Finally the effects of CO_2 induced climatic change on crop production in Europe are investigated.
The chapters in this thesis are written in the form of articles. They are, however, not in their sequence of publication as scientific papers. Hence earlier chapters refer to later ones.
This study was started as a project on the effects of climatic change and higher atmospheric CO_2 concentrations on crop yields in Europe. The effects of climatic change on yields can not be studied in a field experiment because it is impossible to change the weather conditions. Crop growth models simulate crop growth in relation to weather conditions and can be a useful tool in this type of research. Through changing the input variables (weather data!) in accordance with the expected climatic change the effect on final yield can be observed. This subject is discussed in chapters 6 and 7 for spring wheat. In chapter 6 the spring wheat crop growth model is described and it is validated for conditions in The Netherlands. Also effects of higher CO_2 concentration and

temperature rise individually and in combination are studied. For validation of the model comparison was made between observed and simulated yields over a large number of years. No weather data from the field experiments were available; and weather data from a distant meteorological station had to be used as input for the model. To be able to draw conclusions on the capacity of the model to simulate observed yields, it was important to know whether the deviation between simulated and observed yields was caused by improper weather data or by incorrect simulation of crop growth.

For all weather elements required as input in the model (described in chapter 6, *)) the inaccuracy is estimated on the basis of literature and the effect of this inaccuracy on the simulation results is studied. This is done for air temperature data and the effect for the simulated potential production in chapter 2 and for global radiation data for the simulated potential production in chapter 3. In chapter 4 the effect of inaccuracies in air temperature, global radiation, precipitation, vapour pressure and wind speed data on the water-limited production is studied.

In chapter 7 the effect of climatic change on spring wheat yields in different regions in Europe is investigated. For this study daily weather data from several sites in Europe over a large number of years (20-30) were required. The data used were obtained from a data bank. In the data sets many data were missing. Because the model needed daily data, a proper method to estimate missing values was required.

Accordingly several methods for estimating missing values are compared in chapters 2, 3 and 4. It is likely that the quality of an estimation method depends on the climate. When temperature is constant, use of temperature of the previous day is a good method to estimate missing temperature data. However, when large variability from day to day exists this method is not useful. Therefore, in chapter 5 the effect of a frequently used estimation method (use of average values) is studied for three different climates: the temperate maritime climate of The Netherlands, the mediterranean of Israel and the humid tropical of the Philippines. The knowledge obtained in these chapters is used in chapter 7 to repair the damaged weather data sets.

*) The complete listing of the simulation model can be requested at: Department of Theoretical Production Ecology, P.O. box 430, 6700 AK Wageningen, The Netherlands.

Chapter 2

Inaccuracies in weather data and their effects on crop growth simulation results: I Air temperature

Abstract In weather data sets used by crop modellers irregularities occur as inaccuracies in data or as missing values. The effect of these irregularities on simulation results is studied for a spring wheat crop growth simulation model. This chapter is focussed on air temperature data; the effects of irregularities in other weather variables on simulation results are discussed in chapter 3 and 4. The inaccuracy in temperature data was estimated on the basis of literature and was about: 1 °C. A systematic under or overestimation of temperature data by 1 °C resulted in deviations in simulated yields of 7 %. Four methods to estimate missing values were compared: use of average values over 30 years, over one month and over 10 days and use of daily data from another meteorological station. When all daily data were replaced by estimates, data from a nearby station gave the best results: only a small deviation in simulated yield was found. The use of averages resulted in overestimations of the yield up to 35 % in some years. When, instead of all, only 10 % of the daily values were replaced randomly by estimates no effects on simulation results were found.

Introduction

Crop growth and yield are largely determined by the weather conditions during the growing season. In crop growth simulation models most important relations between weather and crop growth are therefore quantified and weather data are important input values for these models. Crop growth models differ in their input requirements. Most of them require data on (air) temperature, radiation and precipitation on a daily or hourly basis, while others also require data on wind speed and vapour pressure (Whisler et al. 1986). The number of sites from which hourly weather data can be obtained is very limited, so that application possibilities of models on a hourly basis are quite restricted. Daily weather data can be obtained from nearly all meteorological stations and thus crop growth models requiring daily data as input are used more frequently.

In modelling practice weather data are obtained from databases and these data are accepted on their face value. This is not realistic. Like all measured values, weather data are subject to inaccuracies and since models are sensitive to weather data used as input, inaccuracies in weather data can affect the simulation results. The quality of crop growth models has improved over the last decades and some models are well able to simulate the production observed in the field. In this stage of crop model development it is important to know whether the difference between the observed and simulated growth can be caused by the errors in weather data or is due to incorrect simulation of crop growth. In this study frequently occurring irregularities in weather data sets are therefore discussed and their effects on simulation results are investigated.

Several sources of irregularities in weather data can be distinguished. In the first place, there is the deviation in measured value due to inaccuracy of the instrument. Another problem is the occurrence of missing values in data sets. Due to break down of instruments or to problems with the data collecting computer, the value of a weather variable is not recorded for a couple of days. In the worst case there are no data available at all. Crop growth models require data for every day, so the values of the missing data have to be estimated. Depending on the method used, the estimated value can deviate considerably from the original one. A third source of errors is the fact that meteorological data are recorded at a limited number of sites. In general the field experiment is not located in the immediate surroundings of the site where meteorological data are recorded. The distance between the two sites may mean that weather conditions are not the same.
The magnitude of the deviation between the recorded value on the meteorological site and the one occurring on the field experiment is estimated on the basis of literature and various estimation methods are compared. The effects of these inaccuracies in weather data and estimation methods are studied for simulation results of a spring wheat crop growth model. The model simulates potential and water-limited production. In the former the production is determined by crop characteristics, radiation and temperature and in the latter also by limited availability of water. In both production levels the crop is supposed to be free from pests, diseases and weeds and is optimally supplied with nutrients (de Wit & Penning de Vries 1982). The model is well able to simulate production obtained in the field (for validation see chapter 6).
This chapter focuses on the errors in temperature data and the effect on potential production. Chapter 3 will discuss the effects of errors in radiation data on potential production and chapter 4 the effects of errors in weather data on water-limited production.

Material and methods

Simulation model

A spring wheat version of the SUCROS87 (Simple and Universal CROp growth Simulator, version 1987) Spitters et al. (1989) was used. The core of this model is formed by the calculation procedure for canopy photosynthesis and respiration on the basis of processes at organ level. The model operates with time intervals of one day, but allows for the diurnal course of the radiation. The allocation of dry matter production among the different plant organs depends on

the stage of development of the plant. Numerical integration over time gives the time course of dry matter. SUCROS requires daily weather data on minimum air temperature, maximum air temperature and global radiation for simulation of potential crop production.
This spring wheat version of SUCROS simulates crop growth and development from sowing to maturing of the crop. Development of the crop is mainly driven by temperature: development from sowing to emergence according to Porter (1987), emergence to heading according to Miglietta (1991) and heading to maturing according to van Keulen & Seligman (1987). Dry matter distribution is simulated according to van Keulen & Seligman (1987). Sowing date of the crop was set on March 11th and a variety adapted to the Dutch circumstances was used.
Crop production during grain filling period is sink limited, which implies that weather conditions during this period hardly effect final yield (grains!). The size of the sink (the number of grains) is determined during vegetative period of the crop (Spiertz & van Keulen 1980) and conditions during this part of the growing season have a large effect on final yield. For a high final yield a long vegetative period under high radiation levels is required. Therefore much attention is paid to the effects of inaccuracies in weather data on the growing conditions during the vegetative period of the crop.
Air temperature influences a number of processes in the simulation model. Most important is the development rate of the crop, through which temperature determines duration and timing of the growing season. Temperature also affects assimilation rate, death rate of the leaves and maintenance respiration. In general the relation between temperature and the rates mentioned above is not linear.

Meteorological data

The starting point of this study was a data set with daily weather data from Wageningen, The Netherlands (figure 2.1) from 1954 till 1987. The set contains daily values for minimum air temperature (°C), maximum air temperature (°C), total global radiation (J m^{-2} d^{-1}), total precipitation (mm), vapour pressure at 9.00 am (mb) and average wind speed (m s^{-1}). The data were collected at the meteorological station Haarweg of the Wageningen Agricultural University, the station is a climatological station of the Royal Netherlands Meteorological Institute (KNMI).
The difference that could exist between the recorded value at the meteorological station and the value occurring in a nearby field experiment was estimated for all variables. Only differences that could be expected when measurements were taken according to the regulations of the World Meteorological Organization were considered (WMO 1983). The very large

errors as a result of insufficient maintenance or improper exposition of the instrumentation were not taken into account. The effect of the inaccuracy for the simulation result was determined by making three simulation runs with the model. One with the original data set, one with the data set in which variable under interest was diminished by its inaccuracy and one in which this variable was increased with its inaccuracy. All other elements were kept unchanged.

Figure 2.1 Location of the sites mentioned in the text. 1: Wageningen, 2: de Bilt and 3: de Kooy.

Inaccuracies in air temperature

The temperature of a system is seldom measured directly. In general a thermometer is added to the system and when the new system has reached an equilibrium the temperature of the thermometer is recorded (Bell & Rose 1985). Several instruments and techniques exist to determine temperature of a system. The accuracy of the instruments varies from 0.001-1.0 K (for detailed information on techniques and instruments see Fritschen & Gay (1979) and Bell & Rose (1985)). Due to the poor coupling between atmosphere and thermometer it is difficult to achieve an equilibrium situation between thermometer and surrounding air and errors associated with thermometer exposure can be of order of magnitude greater than the calibration errors of the

instruments (Bell & Rose 1985). Radiation in particular can cause large differences between thermometer temperature and air temperature. A thermometer in full sun can reach a 25 °C higher temperature than the surrounding air (WMO 1983). For this reason air temperature is measured in thermometer screens. The design of the screen affects the temperature measured and differences of 1 °C are found between various screen types (Sparks 1972).
Temperature is not distributed homogeneously over an air mass. Air temperature is affected by soil type, ground cover, the existence of water surfaces, etc. Differences in air temperature of several °C are observed over distances of less than one kilometer (Können 1983).
So it is rather likely that air temperature above the field experiment deviates 1 °C or more from the value measured above the grass surface of the meteorological station. The effect of an inaccuracy of 1 °C in temperature data on simulation results was studied through increasing or diminishing both maximum and minimum air temperatures by 1 °C.

Estimation of missing values

Four methods were considered for estimating missing values: use of (1) averaged monthly values over 30 years (climatic averages), these data, only 12 values per weather variable, are rather easy to obtain, (2) monthly averages, which are published in most monthly reports of national meteorological organizations, (3) average values over 10 days, also published in the monthly reports and (4) daily data from another meteorological station. Simulation runs were made in which all daily values of the variable of interest were replaced by estimated values.

In this study the average values were not obtained from literature, but were derived from the data set with daily data. The average values were used as follows: the average value per month for each element was calculated from the original weather data set. It was assumed that these average values occurred at the 15th of every month and that on the days in between the value for the element could be derived by linear interpolation. The same method was applied for averages over 10 days, but then the average values were expected to occur at the fifth day of the interval. Climatic averages were derived by using the monthly averages of 1954-1983. Use of averages over 30 years implied that in all years the variable of interest was the same, the years varied only with respect to the values of the other weather variables.

The effect of using another meteorological station as the source of weather variables was investigated by replacing data from Wageningen by data from de

Bilt (figure 2.1). De Bilt is a synoptical station of the Royal Netherlands Meteorological Institute. The distance between Wageningen and de Bilt is only 40 km and both sites are located in the same climatic district, so it can be expected that weather on both sites is more or less the same. Daily weather data from de Bilt were available from 1961 till 1987.
The effect of the use of data from a station in another climatological district was studied by using weather data from de Kooy (figure 2.1). De Kooy is also a synoptical station of the KNMI and is located in the north western part of the country, very close to the North Sea. The weather in this region is strongly influenced by the sea, resulting in, for instance, higher radiation levels and lower temperatures in spring and higher temperatures in autumn (Können 1983). Weather data from de Kooy were available from 1976 till 1985.
Finally the effects of only a few missing values on simulation results were also studied. With the use of a random number generator 10 % of the daily values during the growing period of the crop were replaced by climatic averages.

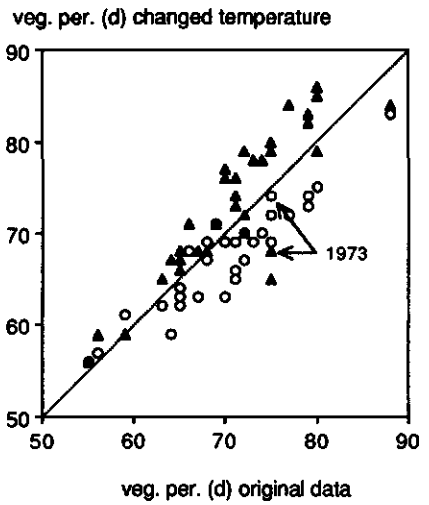


Figure 2.2 Comparison between duration of the vegetative period simulated with the original data set (Wageningen 1954-1987) and duration of this period when temperature in this data set was underestimated by 1 °C (▲) or overestimated by 1 °C (○).

Results and discussion

The effect of 1 °C deviation in temperature on simulated duration of the vegetative period (number of days between crop emergence and flowering) is shown in figure 2.2. Changes up to 10 days were found in duration of this period. In most years overestimation of temperature led to a shorter vegetative period and an underestimation to a longer one. However, in a quarter of the years the opposite effect was found. In 1973 both over and underestimation of temperature led to a shorter vegetative period. This indicates that duration of the vegetative period is not linearly related to temperature.

To achieve a better insight in the effect of changes in temperature on duration of the vegetative period, simulation runs were made in which temperature was increased in increments of 0.2 °C from –6 °C to + 6 °C. So in the first run all daily minimum and maximum temperatures were diminished by 6 °C, in the second run by 5.8 °C etc. This was done with daily data from 1973 and with the climatic averages. Large differences in the effect of deviations in temperature between average and daily weather were found (figure 2.3). In the simulation runs with climatic data overestimation of temperature resulted in a decline in duration of the vegetative period, underestimation up to 2 °C in an increase and a larger underestimation had no effect on the duration anymore. With the 1973 data, however, an underestimation of 1 °C in temperature resulted in a sharp decline in the duration of the vegetative period.

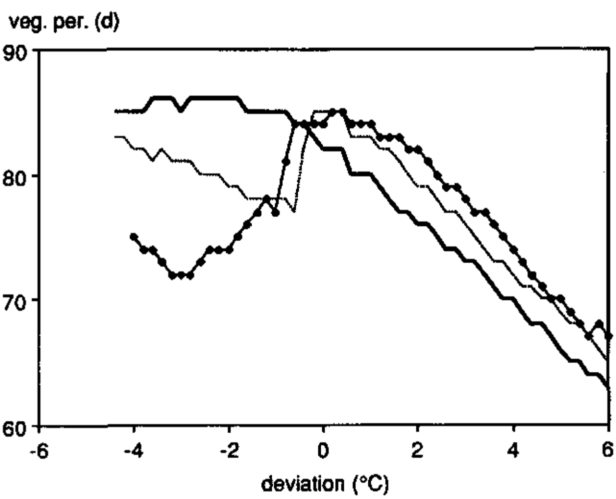


Figure 2.3 The effect of a deviation in temperature up to 6 °C on simulated duration of the vegetative period when climatic averages (——), daily weather data from 1973 (•–•–•) and adjusted climatic averages (see text) (·······) were used as input data.

The effect of a deviation of 1 °C on simulated yield (grains, dry matter) is shown in figure 2.4, changes in yield of 10 % were found. In about half of the years underestimation of temperature resulted in underestimation of the yield and in the other half in overestimation of the yield. In 1982 both over and underestimation of temperature resulted in an increase in simulated yield. The effect of an increase in temperature from –6 °C to +6 °C on simulated yield with daily data from 1983 and with the climatic data is shown in figure 2.5.

Completely different effects were found when climatic averages or daily data were used. With climatic data overestimation of temperature led to a decline in yield, a small underestimation of 1 °C led to an increase and a larger underestimation resulted in a decrease in yield. With daily weather data of 1982, over as well as underestimation of temperature by 2 °C resulted in a yield increase, larger over or underestimation had only a small effect on simulated yield.

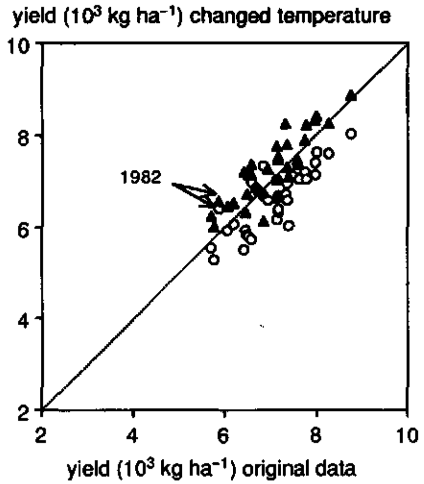


Figure 2.4 Comparison between simulated yield with the original data set (Wageningen 1954-1987) and simulated yield when temperature in this data set was underestimated by 1 °C (▲) or overestimated by 1 °C (o).

The average air temperature based on averages over 30 years shows a sinusoidal curve over the year, gradually increasing in spring and decreasing in autumn (figure 2.6a). The same can be said about the amount of daily global radiation (see chapter 3, figure 3.5). When temperature during growing season shows such a curve, the impact of over and underestimation of temperature on duration of vegetative period and on final yield can be explained easily. A small underestimation of temperature results in later crop emergence, a longer vegetative period (at higher radiation levels) and thus in a higher yield (figures 2.3 and 2.5). When underestimation is more than 1- 2 °C, too much of the grain filling period occurs during the time of low radiation levels in autumn and yield is reduced. When temperature is underestimated by more than 4 °C, the crop does not mature before the end of the year. An overestimation of temperature leads to a shorter vegetative period and to a lower yield. The optimum in the yield curve (figure 2.5) is very close to the present situation (0 deviation). However, it can not be concluded that the present situation is the only optimal one. Spring wheat variety and sowing date in the model are adapted to the present situation. Deviation from this situation results, therefore, in a lower yield.

Other varieties and sowing dates are required for obtaining high yields in changed circumstances.

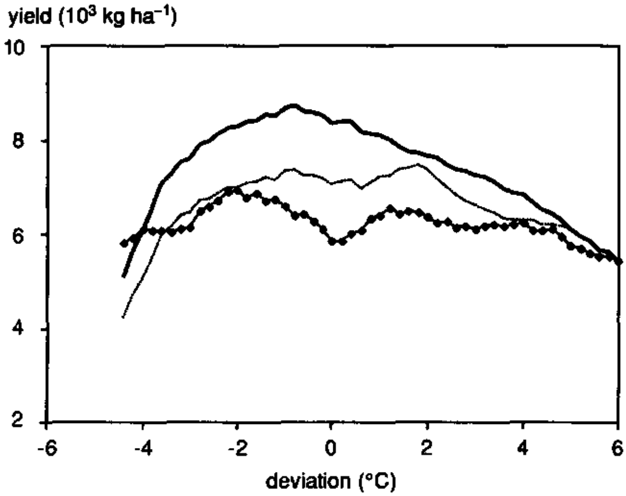


Figure 2.5 The effect of a deviation in temperature up to 6 °C on simulated yield when climatic averages (——), daily weather data from 1982 (•–•–•) and adjusted climatic averages (see text) (.......) were used as input.

The course of the actual temperature over the year can differ substantially from the average (figure 2.6a), causing changes in temperature to have an unexpected effect on simulated yield and vegetative period duration as was shown for 1982 and 1973. The strange effect of a decrease in temperature on duration of the vegetative period is caused by a period with very low temperatures just after crop emergence in 1973. With the original data the crop emerges just before a period with very low temperatures starts. During this cold period the development of the crop comes to a stand still and the vegetative period of the crop is prolonged. When temperature is underestimated, the crop has not emerged at the moment the cold period starts and emergence is delayed till the cold period is over. Emergence after the cold period implies that vegetative development is not delayed by the low temperatures resulting in a shorter vegetative period. In 1973 underestimation of only 1 °C leads to a difference in vegetative period duration of 10 days. By changing the temperature data in the set with climatic averages this effect can be reproduced. In the simulation run with climatic averages crop emerges on April 1st. Merely by reducing minimum and maximum air temperatures to respectively 0 and 5 °C on 2-11 April the same effect of underestimation temperature on vegetative period duration is achieved (figure 2.3).

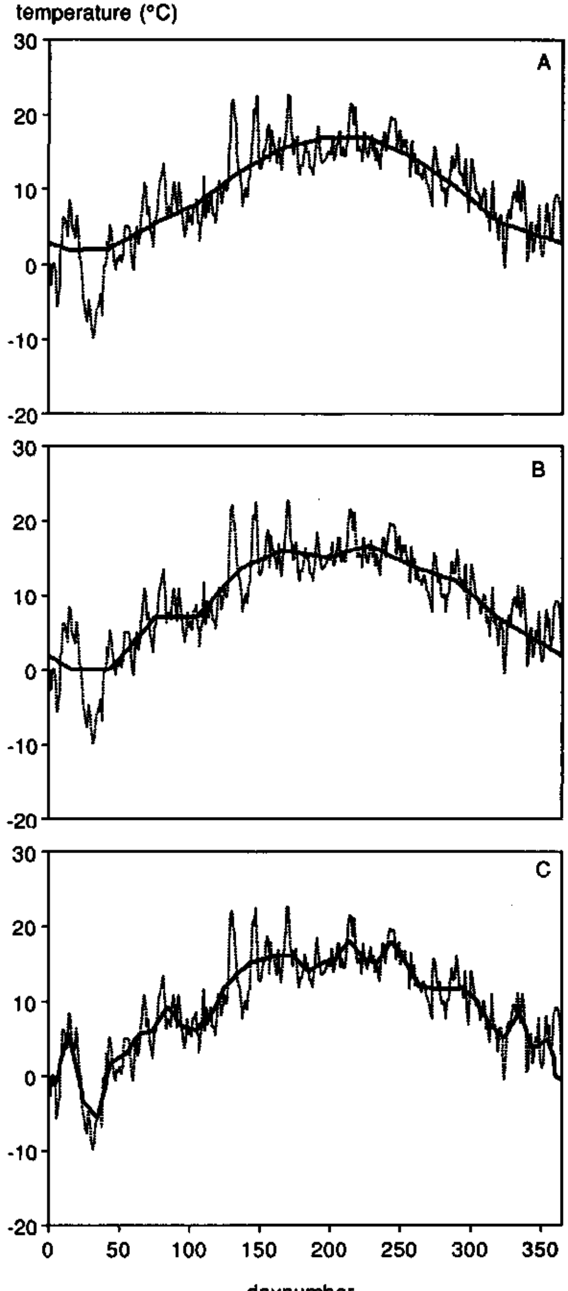


Figure 2.6 Comparison between average day temperature ($0.5*(T_{max}+T_{min})$) in 1954 in Wageningen (·······) and estimated values (——) based on: A climatic averages, B monthly averages, C averages over 10 days.

The explanation for the local minimum in the curve for simulated yield in 1982 is found in a period of unfavourable weather conditions (low temperature and low radiation) just before flowering of the crop. An overestimation of temperature lead to earlier crop emergence and earlier flowering, so that the unfavourable weather period occurs in the grain filling period of the crop. The model is less sensitive to unfavourable weather conditions during the grain filling period than during the vegetative period and a yield increase is obtained. The longer vegetative period as a result of underestimation of temperature compensates for the effect of the adverse weather conditions in this period resulting in a yield increase. The local minimum as found for 1982 can be reproduced by decreasing global radiation (in the set with climatic averages) to 5 MJ m^{-2} d^{-1} in the 10 days before flowering of the crop (9-18 June) (figure 2.5).

Table 2.1 Average deviation (°C) between the original value (x_{oi}) on day i in the Wageningen data set and the estimated value (x_{ei}), for minimum (T_{min}) and maximum temperature (T_{max}) for various estimation methods, where n is the number of days (= 3650, 10 years * 365 days). Methods considered are: data from another station (de Bilt, de Kooy) and average values over various intervals from Wageningen (10 days, one month or climatic averages).

	$\frac{\sum_{i=1}^{n}(x_{oi}-x_{ei})}{n}$		$\sqrt{\frac{\sum_{i=1}^{n}(x_{oi}-x_{ei})^2}{n}}$	
	T_{min} °C	T_{max} °C	T_{min} °C	T_{max} °C
De Bilt	−0.4	−0.4	1.8	2.0
De Kooy	−1.2	1.1	2.7	2.7
10 day averages	0	0	2.9	2.8
monthly averages	0	0	3.5	3.6
climatic averages	−0.3	−0.2	3.8	4.0

The model is rather sensitive to inaccuracies in temperature. Even an underestimation of 1 °C can result in a change in duration of the vegetative period of 10 days. Since inaccuracies can have such a large effect on the simulation results, it is vital to replace missing values by realistic data.

For all estimation methods considered, the average deviation from the original values was calculated according to two equations (table 2.1). The values in table 2.1 are calculated for 1976-1985. For these years data from all estimation methods were available. The deviations in the first two columns indicate whether temperatures are on average higher or lower than the original value.

Deviations in column 3 and 4 are comparable to the standard deviation of a population and are measures of the absolute difference from the original data. Since averages over 10 days and monthly averages are derived from the daily data, the average temperatures are the same and deviations in column 1 and 2 are zero (table 2.1). Climatic averages are based on daily data from 1954-1983, for which average temperature is not equal to the average of the daily data. The minimum temperature in de Kooy is higher than in Wageningen and the maximum lower, due to the effect of the sea. Both maximum and minimum temperature in de Bilt are 0.4 °C higher than in Wageningen. Deviation in column 3 or 4 gives a different picture: deviation of the data from the other sites is smaller than from average data. The deviation increases with increasing length of the averaged interval. This is in accordance with the data shown in figure 2.6: the temperature data based on 10 day averages give a better estimate of the daily values than averages over longer intervals, but large differences remain. It is striking that the average over 10 days gives a larger deviation from the original values than data from a station at a distance of 130 km (de Kooy).

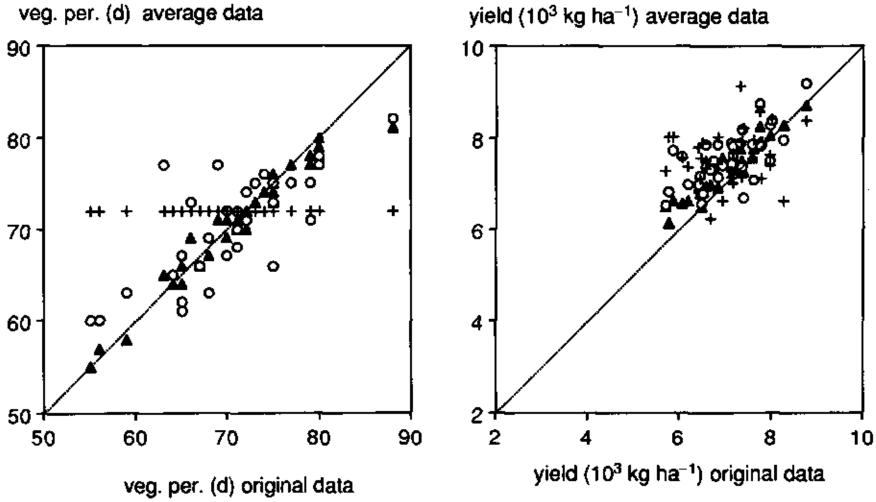
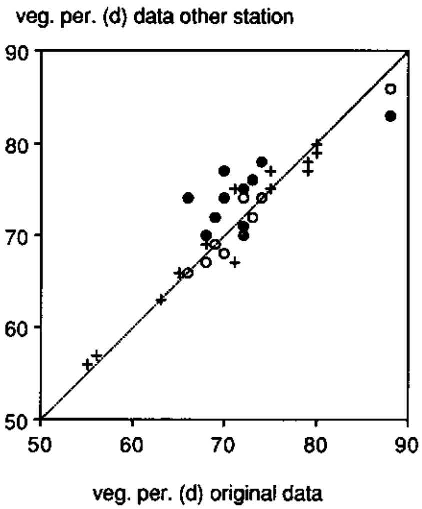


Figure 2.7 (left) Comparison between duration of the vegetative period simulated with the original data set (Wageningen 1954-1987) and duration of this period when temperature values were estimated from average data. Averages over 10 days (▲), monthly averages (o), climatic averages (+).

Figure 2.8 (right) Comparison between yield simulated with the original data set (Wageningen 1954-1987) and simulated yield when temperature values were estimated from average data. Averages over 10 days (▲), monthly averages (o), climatic averages (+).



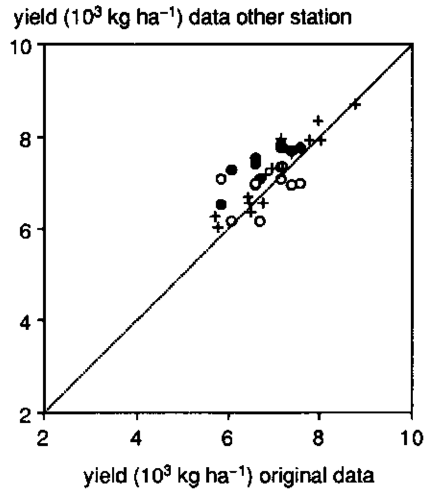


Figure 2.9 (left) Comparison between duration of the vegetative period simulated with the original weather data set (Wageningen (1961-1987)) and duration of this period when temperature values in this set were replaced by data from another meteorological station. Data de Bilt (1976-1985): o , data de Kooy (1976-1985): ● and data de Bilt (1961-1975 and 1986, 1987) : +.

Figure 2.10 (right) Comparison between yield simulated with the original weather data set (Wageningen (1961-1987)) and simulated yield when temperature values in this set were replaced by data from another meteorological station. Data de Bilt (1976-1985): o , data de Kooy (1976-1985): ● and data de Bilt (1961-1975 and 1986, 1987) : +.

In figures 2.7 and 2.8 the effect of average temperature data on simulation results is given. Use of averages over 10 days gave the smallest deviation in simulation results. The deviation in duration of the vegetative period was in the order of magnitude of days. Use of climatic averages implies that temperature was the same in all years, for which simulated duration of the vegetative period was the same (72 days). Actual temperatures can be quite different to cause differences in duration of over 20 days. Use of monthly averages resulted in a deviation in simulated duration of 5-10 days. Overestimation of the yield by 25 % occurred when climatic averages or monthly averages were used. Averages over 10 days gave a smaller deviation. These results imply that it is not advisable to use average data for estimation of missing values.

Use of data from another station gave far better results. Deviations in the order of magnitude of 5 % were obtained when data from de Bilt were used (figures 2.9 and 2.10, solid and empty circles cover same time interval). Data from de Kooy resulted in a larger deviation.

Replacing 10 % of the daily data randomly by climatic averages had hardly any effect on simulation results. So when only a few data are randomly missing, there is no need to pay much attention to the estimation procedures. Missing data, however, are often clustered, since it takes some days to repair the instruments. It was shown that only 10 days of incorrect data can have large effects on simulation results. When missing values are clustered, it is better to replace them by data from a nearby station. The effects of inaccuracies in weather data for other simulation models and on other locations are discussed in section 4.8.

Conclusions

Differences in temperature between the meteorological station and a field experiment of 1 °C can be expected. These differences can cause a deviation in simulated yield up to 1 ton ha^{-1} and a deviation of the duration of the vegetative period of 10 days. Due to the irregular course of the temperature in most years the use of averages is unsuitable for simulation of crop production on a daily basis. Use of these data nearly always results in an overestimation of yield in comparison with yield simulated with daily values. Missing values in a data set can be replaced best by data from another meteorological station located in the same climatic district.

Chapter 3

Inaccuracies in weather data and their effects on crop growth simulation results: II Global radiation

Abstract In weather data sets used by crop modellers irregularities occur in the form of inaccuracies in given data or missing values. In the previous chapter the effects of irregularities in temperature data on results of a spring wheat simulation model were discussed. In this chapter the effects of irregularities in global radiation data on potential production are studied. From literature the inaccuracy in global radiation data was estimated to be 10 %. A systematic over or underestimation of global radiation by 10 % resulted in a deviation of about 10 % in simulated yield. Five ways of estimating missing global radiation values were considered: use of climatic averages, averages over one month and averages over 10 days, data from another weather station and sunshine duration data. When all daily data were replaced by estimates, data from a nearby station and estimates based on sunshine duration data gave the smallest deviation in simulation result. Use of average values resulted in an overestimation of simulated yield up to 30 % in some years. When only 10 % of the daily data were replaced randomly by estimates, no effects on simulation results were found.

Introduction

Most crop growth simulation models require daily weather data as input (Whisler 1986). In weather data sets irregularities occur such as inaccuracies in data or missing values. Since models are sensitive to data used as input, it is likely that these irregularities in weather data sets affect the simulation results. This study is intended to determine the magnitude of the errors in these data and to analyse their effects on simulation results. In chapter 2 the effects of inaccuracies in temperature data on simulated potential production were studied. This chapter is focussed on the influence of errors in global radiation data on simulated potential production. In chapter 4 the effects of irregularities in weather data on simulated water-limited production will be discussed.
Global radiation includes both direct and diffuse solar radiation and is an important weather factor for agricultural research, since this type of radiation provides the energy for crop growth. The instruments for measuring global radiation were developed during the nineteen twenties (Moll 1923, Gorczynski 1926, Gulik 1927). In the late twenties regular measurements were started in Wageningen in The Netherlands (Gulik 1929). In the early forties global radiation was also measured in Rothamsted in England and in Versailles in France. Since the sixties the number of sites where global radiation is recorded has increased, but presently global radiation is still measured at only a small number of meteorological stations. In some countries different networks exist:

one maintained by the national meteorological institute (measuring temperature, rainfall, etc.) and another one maintained by the national institute for solar energy (measuring several types of solar radiation, including global radiation). Accordingly global radiation data are often published in other reports than data on temperature and rainfall.
The fact that long period records of global radiation only exist from a very few sites in Europe and that even now this variable is recorded at only a few sites makes global radiation the limiting factor in most weather data sets.

Sunshine duration (hours of bright sunshine per day) is recorded at far more locations than global radiation. In The Netherlands 35 stations record sunshine duration and 17 global radiation (KNMI 1988); in the former Federal Republic of Germany the numbers are 68 and 8 (Golchert 1981), in Great Britain 132 and 25 (Cowley 1978) and in Italy 70 and 28 (Andretta et al. 1982). Sunshine duration and the amount of global radiation are related (on a day with a large number of hours of sunshine, global radiation is high). Sunshine duration data are often used to estimate the global radiation. Therefore in this chapter, besides the effects of the estimation methods mentioned in chapter 2, attention is paid to the effects of the use of sunshine duration data instead of global radiation data on simulation results.

Methods

The same procedure as described for temperature data in the previous chapter was used. The inaccuracy that could be expected in given global radiation data was estimated on the basis of literature and effects of permanent over and underestimation of the values by this inaccuracy on simulation results were studied. Various ways of estimating missing values were compared: use of average data over various intervals and data from another station. Details of the method are given in chapter 2.
The effects of inaccuracies in global radiation data on simulation results were studied for the same simulation model as used in chapter 2. In contrast with temperature, radiation affects only two processes in the simulation model: photosynthesis and transpiration. In this chapter only the effect on photosynthesis is considered (potential production). The effect through transpiration on the water-limited production is discussed in chapter 4.

Not all wave lengths within the global radiation spectrum can be used for photosynthesis: only photosynthetically active radiation (PAR, 400-700 nm) provides the energy for photosynthesis. The model assumed that half of the global radiation consists of PAR (Spitters et al. 1989). The basis for calculation of the crop assimilation is the photosynthesis-light response curve of individual leaves of the crop (de Wit 1965, Goudriaan & van Laar 1978a). Since this relation is not linear, average radiation does not result in average photosynthesis (figure 3.1).

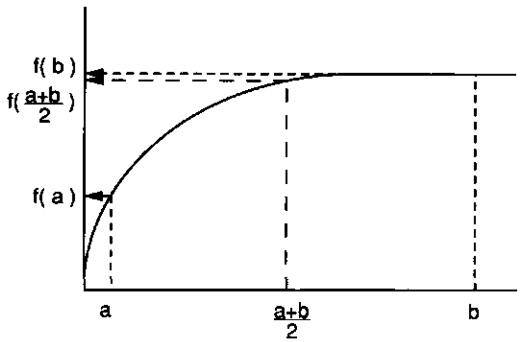


Figure 3.1 The form of the photosynthesis-light response curve, and the effect of using average radiation data on the calculated assimilation.

Global radiation can be recorded with several instruments (Fritschen & Gay 1979). The series in Wageningen are recorded with the Kipp-Solari meter (Gulik 1927, de Vries 1955). When this type of instrument is maintained well inaccuracy is limited to 5 % (Bener 1951). De Vries (1955) found random errors of 5 % and systematic errors of 1-10 % for the instrument used in Wageningen. Here the effect of an inaccuracy of 10 % in global radiation data is studied.

To estimate missing values an extra method was available: use of sunshine duration data. For this purpose the so called Ångström formula was used (Ångström 1924, Prescott 1940):

$$\frac{Q}{Q_0} = A + B\frac{n}{N} \tag{3.1}$$

in which Q is the global radiation (J m^{-2} d^{-1}), Q_0 is the total radiation in absence of atmosphere (J m^{-2} d^{-1}), n is the recorded hours of bright sunshine and N is the astronomical daylength (h). The coefficients A and B are site dependent and are affected by optical properties of the cloud cover, ground reflectivity and average air mass (Iqbal 1983). A and B values have been derived for many locations (Cowley 1978, Golchert 1981, Martínez-Lozano et al. 1984).
From de Bilt (1961-1980) both global radiation and sunshine duration data were available on a daily basis. These data were used to study the effect of

estimating global radiation from hours of sunshine on simulation results. A and B values for de Bilt (0.20 and 0.55 respectively) were obtained from the European Solar Radiation Atlas (Palz 1984). Two simulation runs were made with weather data from de Bilt (1961-1980): one with the recorded global radiation data and one with the estimated global radiation on the basis of the sunshine duration data (equation 3.1).

Results and discussion

Inaccuracies in data

Underestimation of global radiation by 10 % resulted in a decline in simulated yield (grains, dry matter) of 5-10 % (figure 3.2) and overestimation in an increase in yield of about 5 % in most years. Small differences in sensitivity existed between the years: in 1976 overestimation of the radiation resulted in a yield increase of only 3 % and underestimation in a yield decline of 5 %, while in 1961 overestimation resulted in a yield increase of 8 % and underestimation in a yield decline of 10 %.

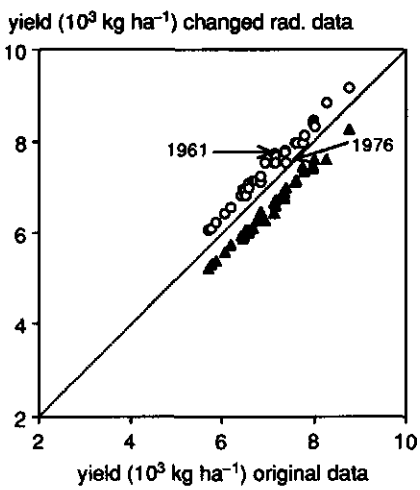


Figure 3.2 Comparison between yield simulated with the original weather data set (Wageningen 1954-1987) and simulated yield when global radiation was overestimated by 10 % (○) or underestimated by 10 % (▲).

To achieve a better understanding of the effects of inaccuracies in global radiation data on simulation results in various years, the sensitivity of the model to deviations up to 6 MJ m^{-2} d^{-1} was studied for the years 1961 and 1976. Sixty simulation runs were made for each year. In the first run daily total global radiation was decreased by 6 MJ m^{-2} d^{-1} on all days, in each following run deviation in global radiation was decreased by 0.2 MJ m^{-2} d^{-1} up to overestimation of radiation by 6 MJ m^{-2} d^{-1}. The results of these simulation runs are plotted in figure 3.3. In 1976 overestimation of the daily radiation up to 6 MJ m^{-2} d^{-1} had no effect on simulated yield and underestimation by 6 MJ m^{-2} d^{-1} resulted in a yield decline by 2 ton ha^{-1}. In 1961 overestimation resulted in a yield increase of 1.5 ton ha^{-1} and underestimation in a yield decline of 4 ton ha^{-1}.

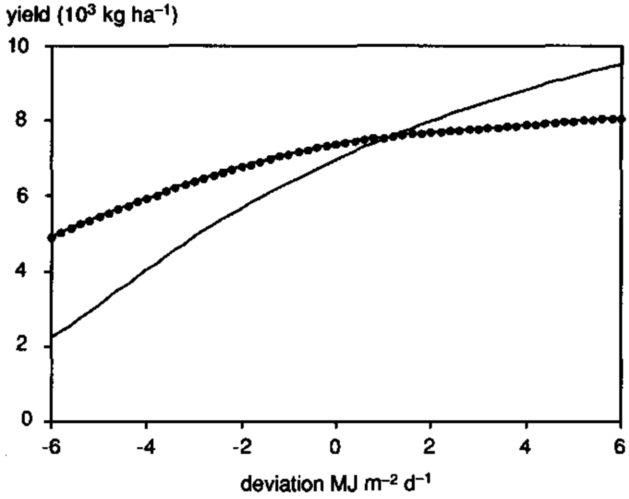


Figure 3.3 The effect of deviation in global radiation up to 6 MJ m^{-2} d^{-1} on simulated yield with daily weather data from Wageningen 1976 (•—•—•) and 1961 (———).

The effects of over and underestimation of radiation in different years can be explained by the form of the photosynthesis-light response curve (figure 3.1). At high radiation levels saturation occurs. Hence inaccuracies at high radiation levels have no effect on photosynthesis and crop yield. Large differences in radiation levels between growing seasons exist. In some years average radiation during the vegetative period is just over 12 MJ m^{-2} d^{-1}, while in other years average radiation levels over 18 MJ m^{-2} d^{-1} are recorded (figure 3.4). In 1976 radiation levels were high so inaccuracies had little effect on crop production, while in 1961 levels were low so inaccuracies in global radiation had a larger effect on crop production.

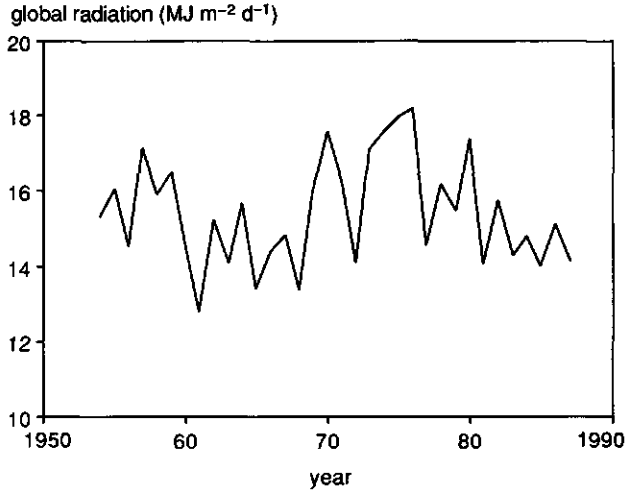


Figure 3.4 The average daily global radiation during vegetative period of the crop when daily weather data from Wageningen (1954-1987) were used as input in the simulation model.

Estimation of missing values

In table 3.1 the average deviation from the original value (recorded global radiation in Wageningen, 1976-1985) is given for the estimation methods considered (see chapter 2). Since averages over 10 days or over one month are obtained from the original daily values, average radiation levels are the same, resulting in a zero deviation in the first column. The climatic data are based on data from 1954-1983 and cover a different period, through which a small difference in average radiation levels is found. Since no sunshine duration data from Wageningen were available, deviation for sunshine duration is based on data from de Bilt (1961-1980). The deviation from the original value is smallest when sunshine duration data are used.

Table 3.1 Average deviation in global radiation (MJ m^{-2} d^{-1}) between the original value (x_{oi}) on day i and the estimated value (x_{ei}) for various estimation methods. Methods considered are: data from another station (de Bilt, de Kooy), averaged data from Wageningen over various intervals (10 days, one month and climatic data) and estimates based on sunshine duration data (see text). n is the number of days (7300 for the sunshine duration data and 3650 for the other estimation methods)

	$\dfrac{\sum_{i=1}^{n} (x_{oi}-x_{ei})}{n}$	$\sqrt{\dfrac{\sum_{i=1}^{n} (x_{oi}-x_{ei})^2}{n}}$
De Bilt	−0.3	3.0
De Kooy	−1.0	4.0
10 day averages	0	3.8
monthly averages	0	4.2
climatic averages	0.1	4.4
sunshine duration	−0.1	1.4

A gradient in radiation levels exists over the country with levels increasing towards the west. Differences in radiation of 5-10 % are found between de Bilt and Wageningen (Prins & Reesinck 1948) and differences over 10 % between de Kooy and Wageningen (Prins 1944). This gradient is also to be seen in the difference in average radiation levels between Wageningen, de Bilt and de Kooy (table 3.1). Radiation levels in de Kooy are on average 1 MJ m^{-2} d^{-1} higher than in Wageningen. Since radiation levels in de Bilt and de Kooy are on average higher than in Wageningen, it is not surprising that use of these data results in an overestimation of simulated yield (figure 3.6). The overestimation of yield with data from de Kooy is of the same order of magnitude as the overestimation by 10 % (figures 3.2 and 3.6), which is in accordance with the fact that radiation levels are 10 % higher in this part of the country. However, use of averages over 10 days or one month as estimates also resulted in overestimation of yield, while average levels are identical to these of the original data. This overestimation is due to the very large variability in the daily total global radiation (figure 3.5). When large differences exist, use of average values leads to overestimation of photosynthesis (figure 3.1). Large differences in radiation levels between individual years (figure 3.4), ensure that estimates based on climatic averages have little to do with the original value. In some years use of climatic averages gives the same simulation result as with the original data set, but in most years there is overestimation (figure 3.7). Use of climatic averages as estimates implies that radiation levels are the same in all years. Differences in simulated yield, when these averages are used, are due to differences in air temperature in individual years, through which differences in duration of growing season occur, resulting in differences in the amount of radiation intercepted by the crop.

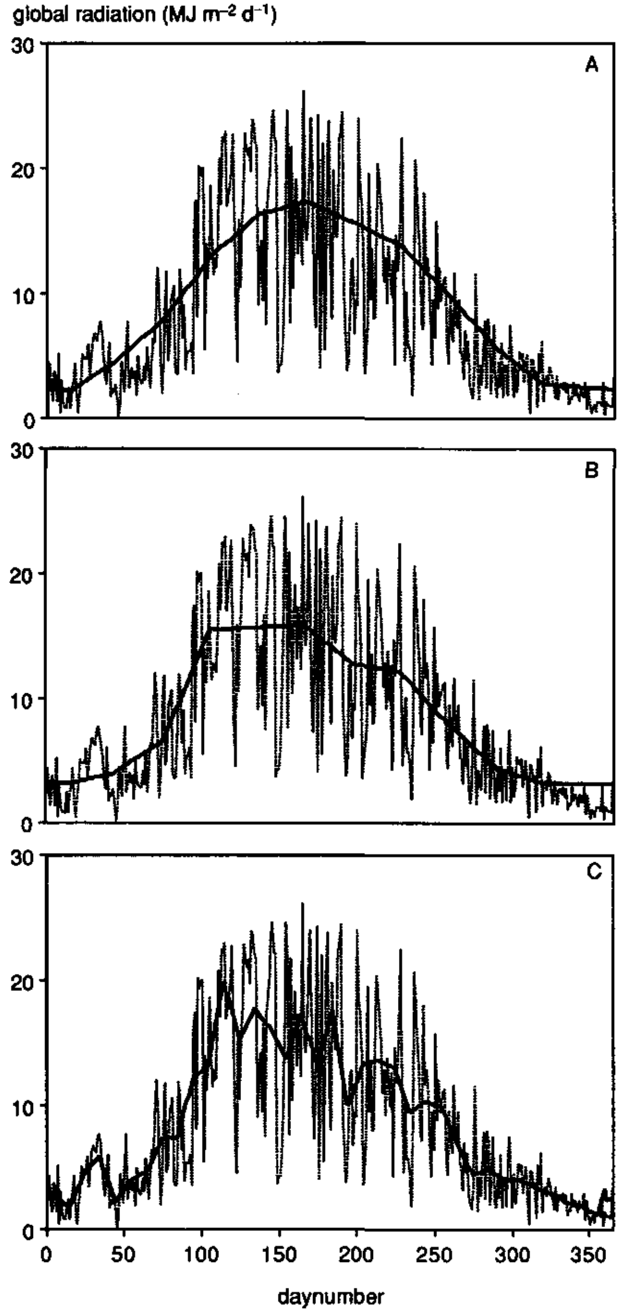
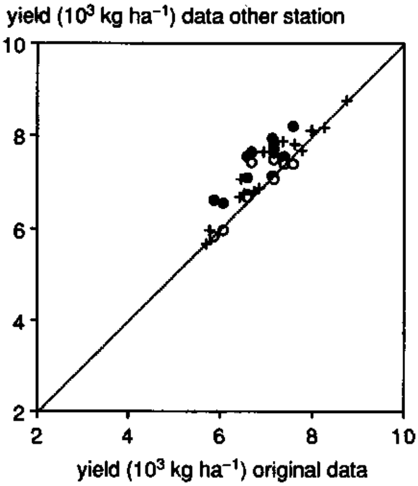


Figure 3.5 Comparison between the measured daily global radiation in 1954 in Wageningen (·······) and the estimated values (———) derived from: A climatic averages, B monthly averages and C averages over 10 days.



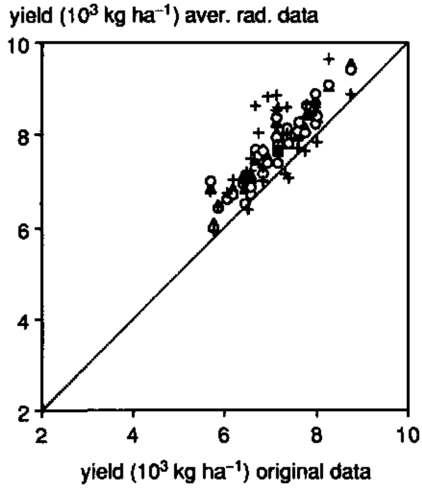


Figure 3.6 (left) Comparison between yield simulated with the weather data from Wageningen (1961-1987) and simulated yield when global radiation data were obtained from another meteorological station. Data de Bilt (1976-1985): o , data de Kooy (1976-1985): • , and data de Bilt (1961-1975 and 1986,1987): +.

Figure 3.7 (right) Comparison between simulated yield using daily weather data (Wageningen 1954-1987) and simulated yield when average values for global radiation from this station were used. Averages over 10 days (▲), monthly averages (o) and climatic averages (+).

Data from de Bilt gave reasonable simulation results in most years. Use of radiation data from a nearby station is, however, not a realistic solution for replacing missing values. As mentioned before, global radiation is recorded on only a limited number of meteorological stations, so it is very unlikely that data are measured at more than one site in the same climatic district.

Use of sunshine duration data of the same station to estimate missing values is therefore the best solution (figure 3.8). However, several versions of the Ångström formula (equation 3.1) are in use. Some authors define daylength (N) as the value the sunshine recorder will record on a completely clear day. Using this definition daylength is much shorter, since sunshine recorders often do not record sunshine when sun is less that 5° above horizon (Iqbal 1983). Also several definitions for Q_0 are used (Martínez-Lozano et al. 1984). The use of different definitions for N and Q_0 results in other values for A and B, so care should be taken when A and B values are obtained from literature. Another important aspect is that sunshine duration is often recorded with a Campbell-Stokes sunshine recorder which has inaccuracies up to 20 % (Painter 1981). Accordingly the inaccuracies in sunshine duration data can be quite large.

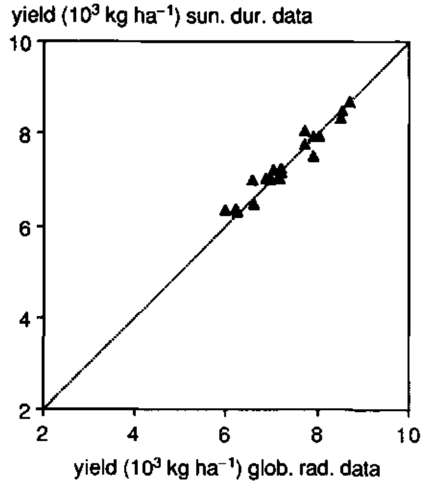


Figure 3.8 Comparison between the simulated yield using daily weather data from de Bilt (1961-1980) and the simulated yield when global radiation was estimated from sunshine duration data from this station.

When 10 % of the global radiation data were replaced randomly by climatic averages, hardly any effect was found on simulated yield. This phenomenon was also found in the previous chapter on temperature data. So, when only a few data are missing randomly, not much attention needs to be paid to the estimation procedure. However, as soon as missing data are clustered care should be taken: in chapter 2 is shown that incorrect values of global radiation during the 10 days before flowering of the crop have a large effect on final simulated yield.

Conclusions

The inaccuracies in global radiation data are large (10 %), resulting in deviation in simulated yield up to 10 %. Due to the variation in daily and annual global radiation and the non-linear relation between radiation and photosynthesis, the use of average data (even over short periods) to replace missing values must be avoided. When global radiation data are missing they can be replaced best by estimates based on sunshine duration data or by global radiation data from a station in the same climatic district.

Chapter 4

Inaccuracies in weather data and their effects on crop growth simulation results: III Water-limited production

Abstract In weather data sets used by crop modellers irregularities occur as inaccuracies in given data and as missing values. In chapters 2 and 3 the effect of irregularities in temperature and global radiation data on potential production were discussed. In this chapter the effects of irregularities in weather data on simulated water-limited production are studied. The same methods as described in the previous chapters were used.
In general the model was not sensitive to inaccuracies in vapour pressure data and wind speed and average data for these variables could be used to replace missing values. The sensitivity of the model to inaccuracies in other weather data depended on the amount of water available to the crop. In dry years the model was sensitive to inaccuracies in precipitation and radiation data but less to inaccuracies in air temperature. When water was not limiting, the model was not sensitive to inaccuracies in precipitation, but was sensitive to inaccuracies in temperature and radiation data. Use of average values for temperature, global radiation and precipitation led to large deviations in simulation results.
For all variables, except precipitation, data from a nearby weather station were good estimates for missing values. Rainfall data should be obtained from a site in the immediate surroundings. However, when the complete data set from a nearby station was used as input for the model, deviations up to 2 ton ha^{-1} (=30 %) in simulated yields were found.

Introduction

Weather data are important input variables in crop growth simulation models and simulation results are largely determined by these input data. Therefore it is important to analyse the errors that can occur in weather data and the effect of these errors on the simulation results. In previous chapters inaccuracies in air temperature and global radiation data were estimated and the effects on the simulated potential production were discussed. It was shown that inaccuracies in weather data can have large effects on the simulation results. Crops hardly ever reach their potential production level, since water shortage occurs to a lesser or greater extent during growing season. Analysis of the effects of inaccuracies in weather data on the simulated water-limited production is therefore a logical follow-up to the previous chapters.
Daily data on maximum and minimum air temperature, global radiation, precipitation, vapour pressure and wind speed are required for simulation of water-limited production. Basically air temperature and global radiation determine the potential production and the precipitation determines to what

extent this production is reached.
One of the characteristics of precipitation is its very irregular distribution in space and time. In de Bilt (The Netherlands, see figure 2.1) annual precipitation varied from less than 400 mm (1921) to more than 1100 mm (1965) (Buishand & Velds 1980). This implies that the degree of the water deficit varies from one year to another. It is to be expected that differences in water deficit will affect the sensitivity of the simulation model to inaccuracies in certain weather data. Vapour pressure and wind speed, for instance, are used to calculate the evapotranspiration only. When enough water is available, errors in evapotranspiration are not likely to affect the final yield. In dry years, in contrast, an accurate calculation of evapotranspiration is vital for a good simulation of crop production. So the sensitivity of the model to inaccuracies in weather variables will differ from year to year. Distinction is therefore made between effects in dry and wet years.
At the potential production level a good vegetative growth is essential for a high yield (chapters 2 and 6). The effects of temperature and global radiation on simulated potential yield can be explained by their effects on the growth in the vegetative period. This is no longer the case for the water-limited situation. A high dry matter production during the vegetative growth implies that a large amount of water is used during this period. In the worst case all the water is used before grain filling starts, so that no grain yield is obtained at all. For high yields the dry matter production in the vegetative period and the amount of water available during grain filling period must be balanced.

In this chapter the effect of inaccuracies in temperature and global radiation, as estimated in chapters 2 and 3, on water-limited production is examined. The inaccuracies in precipitation, vapour pressure and wind speed data are estimated and their effects on simulation results determined. For each weather variable the effect of using averages is determined as well as the effect of using data from a nearby station. The results are discussed for each weather variable separately. Finally, the combined effect of the inaccuracies in all weather data on simulation results as well as the use of all data from another station is studied.

Methods

The crop growth simulation model used in the previous chapters was extended with an evapotranspiration routine and a soil water balance. Potential soil evaporation and crop transpiration were simulated according to the Big-Leaf model (Penman Monteith equation, Monteith 1965), and a soil water balance based on van Keulen & Seligman (1987) was used. The soil is treated as a multi-layered system with 10 layers. When precipitation occurs, the first layer is filled up to field capacity and all excess water entering the layer drains to next

layers. Soil moisture losses occur by drainage below the potential rooting zone, by crop transpiration and by soil evaporation. When water shortage occurs, the assimilation rate is reduced proportional to the ratio between actual transpiration (depending on the available amount of water) and the potential transpiration (de Wit 1958). Other processes are not affected by water shortage.
In here the profile was regarded as homogeneous and soil parameters of hypothetical soil with a low water holding capacity were used (200 mm m^{-1}), depths of successive soil layers were set at 2, 8, 10, 10, 10, 10, 10, 10, 10, 20 cm and on sowing the profile was at field capacity.
The same methods as described in chapters 2 and 3 were used to study the effects on simulation results of: inaccuracies in data, use of averages and use of data from another meteorological station.
When crop production was simulated with the original weather data set (Wageningen 1954-1987), severe water shortage only occurred in 5 years (1957,1959,1973,1976,1986) resulting in yields of 2-5 ton ha^{-1}. In all other years water shortage was much smaller and yields were higher.

4.1 Air temperature

Introduction

Air temperature data affects simulated water-limited production in two ways: first, temperature determines timing and duration of the growing period of the crop and second it is used to calculate the vapour pressure deficit of the air. The effects of inaccuracies in temperature data on duration and timing of the growing period are discussed elaborately in chapter 2. When, during the growing season periods with unfavourable weather conditions exist, correct temperature data are essential, since temperature determines whether these periods occur during the sensitive period of the growth or not. For the water-limited production correct timing of the growing period is even more important than for potential production. Precipitation is distributed irregularly over the year, a shift of the growing period can have large consequences for the amount of rain during this period.
In the model daily vapour pressure deficit of the air (VPD, in mb) is calculated from the saturated vapour pressure (SVP) at the average day temperature ($T= 0.5 * (T_{min}+T_{max})$) and the recorded vapour pressure (VAP) (Goudriaan 1977):

$$SVP = 6.11 e^{\left(\frac{17.4\,T}{T+239}\right)} \qquad (4.1)$$

$$VPD = SVP - VAP \qquad (4.2)$$

When temperature is overestimated, saturated vapour pressure is overestimated and so is the vapour pressure deficit. At 15 °C overestimation of temperature by 1 °C results in an overestimation of the vapour pressure deficit by about 1.0 mb.

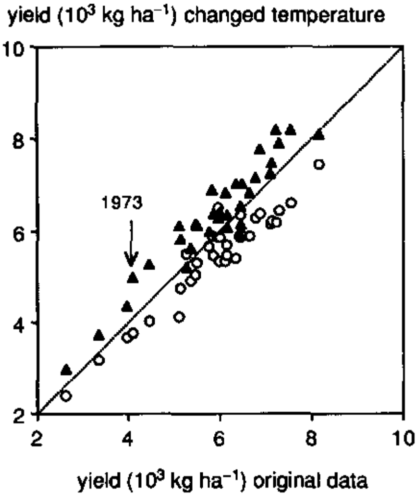
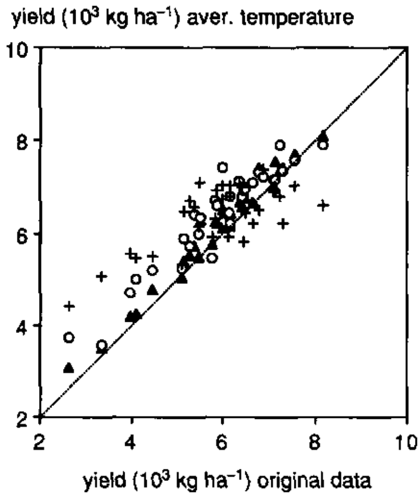


Figure 4.1 Comparison between water-limited yield simulated with the *original* weather data set (Wageningen 1954-1987) and simulated yield when daily minimum and maximum air temperatures in this set were increased by 1 °C (○) or decreased by 1 °C (▲).

Results

In most years underestimation of air temperature resulted in a higher simulated yield (grains, dry matter) and overestimation of air temperature resulted in a lower yield (figure 4.1). In comparison with the potential yield (chapter 2, figure 2.4) fewer years occurred in which an opposite effect was achieved (underestimation of temperature resulting in a lower yield). In a number of years inaccuracies of 1 °C in temperature data resulted in deviation in the amount of precipitation received during crop growth of over 50 mm (deviation of 15-30 %, due to shift of growing season), but in most years this amount was not affected.

Use of average values over 10 days resulted in a rather good simulation of the yield although in some years a deviation of nearly 1 ton ha^{-1} was obtained (figure 4.2). Use of monthly averages led to a larger deviation in simulated yield and when climatic averages were used, yields in low yielding years were overestimated and yields in high yielding years were underestimated (figure 4.2). Using temperature data from de Bilt resulted in a deviation of the simulated yield of the same order of magnitude as the use of averages over 10 days (figure 4.3). Data from de Kooy led to an overestimation of the simulated yield of 0.5-1.0 ton ha^{-1} in nearly all years (figure 4.3).



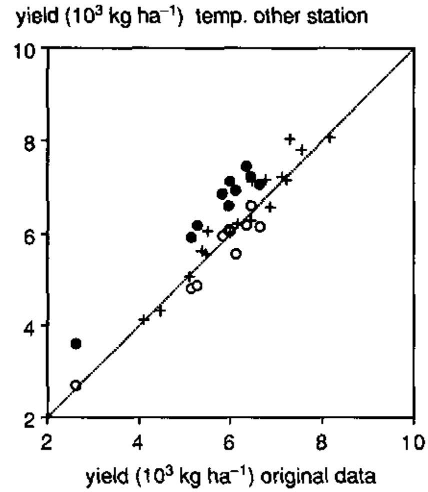


Figure 4.2 (left) Comparison between simulated water-limited yield using daily weather data from the original data set (Wageningen 1954-1987) and simulated yield when daily values for air temperature were estimated from averages values. Averages over 10 days (▲), monthly averages (o) and climatic averages (+).

Figure 4.3 (right) Comparison between simulated water-limited yield using daily weather data from the original set (Wageningen 1961-1987) and simulated yield when temperature data in this set were replaced by temperature data from another station. Data de Bilt (1976-1985): o , data de Kooy (1976-1985): • , and data de Bilt (1961-1975 and 1986,1987): +.
(empty and solid circles cover same time interval)

Discussion

Air temperature affects the simulated water-limited production via different processes. First it determines duration of growing season. The growing season determines the potential production (chapter 2), but also the amount of water available to the crop. Second temperature influences the water requirements of the crop via the calculation of the saturated vapour pressure of the air (equation 4.1). The effects of inaccuracies in temperature data on simulated yields are therefore not easy to explain.
To study the effect of overestimation of vapour pressure deficit only (as a result of overestimation of temperature) on the water requirements of the crop, a simulation run was made in which vapour pressure deficit was increased by 1.0 mb on all days (temperature was not changed !). Total water requirements of the crop increased by 10 % (about 40 mm season^{-1}) in all years. The total effect of the overestimation of temperature on the water requirements of the crop

will, however, be smaller. As shown in chapter 2 duration of the growing period is determined by temperature. An increase in temperature of 1 °C results in a reduction of the growing season of the crop of about 10 days. Under Dutch conditions a spring wheat crop uses 3-4 mm day^{-1}. The effect of overestimation of temperature on water requirements of the crop, through duration of the growing season, compensates the effect through vapour pressure deficit. So, in general, deviations in simulated yield as a result of inaccuracies in temperature can not be explained by changed water requirements of the crop. However, in chapter 2 it is shown that in a number of years a temperature decrease resulted in a shortening of the growing period instead of in a lengthening. In those years inaccuracies in temperature data affect the water requirements of the crop. In 1973, for example, underestimation of temperature resulted in a shorter growing season instead of a longer one. So in 1973 underestimation of temperature resulted in underestimation of the water requirements of the crop (combination of a shorter growing season and a lower vapour pressure deficit) which led to an overestimation of the water-limited yield in that year (figure 4.1). Through the influence of temperature on water requirements of the crop, the effects of overestimation temperature on water-limited production were more regular than the effects on potential production (chapter 2, figure 2.4).
Under Dutch conditions spring wheat crops mature in August. In this month precipitation falls mainly in showers (Können 1983). An inaccuracy of 1 °C in temperature results in a shift of the end of the growing season of 10-15 days. The large deviations in the amount of precipitation during the growing season are caused by some heavy showers (10-20 mm) in the 10 days that the crop is delayed or advanced. The effect of this extra water on the simulated yield is small. Leaf area is strongly declining in this period as a result of the ripening of the crop. Weather conditions during the last two weeks of the growing season have therefore only a small effect on the final yield.
So inaccuracies in temperature data hardly affect the water requirements of the crop or the amount of water available to it. In very low yielding years (2-5 ton ha^{-1}) the amount of water available is the major limiting factor. This amount is not affected by inaccuracies in air temperature data. Through which in dry circumstances the model in not sensitive to inaccuracies in temperature data.
Since temperature does not affect this amount, the sensitivity of the model to inaccuracies in temperature data is less in dry circumstances. This is also to be seen in the effect of the use of average values over 10 days or one month and data from another station on the simulation results: the deviation in dry years is smaller than in the wet years (figures 4.2 and 4.3).
Overestimation of the yield in low yielding years and underestimation in high yielding years when climatic averages are used (figure 4.3) can be explained as follows. Weather variables are often correlated. On warm days, for instance, radiation levels will be high and there will be no precipitation. Therefore dry

summers are usually summers with temperatures higher than the average temperature. In dry summers yield is low as a result of the water shortage of the crop. So when average temperatures over 30 years are used, temperatures are underestimated in the low yielding (dry) years (resulting in a higher yield). In years with enough water (rain!) temperatures are lower than average, so use of average values overestimates temperature resulting in a lower yield.

Conclusions

Underestimation of air temperature results in overestimation of the yield and vice verse. The model is less sensitive to inaccuracies in air temperature data under dry conditions than under wet conditions. In most years water status of the crop is not influenced by these inaccuracies. Use of averages over months or years should be avoided. Use of data from a nearby station is the best solution for replacing missing air temperature values.

4.2 Global radiation

Introduction

Global radiation influences two important processes in the water-limited production. First it drives photosynthesis. The effect of inaccuracies in global radiation data on photosynthesis is discussed in chapter 3. Due to the non-linear relation between light intensity and assimilation rate an overestimation of the global radiation by 10 % led to an overestimation of the yield by 5 %, underestimation by 10 % to an underestimation of the yield by 9 % and use of average values led to an overestimation of the yield by 10-30 %.
The other process in which global radiation plays an important part is the evapotranspiration of the crop and the soil. An increase in global radiation leads to an increase in evapotranspiration (Monteith 1965). In years in which enough water is available, increase of global radiation leads to a higher yield (potential production level). However, when water is limiting higher global radiation levels can increase water shortage, which can counterbalance the effect of higher assimilation rates.

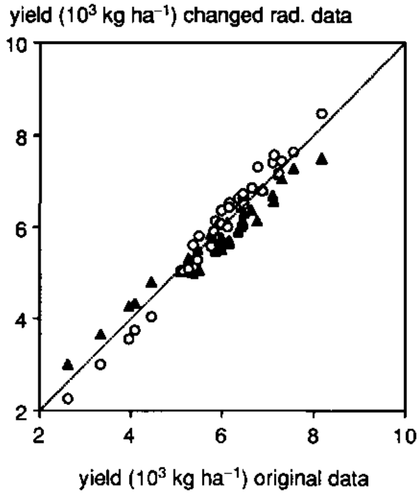


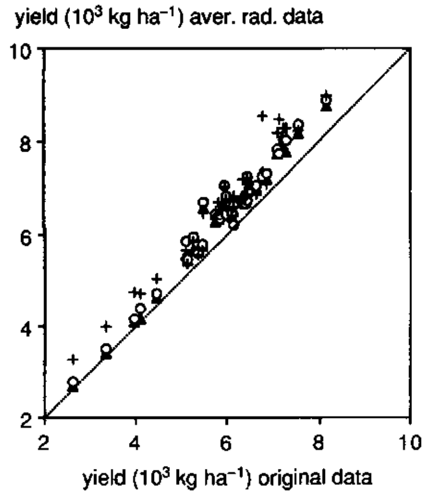
Figure 4.4 Comparison between water-limited yield simulated with the original weather data set (Wageningen 1954-1987) and simulated yield when daily global radiation in the original set was increased by 10 % (o) or decreased by 10 % (▲).

Results

The effect of under and overestimation of global radiation by 10 % on simulated water-limited yield is shown in figure 4.4. In low yielding years overestimation resulted in underestimation of yield and underestimation of global radiation in overestimation of the yield. In high yielding years the effect was the other way round. The deviation in the simulated yield in high yielding years was smaller than for the potential production (chapter 3, figure 3.2).

Use of averages over short periods (10 days or one month) had hardly any effect in low yielding years but in high yielding years an overestimation of yield was obtained (figure 4.5). Climatic averages resulted in overestimation of yield by nearly 1 ton ha^{-1} in all years (figure 4.5). Use of data from de Bilt had the same effect on simulated yield as in the potential production situation: only a small deviation was found (figure 4.6). Data from de Kooy resulted in underestimation of yield in low yielding years and overestimation of the yield in high yielding years (figure 4.6).

Use of sunshine hours to estimate global radiation data led to a very small deviations in the simulation results (figure 4.7).



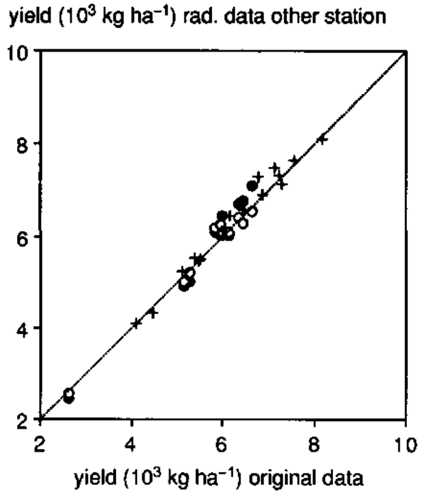


Figure 4.5 (left) Comparison between simulated water-limited yield using daily weather data from the original data set (Wageningen 1954-1987) and simulated yield when daily values for global radiation were estimated from average values. Averages over 10 days (▲), monthly averages (o) and climatic averages (+).

Figure 4.6 (right) Comparison between simulated water-limited yield using the original data from Wageningen (1961-1987) and simulated yield when global radiation data in this set were replaced by global radiation data from another station. Data de Bilt (1976-1985): o , data de Kooy (1976-1985): ● , and data de Bilt (1961-1975 and 1986,1987): +.

Discussion

In cereals most of the dry matter is produced during the vegetative part of the growing season. The yield (grains), however, is formed during the grain filling period at the end of the growing season. In Dutch conditions water hardly ever limits growth in the vegetative period of the crop. Water shortage occurs during the grain filling period. In dry years overestimation of radiation leads to a larger dry matter production and to higher transpiration rates during the vegetative period. Thus the amount of water available at the start of the grain filling period is smaller resulting in a larger water shortage and a lower yield (figure 4.4). The effect of underestimation of the radiation on the simulated yield is opposite. Lower radiation levels result in a lower transpiration during the vegetative period of the crop. Hence more water is available during the grain filling period resulting in less shortage and a higher yield. In years in which yields of 6 ton ha^{-1} are achieved the effect changes. In those years the effect of increased water shortage is counterbalanced by higher photosynthetic rates. In high yielding years water shortage is rare. Production is water-limited only a few

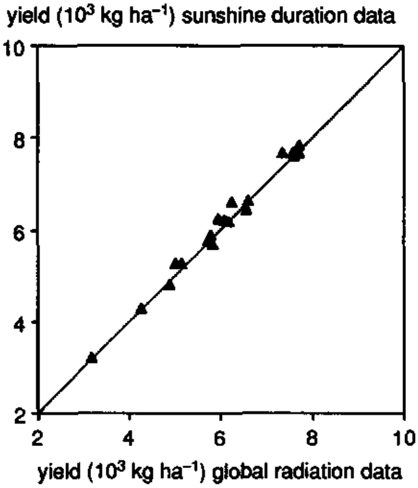


Figure 4.7 Comparison between simulated water-limited yield using daily weather data from de Bilt (1961-1980) and simulated yield when global radiation data were estimated from sunshine duration data from this station.

days in the whole season. On these dry days overestimation of radiation will not increase the production. Underestimation of radiation results in underestimation of transpiration during the season. Consequently more water is available and hence production is higher on dry days. Therefore water-limited production is less sensitive to inaccuracies in radiation data than potential production.

Radiation levels in de Kooy are higher than in Wageningen (chapter 3). So, in general, radiation is overestimated when data from de Kooy are used, resulting in underestimation of the yield in dry years and overestimation of the yield in wet years (figure 4.6).

The relation between radiation and transpiration is linear, so use of average values will not affect the total transpiration through the season. This implies that use of averages over 10 days or one month does not affect the simulated amount of water available at the start of the grain filling period. In dry years, therefore, the effect of using average values on the simulation results is very small (figure 4.5). In the high yielding years the non-linear relation between radiation and photosynthesis (chapter 3, figure 3.1) is the explanation for the overestimation of the yield.

In general, dry years are years with high radiation levels and high temperatures. So use of average values over several years means that radiation is underestimated in the dry years (resulting in overestimation of the yield, figure 4.4) and that radiation is overestimated in the dark, wet years also resulting in an overestimation of the yield.

Conclusions

Water-limited production is less sensitive to inaccuracies in global radiation data than potential production. In dry years overestimation of radiation leads to underestimation of the yield and in wet years to an overestimation. Under dry conditions averages over short periods can be used. In wet conditions use of averages must be avoided. When data are missing they can be replaced best by estimates on the basis of the sunshine hours or by data from a nearby station.

4.3 Precipitation

Introduction

In the simulation model used, the precipitation during the growing season, plus the moisture in the soil profile at sowing, determines the amount of water available for crop growth. However, not all the water that reaches the soil as precipitation is available for crop growth. Part of it will evaporate from the top layer of the soil and part will descend to deeper soil layers. Only moisture in the rooted zone of the profile is available for uptake by the plant.
According to the WMO (1983) the amount of precipitation should be determined with an accuracy of 2 %. It is no problem to determine the amount of precipitation in a rain gauge with this accuracy. However, the amount of precipitation reaching the soil surface can deviate considerably from the amount collected in a rain gauge (de Zeeuw 1963, Rodda 1971). A rain gauge is an obstacle in the air stream and causes turbulence. Raindrops entering the gauge are hampered by this turbulence through which less rain is collected in the gauge than reaches the soil. The effect can be very large in situations with strong wind and light rain or snow. It was found that on windy sites a gauge at a height of 1.5 m above ground registered 15 % less precipitation than one in the ground and a gauge at 0.4 m 5 % less (de Zeeuw 1963, Buishand & Velds 1980). Installation of the gauge in the ground is not always possible due to technical problems such as high groundwater tables, rocky unlevel surface etc. No standards exist with respect to the height at which precipitation should be measured, so a deviation of 10 % or more can occur between precipitation recorded and the amount of water reaching the soil. Here the effect of 10 % over estimation and 10 % underestimation of the precipitation on simulated yield is examined.

An important phenomenon with respect to precipitation is its spatial variability. Therefore rainfall is recorded at far more sites than the other meteorological elements are (Duivenvoorden 1986). The KNMI recognizes 15 rainfall districts, and precipitation data from over 300 stations are published, while daily maximum and minimum air temperatures are only recorded at about 50 stations. Summer showers in particular can cause large local variation in the daily precipitation. In the Netherlands differences in daily precipitation of 30 mm over a distance of 5 km are found (de Bruin 1973). Because of this local variability it can hardly be expected that the amount of precipitation in de Bilt (at 40 km) is comparable to that in Wageningen. Precipitation data from Arnhem (10 km from Wageningen) in 1975 were used to determine the effect of using data from a more nearby station on simulated yield.

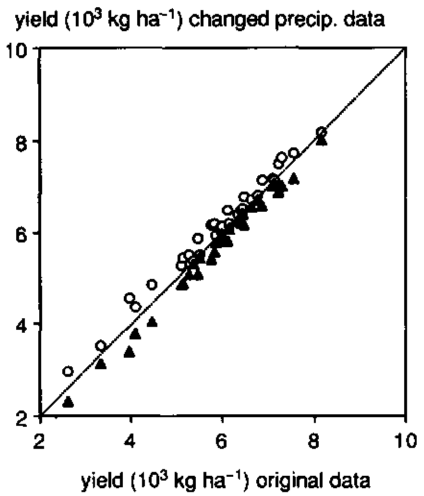


Figure 4.8 Comparison between water-limited yield simulated with the original weather data set (Wageningen 1954-1987) and simulated yield when daily precipitation in the original set was increased by 10 % (o) or decreased by 10 % (▲).

Results and discussion

Overestimation of precipitation leads to increase of the amount of water available to a plant and so to an increased yield. Underestimation leads to a decline in yield (figure 4.8). Over or underestimation of precipitation by 10 % does not result in increase or decrease of the amount of water available by exactly 10 %. When, for instance, the profile is saturated, the 10 % extra water will percolate to deeper soil layers and will never be available to the plant.

In high yielding (wet) years the effect of inaccuracies in precipitation data on the final yield is very small because production is only affected on the very few days that water is limiting growth. In dry years water-limitation occurs far more often and the effect of inaccuracies in precipitation data on final yield is therefore much larger.

The average deviation from the original precipitation data is given for the estimation methods used (table 4.1). In the ten years considered the annual precipitation in de Bilt was about 100 mm higher (365*0.3 mm) than in Wageningen and in de Kooy 40 mm than in Wageningen. This is in accordance with the average annual precipitation over 1951-1980 (Können 1983). The deviation in 1975 is also given, in 1975 the amount of precipitation in de Bilt was 100 mm less than in Wageningen, data from the nearer station Arnhem resulted in smaller deviations.

Table 4.1 Average deviation in precipitation (mm day^{-1}) between the original value (x_{oi}) on day i in the data set from Wageningen and the estimated value (x_{ei}) using various estimation methods. Methods considered are data from another station (de Bilt, de Kooy and Arnhem) and average values over various intervals from Wageningen (10 days, one month or climatic data). n is the number of days (365 for de Bilt 1975 and Arnhem 1975 and 3650 for the other estimation methods 1976-1985).

	$\frac{\sum_{i=1}^{n}(x_{oi}-x_{ei})}{n}$	$\sqrt{\frac{\sum_{i=1}^{n}(x_{oi}-x_{ei})^2}{n}}$
De Bilt	−0.3	4.1
De Kooy	−0.1	4.5
10 day averages	0.0	3.6
monthly averages	0.0	3.8
climatic averages	0.2	4.0
Arnhem 1975	0.0	2.3
De Bilt 1975	0.2	4.8

Since data of the 10 day and monthly averages are based on the daily data set (i.e. Wageningen), average precipitation is the same and deviation in the first column is zero. Climatic data are based on data from 1954-1983 and cover a different period resulting in a small deviation. Based on this time interval average annual precipitation in Wageningen was 0.2*365=80 mm less than in the period 1976-1985.

In contrast with the other weather variables, use of precipitation data from another station resulted in a larger absolute deviation (column 2) from the original value than the estimates based on average values. Moreover the effect on simulation results of these estimation methods can not be completely explained from the deviations calculated.

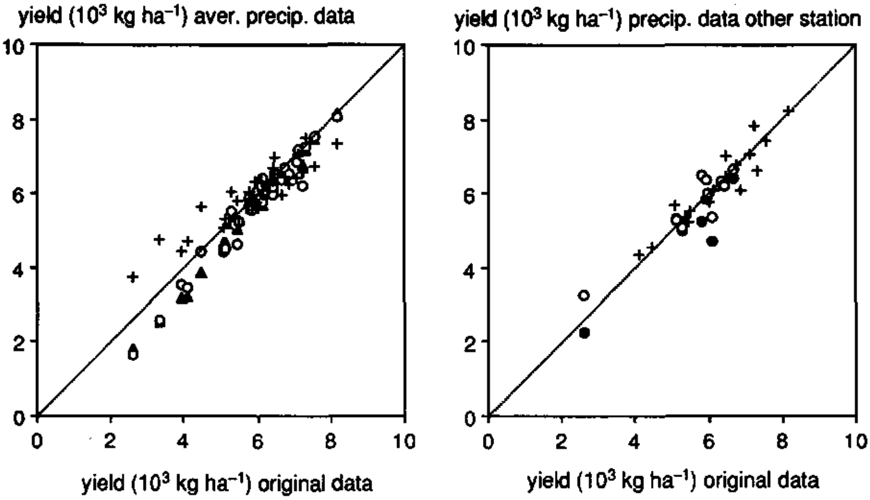


Figure 4.9 (left) Comparison between simulated water-limited yield using daily weather data from the original data set (Wageningen 1954-1987) and simulated yield when daily precipitation was estimated from average values. Averages over 10 days (▲), monthly averages (o) and climatic averages (+).

Figure 4.10 (right) Comparison between simulated water-limited yield using daily weather data from the original set (Wageningen 1961-1987) and simulated yield when precipitation data in this set were replaced by precipitation data from another station. Data de Bilt (1976-1985): o , data de Kooy (1976-1985): ● , and de Bilt (1961-1975 and 1986,1987): +.

Data from another station gave, especially in dry years, better simulation results than the average data (figures 4.9 and 4.10). However, deviation from original values was larger for the data from another station than for the average data (table 4.1). In the wet years average data and data from another station led to the same simulation results. This is reasonable since in wet years the model is less sensitive to inaccuracies in precipitation data (figure 4.8). In dry years averages over 10 days or one month led to underestimation of the yield while climatic averages led to overestimation (figure 4.9).

The amount of water available to the crop is largely influenced by the distribution of the precipitation. One shower of 50 mm has a different effect than 25 showers of 2 mm. Water in the top layer of the soil is subject to evaporation, evaporation stops when this layer is dry. Many small showers imply that the layer is wetted regularly and relatively large amount of water is lost by evaporation. This in contrast with one big shower in which the top layer is only wetted once. Use of averages means that on every day about 2 mm of rain falls, through which evaporation losses are overestimated which results in an important underestimation of the yield in dry years.

Use of climatic data means that in all years the same amount of precipitation falls (760 mm). In dry years this results in an overestimation of the total precipitation. This overestimation is larger than the increased evaporation losses due to rain on every day, through which yield is overestimated.
When data from another station are used, the rainfall pattern of dry and wet days is retained. Hence, evaporation losses are not overestimated and one gets a better simulation result in dry years (figure 4.10).
Precipitation data from de Bilt led to large deviations in simulated yields in comparison with use of global radiation or air temperature data from this station (figures 4.3 and 4.6). In 1975 rainfall data from de Bilt even resulted in underestimation of the yield by more than 10 %. Data from Arnhem led to a better result: only a 2 % underestimation of the yield.
For crop growth simulation purposes models have been developed to simulate a rainfall distribution from climatic averages. The effect of the use of these rainfall simulators on simulated yield is beyond the scope of this thesis, for description and results of these rainfall simulators is referred to Geng et al. (1986).

Conclusions

In precipitation data inaccuracies of 10 % can be expected. In general precipitation is underestimated. In years with water shortage these inaccuracies in rainfall data can cause deviations in simulated yields of over 15 %. Use of averages for estimation of missing rainfall data is meaningless and must be avoided. As a result of the regional variation in rainfall, precipitation data from a station at a distance of 40 km can not be used to replace missing values.

4.4 Vapour pressure

Introduction

In the model vapour pressure is used to determine the evaporative demand of atmosphere (equation 4.2). Overestimation of vapour pressure leads to underestimation of vapour pressure deficit and thus to underestimation of evapotranspiration. In general, vapour pressure is measured with a psychrometer (WMO 1983): the humidity of the air is determined from the difference in wet and dry bulb temperature. In chapter 2 is shown that inaccuracies of 1 °C can be expected in temperature measurements. With respect to the determination of the vapour pressure, an inaccuracy of 1 °C in the difference between the wet and the dry bulb temperature results in an inaccuracy of about 1.0 mb in vapour pressure. The inaccuracies in air temperature, however, were mainly caused by the location of the instrument. The temperature difference between two thermometers at the same spot is not liable to this type of error, so the inaccuracy in the vapour pressure data will be smaller than 1.0 mb. In a comparative research between several types of psychrometers deviations up to 0.5 mb between different instruments were found (Kramer et al. 1954). The effect of the inaccuracy of 0.5 mb in vapour pressure data on the simulated yield is investigated in this section.

The moisture content of the air is not always recorded as its vapour pressure. On some stations the relative humidity of the air is measured. In contrast to vapour pressure, relative humidity of the air is temperature dependent. When air temperature is known, vapour pressure can be derived from relative humidity data by multiplying saturated vapour pressure at this air temperature (equation 4.1) with the relative humidity. However, in most data sets temperature at which relative humidity was determined is not given. At best the time of the day at which this was done is mentioned (often early in the morning). In most sets the only temperature data are minimum and maximum temperatures. The most simple method to derive vapour pressure from relative humidity data is to determine saturated vapour pressure at the minimum temperature of that day, presuming that the early morning temperature is very near to the minimum temperature.
Another possibility is the estimation of the temperature at the moment the measurement was done. According to Parton & Logan (1981) the air temperature at any moment during daytime (T_h) can be estimated from the minimum and maximum air temperature by:

$$T_h=T_{min}+(T_{max}-T_{min}) \sin \left(\pi \frac{(H-12+0.5D)}{D+3} \right) \qquad (4.3)$$

in which T_{min} is minimum air temperature (°C), T_{max} is maximum air temperature (°C), D is daylength (h) and H is time of the day (h).

Data for both vapour pressure and relative humidity data were available from Wageningen only for 1979. Relative humidity was determined at 9.00 hr (Central European Time, CET). Comparison was made between the vapour pressure recorded and the vapour pressure calculated from relative humidity data using minimum air temperature and the estimated temperature at 9.00 CET using equation 4.3.

Results and discussion

In the low yielding years, overestimation of the vapour pressure by 0.5 mb resulted in a small overestimation of the simulated yield and underestimation in a small underestimation of the yield (figure 4.11). In the high yielding years, inaccuracies in vapour pressure had hardly any effect on the simulation results. In the model overestimation of vapour pressure results in underestimation of evapotranspiration. In dry years this leads to an underestimation of the water shortage and overestimation of the yield. In wet years underestimation of the water shortage only influences simulated production in a few days. Even in dry years the model is not very sensitive to inaccuracies in vapour pressure data: deviations in simulated yield of less than 5 % were found.

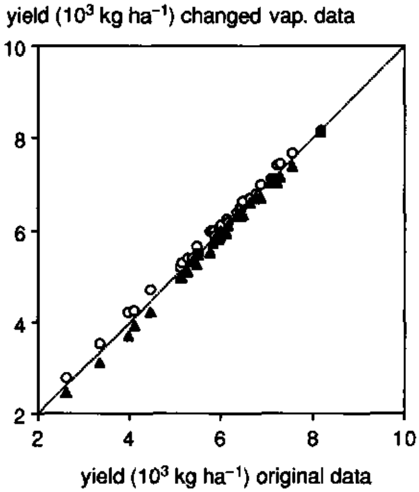


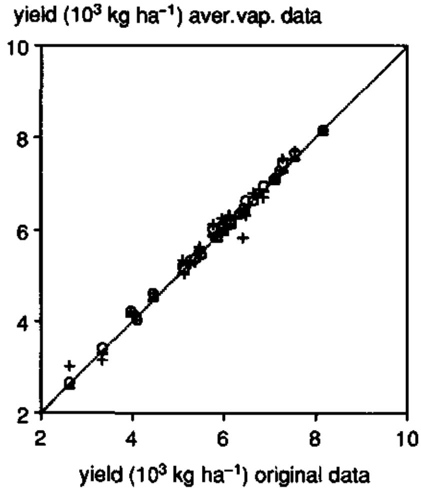
Figure 4.11 Comparison between water-limited yield simulated with the original weather data set (Wageningen 1954-1987) and simulated yield when daily vapour pressure in the original set was increased by 0.5 mb (○) or decreased by 0.5 mb (▲).

Deviation from the original value was small for all estimation methods used (table 4.2). Variability of vapour pressure from day to day is small: use of average values resulted in a small deviation from the original data in comparison with other weather variables. The minor sensitivity of the model for vapour pressure data, the fact that in only a few years severe water shortage occurred and that variability of the vapour pressure is low, is the explanation for the good results obtained when average data were used (figure 4.12).

Vapour pressure levels in de Bilt and de Kooy are 0.3-0.4 mb higher than in Wageningen. Due to the small overestimation of the vapour pressure when data from these stations were used, yield was overestimated in low yielding years. In high yielding years hardly any effect was found (figure 4.13).

Table 4.2 Average deviation in vapour pressure (mb) between the original value (x_{oi}) on day i in the data set from Wageningen and the estimated value (x_{ei}) using various estimation methods. Methods considered are: data from another station (de Bilt, de Kooy) and average values over various intervals from Wageningen (10 days, one month or climatic data). n is the number of days: 3650 (1976-1985).

	$\frac{\sum_{i=1}^{n}(x_{oi}-x_{ei})}{n}$	$\sqrt{\frac{\sum_{i=1}^{n}(x_{oi}-x_{ei})^2}{n}}$
De Bilt	−0.3	1.3
De Kooy	−0.4	1.3
10 day averages	0.0	1.6
monthly averages	0.0	2.0
climatic averages	−0.3	2.2



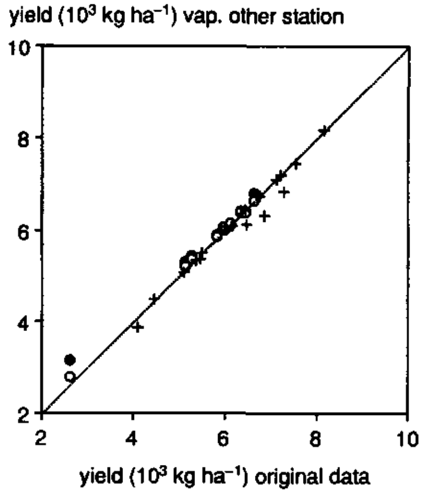


Figure 4.12 (left) Comparison between simulated water-limited yield using daily weather data from the original data set (Wageningen 1954-1987) and simulated yield when daily vapour pressure was estimated from average values. Averages over 10 days (▲), monthly averages (o) and climatic averages (+).

Figure 4.13 (right) Comparison between simulated water-limited yield using daily weather data from Wageningen (1961-1987) and simulated yield when vapour pressure data in the original set were replaced by vapour pressure data from another station. Data de Bilt (1976-1985): o , data de Kooy (1976-1985): ● , and data de Bilt (1961-1975 and 1986,1987): +.

The use of 9.00 hr estimates of the temperature gave a much better estimation of the vapour pressure than the use of the minimum temperature (figure 4.14). Especially on days with high values for vapour pressure the difference was large (up to 10 mb). High values for vapour pressure occur during the summer season when temperatures are high. In this season the difference between the minimum temperature occurring during the night and the temperature at 9.00 am is very large. In the summer season the sun rises at about 5.00 am so the sun has been heating earth for 4 hours at 9.00 am. In winter time sun rises at 8.30 am and difference between minimum temperature and temperature at 9.00 am will be very small.

The effect of relating relative humidity to the minimum temperature on the simulation results for 1979 was very small: an underestimation of only 1 % was found. However, use of averages, data from another station or relating relative humidity to the 9.00 hr temperature led to much better results (less than 0.1 % deviation). Because 1979 was a very wet year inaccuracies in vapour pressure data had almost no effect on simulation results. In dry years a very large underestimation of the yield can be expected when relative humidity data are related to the minimum temperature.

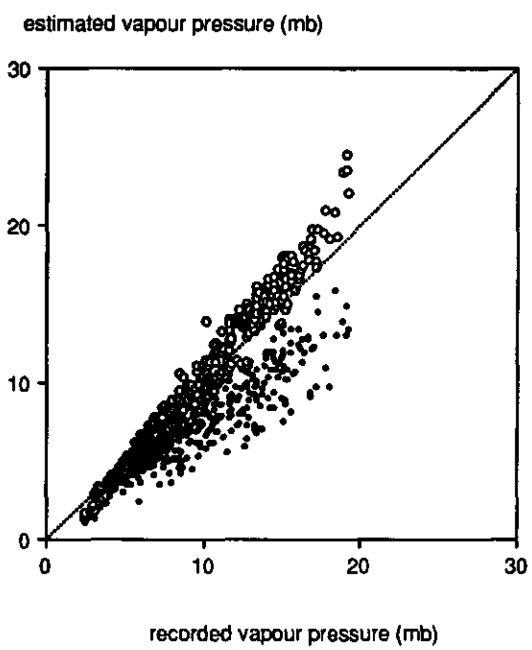


Figure 4.14 Comparison between recorded vapour pressure in Wageningen in 1979 and estimated values from relative humidity data, using minimum air temperature (•) and the estimated 9.00 hr air temperature (o).

Conclusions

Inaccuracies of 0.5 mb can occur in vapour pressure data. The model is not sensitive to these inaccuracies. In very dry years a deviation in simulated yield of 5 % can be expected. When data are missing they can be replaced by average values (even averages over several years) or data from another station. Relative humidity data can be used to estimate vapour pressure, but it is essential to relate relative humidity to the air temperature at observation time.

4.5 Wind speed

Introduction

In the model daily average wind speed is used to determine the resistance of the crop against transpiration (Goudriaan 1977). A high wind speed results in a low resistance and so in a higher evapotranspiration. Wind speed varies with the height above ground and obstacles have a large effect on the wind speed in the surroundings of the obstacle (Wieringa & Rijkoort 1983). According to the WMO (1983) wind speed should be measured at 10 meters above open terrain, with an accuracy of 10 %. Open terrain is defined as 10 times the height away from the obstruction. In this section the effect of 10 % deviation in wind speed data on simulation results is studied.
In most crop growth models wind speed at crop height is required. The wind speed at crop surface is about half the wind speed at 10 meters above ground (logarithmic wind profile). When the correction of the wind speed to crop height is not made, the model overestimates the wind speed at crop height and so overestimates the transpiration. Another problem in wind speed data is that some stations publish wind speed data in knots (0.5 m s^{-1}). When these data are not corrected to the proper dimensions, wind speed is overestimated by 100 %. Therefore the effect of overestimation wind speed by a factor 2 is also studied.

Results and discussion

The effect of over and underestimation of the wind speed by 10 % on simulated yield was very small: resulting in over and underestimation of the yield by only 2 % in the dry years and even less in the wet years. The effect of doubled or halved wind speed (due to wrong reference level or wrong dimensions) on the simulated yield is shown in figure 4.15: in dry years a deviation in simulated yield of 10 % was obtained. In other years no effect was found. So the model is not sensitive to inaccuracies in wind speed data.

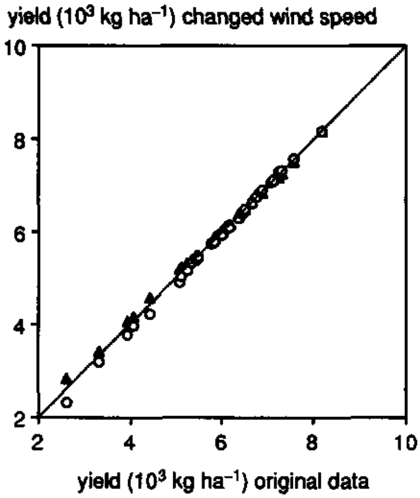


Figure 4.15 Comparison between water-limited yield simulated with the original weather data set (Wageningen 1954-1987) and simulated yield when wind speed in the original set was doubled (o) or halved (▲).

The average wind speed in de Bilt over 1976-1985 is 0.3 m s^{-1} higher and in de Kooy 3 m s^{-1} higher than in Wageningen (table 4.3), which is in accordance with data in Wieringa & Rijkoort (1983). Use of average values implied a small deviation from the original data.

Use of average values, even the ones over several years, and data from de Bilt resulted in the same deviation in simulated yield (2 % in dry years). When data from de Kooy were used, although wind speed in this part of the country is 30 % higher than in Wageningen, the effect was small: an underestimation in the simulated yield of less than 3 % was obtained in nearly all years.

Table 4.3 Average deviation in wind speed (m s^{-1}) between the original value (x_{oi}) on day i in the data set from Wageningen and the estimated value (x_{ei}) using various estimation methods. Methods considered are data from another station (de Bilt, de Kooy) and average values over various intervals from Wageningen (10 days, one month or climatic data). n is the number of days: 3650 (1976-1986).

	$\frac{\sum_{i=1}^{n}(x_{oi}-x_{ei})}{n}$	$\sqrt{\frac{\sum_{i=1}^{n}(x_{oi}-x_{ei})^2}{n}}$
De Bilt	−0.3	0.9
De Kooy	−3.0	3.4
10 day averages	0.0	1.1
monthly averages	0.0	1.2
climatic averages	0.0	1.3

Conclusions

The model is not sensitive to irregularities in wind speed data and there is no need to take the effects of inaccuracies in these data into account. When wind speed data are missing, they can be replaced by average data (even the ones over several years will do) or by data from another station. It is important to verify the height at which data are recorded and the dimensions used, since frequently occurring mistakes in reference height or dimensions can result in deviations in simulated yield of 10 % in dry years.

4.6 Random errors in all weather data

In the previous paragraphs the effect of inaccuracies in individual weather variables on the simulation result was studied. In practice, errors will occur in all data on all days. Often data are not systematically over or underestimated. Therefore the effect of random errors in all data on the simulation results is studied.
It was assumed that each weather variable was under or overestimated with its inaccuracy as estimated in this study. A random number generator was used to generate a value x in the interval [0,1]. When x was smaller than 0.5 the value of the weather element in the original data set was decreased with its inaccuracy and when x was equal to or larger than 0.5 the value was increased. This was done for all weather elements on all days. To get insight in the extremes that could occur due to these random errors a large number of simulation runs was made (100) for each year.
The effect of random errors on the simulated yield was very small. The largest deviation in simulated yield found in the 34 years * 100 runs was only 400 kg ha^{-1}. So when only random errors occur in weather data there is no need to take them into account. In practice, however, weather data are subject to systematic errors. Precipitation, for instance, is always underestimated (Buishand & Velds 1980) and the systematic errors are sometimes larger than the random errors (de Vries 1955). The effects of systematic over or underestimation of weather data on the simulation results, as discussed in the previous paragraphs, give therefore a better indication of the possible effects of irregularities in weather data on the simulation results.

4.7 All data from another station

Introduction and method

When a simulation model is used in combination with a field experiment, in principle, weather data from this field are required to simulate the production in this experiment. In practice weather data are obtained from a nearby weather station, so differences exist between the weather circumstances at the field experiment and at the weather station. The effect of the use of data from a station at a certain distance is studied by running the model with the complete data sets from de Bilt (1961-1987) and from de Kooy (1976-1985). This is done for the potential production and for the water-limited production.

Results and discussion

For both potential and water-limited production the average simulated yield was the same when weather data from Wageningen or de Bilt were used (figures 4.16 and 4.17). However, on both production levels differences in simulated yield in individual years of 2 ton ha^{-1} occurred. When weather data from de Kooy were used, the average simulated yield was higher than when Wageningen data were used (figures 4.16 and 4.17).

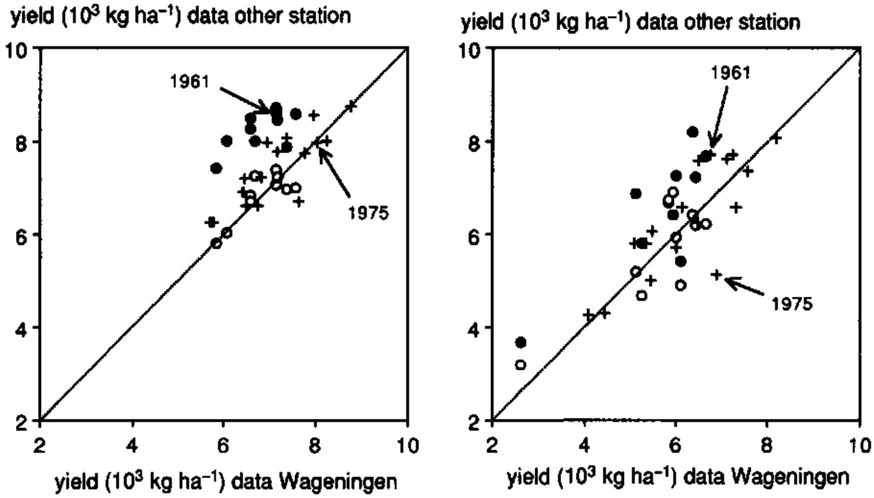


Figure 4.16 (left) Comparison between potential yield simulated with the weather data from Wageningen (1961-1987) and yield simulated with the weather data from de Bilt (1976-1985): o , de Kooy (1976-1985): ● , and de Bilt (1961-1975 and 1986,1987): +.

Figure 4.17 (right) Comparison between water-limited yield simulated with the weather data from Wageningen (1961-1987) and yield simulated with the weather data from de Bilt (1976-1985): o , data de Kooy (1976-1985): ● , and de Bilt (1961-1975 and 1986,1987): +.

The large deviation in simulated yield when data from de Kooy are used is not surprising: in the previous paragraphs was shown that individual weather data from de Kooy can not be used to replace missing values in the data set.

Individual data from de Bilt were good estimates for missing values from Wageningen, however, the complete data set from de Bilt resulted in important deviations in simulated yield. The explanation for this is found in the fact that weather variables are correlated. High radiation levels occur in combination with high air temperatures and low precipitation amounts.
The deviation in 1961 is caused by the higher radiation levels in de Bilt in that particular year, through which a higher potential yield is obtained and since no water shortage exists the water-limited production is also overestimated. The underestimation of the water-limited yield by 2 ton ha^{-1} in 1975 is caused by the far lower precipitation amount in de Bilt (100 mm less during the growing season) in combination with higher radiation levels and higher temperatures. Higher air temperatures lead to a decline in yield (section 4.1), lower precipitation to increased water shortage and so to a yield decline (section 4.3) and higher radiation levels in dry circumstances also to a decline in yield (section 4.2)
When in the data set from de Bilt (1975) precipitation data were replaced by the ones from Arnhem, the deviation in simulated yield was reduced to less than 1 ton ha^{-1} (see section 4.3).

Conclusions

Even when two sites are in the same climatic district, differences in daily weather exist between the two sites. These differences are such that large deviations in simulated yield can occur. An important part of the deviation is caused by the differences in precipitation. When no weather data from the field experiment are available for simulation of the water-limited production, the best solution is to use air temperature, radiation, vapour pressure and wind speed data from a nearby weather station and rainfall data from the nearest rainfall station.

4.8 General discussion

The sensitivity of a crop growth simulation model to inaccuracies in weather data is strongly determined by the way effects of weather on crop growth are simulated. In models consisting only of linear relations, use of average values instead of daily data will not influence the simulation result.
The type of crop simulated will also affect the sensitivity. From wheat only the production during the last weeks of the growing season is harvested. Hence overestimation of global radiation can result in a decline in yield (section 4.2). When total biomass of a crop is harvested this will not occur, because the overestimated production early in season is included in the yield.
The effect of use of averages and data from another station on the simulation output is dependent on the climate. In the Netherlands large variation exists

between the weather conditions from one day to another, as was shown for temperature and radiation in chapters 2 and 3. This variation implies that an average value is not a good estimate for a daily one. In climates where differences in weather between successive days are smaller, averages are likely to be better estimates for daily values, through which the deviation in simulation results can be smaller. The effect of use of averages in other climates will be discussed in chapter 5.

The Dutch climate is largely influenced by the sea. Hence a gradient exists in all weather elements from west to east over the country. Due to this gradient and the very irregular distribution of the precipitation, large differences in weather can exist over relatively small distances (40 km). In climates where the regional differences are smaller the effect of the use of data from another station on the simulation results can be smaller than found in here. On the other hand, the density of meteorological stations in western Europe is highest in the world and use of data from another station is a realistic option. In other continents the nearest station is often too far away.

The effects of irregularities in weather data on the simulation results as found in here are therefore not entirely applicable to other models and other climates. It was, however, shown that inaccuracies in weather data are such that they can influence the simulation results to a large extent. Users of simulation models should be aware of them and realise that deviations between simulation and field experiment can be caused by the irregularities in weather data. It was also shown that use of average weather data as input in models developed for daily values is not without risk and that choice of the site where weather data are obtained from has a large effect on the simulation results. Therefore weather data should not be considered errorless and should not be taken at face value.

Chapter 5

The effects of use of average instead of daily weather data in crop growth simulation models

Abstract Development and use of crop growth simulation models has increased in the last decades. Most crop growth models require daily weather data as input values. These data are not easy to obtain and therefore in many studies daily data are generated, or average values are used as input data for these models. In crop growth models non-linear relations often occur. Thus the simulation result with average data can be different from the average result with daily data. In this chapter the effects of using average weather data on simulated yield were investigated with a spring wheat crop growth model. This was done with weather data from sites in three different climates: a temperate maritime, a mediterranean and a humid tropical climate. For all three sites the variability of weather during the growing season was quantified. It was shown that sites hardly differed in this variability. The explanation of this result was found in the fact that all over the world crops are grown during seasons in which rain falls. The existence of dry and wet days results in a day to day variation in weather.

For all sites a 5-15 % overestimation of simulated potential yield was found as a result of using average weather data. For water-limited production the use of average data resulted in overestimation of yield in the wet conditions and underestimation of yield in dry conditions.

Introduction

In the last decades the quantitative approach of crop growth has taken a high flight, resulting in the development of crop growth simulation models by various research groups in the world (Whisler et al. 1986). These models simulate crop growth and development under specified conditions and vary in background and structure. Crop growth is strongly influenced by weather conditions. In crop growth simulation models vital effects of weather conditions on crop growth processes are therefore described and weather data are important input. Presently for major crops like wheat, maize etc. well developed crop growth simulation models exist (Ritchie & Otter 1984, Jones & Kiniry 1986, van Keulen & Seligman 1987, Spitters et al. 1989). In general these models operate with a time interval of one day and require daily weather data as input.

The overall effect of weather conditions on crop production is rather ambiguous. The effect of, for instance, high radiation levels at high temperatures can differ considerably from the effect at low temperatures. In studies involving the effect of weather conditions on crop yields, simulation models can serve as a tool since weather-crop growth relations are quantified in them. In the last years several studies have been published in which crop growth models were used to quantify growing conditions of crops. Examples are studies on production possibilities in various regions of the world (van Keulen & de Milliano 1984, Hodges et al. 1987, van Keulen et al. 1987, Aggarwal & Penning de Vries 1989, van Diepen et al. 1990, Lopez-Tirado & Jones, 1991), or on the effects of climate change on crop production (Wilks 1988, Adams et al. 1990, Cooter 1990, Jansen 1990). When existing crop growth models are used for such large scale type of research, problems often occur with respect to availability of required input data. Daily weather data are seldom available. Therefore in land evaluation studies weather data are generated from average values or averages are used (van Keulen & de Milliano 1984, Aggarwal & Penning de Vries 1989, van Diepen et al. 1990, Lopez-Tirano & Jones 1991). Because weather-crop growth relations in models are often non-linear, simulation results with average input data can deviate from average simulation results with daily data. The use of crop growth models in this large scale type of research is likely to increase in the future; it is therefore important to analyse the effects of using average weather data on the simulation results of these models.

It is expected that deviation in results is related to the variability of the weather. When weather is constant, the average value will not deviate from the daily values and the simulation result will be the same. When large variations in weather exist the deviation from the daily value can be large, causing deviations in simulation results. So the effect of using averages is likely to vary with climate. To investigate the magnitude of this climate effect simulation runs were made with data from sites in three different climates: Wageningen in The Netherlands (temperate maritime climate), Migda in Israel (mediterranean climate) and Los Baños in the Philippines in the humid tropics. Only from these sites daily weather data over many years were available.

The effects of using average weather data as input were studied for a spring wheat crop growth simulation model.

Climate and agricultural practices on locations studied

The Netherlands

In The Netherlands average air temperature varies from 1 °C in January to 17 °C in July and August. Precipitation (mostly from frontal depressions, Können 1983) is distributed homogeneously over the year, with an average of 60-70 mm month^{-1}. Large differences in total annual precipitation may occur (400-1200 mm, Buishand & Velds 1980). Global radiation varies from 2 MJ m^{-2} d^{-1} in winter to 17 MJ m^{-2} d^{-1} in summer (Können 1983). Large differences exist in radiation levels on successive days (chapter 3). Daylength on the longest day is 17 h. Relative humidity of the air is rather constant over the year (70 %). Average wind speed is 4-5 m s^{-1}, short periods with high wind

speeds (gales) occur between October and April (Können 1983).
In The Netherlands spring wheat is sown in March and harvested in August. The average yield is 6 ton ha^{-1} (de Jong 1986). Only in extreme dry years (total precipitation during the growing season less than 250 mm) do spring wheat crops suffer from water shortage (chapter 4).

Israel

Migda is located in the northern Negev. In this region precipitation occurs during the winter period (60 % of the annual precipitation in concentrated in December and January). Average rainfall is 250 mm $year^{-1}$, but large annual variation exists (50-450 mm $year^{-1}$) (van Keulen 1975). Precipitation falls in showers of 10-30 mm. Average air temperatures in January are 13 °C increasing up to 27 °C in August. Daylength on the longest day is 14 h. Radiation increases from 11 MJ m^{-2} d^{-1} in December to 27 MJ m^{-2} d^{-1} in August. Relative humidity is low (40-60 %) and the average wind speed is 2 m s^{-1} (Taha et al. 1981)
In Israel wheat is sown in November / December, when the winter rains start, and harvested in May. Water is the main limiting factor and yields are strongly determined by the amount of precipitation during the growing season. Yields in Migda vary between 0.5 - 3 ton ha^{-1} under rainfed conditions (van Keulen & Seligman 1987).

Philippines

The Philippines are located in the tropical oceans, with average water temperatures of about 27 °C. Therefore the annual variation in air temperature is very small (24-28 °C). With respect to the precipitation, this area is dependent on the monsoon. Hence there are distinct dry and wet seasons. Most of the precipitation occurs in July till November with average amounts of 100 mm $month^{-1}$ in this season, often as tropical showers of over 50 mm. In the dry season the radiation levels are higher than in the wet season (20 MJ m^{-2} d^{-1} in dry season, 15 MJ m^{-2} d^{-1} in wet season; Flores & Balagot 1969, Oldeman & Frère 1982). Since the Philippines are situated near the equator the annual variation in radiation is small (daylength on longest day is 13 hours). Relative humidity of the air is high (80 %) and average wind speed is low (2 m s^{-1}), but since the area is frequently visited by tropical typhoons large deviations of this average occur.
Spring wheat is not a common crop in the Philippines: this area is mainly orientated on rice growing. Some research is done on growing wheat as a second crop after rice. In those cases wheat is sown in November / December and harvested in March (Aggarwal et al. 1987). The growing season is very

short due to the high air temperatures, yields are therefore low (2-3 ton ha^{-1}).

Material and methods

Weather data

Daily weather data were available for Wageningen (lat. 52° N, long. 5° E) from 1954-1987, for Los Baños (lat. 14° N, long. 121° E) from 1959-1984 and for Migda (lat. 31° N, long. 34° E) from 1962-1983 . The data sets contained daily data on minimum air temperature (°C), maximum air temperature (°C), total global radiation (MJ m^{-2} d^{-1}), total precipitation (mm), early morning vapour pressure (mb) and average wind speed (m s^{-1}). Data over complete years were available from Wageningen and Los Baños, while only weather data for the growing season (September- May) were available for Migda. All data in the sets were checked by hand and the values of missing data were replaced by estimates. When data on temperature, global radiation and precipitation were missing for more than one week the complete year was discarded (1964-5, 1967-8 in Migda). When data on vapour pressure and wind speed were missing, average values were used to replace missing data (sections 4.4 and 4.5). The effects of the use of average values over (i) 10 days, (ii) one month and (iii) a complete growing season on the simulation results were studied. The effects of using averages over several years (climatic averages) based on daily values, 10-day averages, monthly averages and seasonal values on the simulation result were also investigated.

Average weather data were derived from the daily weather data sets. For each variable the average value per month was calculated. When these averages were used as input data for the crop growth simulation model, it was assumed the average values occurred on the 15th of every month and that on days in between the value of the variable could be derived by linear interpolation. For precipitation this method implies that total precipitation over a month is averaged over 30 days and hence it rains every day. This contrasts the actual situation in which there are dry and wet days. The same method was applied for the averages over 10 days, but then the average values were expected to occur at day 5 of the interval. The seasonal average was calculated by averaging the daily weather from the 180 days after sowing date on the three sites. Use of these averages implied that the weather was the same on all days of the growing season.

Climatic averages were derived from the sets of daily and averaged data. In the set with climatic data based on daily values global radiation on January 1st is the average global radiation of all January 1st's from the daily data set. So the set with climatic data based on daily data contained 365 days of averaged weather (table 5.1). In the set with climatic data based on monthly values, the global radiation in January is the averaged radiation from all January's in the set with monthly averages. The size of the data sets used for Wageningen is given in table 5.1. For Migda, averages were only calculated for the growing season.

Table 5.1 The size of the data sets for Wageningen.

data set	number of data		composed of	
daily data	74460	= 34 years	*365 days	*6 variables
10 day averages	7344	= 34 years	*36*10 days	*6 variables
monthly averages	2448	= 34 years	*12 months	*6 variables
season averages	204	= 34 years	*1 season	*6 variables
climate based on days	2190	=	365 days	*6 variables
climate based on 10 days	216	=	36 *10 days	*6 variables
climate based on months	72	=	12 months	*6 variables
climate based on seasons	6	=	1 season	*6 variables

To quantify the variation in weather at the three sites, the average deviation (dev) from the daily values was calculated for each weather variable for each averaging interval according to:

$$dev=\sqrt{\frac{\sum_{i=1}^{n}(x_{di}-x_{ai})^2}{n}} \tag{5.1}$$

in which x_{di} is the value in the original daily data set for day i, x_{ai} is the value for day i derived from a set with average data. This was done over all years available.

Variability of the weather differs between seasons: it will be low in the dry hot summer and higher during the wet season. The simulation result is only affected by variability during the growing season (the model only runs from sowing till maturing of the crop). Therefore deviations were only calculated for the 180 days after start of the simulation on the three sites. So for Wageningen n equals 34 (years)*180 (days)= 6120.

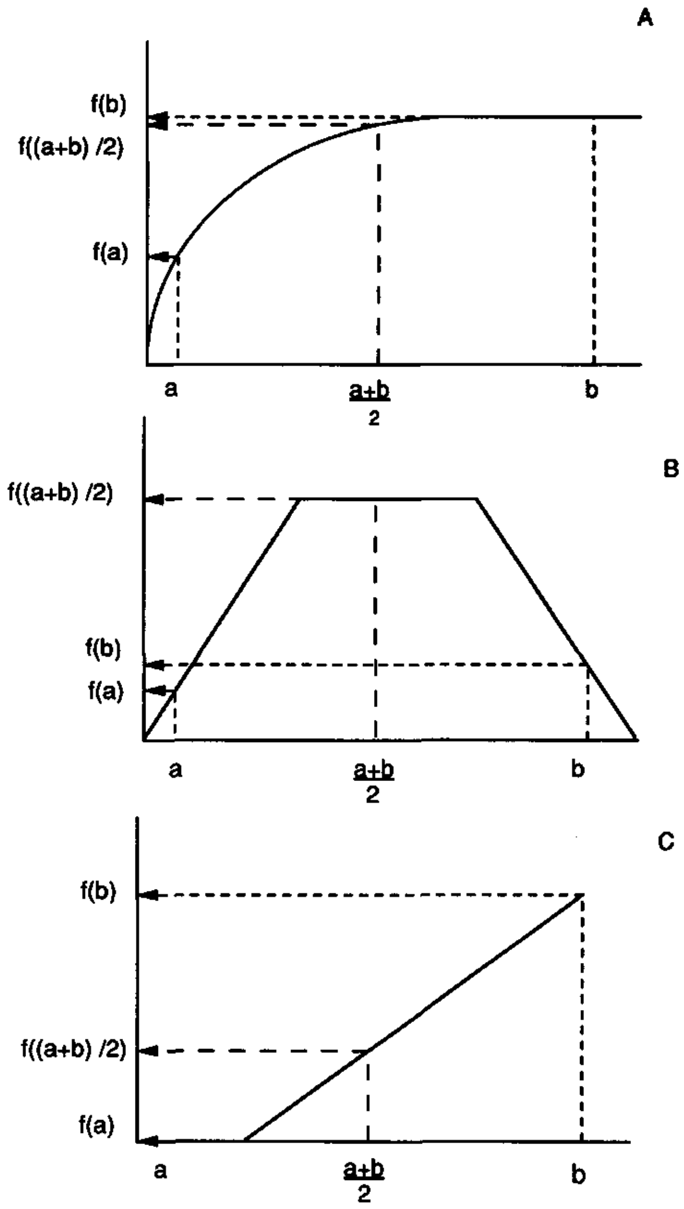


Figure 5.1 Some examples of non-linear relations incorporated in the crop growth simulation model and the effect of using average input data in these functions.
A the photosynthesis-light response curve for individual leaves,
B effect of temperature on the photosynthetic rate at light saturation,
C effect of temperature on crop emergence rate.

Simulation model

The effects of using average weather data were studied for the same model as used in previous chapters (2, 3 and 4). 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/or water-limited production in which growth is also limited by water shortage (de Wit & Penning de Vries 1982). In chapters 2, 3 and 4 it is shown that the sensitivity of this model to changes in weather variables is not the same for both production levels. Therefore the effects of using averaged weather data for both the potential and the water-limited production were studied.
Total assimilation of the crop is calculated from the photosynthesis at leaf level. The basis is the photosynthetic-light response curve for individual leaves. Since this function reaches a saturation level at high light intensities (figure 5.1a), the use of averages for global radiation results in overestimation of photosynthesis (chapter 3). Both low and high temperature have a negative effect on maximum rate of leaf photosynthesis at light saturation. When average temperatures are used these extremes are lost (figure 5.1b). The average temperature is therefore more favourable for crop growth than the daily temperatures. A base temperature exists for most development rates in the model. Below this temperature no development occurs. Use of average data results in temperatures always above the base temperature (figure 5.1c). Hence average data can effect development rate of the crop.
The soil is treated as a multi-layered system with 10 layers. When precipitation occurs, the first soil layer is filled up to field capacity and all excess water entering the layer drains to next layers. 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. The amount of moisture in the profile is strongly determined by the distribution of the precipitation. A large shower (of over 100 mm) causes all layers of the profile to become saturated and water drains below the rooted zone. Very small showers (of less than 2 mm) will saturate only the top layer of the soil. A large part will evaporate and never reach the roots.

Initial conditions, at the start of the simulation, for the three locations were made in accordance with present agricultural practices for rainfed spring wheat. For Wageningen this implies that the crop was sown on March 11th and that the soil profile was at field capacity. For the Migda data, sowing was set to November 1st and soil was at wilting point and for the Los Baños data sowing was at December 1st and the soil profile was at field capacity. For the water-limited production soil characteristics from a hypothetical soil with a low available water holding capacity were used. This was done to achieve large differences in

potential and water-limited production.
Eight simulation runs were made for each production level (potential and water-limited), on each site: using the set with 1) daily data, 2) 10-day averages, 3) monthly averages and 4) seasonal averages and climatic averages over the years available based on 5) daily data, 6) 10-day averages, 7) monthly averages and 8) seasonal averages. Runs 1 to 4 used data for 20-34 years resulting in 20-34 yields, while runs 5 to 8 were each for only one (average) growing season resulting in one yield per run.

Table 5.2 Average deviations from daily values for six weather variables (minimum temperature (Tmin), maximum temperature (Tmax), global radiation (Rad), precipitation (Rain), vapour pressure (Vap), wind speed (Wind)) when averages over several intervals are used. For three sites: Wageningen, The Netherlands; Migda, Israel and Los Baños, Philippines.

site	interval	Tmin °C	Tmax °C	Rad MJ m^{-2} d^{-1}	Rain mm	Vap mb	Wind m s^{-1}
Wageningen	10 days	2.7	3.0	4.8	4.2	2.0	1.3
Wageningen	month	3.1	3.6	5.3	4.4	2.3	1.4
Wageningen	season	5.0	5.7	6.2	4.5	3.8	1.4
Wageningen	climate (days)	3.4	4.0	5.6	4.5	2.5	1.5
Migda	10 days	2.3	3.3	3.6	5.5	2.4	0.7
Migda	month	2.6	3.8	3.8	5.7	2.5	0.8
Migda	season	3.4	5.2	5.5	5.7	3.0	0.8
Migda	climate (days)	2.8	4.1	4.3	5.8	2.7	0.8
Los Baños	10 days	0.9	1.3	4.0	10.3	2.2	0.4
Los Baños	month	1.0	1.5	4.4	10.7	2.4	0.4
Los Baños	season	1.5	2.7	6.0	11.3	2.9	0.5
Los Baños	climate (days)	1.2	1.8	4.7	10.9	2.6	0.5

Results

Weather data

The data in the table 5.2 represent deviations of average values from daily values (equation 5.1), for all weather variables on the three sites. In general the deviation increased with increasing the length of averaged period within the season (10 days < month < season). For minimum temperature, maximum temperature, radiation and vapour pressure, the deviation from the climatic average on a daily basis was smaller than the deviation from the seasonal averages. The average deviation from climatic averages based on 10-day or monthly data was the same as the one calculated for averages based on daily data. The average deviation from climatic averages based on season values was similar to the one calculated for seasonal values in individual years.

The deviation in minimum temperature was smaller than in the maximum temperature and deviation in temperature in Los Baños was very small. Large variations in radiation levels occurred on all sites. Deviations were smallest in Migda, followed by Los Baños. The deviation in precipitation was hardly affected by length of the averaged interval. Deviations were large in Los Baños. Variations in vapour pressure were nearly the same for all sites, and deviations in wind speed were low for all sites.

Simulation results

Wageningen

Simulated potential and water-limited spring wheat yields using daily weather data from Wageningen over 34 years are shown in figure 5.2a. Potential yields varied from 5.7 to 8.7 ton ha^{-1}, whereas water-limited yields varied from 2.6 to 8.2 ton ha^{-1}. Only in a few years (1957, 1959, 1973, 1976 and 1986) was the water-limited yield much (4 ton ha^{-1}) lower than the potential yield.

Use of averages over short periods (10 days or one month) for simulation of potential production resulted in an overestimation of the simulated yield, but between year variability of the yields remained (figure 5.2b, table 5.3). With the exception of a few years, simulation results with 10-day values were the same as those with the monthly values. Yield was underestimated in most years when averages over complete growing seasons were used and the variability of the yields decreased.
The effect of using averages for the simulation of water-limited production differed from the effect for potential production. Figure 5.2c shows that use of short term averages led to underestimation of the yield in dry years and overestimation in wet years, increasing the variability of yields (table 5.3). Use of seasonal averages resulted in overestimation of the yield in most years and a decline in variability.
Small differences in simulated yield were obtained, when climatic averages based on different intervals were used as input (table 5.4). Only the simulated potential yield with climatic averages based on seasonal values was markedly lower.

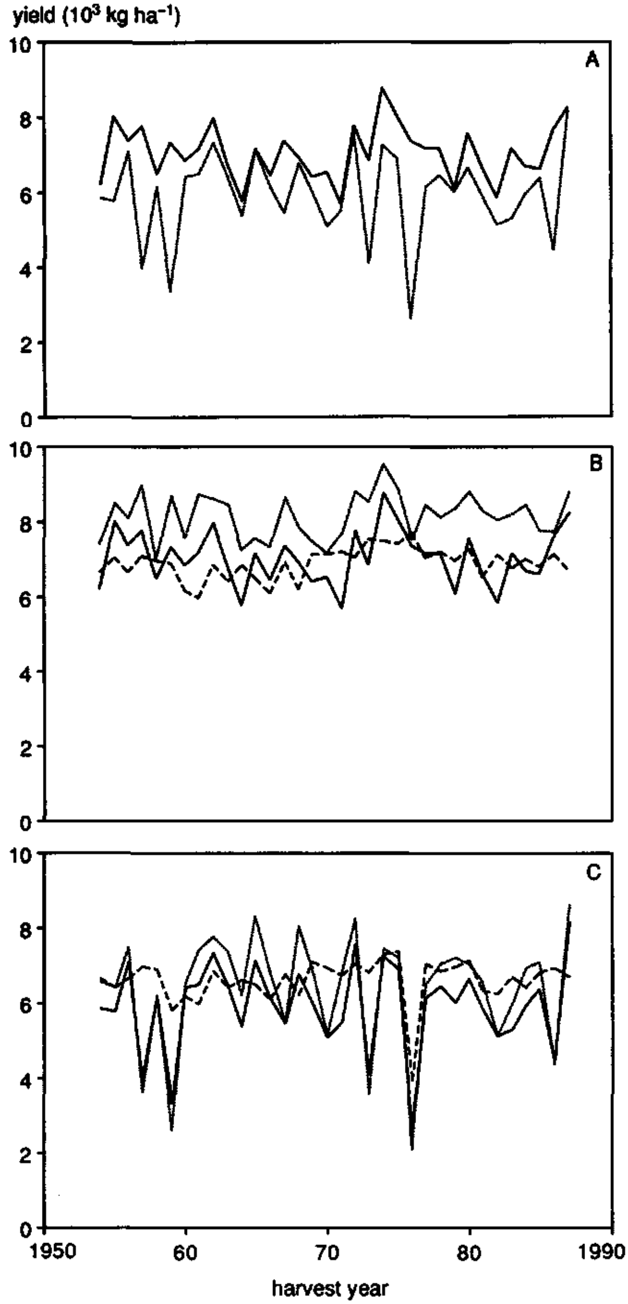


Figure 5.2 Effect of using daily and average weather data as input on simulated potential and water-limited production in Wageningen. A: simulated potential (——) and water-limited (·········) production using daily weather data, B: simulated potential production using daily data (——) and monthly (·········) or seasonal averages (– – –), C: simulated water-limited production using daily data (——) and monthly (·········) or a seasonal averages (– – –).

Table 5.3 Averages of simulated potential yield and water-limited yield and associated standard deviations (ton ha^{-1}) using either daily values, averages over 10 days, monthly averages or seasonal averages as input.

	day	10 days	month	season
potential				
Wageningen	7.0 (0.7)	8.0 (0.6)	8.1 (0.6)	6.9 (0.4)
Migda	8.7 (0.6)	9.2 (0.5)	9.3 (0.6)	9.0 (0.5)
Los Baños	2.0 (0.4)	2.3 (0.4)	2.3 (0.4)	2.3 (0.3)
water-limited				
Wageningen	5.9 (1.2)	6.4 (1.5)	6.6 (1.3)	6.6 (0.6)
Migda	2.6 (1.8)	1.6 (1.5)	1.3 (1.1)	1.0 (0.9)
Los Baños	1.6 (0.2)	1.7 (0.2)	1.8 (0.2)	1.7 (0.4)

Migda

The potential and water-limited production of spring wheat simulated with daily weather data from Migda 1962-1983 (seasons 64-65 and 67-68 were missing) is shown in figure 5.3a. Potential production varied from 7.5-9.5 ton ha^{-1}. Simulated water-limited production was much lower: 0.3-6.0 ton ha^{-1}. Severe water shortage existed in all years.

Use of averages over short periods (10 days or one month) resulted in overestimation of the potential yield by about 0.6 ton ha^{-1} in all years and variability was retained (figure 5.3b, table 5.3). Differences in simulated yields with these averages were very small. The use of seasonal averages led to overestimation of yield in most years. For water-limited production use of averages led to underestimation of yields in nearly all years and a decline in variability was observed. Averages over 10 days gave the smallest deviation (1.0 ton ha^{-1}) (table 5.3). In 1967 an overestimation of the yield was obtained when averages were used (figure 5.3c).

When climatic averages were used as input, hardly any difference in simulated potential yield was found between the intervals. For water-limited production different results were obtained: the climatic average based on daily data yielded highest (table 5.4).

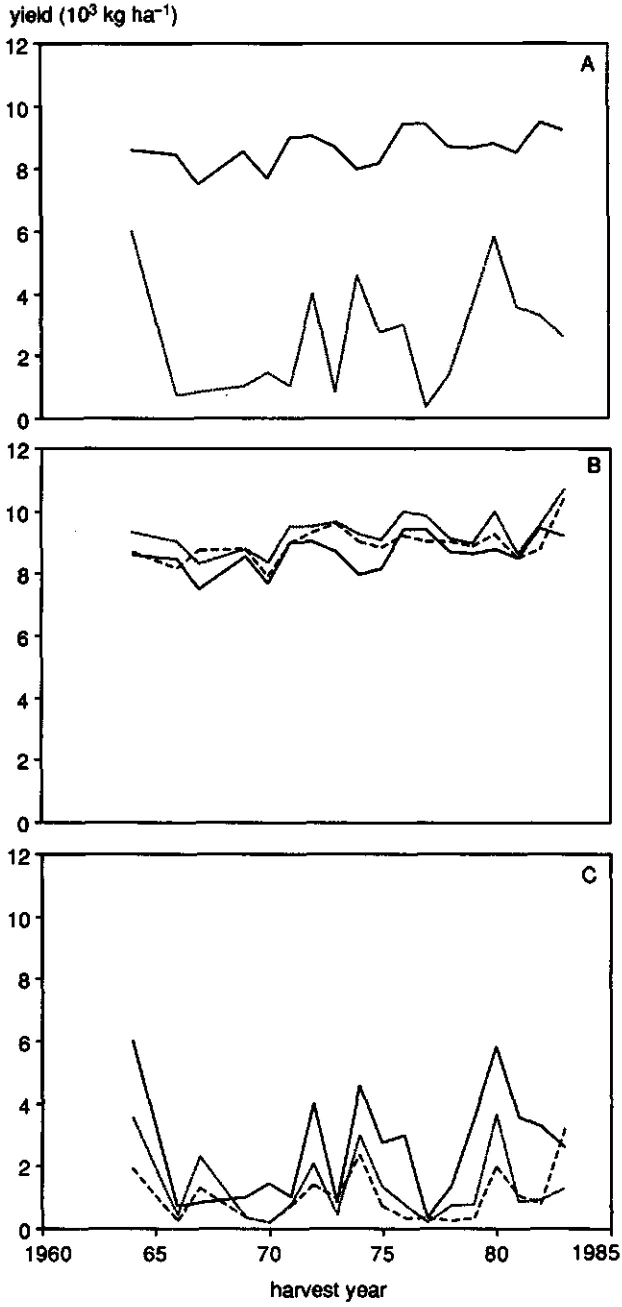


Figure 5.3 Effect of using daily and average weather data as input on simulated potential and water-limited production in Migda. A: simulated potential (———) and water-limited (··········) production using daily weather data, B: simulated potential production using daily data (———) and monthly (··········) or seasonal averages (— — —), C: simulated water-limited production using daily data (———) and monthly (··········) or seasonal averages (— — —).

Table 5.4 Simulated potential yield and water-limited yield (ton ha^{-1}) using climatic averages based on daily weather data, 10 day averages, monthly averages or seasonal averages as input.

	day	10 days	month	season
potential				
Wageningen	8.1	8.4	8.4	7.0
Migda	9.0	9.0	8.9	8.9
Los Baños	2.3	2.4	2.3	2.3
water-limited				
Wageningen	6.7	6.8	6.8	6.9
Migda	1.3	0.9	0.8	0.8
Los Baños	1.8	1.9	1.9	1.8

Los Baños

Simulated potential and water-limited yields using daily weather data from Los Baños (1959-1984) are shown in figure 5.4a. Both potential and water-limited yields were low (1-3 ton ha^{-1}) in comparison with the simulated yields with data from the other locations. The difference between the two production levels was small with a maximum of 1 ton ha^{-1}.
Use of averages over short periods led to small increases in simulated potential yield (up to 0.5 ton ha^{-1}, figure 5.4b). In most years no difference existed in results with 10-day and monthly averages. When seasonal averages were used yields were overestimated in most years. The deviation in the water-limited yield was small when averages over 10 days or one month were used, only 0.1-0.2 ton ha^{-1} (figure 5.4c). The use of seasonal averages resulted in both over and underestimation of simulated yield and variability increased.
For both production levels only small differences were found in simulated yield using climatic averages based on different intervals (table 5.4).

Discussion

When precipitation is left out of consideration, weather in the mediterranean and humid tropics is intuitively far more constant than weather in the temperate maritime climates. This impression is not in accordance with the deviations shown in table 5.2. Only for Los Baños deviations in temperature were importantly smaller than the ones calculated for Wageningen. However, it should be realised that in table 5.2 the deviation during the growing season is given. The growing season in Israel and the Philippines takes place in the

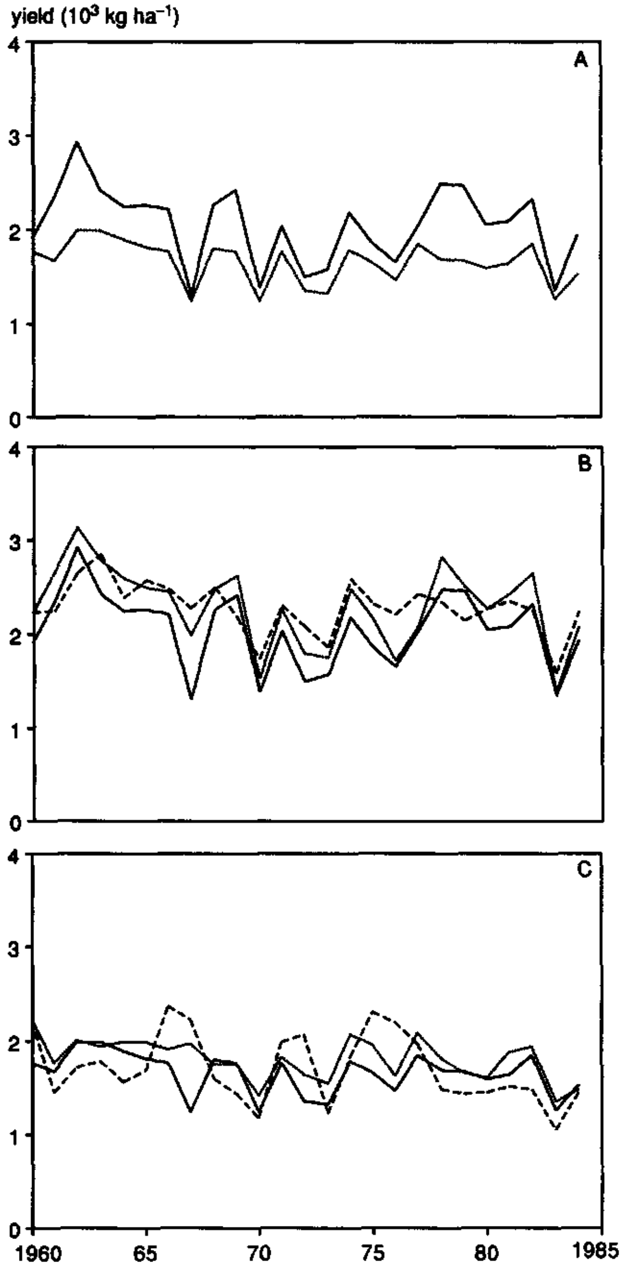


Figure 5.4 Effect of using daily and average weather data on simulated potential and water-limited production in Los Baños. A: simulated potential (———) and water-limited (·········) production using daily weather data, B: simulated potential production using daily data (———) and monthly (·········) or seasonal averages (— — —), C: simulated water-limited production using daily data (———) and monthly (·········) or seasonal averages (— — —).

winter period and in The Netherlands in the summer season. Based on table 5.2 it can be concluded that weather in the summer in The Netherlands is as variable as the weather in the Israeli and Philippine winter.

In general crops are grown in the season in which rain falls. Due to the existence of dry and rainy days in these seasons large variation in radiation occurs on successive days (clouds!) and on most locations also in temperature. So in most growing seasons deviation in simulated yields as result of the use of averages can be expected. When crops are grown exclusively under irrigation in a dry season the deviation is likely to be smaller. Since this not a common practice in agriculture, the effect of using average values in this situation was not studied.

Besides the day to day variability of the weather most weather variables show a certain course during the year (e.g., low temperatures in winter and high temperatures in summer). When seasonal averages are used this trend in lost, leading to a larger deviation from the daily values than the climatic averages in which this trend is retained.

Since on all three sites large variability in weather existed, it is not surprising that the use of averages influenced the simulation results everywhere. The effect of using averages as input depended on the length of the averaged interval and the production level.

Potential production

Potential production is only determined by temperature and radiation. Radiation drives photosynthesis and temperature determines development of the crop. Correct simulation of development is vital, since the effect of certain weather conditions on crop growth can vary with the stage of development. Above the threshold value, the effect of temperature on development rate is linear. When average values over short periods are used, development of the crop is often not affected. In those cases yield is overestimated because of overestimation of photosynthesis (figure 5.1a) and annual variation in yield is remained. When averages over a complete season are used, temperature is overestimated in the early season and underestimated in the late season. This affects individual development stages (the vegetative period becomes shorter and the grain filling period longer). On sites with a large range in temperature during the season (Wageningen and Migda, table 5.2) the effect of using seasonal averages on simulated yield is therefore far different from the effect of averages over shorter periods (figures 5.2b and 5.3b). In Los Baños, where temperature is more or less constant over the season, the effect is much smaller (figure 5.4b).

At Wageningen the similarity between average yield with seasonal averages and average simulated yield with daily data (table 5.3) is a coincidence. It can not be concluded that use of seasonal averages gives a better result than averages over shorter intervals. For spring wheat, in The Netherlands, a long vegetative period is important. Reduction of this period leads to a yield decline. When seasonal averages are used, overestimation of the yield due to averaging radiation is counteracted by the reduction of the vegetative period (due to higher temperatures in spring). For other crops or on sites with a smaller range in temperature through the season (Los Baños) this effect will not occur (table 5.3).

When climatic averages based on short intervals (days, 10 days or months) were used, simulated yields were of the same order of magnitude as averaged yields with 10-day or monthly values. Thus when one is only interested in average potential yield in a region, climatic averages can be used as input. Although it should be kept in mind that the simulated yield is higher than the average yield with daily data. However, one often wishes to compare production possibilities in different regions. The ranking of yields among the study sites is not similar for daily values and climate averages (tables 5.3 and 5.4). The difference in average potential yield between Wageningen and Los Baños based on daily values is 5.0 ton ha^{-1}, but based on climatic averages (on a monthly basis) it is 6.1 ton ha^{-1}.
When annual variability of yield is of interest the average data over months can be used (but yields levels remain higher, than when daily data are used). The use of averages over shorter periods than one month (10 days) did not improve the simulation results either in average yield level or in annual variability. So the greater effort and expense coupled with handling and obtaining 3 times as many data are not worth the trouble. When averages over longer periods than one month are used, the seasonal trend in weather is lost, which can influence simulations results.

Water-limited production

As mentioned before the distribution of precipitation has a large effect on the amount of water available for uptake by the roots. The effect of averaging weather data on water-limited yields depends on the circumstances. In dry conditions averaging precipitation leads to an increase of water losses due to greater evaporation from the top soil layer. These effects are seen clearly when averaged weather data were used to simulate water-limited yields. For The Netherlands average weather data over short periods led to underestimation of yields in the dry years. Use of average weather data for the arid circumstances in Migda led to underestimation of yields in all years. Under wet conditions, averaging precipitation has no effect on water shortage because even when evaporations losses increase there is enough water for growth. In these cases the effects are the same as for the potential situation: averaging weather data leads to overestimation of the yield. In seasons in which only a small number of

days with water shortage exists, these effects level out. On dry days growth is underestimated and on wet days it is overestimated, resulting in only a very small deviation from yield simulated with daily data. These effects are evident in most years for the Philippines and in a number of years in The Netherlands (figures 5.2c and 5.4c).
In The Netherlands and the Philippines water is only limiting a few weeks at the end of the growing season. In the early season a water surplus exists. When averages over longer periods are used, this early season surplus compensates for the shortage at the end. Hence there are fewer years with water shortage. In The Netherlands only 1976 is dry when seasonal averages are used (figure 5.2c).
So the use of average values in the water-limited situation has an effect on the variability of yields. In regions in which dry and wet years occur, variability increases, since use of averages over short periods results in overestimation of yield in wet years and underestimation of yield in dry years. In regions in which yield is mainly determined by the amount of water available, use of averages reduces variability. Even relatively wet years become dry due to increased evaporation losses (Israel, 1964, 1980).
In Israel germination is also affected by precipitation. In the model, the crop starts to grow as soon as water is available. In 1966 first winter rains only occurred at the end of December. Use of monthly averages of precipitation implied that the 1st of December was already a wet day, so the simulated growing season started nearly one month too early, resulting in yield increase in that particular season (figure 5.3c, harvest in 1967!).

Many authors have noted the effect of rainfall distribution on the amount of water available for uptake by roots. Therefore, rainfall generators are often used when only average values are available (van Keulen et al. 1987, van Lanen et al. 1992). These routines simulate a rainfall pattern, through which wet and dry days are created (Geng et al. 1986). The use of daily precipitation values in combination with averages for the other weather variables is also practiced (Lopez-Tirano & Jones 1991). Both methods reduce the evaporation losses in comparison with the averaged rainfall data and will lead to better simulation results in arid conditions.

Concluding remarks

It can be concluded that, for the model used in here, use of average weather data lead to other simulation results than use of daily data. When averages are used, potential production is overestimated and water-limited production is overestimated in wet years and underestimated in dry years.
There are two causes for this deviation in simulation results. First the crop

model used contained non-linear relations through which average input does not result in average output. Second on locations studied a large variability in weather existed from day to day, through which daily data differed from the average value.

Most weather-crop growth relations are non-linear, so most crop growth models will contain non-linear functions. Crops are generally grown in that part of the year in which it rains. The existence of dry and rainy days leads to a large variability in weather during growing seasons all over the world.

Comparable effects as found in this paper can therefore be expected for other crop growth simulation models.

Chapter 6

Effects of changes in temperature and CO_2 concentration on simulated spring wheat yields in 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 and water-limited crop production (growth with ample supply of nutrients and in the absence of damage by pests, diseases and weeds). The model was validated for the present climatic conditions. When daily weather data 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 & Acock 1986) and leads to improved water use efficiency of crops (direct effect, Goudriaan & van Laar 1978b, 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 & Allen 1985) to modelling the effects of climatic change on crop production in various parts of the world (Rosenzweig 1985, Parry & 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 is investigated. This is mainly due to the difference in scale between the direct and indirect effects: effects on photosynthesis and stomatal conductance on the one hand and effects on global climate on the other. When such differences in scale exist, use of crop growth simulation models can be useful. In those models causal relations at various process levels can be integrated to examine the overall

effects on, for instance, growth and yield. But even when simulation models are used, *scaling problems remain. 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) making the model unsuitable for use on a larger scale. 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 winter wheat model. 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.
The input requirements of this model were such that the simulation experiment could be done only for a limited number of sites in Western Europe. In this chapter the effects for only one site in The Netherlands are described. Effects for other sites in Europe will be discussed in chapter 7. Large effort is made to validate the model for present climatic conditions. Because it is likely that agricultural practices would 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 & Velds 1980). Evapotranspiration requirements for a spring wheat crop are about 300-400 mm $season^{-1}$ (Buishand & 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 favourable 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 growth Simulator, version 1987) 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 climatic 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 is not limiting 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 by 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 & Seligman 1987). The distribution of assimilates is dependent on development stage of the crop, as described by functions derived by van Keulen & Seligman (1987). A sink limitation based on Spiertz & van Keulen (1980) was incorporated in the model; the number of grains formed is a function of the total above-ground 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 vapour pressure deficit as driving factors. Stomatal, boundary layer and aerodynamic resistance (the latter two depending on wind speed and crop structure; Goudriaan 1977) co-determine the transpiration rate. Stomatal 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 stomatal resistance. However, because a higher CO_2 concentration also stimulates assimilation per unit leaf area, stomatal 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 & Allen 1985, Cure & 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 & Seligman (1987) was used. The soil is treated as a multi-layered system with 10 layers. When precipitation occurs, the first soil layer is filled till field capacity and all excess water entering the layer drains to the next layer. 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 in proportion to 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. It is the same model as used in the previous chapters.

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 vapour 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 and/or water-limited production. In the former production is determined by crop characteristics, radiation and temperature and in the latter also by limited availability of water. In both production levels the crop is supposed to be free from pests, diseases and weeds and is optimally supplied with nutrients (de Wit & 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 corps 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 homogeneous.

Figure 6.1 Location of sites mentioned in text. 1: Emmercompascuum, 2: Wageningen, 3: Eelde, 4: Wieringermeer, 5: De Kooy.

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 (van Duivenvoorden 1986, chapter 3). The longest available set of daily data that includes global radiation was collected at Wageningen for 1954-1987 (figure 6.1). Other meteorological stations in The Netherlands started recording global radiation only in the late nineteen sixties (chapter 3).
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 years, are also scarce, especially because during the last 10 years the growing area under spring wheat declined (de Jong 1986). Only one set of data longer than 30 years could be constructed. Data were derived from spring wheat variety trials conducted on an experimental farm in Emmercompascuum (figure 6.1) 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 cut-over peat. The water 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 dates in the field experiments 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 (chapter 2, 3 and 4), the simulated and observed yields were compared (figure 6.2). This was done since both sets were unique with respect to the length of the period over which data were available.

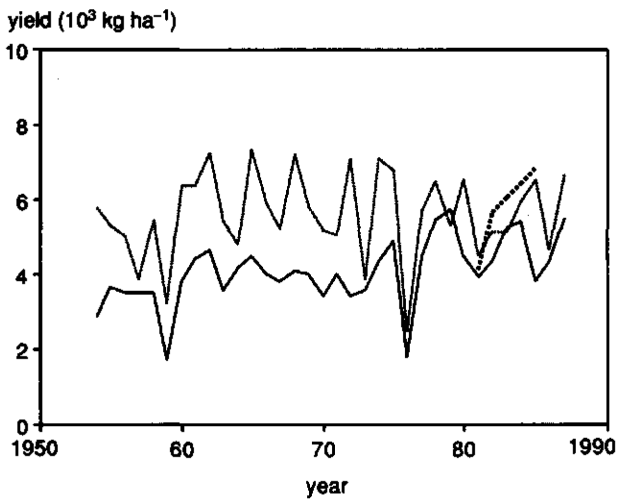


Figure 6.2 Spring wheat yields (grains, dry matter) in field experiments in Emmercompascuum (——), simulated yields with weather data from Wageningen 1954-1987 (·······) and with weather data from Eelde 1981-1985 (– – –).

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 6.2). 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 shortages and pests and diseases on crop yield were reduced. This implies that, for validation of the simulation results, data are required from field experiments conducted in the last 15 years (up to 1975 most crops were grown under suboptimal conditions).

For 5 years (1981-1985) daily weather data from Eelde (figure 6.1) were available. The simulation results with these data used as input are also shown in figure 6.2. 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. 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. 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 6.1) were used, much better simulation results were obtained (figure 6.3).

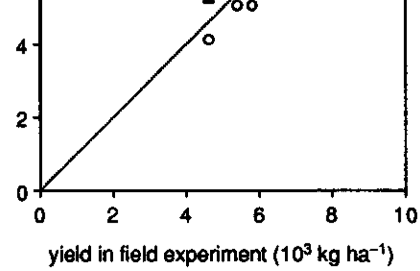


Figure 6.3 Comparison between spring wheat yields in field experiments in Wieringermeer (1976-1985) and simulated yield using weather data from Wageningen (o) and weather data from de Kooy (▲).

The distance between Eelde and Emmercompascuum and de Kooy and Wieringermeer is about 30 km. Chapter 4 illustrates the effects of use of weather data from a site at 40 km distance on simulation results (figure 4.17). Average yields were simulated well, but in individual years deviations up to 2 ton ha^{-1} in simulated yield occurred. Thus, one can not realistically expect a better agreement between observed and simulated yield than is shown in figures 6.2 and 6.3.

Growing conditions and simulated yield

Present situation

As mentioned above spring wheat yield is favoured 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 years 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 & 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 results of these runs are shown in figure 6.4. 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 & 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 favoured grain yield.

Water-limited yield was much lower than the potential one in only 5 out of 34 years (1957, 1959, 1973, 1976 and 1986, figure 6.4). 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. The total biomass produced (leaves, stems etc.) in dry years is hardly lower than in the wet ones, due to the fact that growth is only limited for a few days at the end of the growing season.

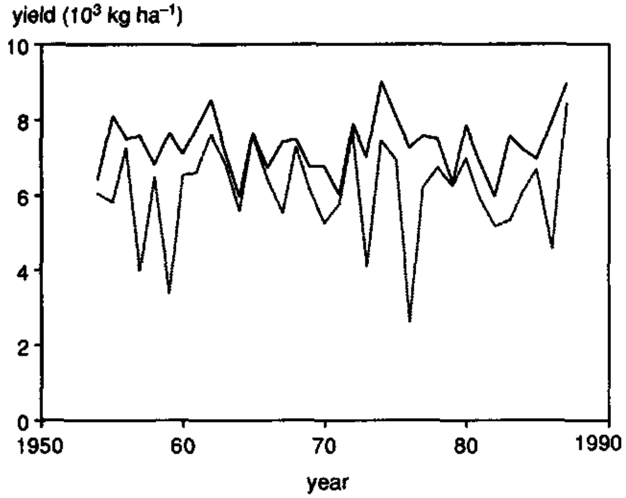


Figure 6.4 Simulated potential (——) and water-limited yield (·······) of a spring wheat crop using weather data from Wageningen 1954-1987.

Simulation of future climate

To simulate the future climate, the data set with daily weather data from Wageningen (1954-1987) and the Report of Working Group I to the Intergovernmental Panel on Climate Change (IPCC) (Houghton et al. 1990) were used as point of departure. The effect of the increasing concentration of CO_2 and other greenhouse gases on global climate is not known. 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 & Cess 1990). For crop growth it is not the global mean that is important but changes in climate during the growing season in the region where the crop is grown. Indications exist that temperature increase in growing season can deviate from the global mean (Mitchell et al. 1990). So, many combinations of temperature rise and CO_2 concentration can occur. The combinations of CO_2 concentration and temperature rise used in this study were based on the IPCC Business-As-Usual-Scenario and the 'best estimate' in the IPCC report. Since confidence in regional estimates is low (Houghton et al. 1990), the global mean temperature rise was used for the future climate. The changes in precipitation as estimated by GCM's were small (5 - 10 %) in comparison with the present inter-annual variability in The Netherlands (100 %, Buishand & Velds 1980) and were not taken into consideration.

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. Temperature rise is above the nineteen-fifty level, because the weather data set used as a baseline starts in 1954. 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 is done for the 650-700 ppm level (Cure & Acock 1986).
For each of the scenarios 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. Future weather was simulated by adding the estimated temperature rise to daily data on minimum and maximum air temperatures. Further, vapour pressure was adjusted in such way that relative humidity of the air was kept constant. Other weather variables like global radiation, precipitation and wind speed were not changed. The present atmospheric CO_2 concentration was assumed to be 350 ppm.

Scenario 2080

Potential production

Figure 6.5 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 6.4). The effect of a temperature 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.
The main effect of temperature in the model is the determination of the timing and duration of the growing period. 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 and the sink limitation was not changed. 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

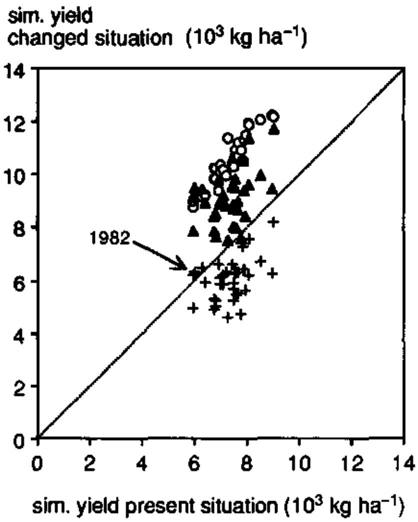


Figure 6.5 The effect of scenario 2080 on simulated potential spring wheat yields in comparison with yields simulated for the present situation. Temperature rise of 3 °C and present CO_2 concentration (+); CO_2 concentration of 700 ppm and present weather (o); temperature rise of 3 °C and CO_2 concentration of 700 ppm (▲).

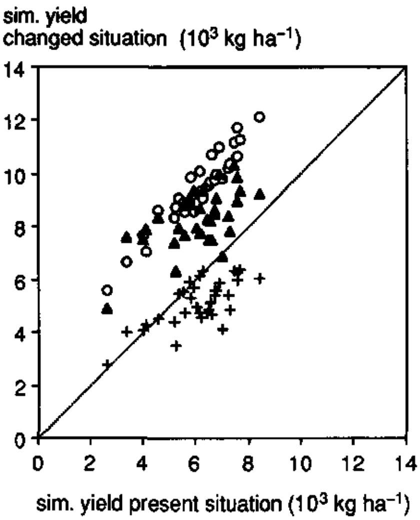
just before flowering of the crop (simulated with the original weather data). An increase in temperature resulted in earlier flowering that year, causing the period with low radiation to coincide with the grain filling period (see chapter 2). Because the production in this period is determined by the 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 6.5). Temperature also affects maintenance respiration, assimilation rate, CO_2 compensation point etc. (Goudriaan et al. 1985, Spitters et al. 1989), but these effects are relatively small in comparison with the large effects of temperature on the duration of the growing season.

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 6.5). 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 6.5). 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}). It seems that the enhanced effect of a high CO_2 concentration on leaf photosynthesis at higher temperatures (Goudriaan et al. 1985) is negated by the effects of temperature on duration of the growing season.

Water-limited production

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 6.6 and 6.7. Simulated water-limited yields in the present situation are also shown in figure 6.4. Dry years can be recognized in figure 6.6 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 present conditions but only varied from 2 to 6 ton ha^{-1} after a temperature rise of 3 °C.



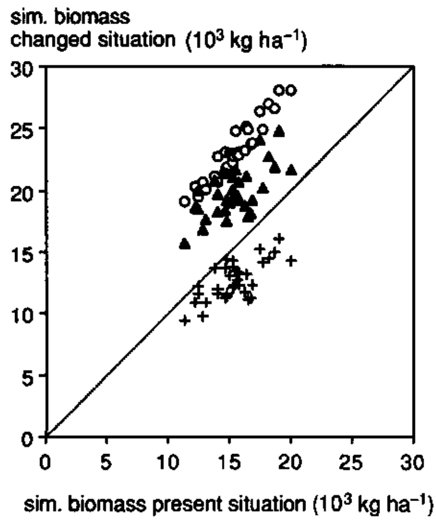


Figure 6.6 (left) The effect of scenario 2080 on simulated water-limited spring wheat yields in comparison with yields simulated for the present situation. Temperature rise of 3 °C and present CO_2 concentration (+); CO_2 concentration of 700 ppm and present weather (o); temperature rise of 3 °C and CO_2 concentration of 700 ppm (▲).

Figure 6.7 (right) 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 (o); temperature rise of 3 °C and CO_2 concentration of 700 ppm (▲).

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 6.7). 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 6.6). Higher CO_2 concentration stimulates water-limited production by increasing the assimilation rate and by reducing transpiration via increase of the stomatal 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 water shortage and increasing the yield. Reduction of total transpiration by 10 % is less than expected on the basis of the increase of stomatal 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 stomatal resistance.
The effect of higher CO_2 levels on total biomass, a 45 % increase, was smaller than the effect on yield (figure 6.7). 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 6.6). 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 literature (Gifford 1979, Sionit et al. 1980, Kimball & Idso 1983, Cure & Acock 1986, Goudriaan & Unsworth 1990)

Use of other varieties and sowing dates

As mentioned above, effects of temperature rise on simulated yields are caused by shortening and shifting the growing season. Both sensitivity of the variety to daylength and sowing date influence timing and duration of the growing season. By changing variety and sowing date in the model it is possible to restore the original growing season 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 6.8. 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).

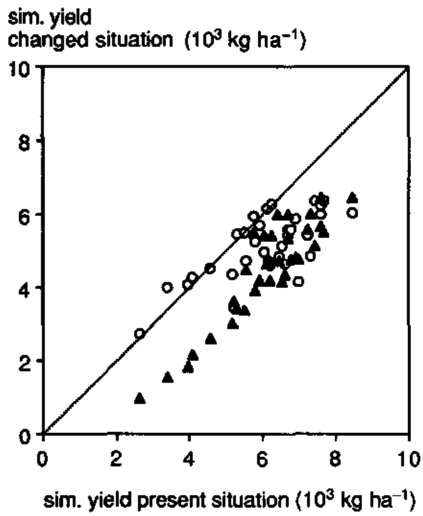


Figure 6.8 The effect changed agricultural practices on simulated water-limited crop yields in comparison with simulated yield for present circumstances. Temperature rise of 3 °C, present sowing date (March 11) and variety (o), temperature rise of 3 °C, sowing at March 21 and northern variety (▲).

Sowing date and variety only affect the vegetative period. By restoring the original growing season 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 increases resulting in a yield decline. Total biomass from the new variety did reach original levels, which is sensible since 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 (Wiegand & Cuellar 1981, van Keulen & Seligman 1987). Often wheat crops ripen due to water and/or nutrient shortage occurring at the end of the growing season 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 6.9. 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.
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 (figure 6.10): as in wet years a yield decline was simulated for this scenario. In dry years, however, 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 6.9) and the yield decline due to the higher temperatures is 2 ton ha^{-1} (figure 6.6).

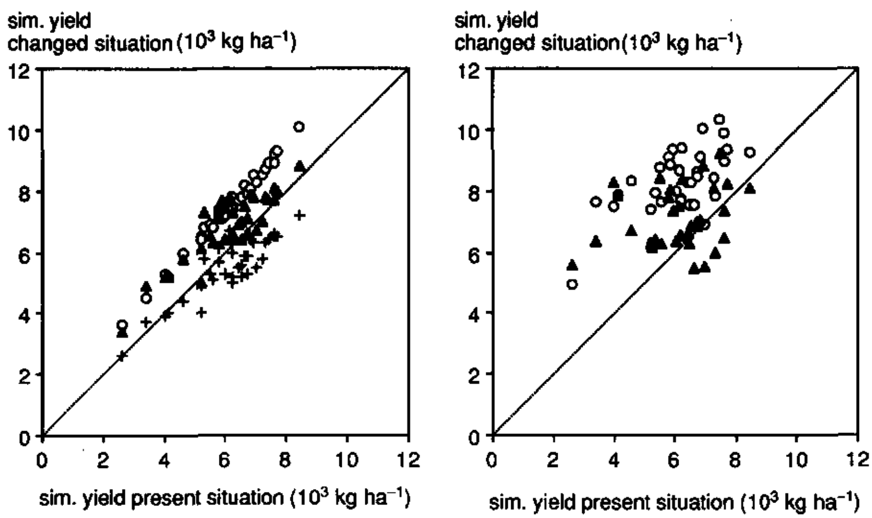


Figure 6.9 (left) The effect of scenario 2030 on water-limited spring wheat yields in comparison with yields simulated for the present situation. Temperature rise of 1.7 °C and present CO_2 concentration (+); CO_2 concentration of 460 ppm and present weather (o); temperature rise of 1.7 °C and CO_2 concentration of 460 ppm (▲).

Figure 6.10 (right) 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 (o) and of 5 °C (▲).

In this chapter only effects from changes in temperature were studied. The wide range in weather conditions in the 34 years used, permits a few conclusions on the effects of changes in other weather elements. If the average precipitation during the summer season declines, the number of dry years will increase. For the 2030 scenario this will result in a decline in average yield (dry years yield less than wet ones). For the 2080 scenario the average yield will not be affected since, with exception of one year, the yield levels in dry years were the same as those in the wet years (6-10 ton ha^{-1}).

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 climatic 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 chapter 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.

Conclusions

The model gives a reasonable simulation of present yield levels and their inter-annual variability, when proper weather data are used as input.
Temperature rise causes a decline in yield in most years, but large differences in the magnitude of this decline are found. Therefore effects of climatic change on crop yields must be studied for a large number of years.
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.
Both higher CO_2 concentrations and temperature rise reduce yield variability.
Use of other sowing dates or different varieties can not reduce the negative effects of temperature rise on simulated crop yields.

Chapter 7

Effects of temperature rise and increase in CO_2 concentration on simulated wheat yields in Europe

Abstract A crop growth simulation model based on SUCROS87 was used to study effects of temperature rise and increase of atmospheric CO_2 concentration on wheat yields in 13 regions in Europe. The model simulated potential and water-limited crop production (growth with ample supply of nutrients and in the absence of damage by pests, diseases and weeds).

For potential production (optimal water) a 3 °C temperature rise led to a yield decline due to a shortening of the growing season. A doubling of the CO_2 concentration caused increase in yield of 40 % due to higher assimilation rates. It was found that effects of higher temperature and higher CO_2 concentration were nearly additive and the combination of both led to a yield increase of 1-2 *ton* ha^{-1}.

When water was a limiting factor in crop production effects of temperature rise and higher CO_2 levels were different. Rise in temperature led to a smaller yield reduction and to a decline in yield variability. Doubled CO_2 concentration to a larger yield increase, due to the improved water use efficiency of the crops. Combination of both led to a large yield increase (3 ton ha^{-1}) in comparison with yields simulated for the present situation.

Both rise in temperature and increase in CO_2 concentration reduced water requirements of the crop. Differences in simulated yield between sites and between years caused by differences in available water became smaller.

Due to the improved water use efficiency of crops at higher CO_2 levels changes in precipitation amount of about 10 % are not likely to affect yields. However, when climatic change also includes a major change in distribution of the precipitation, important changes in yields can be expected.

Introduction

Emissions of gases such as CO_2, methane, chlorofluorocarbons and nitrous oxide as a result of human activities will enhance the natural greenhouse effect and may result in an increase of the 'global average annual mean surface air temperature' (IPCC report, Houghton et al. 1990). Such warming is likely to affect climates all over the world. Agricultural production is strongly affected by the weather conditions during crop growth and changes in present climatic conditions will therefore influence crop production. In the last decades many studies have been published on the effects of possible climatic changes on crop yields in various parts of the world (Rosenzweig 1985, Santer 1985, Wilks 1988, Parry & Carter 1989, Cooter 1990).

The greenhouse gas CO_2 also plays an important direct role in crop growth: CO_2 is the primary source of carbon for the plant and its present concentration is suboptimal. Elevated CO_2 concentrations lead to higher assimilation rates (Lemon 1983, Cure & Acock 1986) and to an increase in stomatal resistance

resulting in a decline in transpiration and improved water use efficiency of crops (Goudriaan & van Laar 1978b, Gifford 1979, Sionit et al. 1980).
Thus the increasing atmospheric CO_2 concentration affects global agricultural production via a change in climate and via changes in photosynthesis and transpiration rates. The final effect of higher CO_2 concentrations on crop yields is therefore difficult to assess. In such situations application of simulation models can be useful. By integrating the effects of CO_2 concentration on different crop growth processes into one model the overall effect on crop growth can be studied.
In chapter 6 a crop growth simulation model is described in which effects of atmospheric CO_2 concentration on assimilation and transpiration rates were included. The model simulated wheat crop production under given (= input) weather conditions and CO_2 concentration. The effects of increased CO_2 concentration and rise in air temperature individually and in combination were discussed in detail for one site in The Netherlands. Temperature rise led to a decline in yield, with exception of the dry years in which temperature rise had no effect on simulated yields. Doubling of the CO_2 concentration led to a yield increase of 40 % in wet years and 70 % in dry years. The effects of doubled CO_2 and temperature rise were nearly additive, so that high temperatures and high CO_2 concentrations led to a larger yield increase in dry years than in wet years. Large variation in the magnitude of the effect of temperature rise on yields in individual years was found. It was therefore concluded that, for reliable estimates, the effect of temperature rise should be studied for a long series of weather data (over 20 years).
Wheat is grown in very different climates and a large variety of cultivars exists. It is likely that effects of climatic change on wheat crops grown in other conditions will differ from what was found for crops in The Netherlands. To obtain better insight in possible effects of increased CO_2 concentrations on wheat yields, the model developed in chapter 6 was used to examine the effects of elevated CO_2 concentration and temperature rise on yields in various regions in Western Europe.

Climate of Western Europe

The part of Europe of interest stretches from Scotland to northern Italy (60-40° N. Lat.) and from England to Germany (10° W. Long. to 20° E. Long., figure 7.1). Distances between Stirling and Toulouse are about 1500 km and between Rothamsted and Hannover 750 km.

Figure 7.1 Location of the sites mentioned in text.
1 Stirling,
2 Haddington,
3 Rothamsted,
4 Wageningen,
5 Bremen,
6 Hannover,
7 Munster,
8 Lille,
9 Nancy,
10 Orleans,
11 Toulouse,
12 Bologna,
13 Pisa.

The area along the west coast is largely influenced by the warm Gulf Steam from south-west to north-east in the Atlantic. Winters are mild (2-3 °C) and the temperatures in January decline with increasing distance from the ocean (table 7.1). In summer, due to the higher insolation in the south, a zonal gradient in temperature develops, with 14 °C in Scotland to 24 °C in Italy. Mountainous areas can cause large differences in climate over short distances, an example is found in Italy. The distance between Pisa and Bologna is only 120 km. The Apennines, in between these cities, act as a barrier for the cold winter winds from eastern Europe. Hence winter temperatures in Pisa are 6 °C higher than in Bologna.

Precipitation comes mainly from frontal depressions connected to the general circulation pattern, which generally cross Europe from west to east. Most low land areas receive 500-700 mm year^{-1}. Mountainous areas receive more (over 1000 mm year^{-1}). In regions on the leeward sides of mountain barriers rainfall can be less than 500 mm. Precipitation is evenly distributed over the year in the middle latitudes of Europe. In the south, in summer, weather is under influence of the Azores High and in this season the amount of rain can be very small (less than 30 mm month^{-1}). In these regions most precipitation falls in autumn and winter (Wallén 1970, table 7.2).

Table 7.1 Average air temperature in January (T_{jan}) and July (T_{jul}), the average annual precipitation (rain) and the daylength at longest day (dayl.) on the meteorological sites under interest and the years from which daily weather data were available. (Climatic data were derived from Wallén (1970))

	T_{jan} (°C)	T_{jul} (°C)	rain (mm)	dayl. (h)	years
Haddington	3.	14.	700	19	61-80
Stirling	3.	14.	800	19	61-80
Rothamsted	3.	16.	600	17	61-80
Wageningen	2.	16.	700	17	54-87
Hannover	0.	18.	700	17	51-80
Bremen	1.	17.	700	17	51-80
Munster	1.	17.	700	17	51-80
Lille	3.	17.	700	17	49-80
Nancy	1.	19.	800	16	50-80
Orleans	3.	19	600	16	50-80
Toulouse	5.	21.	600	15	49-80
Bologna	2.	24.	700	15	58-77
Pisa	8.	23.	800	15	58-77

Table 7.2 Average air temperature (T), global radiation (rad) and total precipitation (rain) per month for Wageningen and Pisa. Data for Wageningen were derived from the weather data set, data from Pisa were derived from Cantù (1977).

	Wageningen			Pisa		
	T (°C)	rad (MJ m^{-2} d^{-1})	rain (mm)	T (°C)	rad (MJ m^{-2} d^{-1})	rain (mm)
Jan	1.5	2.2	65	6.2	5.1	86
Feb	1.9	4.5	45	7.0	7.2	79
Mar	5.0	7.7	56	10.0	10.3	75
Apr	8.0	12.7	51	13.0	14.3	70
May	12.2	16.0	58	16.8	17.5	57
June	15.3	17.2	68	20.3	19.3	37
July	16.8	15.7	77	22.6	19.8	19
Aug	16.7	13.9	74	22.8	16.9	38
Sep	14.3	9.9	64	19.7	13.7	90
Oct	10.5	5.7	66	15.4	9.2	131
Nov	5.8	2.8	67	10.8	5.3	111
Dec	3	1.7	72	7.8	3.9	126

Average radiation levels show a sinusoidal course over the year: radiation levels in May, June and July are nearly the same and so are the levels in the winter period: November, December, January and February. In spring and autumn levels are changing rapidly (table 7.2, chapter 3: figure 3.5). Average air temperature follows the same pattern but highest values occur in July and August and the lowest in January and February (table 7.2, chapter 2: figure 2.6).

Growing season of wheat

The development of wheat can be divided in two different phases. The first is the vegetative period in which the crop germinates and forms leaves, tillers and ears. Flowering marks the end of this period. Then comes grainfilling period from flowering till maturation in which the grains are filled with the assimilates produced by the leaves. For optimal yields both stages must balance (chapter 6). In principle a long growing season is favourable for high yields, because in a long season a large amount of solar radiation can be intercepted for assimilation. However, in most places climatic conditions are not whole year round suitable for crop growing. In the northern part of Europe (Norway) winters are too cold and too dark for primary production, and in Southern Europe (Italy) summers are too hot.

Table 7.3 Agronomic data for wheat crops grown in several regions in Europe. Data are based on Broekhuizen (1969) and represent the center of the time span in which various events take place. Regions are named after the meteorological site in the region.

	Spring wheat			Winter wheat		
	sowing	anthesis	harvest	sowing	anthesis	harvest
Haddington	Apr 1	Jul 20	Oct 1	Nov 1	Jun 25	Sep 20
Stirling	Apr 1	Jul 20	Oct 1	Nov 1	Jun 25	Sep 20
Rothamsted	Mar 10	Jun 25	Sept 1	Nov 1	Jun 15	Aug 20
Wageningen	Mar 15	Jul 1	Sept 1	Nov 1	Jun 20	Aug 10
Hannover	Apr 1	Jun 25	Sept 1	Nov 5	Jun 20	Aug 20
Bremen	Apr 1	Jun 25	Sept 1	Nov 5	Jun 20	Aug 20
Munster	Mar 25	Jun 25	Sept 1	Nov 1	Jun 25	Sep 1
Lille	Mar 20	Jun 30	Aug 1	Nov 5	Jun 20	Aug 1
Nancy	Mar 10	Jun 20	Aug 1	Oct 10	Jun 1	Aug 1
Orleans	Mar 20	Jun 20	Aug 1	Nov 1	Jun 10	Jul 20
Toulouse	Feb 10	Jun 1	Jul 20	Nov 15	Jun 10	Jul 20
Bologna				Nov 1	May 10	Jun 20
Pisa				Dec 1	May 20	Jun 20

In table 7.3 the average sowing, flowering and harvest date of wheat grown in various regions in Europe is given. Data are obtained from Broekhuizen (1969) and give an indication of the growing season in various regions. In individual years large deviations from the average growing season can exist. In The Netherlands the moment of sowing of spring wheat varies from the beginning of February to the first half of April (Albias et al. 1987). In the United Kingdom, The Netherlands, Germany and France two growing systems are practiced: the autumn sown winter wheat and the spring sown spring wheat. In general winter wheat yields are higher due to a longer growing season. The acreage under winter wheat is much larger than under spring wheat (de Jong 1986). When autumn sowing is not possible, for instance when the previous crop is not harvested in time, spring wheat is grown. In Southern France the difference between the two systems becomes indistinct. Early sowing of spring wheat can occur as soon as January and a late sowing of the autumn crop as late as December. Further to the south the spring sowing system disappears completely.

One of the main differences between the autumn and spring sown varieties in Western Europe is that winter sown varieties require a period with low temperatures (between 0-10 °C) before the crops become generative (vernalization). This need for vernalization delays development of the crop and improves its resistance to frost damage (de Jong 1986). Large differences in vernalization requirements exist between varieties. The autumn sown varieties in Southern Europe often do not require vernalization at all.

Besides differences in vernalization requirements, large differences in daylength sensitivity exist. Wheat is a long day plant, which implies that development is faster in longer days. In experiments with wheat varieties from all over Europe it was shown that varieties from northern Europe were far more sensitive to photoperiod than the varieties from lower latitudes (Feekes 1941, van Dobben 1965). This difference in daylength sensitivity can be understood by comparing agricultural practices in the different parts of Europe. In Southern Europe, where wheat is sown in winter, the wheat varieties should not be delayed in their development by short days otherwise their grainfilling period will occur during the dry summer. So varieties in the south are selected for their insensitivity to daylength. In Northern Europe, varieties should flower near the longest day of the year otherwise they will not mature before the unfavourable season (winter) starts. So varieties grown at higher latitudes are selected for their sensitivity to daylength.

Varieties are only sensitive to vernalization and daylength in the vegetative period. Both attributes play an important role in timing of the anthesis and through this in timing of the grainfilling period.

The duration of the grainfilling period is only determined by temperature and no differences between varieties have been found yet (Wiegand & Cuellar 1981, van Keulen & Seligman 1987, chapter 6)

Material and methods

Crop growth simulation model

The wheat crop growth model as described in chapter 6 was used. The model based on SUCROS87 (Simple and Universal CROp Simulation model, Spitters et al. 1989), operates with a time interval of one day and simulates potential and/or water-limited production. In the former production is determined by crop characteristics, radiation and temperature and in the latter also by limited availability of water. In both models the crop is supposed to be free from pests, diseases and weeds and is optimally supplied with nutrients (de Wit & Penning de Vries 1982). The model requires as input: daily weather data on minimum and maximum air temperature (°C), total global radiation (J $m^{-2} d^{-1}$), early morning vapour 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 wheat variety used (as indication for its daylength sensitivity, Miglietta 1991), available water holding capacity of the various layers of the soil, thickness of the layers and soil moisture at sowing date are also required.
The input requirements of the model greatly limit its potential applications. In the first place, daily weather data are very scarce especially over long periods (20 years). The number of sites from which daily data can be obtained, therefore, determines the number of simulation runs possible. Secondly, detailed data on soils are lacking. In this study, data on soils are only required for simulation of the amount of water available to the plant. It was decided to simulate both potential and water-limited production for all situations. For the water-limited production, data for a hypothetical soil with a very low available water holding capacity were used. The simulated potential production can be regarded as the upper limit of the production possibilities in the region and the water-limited yields as the lower limit for crops free from other stresses (pests, nutrient shortage etc.). Crops on a clayey soil, with a high available water holding capacity, will approach the potential yield and so will irrigated crops. Yields of rainfed crops on sandy soils will approach the simulated water-limited production. (Soils with lower available water holding capacity than used in here exist, but they are generally not used for agricultural practices). For all sites it was assumed that soil profile was at field capacity at sowing date.

Within Europe a large diversity of cultivars is grown in different parts of the year. For studying the effects of climatic change on various growing systems the present situation was used as a starting point. The vernalization process and its effects on crop development is not included in the model, therefore the effects of climatic change for wheat varieties with no vernalization requirements were examined. For each site sowing date and daylength sensitivity of the variety (Miglietta 1991) were selected so that phenology of the crop was in accordance with data given in table 7.3. For Toulouse two simulation runs were made, one with the sowing date of the spring crop and one with the sowing date of the autumn crop.

Weather data

Weather data were available from the sites shown in figure 7.1. The data originated from an European weather data bank and were made available by the Climate Research Unit of the University of East Anglia. Dimensions and format of the weather variables were made in accordance with the requirements of the model. From most sites only data on sunshine duration were available. For crop growth simulation purposes global radiation can be estimated from these data by using the Ångström formula (chapters 3 and 4, equation 3.1). A and B values of various sites, where possible, were calculated by comparing global radiation data of one year from another source with sunshine duration data of the same year from the data set. When global radiation data were not available A and B values were obtained from the literature or values from a nearby station were used.
Since errors and missing data in weather data sets can have large effects on the results of crop growth simulation models (chapters 2, 3 and 4), a large effort was made to check the weather data. All data were examined and missing or unrealistic values were replaced by estimates. Missing precipitation data were replaced by 0.0 mm, missing values for wind speed and vapour pressure by the monthly average. When temperature data were missing, values of a comparable day (same radiation level and precipitation amount) in the same month were used. The same method as for temperature was applied for missing data on global radiation or sunshine hours. When data on temperature, global radiation or precipitation were missing over more than two weeks during the growing season, the complete year was discarded. For stations Bologna and Pisa this implied that only 13 out of the 20 years were suitable for input in the model. (In these sets so many data were missing, that even when the limit was set to 4 weeks, the number of years available for input did not increase). Finally the weather data were randomly compared with data from other data sets or with published data from the national meteorological offices (to trace possible mistakes in dimensions etc.). In total over 0.6 million data were handled (13 stations * 20-30 years * 365 days * 6 variables)

With respect to the simulation of the future weather, the same method as described in the previous chapter was used. For derivation of the scenarios is therefore referred to chapter 6. The only scenario explored was that for the year 2080 (700 ppm CO_2 and temperature rise of 3 °C). The simulation for 2030 was excluded because simulation runs with this scenario (2030) did not give extra information on the effects of climatic change on crop production. The estimated temperature rise was added to the daily minimum and maximum temperature and vapour pressure was adjusted in such a way that relative humidity of the air remained the same. All other weather variables like global radiation etc. were not changed. Since confidence in regional estimates of the Global Circulation Models (GCM's) is low (Houghton et al. 1990), it was decided to apply the same temperature rise to all sites.

To be able to study the effects of temperature rise and increase of CO_2 concentration individually and in combination four simulation runs were made for each site and each production level (potential and water-limited): 1) present weather and present (350 ppm) CO_2 concentration, 2) temperature rise of 3 °C and present CO_2 concentration, 3) present weather and doubled (700 ppm) CO_2 concentration and 4) temperature rise of 3 °C and doubled CO_2 concentration.

Validation of simulation results

It was tried to validate the model for present growing conditions in Europe. Despite a great effort, it was impossible to construct such a long time series as was done for The Netherlands in chapter 6. The model simulates potential and water-limited production. For validation data from crops free from nutrient shortage, pests and diseases and weeds were required. The application of sufficient fertilizers and biocides for optimal crop growth came only into practice in the late seventies, through which before 1975 crops were generally grown under suboptimal conditions, resulting in low yields. Accordingly only field data from the last 10-15 years were suitable for validation. For all sites only weather data up to 1980 were available, which strongly curtailed the validation possibilities.

In chapter 4 was shown that weather data measured in the immediate surroundings of the field experiments are required as input, data from a site at 40 km distance could cause deviations in simulated yield of 2 ton ha^{-1}. It was not possible to find data suitable for validation of the model in the immediate surroundings of the sites from which weather data were available (figure 7.1).

However, the fact that average yield level and its variability were simulated reasonable well for the Dutch conditions (chapter 6) and that simulation results for completely different climates like the humid tropics and the mediterranean climate were in accordance with yields levels observed in the field (chapter 5) allows the conclusion that weather-crop growth relations in the model are properly quantified. This makes the model a useful tool for studying the effects of climatic change on crop production.

Results and discussion

Present situation

The *average potential yield* and its *relative standard deviation* calculated for the 13 locations are given in table 7.4. The data for Wageningen are the same as presented in chapter 6. The simulated yield varied between 7.0 ton ha^{-1} in Germany and 9.1 ton ha^{-1} in Italy (Pisa). For all sites standard deviation of the yields was low: 7-12 %. A small decline in growing season duration for spring sown crops was found from north to south over Europe (table 7.5). The main difference between autumn and spring sown crops was the duration of the vegetative period. In Toulouse the vegetative period of the spring sown crop lasted 90 days and of the autumn sown crop 173 days, while the grainfilling periods in both systems were nearly the same. It seems that for autumn sown crops the vegetative and grainfilling period were more balanced resulting in a higher yield. The differences in climate between Pisa and Bologna come to expression in the yields: a difference of 1.5 ton ha^{-1} was simulated.

Table 7.4 Average potential grain yields (dry matter in ton ha^{-1}) and relative standard deviations (σ, as percentage of yield) for 13 sites in Europe, simulated with present weather and CO_2 concentration of 350 ppm, 3 °C rise in temperature and 350 ppm CO_2 (T+3), present weather and doubled CO_2 concentration (700) and combination of temperature rise and higher CO_2 concentration (T+3, 700). For the 'ww' marked sites autumn sown crops are studied, for the other sites the spring sown crops.

site	present		T+3		700		T+3, 700	
	yield	σ	yield	σ	yield	σ	yield	σ
Haddington	8.0	(10)	7.1	(11)	10.9	(10)	10.2	(11)
Stirling	8.0	(9)	7.0	(10)	11.0	(9)	10.1	(10)
Rothamsted	8.6	(9)	7.4	(10)	12.1	(8)	10.7	(8)
Wageningen	7.3	(10)	6.0	(13)	10.5	(9)	9.0	(11)
Hannover	7.2	(12)	5.9	(14)	10.3	(11)	8.9	(11)
Bremen	7.0	(12)	5.7	(14)	10.0	(11)	8.6	(11)
Munster	7.1	(11)	5.8	(12)	10.3	(9)	8.8	(10)
Lille	7.7	(11)	6.3	(9)	11.0	(10)	9.4	(7)
Nancy	7.3	(10)	5.9	(13)	10.6	(8)	9.0	(10)
Orleans	8.1	(11)	6.5	(11)	11.8	(10)	9.9	(9)
Toulouse	7.7	(9)	6.4	(9)	11.1	(9)	9.8	(8)
Toulouse ww	8.9	(11)	7.0	(15)	12.1	(15)	10.1	(15)
Bologna ww	7.7	(7)	6.1	(22)	11.3	(9)	9.4	(20)
Pisa ww	9.1	(9)	6.2	(17)	13.4	(12)	9.4	(15)

Water-limited yields varied only between 5.2 and 6.9 ton ha^{-1} (table 7.6). An important feature of precipitation is the enormous difference in annual amounts. Precipitation in dry years can be half of the amount in wet years (In The Netherlands annual precipitation varied between 400 and 1200 mm, Buishand

& Velds 1980). These large differences in available water caused large differences in yield. Yields could be less than 2 ton ha^{-1} in dry years, while in wet years yield levels of over 8 ton ha^{-1} could be reached (chapter 6). This phenomenon was also reflected in the standard deviations, which were much larger for the water-limited than for the potential yields (tables 7.4 and 7.6). The differences in average potential and water-limited yield on most sites were therefore not caused by lower yields in all years, but by the occurrence of a few very dry years with very low yields.

Table 7.5 Average durations of vegetative and grainfilling periods in days of wheat on various sites, simulated with present weather and with a temperature rise of 3 °C (T+3). For the 'ww' marked sites autumn sown crops are studied, for the other sites the spring sown crops.

site	present		T+3	
	vegetative	grainfilling	vegetative	grainfilling
Haddington	84	65	71	53
Stirling	82	63	69	52
Rothamsted	87	58	76	50
Wageningen	81	54	72	48
Hannover	79	54	71	47
Bremen	77	53	70	46
Munster	79	53	71	47
Lille	83	54	72	48
Nancy	80	52	71	46
Orleans	81	51	70	46
Toulouse	90	47	78	45
Toulouse ww	173	51	137	56
Bologna ww	173	49	142	52
Pisa ww	140	50	115	51

As an indication for the magnitude of water shortage the number of days per season in which assimilation was reduced by more than 50 % due to drought was used. The average number of these so called 'dry days' is given in table 7.7. Locations with a large number of dry days also showed large variability in yields (table 7.6). When the number of dry days was compared with the average annual precipitation (table 7.1) not much correlation was found. Only for sites close to each other, could differences in the number of dry days be explained by differences in annual precipitation (compare Wageningen-Rothamsted and Lille-Orleans). Stirling and Pisa receive the same amount of rain per year (800 mm, table 7.1). In Stirling hardly any water shortage existed, whereas in Pisa water was an important limiting factor. Differences between the sites were caused by the distribution of precipitation over the year. In Stirling it is evenly distributed but in Pisa the amount of precipitation in June, the last part of the growing season, is very low (less than 30 mm month^{-1}, table 7.2) and crops face water shortage.

Table 7.6 Average water-limited grain yields (dry matter in ton ha^{-1}) and relative standard deviations (σ, as percentage of yield) for 13 sites in Europe, simulated with present weather and CO_2 concentration of 350 ppm, 3 °C rise in temperature and 350 ppm CO_2 (T+3), present weather and doubled CO_2 concentration (700) and combination of temperature rise and higher CO_2 concentration (T+3, 700). For the 'ww' marked sites autumn sown crops are studied, for the other sites the spring sown crops.

site	present		T+3		700		T+3, 700	
	yield	σ	yield	σ	yield	σ	yield	σ
Haddington	6.5	(12)	5.6	(12)	9.9	(8)	9.1	(9)
Stirling	6.9	(12)	5.8	(16)	10.3	(9)	9.2	(10)
Rothamsted	6.2	(25)	5.6	(21)	10.0	(16)	9.5	(15)
Wageningen	6.0	(22)	5.0	(18)	9.4	(15)	8.2	(13)
Hannover	5.9	(22)	4.7	(22)	9.3	(16)	7.9	(14)
Bremen	5.7	(21)	4.6	(20)	9.2	(14)	7.8	(13)
Munster	5.9	(19)	4.7	(17)	9.3	(14)	7.9	(11)
Lille	6.0	(23)	5.1	(18)	9.6	(16)	8.5	(12)
Nancy	5.9	(23)	4.8	(19)	9.4	(16)	8.0	(13)
Orleans	5.2	(32)	4.6	(24)	9.0	(23)	8.3	(17)
Toulouse	5.3	(30)	4.9	(24)	8.9	(22)	8.4	(17)
Toulouse ww	6.3	(30)	6.1	(16)	10.1	(23)	9.5	(14)
Bologna ww	5.4	(23)	5.5	(21)	8.9	(18)	9.0	(20)
Pisa ww	6.3	(20)	5.7	(17)	10.7	(16)	9.0	(14)

Effects of rise in temperature

The main influence of temperature in the model is that it determines the development rates of the crop. Higher temperatures lead to higher development rates. Therefore rise in temperature led, in general, to earlier crop emergence, advanced flowering and earlier ripeness of the crop, and thus to a shorter growing season earlier in the year (table 7.5).

For crops flowering at the end of June, temperature rise led to an enhanced flowering of 15 days. This caused small changes in weather conditions experienced by the crop during the growing season (a shift of 2 weeks in June does not have much effect on temperature and radiation levels, table 7.2). Reduced duration of the growing season was the main reason for the simulated yield decline. In Southern Europe a shift of the growing season had a large effect on growing conditions of the crop. A rise in temperature of 3 °C led to a shift in the start of the grainfilling period from May to April. Between March and May large increases in radiation and temperature take place (table 7.2). A 3 °C temperature rise had therefore no effect on duration of grainfilling period in Southern Europe (table 7.5) (future temperature in April equals present temperature in May). Also earlier flowering implied an enormous decline in total radiation during the vegetative period; the month with the highest radiation levels (June) was lost. Radiation became an important limiting factor in this period. There were large differences in yields in sunny and cloudy years, resulting in an increase in yield variability for the autumn sown crops (table 7.4).

Table 7.7 Average number of 'dry days' (see text) during growing seasons on the various sites, simulated with present weather and CO_2 concentration of 350 ppm, a 3 °C rise in temperature and 350 ppm CO_2 (T+3), present weather and doubled CO_2 concentration (700) and combination of temperature rise and higher CO_2 concentration (T+3, 700). For the 'ww' marked sites autumn sown crops are considered, for the other sites the spring sown crops.

site	present	T+3	700	T+3, 700
Haddington	3.6	2.9	0.0	0.0
Stirling	1.0	2.5	0.0	0.0
Rothamsted	8.5	7.0	3.7	2.0
Wageningen	4.5	3.3	2.1	1.0
Hannover	4.7	4.3	2.0	1.2
Bremen	4.4	3.0	0.3	0.2
Munster	4.0	2.9	2.1	1.0
Lille	6.6	4.5	2.3	1.2
Nancy	5.5	4.1	2.3	2.1
Orleans	14.5	9.9	7.6	5.3
Toulouse	9.9	6.0	2.9	2.3
Toulouse ww	8.7	2.7	2.5	0.7
Bologna ww	7.1	1.4	2.1	0.0
Pisa ww	6.7	0.0	1.2	0.0

Because water shortages generally occur at the end of the growing season when grains are being filled, water shortage have a large influence on yield.
A higher development rate (leading to advanced ripening) can ensure that the crop escapes water shortage. In dry years a reduction of the water shortage can counterbalance the effects of a shorter growing season. These effects were found in the water-limited simulation runs for Wageningen in chapter 6. In wet years a yield decline was found (due to shorter growing season) and in dry years a small yield increase (due to reduction of the water shortage). Comparable effects were found in this study for most locations. Temperature rise reduced the number of dry days (table 7.7). In the autumn sown wheat growing systems in Southern Europe the water shortage nearly disappeared completely and yields were hardly affected by the temperature rise. In spring sown systems in Western Europe the variability of yields decreased due to reduction of the water shortage. In Southern Europe an increase in variability was found, but this increase was the same as for potential production and was the result of the lower radiation levels.
In Stirling the number of dry days increased, in combination with increased variability. This increase of water shortage was caused by two years with a dry

August. In present conditions rains in the next month prevented water shortage of the crop. In the T+3 situation the crop ripened before the September rains, through which shortage occurred.
Because of the reduction in water shortage, the differences between potential and water-limited yields were smaller than in present situation.

Effects of doubled atmospheric CO_2 concentration

A doubling of the atmospheric CO_2 concentration led to a yield increase of 40 % for potential production at all sites. This is similar to what was found in individual years in chapter 6 and in accordance with other data from the literature (Cure & Acock 1986, Goudriaan & Unsworth 1990). Since the effect was the same for all sites, the yield pattern over Europe was not changed. This was not the case for water-limited production. Higher CO_2 concentration affects the stomatal resistance, thereby decreasing transpiration. For all sites doubled CO_2 reduced the number of dry days and yield variability. The effect of doubled CO_2 was largest in dry regions (Orleans), where there was an increase of 70 % in the average simulated yield. This large yield increase under water-limited circumstances is also found in CO_2 enrichment experiments (Kimball & Idso 1983, Cure & Acock 1986). Because the effect of high CO_2 was smaller in regions with enough water (Haddington, 40 %), than in regions with water shortage (Orleans, 70 %), the difference in average yield between sites declined.

Effects of combination of doubled CO_2 concentration and temperature rise

The effects of both high temperature and doubled CO_2 on simulated potential wheat yields are given in table 7.4. A yield increase of about 2 ton ha^{-1} was achieved in comparison with the present yields. Only in Pisa, where a large yield decline was found due to temperature rise, higher CO_2 concentration did not lead to yield increase. As found in the previous study, the effect of a temperature rise and CO_2 doubling showed little interaction. For the water-limited production there was a decline in yield variability, due to a further decline in number of dry days on all sites (table 7.6). Through the reduction of water shortage (table 7.7) the difference between potential and water-limited yields declined. On sites where the number of dry days was reduced to less than 1.0 days, variability of the water-limited yields approximated variability of the potential yields.

Importance of the precipitation pattern for crop yields

In general, changes in available amount of water can have far greater effects on

crop yields than changes in temperature or radiation. The importance of sufficient water is reflected in the present timing of the growing season in various regions: dry seasons are avoided. In Southern Europe it is more favourable to grow a crop in spring under low radiation levels with sufficient water than under high radiation levels and water shortage in summer. The outcome of the various simulation runs show equivalent effects. On most sites differences between potential and water-limited production were larger than differences in present yields and yields after a temperature rise.
A change in climate will not only involve a change in air temperature, but will also affect other weather variables. When total precipitation changes by 10-15 % (as estimated in the IPCC report, Houghton et al. 1990) but the current seasonal pattern remains, no effects on yields are expected. In chapter 4 it was shown that over and underestimation of precipitation by 10 % only affected yields in dry years. The number of dry years (and dry days) is reduced under higher CO_2 levels due to improved water use efficiency of the crops. So changes in precipitation amounts of the order of 10 % will not result in major yield changes.
When climatic change includes a change in precipitation pattern, changes in yield levels can occur. If, for instance, the summer season in Western Europe were to become dry, like the present situation in southern Europe, a shift in the growing season would be needed to evade water shortage in summer. The low radiation levels in spring and autumn in Western Europe (table 7.2) would cause a decline in yield.

Conclusions

Based on simulation results one can conclude that when no major changes in precipitation pattern occur, the CO_2 induced climatic change will not cause major changes in wheat production. Negative effects of rise in temperature are counterbalanced by the positive effects of the higher CO_2 levels. In general a yield increase is obtained and annual variability of the yields is reduced. Because the water requirements of crops decline, yield differences between sites caused by differences in available water are reduced.

Summary

Crop growth and yield are largely determined by the weather conditions during growing season of the crop. The overall effect of weather on crop production is rather ambiguous. The effect of, for instance, high radiation levels at high temperatures can differ considerably from the effect at low temperatures. Only when conditions are so extreme that the crop is seriously damaged, for instance due to frost or severe water shortage, the effects of weather on crop yield are obvious.

In recent decades models have been developed in which crop growth is simulated in relation to observed weather conditions. These models integrate knowledge about the most important effects of weather on individual crop growth processes (global radiation on photosynthesis, air temperature on development etc.). Crop growth models differ in their input requirements. Most of them require data on (air) temperature, radiation and precipitation on a daily or hourly basis, while others also require data on wind speed and vapour pressure. The number of sites from which hourly weather data can be obtained is very limited, so that application possibilities of models on an hourly basis are quite restricted. Daily weather data can be obtained from nearly all meteorological stations and thus crop growth models requiring daily data as input are used more frequently.

Weather data are important input data for models since they describe the conditions under which growth takes place. Different data (other season, other site) lead to different simulation results.

In modelling practice weather data are obtained from databases and these weather data are accepted at their face value. This is not realistic. Like all measured values, weather data are subject to inaccuracies and since models are sensitive to weather data used as input, the inaccuracies in weather data can affect the simulation results. The quality of the crop growth models has improved over the last decades and some models are well able to simulate the production observed in the field. In this stage of crop model development it is important to know whether the difference between the observed and simulated growth can be caused by errors in weather data or whether it is due to incorrect simulation of crop growth. In this study frequently occurring irregularities in weather data sets are therefore discussed and their effects on simulation results are examined.

Simulation model

A spring wheat version of SUCROS87 (Simple and Universal CROp growth Simulator, version 1987) was used to study effects of errors in weather data on

simulation results. The model is well able to simulate production obtained in the field (chapter 6). The effects of inaccuracies in weather data were studied for two different production levels: the potential and the water-limited production. In the former, production is determined by crop characteristics, radiation and temperature and in the latter also by limited availability of water. In both production levels the crop is supposed to be free from pests, diseases and weeds and is optimally supplied with nutrients.

The core of this model is formed by the calculation procedure for canopy photosynthesis and respiration on the basis of processes at the organ level. Allocation of dry matter production among the different plant organs depends on stage of development of the plant. The model operates with time intervals of one day. Numerical integration over time gives the time course of dry matter. SUCROS requires daily weather data on minimum air temperature, maximum air temperature and global radiation for the simulation of potential crop production.

For simulation of the water-limited production the model was extended with an evapotranspiration routine and a soil water balance. The Penman-Monteith-equation is used to simulate potential soil evaporation and crop transpiration. The soil is treated as a ten-layered system. When precipitation occurs, the first layer is filled up to field capacity and all excess water entering the layer drains to next layers. Soil moisture losses occur by drainage below the potential rooting zone, by crop transpiration and by soil evaporation. When water shortage occurs, the assimilation rate is reduced in proportion to the ratio between actual transpiration (depending on the available amount of water) and potential transpiration. Other processes are not affected by water shortage. For simulation of water-limited production daily data on precipitation, vapour pressure and wind speed are required as well.

Meteorological data

The starting point of this study was a data set with daily weather data from Wageningen, The Netherlands from 1954 to 1987. The set contained daily values for minimum air temperature (°C), maximum air temperature (°C), total global radiation (J m^{-2} day^{-1}), total precipitation (mm), vapour pressure (mb) at 9.00 am and average wind speed (m s^{-1}). The data were collected at the meteorological station Haarweg of the Wageningen Agricultural University. The station is a climatological station of the Royal Netherlands Meteorological Institute (KNMI). When crop production was simulated with this weather data set, effects of severe water shortage were only found for 5 years (1957, 1959, 1973, 1976, 1986), resulting in yields of 2-5 ton ha^{-1}. In all other years water shortage was small and yields were higher.

Inaccuracies in weather data

For all weather variables required as input in the model, the inaccuracy was estimated on the basis of literature.
When a simulation model is used in combination with a field experiment, in principle, weather data from this field are required. In practice, data from the nearest meteorological station are used. Weather conditions may differ at the two sites, which may affect simulation results. Therefore besides errors in instruments and the measuring procedure the spatial variability of the variable under interest was included in the estimated inaccuracy.
The effect of this inaccuracy on simulation results was determined by making three simulation runs with the model: one with the original data set from Wageningen, one with the data set in which the variable considered was diminished with its inaccuracy and one in which this variable was increased with its inaccuracy. All other elements were kept unchanged.

The inaccuracy in air temperature is at least 1 °C. Permanent overestimation of the temperature by 1 °C led to a decline in simulated yield with 7 % and to a reduction of the vegetative period duration by 10 days. An underestimation of temperature had the opposite effect: a yield increase and a longer vegetative period. The effect on the simulated water-limited yield was even larger: a 10 % decline in yield was found as a result of overestimation of temperature (chapters 2 and 4).
Inaccuracies of 10 % can be expected in global radiation measurements. Overestimation of radiation with 10 % led to a 10 % increase in simulated potential yield and underestimation to a yield decline of 10 %. When water was limiting the effect was the other way round: overestimation of radiation resulted in a lower yield and underestimation in a higher yield (chapters 3 and 4).
A typical deviation in precipitation of 10 %, caused a 10 % deviation in simulated yield in dry years (overestimation of precipitation led to a higher yield and underestimation to a lower yield).
The inaccuracy in vapour pressure is only 0.5 mb and in wind speed 10 % (chapter 4). The model was not sensitive to inaccuracies in these data and hardly any effect on simulation results was found.

Estimation of missing values

Another problem is the occurrence of missing values in data sets. Due to breakdown of instruments or to problems with the data collecting computer, the value of a weather variable may be not recorded for a couple of days. In the worst case there are no data available at all. Crop growth models require data for every day, so the values of the missing data have to be estimated.

Depending on the method used, the estimated value can deviate considerably from the original one. The effects of estimation methods used in practice were studied for all weather data. For temperature the best estimation method was use of data from another station in the same climatic district. Global radiation was replaced best by estimates based on sunshine duration data. For rain fall data from a nearby station (10 km) were best. Missing vapour pressure and wind speed values could be replaced by averages. The model was not sensitive to inaccuracies in these data and their variability was small. For temperature, radiation and precipitation use of averages (even averages over 10 days) led to enormous deviations in simulated yields, sometimes up to 30 %. This was because most relations between weather and growth are non-linear, and hence average input does not result in an average output.

The effects of use of average weather data in other climates

Deviations in simulation results due to use of average weather data are related to the variability of the weather. When weather is constant, the average value will not deviate from the daily values and the simulation result will be the same. The effect of using averages is likely to vary between different climates. To investigate the magnitude of this climate effect, simulation runs were made with average weather data from sites in three different climates: Wageningen in The Netherlands (temperate maritime climate), Migda in Israel (mediterranean climate) and Los Baños in the Philippines in the humid tropics (chapter 5). The effects were studied for the same spring wheat model as used for studying the effects of inaccuracies in weather data.
When precipitation is left out of consideration, weather in the mediterranean climate and in the humid tropics is intuitively far more constant than the weather in the temperate maritime climates. So it is to be expected that use of averages for these sites lead to smaller deviations in simulation results.
For all three sites the variability of the weather during the growing season was quantified, through calculation of the average deviation between daily and averaged value. Sites hardly differed in this variability. The explanation of this unexpected result was found in the fact that crops were grown during different parts of the year. In The Netherlands wheat is grown in summer, but in Israel and the Philippines it is grown in winter. Weather in Israeli and Philippine winter turned out to be as variable as weather in Dutch summer.
An overestimation of the simulated potential yield of 5-15 % was found as a result of the use of average weather data for all sites. Use of average data resulted in overestimation of the water-limited yield in the wet conditions and underestimation of yield in dry conditions.
All over the world crops are grown in that part of the year in which it rains. The existence of dry and wet days (clouds!) in this season leads to a large day to day variation in weather. Most crop growth simulation models contain non-

linear functions. Thus at any site use of average weather data in simulation models developed for daily data can be risky.

Climatic change

Emissions of gases as CO_2, methane, chlorofluorocarbons and nitrous oxide as a result of human activities will enhance the natural greenhouse effect and may result in an increase of the 'global average annual mean surface air temperature'. Such warming is likely to affect the climates all over the world and with this the agricultural production.
The greenhouse gas CO_2 also plays an important direct role in crop growth: CO_2 is the primary source of carbon for the plant and its present concentration is suboptimal. Elevated CO_2 concentrations lead to higher assimilation rates and *to an increase in stomatal resistance, resulting in a decline in transpiration and* improved water use efficiency of crops.
Thus the increasing atmospheric CO_2 concentration affects global agricultural production via a change in climate and via changes in photosynthetic and transpiration rates. The final effect of higher CO_2 concentrations on crop yields is therefore hard to assess. In such cases simulation models can be useful.
A crop growth simulation model was constructed in which effects of atmospheric CO_2 concentration on assimilation and transpiration rates were included (chapter 6). The model simulates wheat crop production under given (= input) weather conditions and CO_2 concentration. Through changing weather data in accordance with the expected climatic change the effects on final yield can be observed. The data set from Wageningen 1954-1987 was used as starting point. The effects of several combinations of temperature rise and CO_2 concentrations were examined in detail for this site. A climatic change will also affect the other weather variables such as global radiation and precipitation. However, presently no assessments exist on the effects of increased atmospheric CO_2 concentration on these variables, therefore they are not considered in here.
Large variation existed in the effect of temperature rise in individual years. It was concluded that for reliable estimates, the effect of temperature rise must be studied for a long series of weather data (over 20 years). The effect of changed agricultural practices such as use of other varieties or other sowing dates on simulated yield was also studied. Neither change in sowing date nor change in variety could prevent the yield decline as result of a temperature rise.

Wheat is grown in very different climates and a large variety of cultivars exist. It is likely that effects of climatic change on wheat grown in other countries will differ from the situation in The Netherlands. To obtain better insight into the possible effects of increased CO_2 concentrations on wheat yields, the model described in chapter 6 was used to examine the effects of elevated CO_2 concentration and temperature rise on yields in various regions of Western Europe (chapter 7). The number of sites from which daily weather data over 20-30 years could be obtained (only 13 stations) limited the number of simulation runs.

For potential production (optimal water) a 3 °C temperature rise caused a yield decline due to a shortening of the growing season. Doubling of the CO_2 concentration caused an increase in yield of 40 % due to higher assimilation rates. Effects of higher temperature and higher CO_2 concentration were nearly additive and the combination of both led to a yield increase of 1-2 ton ha^{-1}.

When water was a limiting factor in crop production, effects of temperature rise and higher CO_2 levels were different: a rise in temperature led to a smaller yield reduction and to a decline in yield variability and doubled CO_2 concentration to a larger yield increase, due to the improved water use efficiency of the crops. The combination of both led to a large yield increase (3 ton ha^{-1}) in comparison with yields simulated for present situation.

Both rise in temperature and increase in CO_2 concentration reduced water requirements of the crop. Thus differences in simulated yield between sites and between years caused by differences in available water became smaller.

Samenvatting

De weersomstandigheden tijdens het groeiseizoen kunnen grote invloed hebben op groei en opbrengst van landbouwgewassen. De opbrengst na een warme en droge zomer verschilt vaak van die na een nat en koel groeiseizoen. Wat precies de invloed van bepaalde weersomstandigheden op de gewasopbrengst is, is bijzonder onduidelijk. De gevolgen van bijvoorbeeld iets meer zon in mei of iets minder regen in juni voor de opbrengst zijn niet te achterhalen. Alleen van extreme weersomstandigheden zoals zware hagelbuien, strenge vorst of grote droogte, die het gewas ernstig kunnen beschadigen, is de invloed duidelijk waarneembaar.
In de afgelopen decennia zijn er door diverse onderzoeksgroepen wiskundige modellen ontwikkeld waarmee de groei en ontwikkeling van gewassen kunnen worden nagebootst: de zogenaamde gewasgroei-simulatiemodellen. Om de gewasgroei te kunnen simuleren is een beschrijving van de groeiomstandigheden van het gewas nodig. Weersgegevens zijn dan ook belangrijke invoergegevens voor deze modellen. De eisen met betrekking tot de invoergegevens verschillen van model tot model: meestal zijn gegevens over minimum en maximum temperatuur, globale straling en neerslag nodig en soms ook gegevens over de relatieve luchtvochtigheid en de windsnelheid. De meest gebruikte modellen rekenen met daggegevens. Er bestaan ook modellen die met een tijdstap van een uur werken en uurlijkse weersgegevens nodig hebben. De meeste meteorologische stations verstrekken daggegevens. Het aantal plaatsen waar uurlijkse gegevens worden verzameld is erg klein. De toepasbaarheid van de laatst genoemde modellen is daardoor erg beperkt.

De weersgegevens die als invoer voor gewasgroeimodellen gebruikt worden, worden vaak beschouwd als foutloos. Dit is niet realistisch. Weersgegevens zijn meetresultaten. In deze gegevens zijn dus meetfouten en andere onregelmatigheden te verwachten.
In de afgelopen jaren is de kwaliteit van de modellen sterk verbeterd. Sommige zijn goed in staat de in het veld waargenomen groei te simuleren. Het is van belang te weten of, en zo ja in hoeverre, verschillen tussen waargenomen en gesimuleerde groei veroorzaakt kunnen zijn door onregelmatigheden in de weersgegevens of dat ze het gevolg zijn van onjuiste simulatie van de gewasgroei. In dit proefschrift worden de meest voorkomende fouten in weersgegevens besproken en de effecten daarvan op de simulatieresultaten bestudeerd.

Het gewasgroei-simulatiemodel

Voor het bestuderen van de effecten van onjuistheden in weersgegevens op de

simulatieresultaten werd gebruik gemaakt van een zomertarweversie van SUCROS87 (Simple and Universal CROp growth Simulator, version 1987). Het model simuleert de waargenomen produktie goed (hoofdstuk 6). De effecten werden bestudeerd voor twee produktieniveaus: potentiële produktie en water-beperkte produktie. De potentiële produktie van een gewas wordt bepaald door de gewaseigenschappen, de temperatuur en de globale straling. De water-beperkte produktie wordt behalve hierdoor ook bepaald door de hoeveelheid voor het gewas beschikbaar water. Voor beide produktieniveaus wordt ervan uitgegaan dat er geen nutriëntentekorten zijn en dat het gewas geen hinder ondervindt van ziekten en plagen of van onkruiden.
Uitgangspunt van het model is de berekening van de fotosynthese en de respiratie op orgaanniveau. Het ontwikkelingsstadium van de plant bepaalt hoe assimilaten verdeeld worden over de diverse organen. Het model rekent met een tijdstap van een dag. Numerieke integratie resulteert in het verloop van de biomassa in de tijd. Voor simulatie van de potentiële produktie zijn daggegevens over minimum en maximum luchttemperatuur en globale straling nodig. Om de water-beperkte produktie te kunnen berekenen werd het model uitgebreid met een bodemwaterbalans en een routine voor de berekening van de evapotranspiratie van de bodem en het gewas. De evapotranspiratie werd berekend met de Penman-Monteith-vergelijking. De bodem werd voorgesteld als een meerlagig systeem. Wanneer het regent wordt de bovenste laag van het systeem nat, wanneer deze laag verzadigd is, sijpelt het water door naar de daaronder gelegen laag. Op verschillende manieren kan er water verdwijnen uit het profiel: door verdamping uit de bovenste bodemlaag, door transpiratie uit de bewortelde zone en door percolatie naar diepere grondlagen. Voor de berekening van de water-beperkte produktie zijn ook gegevens over neerslag, dampdruk en windsnelheid nodig.

Meteorologische gegevens

Voor deze studie werd gebruik gemaakt van de weersgegevens van het meteorologisch station 'De Haarweg' van de Landbouwuniversiteit Wageningen. De gebruikte set bevatte dagelijkse weersgegevens van de jaren 1954 t/m 1987 (minimum temperatuur, maximum temperatuur, globale straling, neerslag, dampdruk en windsnelheid). In deze periode kwamen 5 'droge jaren' voor: 1957, 1959, 1973, 1976 en 1986. De gesimuleerde opbrengst voor deze droge jaren was laag: 2 - 5 ton ha^{-1}. In de overige jaren was er nauwelijks sprake van een watertekort voor het gewas en waren de gesimuleerde opbrengsten aanzienlijk hoger.

Onnauwkeurigheden in weersgegevens

Er bestaan een aantal mogelijkheden waardoor de waarde van bijvoorbeeld de

luchttemperatuur in een data set afwijkt van de luchttemperatuur die door het gewas is 'waargenomen'. Er kan een afleesfout gemaakt zijn, de thermometer kan een afwijking vertonen, het instrument kan verkeerd zijn opgesteld etc. Het is ook heel goed mogelijk dat de luchttemperatuur op de plaats waar het gewas groeide anders was dan die op het veld waar de meteorologische waarnemingen gedaan zijn. In dit proefschrift wordt aan de hand van literatuurgegevens de afwijking die kan voorkomen tussen de gemeten waarde op het meetveld en de voorgekomen waarde op een nabij gelegen proefveld geschat (hoofdstukken 2, 3 en 4).
In de gemeten waarden van de luchttemperatuur bleken afwijkingen van 1 °C voor te kunnen komen. Een permanente overschatting van de temperatuur met 1 °C leidde tot een verlaging van de gesimuleerde potentiële produktie van 7 % en een reductie in de duur van de vegetatieve periode van het gewas van 10 dagen. Een permanente onderschatting van de luchttemperatuur had het omgekeerde effect: de gesimuleerde potentiële produktie nam toe met 7 % en de vegetatieve periode werd 10 dagen langer. Voor de water-beperkte produktie was het effect groter: een overschatting van de luchttemperatuur met 1 °C leidde tot een afname van de gesimuleerde produktie met 10 % en een onderschatting tot een toename met 10 %.
De te verwachten onnauwkeurigheden in globale-stralingsgegevens waren in de orde van grootte van 10 %. Overschatting van de straling met 10 % leidde tot een toename van de potentiële opbrengst met 10 % en een onderschatting tot een reductie van 10 %. Wanneer er sprake was van grote watertekorten voor het gewas, leidde 10 % overschatting van de globale straling tot een reductie van 15 % in de gesimuleerde opbrengst, 10 % onderschatting van de straling gaf een 15 % hogere opbrengst.
De te verwachten afwijking in de neerslag van 10 % leidde tot afwijkingen in de gesimuleerde water-beperkte produktie van 10 % (overschatting van de neerslag leidde tot een overschatting van de produktie en vise versa). De onnauwkeurigheden in dampdruk en windsnelheid waren respectievelijk 0.5 mb en 10 %. Het model was niet gevoelig voor deze afwijkingen en er werd geen effect op de simulatieresultaten gevonden.

Het ontbreken van weersgegevens is een veel voorkomend verschijnsel in data sets. De waarde van een weersvariabele kan gedurende een aantal dagen niet gemeten zijn, doordat het meetinstrument kapot was gegaan, of door een storing in de computer waarmee de gegevens werden geregistreerd. De periodes waarover geen gegevens beschikbaar zijn, zijn soms zelfs langer dan een maand.
Gewasgroeimodellen hebben dagelijkse gegevens nodig, als er gegevens ontbreken, moeten deze worden geschat. Er zijn verschillende methodes in gebruik om ontbrekende waarden te schatten. Deze methodes worden

besproken en de gevolgen voor de uitkomsten van het simulatiemodel bestudeerd (hoofdstukken 2, 3 en 4).
De beste manier om ontbrekende temperatuurwaarden te schatten was gebruik te maken van de temperatuurgegevens van een ander station in hetzelfde klimaatdistrict. Globale-stralingsgegevens konden het best geschat worden aan de hand van zonneduurgegevens, neerslaggegevens konden het best worden afgeleid uit de gegevens van een nabij (10-15 km) gelegen neerslagmeetpunt. Dampdruk en windsnelheid konden vervangen worden door gemiddelde waarden. De variabiliteit in deze twee weerselementen was nl. erg klein en het model was er niet erg gevoelig voor. Wanneer daggegevens van temperatuur, globale straling of neerslag werden vervangen door gemiddelde waarden, ontstonden er grote afwijkingen in de simulatieresultaten. Afwijkingen in de opbrengst van 30 % kwamen voor. De verklaring hiervoor werd gevonden in het grote aantal niet-lineare relaties in het model, waardoor gemiddelde invoer niet leidde tot een gemiddelde uitvoer.

De kwaliteit van een bepaalde schattingsmethode hangt af van het klimaat. Wanneer de temperatuur in een bepaald gebied constant is, is de temperatuur van de vorige dag een goede schatting voor een ontbrekende waarde. Wanneer de temperatuur van dag tot dag erg verschilt, is dat niet het geval.
Voor een vaak gebruikte schattingsmethode (het gebruik van gemiddelde waarden) worden de gevolgen bekeken voor 3 verschillende klimaattypen (hoofdstuk 5): het gematigde zeeklimaat van Wageningen in Nederland, het mediterrane klimaat van Migda in Israël en de natte tropen van Los Baños in de Filippijnen.
Gevoelsmatig is het weer in de laatste twee klimaatzones veel constanter dan in Nederland. De verwachting was dat voor de stations in Israël en de Filippijnen gemiddeld weer een betere schatting zou geven voor ontbrekende dagwaarden dan voor Wageningen en dat het gebruik van gemiddeld weer tot kleinere afwijkingen in de simulatieresultaten zou leidden. Voor de drie lokaties werd de variatie in het weer tijdens het groeiseizoen gekwantificeerd door de afwijking van de dagwaarde van de gemiddelde waarde te berekenen. Deze afwijking bleek voor alle drie de lokaties ongeveer gelijk te zijn. Het weer tijdens het groeiseizoen was op alle lokaties dus even variabel. In Nederland wordt zomertarwe gezaaid in maart en geoogst in augustus. In Israël vindt de zaai in november plaats en de oogst in mei, in de Filippijnen is de zaai in december en de oogst in april. Het weer in de Nederlandse zomer is dus net zo variabel als het weer in de Israëlische en Filippijnse winter. Het gevolg hiervan was dat voor alle drie de lokaties het gebruik van gemiddelde-weersgegevens in plaats van daggegevens tot afwijkingen in de simulatieresultaten leidde. De potentiële produktie werd overschat en de water-beperkte produktie onderschat.
Overal verbouwt men bij voorkeur de gewassen in het seizoen waarin het

regent, het droge seizoen wordt zoveel mogelijk gemeden. In het groeiseizoen met droge en natte dagen is een grote variatie van weersomstandigheden van dag tot dag en in de meeste gewasgroeimodellen komen niet-lineaire relaties voor. Hierdoor kan, waar dan ook, het gebruik van gemiddeld weer in gewasgroeimodellen ontwikkeld voor dagelijks weer tot afwijkingen in simulatieresultaten leiden.

Klimaatverandering

De uitstoot van gassen zoals kooldioxide (CO_2), methaan, koolfluorwaterstoffen en stikstofoxides, als een gevolg van o.a. de industrialisering, zal het natuurlijke broeikaseffect kunnen versterken. Dit kan leiden tot klimaatverandering op aarde. Deze klimaatverandering zal de landbouwproduktie beïnvloeden. CO_2 heeft ook direct effect op de gewasgroei. CO_2 is de koolstofbron voor planten en de huidige concentratie van dit gas is sub-optimaal. Een verhoging van de CO_2-concentratie in de atmosfeer leidt tot een hogere fotosynthesesnelheid en tot een toename van de huidmondjesweerstand, waardoor de transpiratie afneemt en de efficiëntie van het waterverbruik van gewassen wordt verhoogd. Een stijging van de atmosferische CO_2-concentratie heeft daardoor op twee manieren invloed op de gewasgroei. Ze draagt bij aan de verandering van het klimaat en verandert de fotosynthese- en de transpiratiesnelheden. Hierdoor is het moeilijk om uitspraken te doen over het totale effect van een CO_2-verhoging op de gewasproduktie. In dit soort gevallen kan het gebruik van simulatiemodellen nuttig zijn. In hoofdstuk 6 worden de aanpassingen aan het zomertarwemodel beschreven waardoor het effect van een hogere CO_2-concentratie op de fotosynthese en de transpiratie gesimuleerd kan worden.
Het model was goed in staat de produktie in de huidige omstandigheden (weer en CO_2-concentratie) te simuleren. Door de invoer (huidig weer en CO_2-concentratie) te veranderen in overeenstemming met de te verwachten klimaatverandering kon het totale effect op de gewasgroei bestudeerd worden. De weersgegevens van Wageningen (1954-1987) werden gebruikt als uitgangspunt. In deze set werden alleen de minimum en maximum luchttemperaturen veranderd. Een klimaatverandering zal zich niet alleen manifesteren in luchttemperatuur, maar ook in hoeveelheid straling en neerslag. De huidige klimaatmodellen geven nog geen betrouwbare schattingen van de te verwachten veranderingen in deze elementen en daarom zijn ze in dit onderzoek buiten beschouwing gelaten. De gevolgen van verschillende combinaties van CO_2-concentratie en temperatuurstijging op de tarweopbrengsten werden bestudeerd.

De gevolgen van een temperatuurverhoging verschilden van jaar tot jaar, in de meeste jaren werd een opbrengstdaling gesimuleerd, maar in 30 % van de

jaren werd een opbrengstverhoging gevonden. Hieruit werd geconcludeerd, dat voor een betrouwbare schatting van de gevolgen van een temperatuurverhoging voor de tarweopbrengsten de gegevens van een groot aantal jaren (meer dan twintig) moeten worden gebruikt. Het gebruik van een ander ras en/of van een ander zaaitijdstip kon de opbrengstverlaging als gevolg van een temperatuurstijging niet beïnvloeden.
Tarwe wordt over vrijwel de gehele wereld verbouwd, in zeer verschillende klimaatomstandigheden. De gevolgen van een klimaatverandering kunnen verschillen voor de verschillende klimaattypen. Om een beter inzicht te krijgen in de mogelijke gevolgen van een klimaatverandering voor de tarweproduktie worden voor een aantal plaatsen in West-Europa de gevolgen van hogere CO_2-concentraties en temperatuurstijgingen nagerekend (hoofdstuk 7). Het geringe aantal plaatsen waarvan dagelijkse weersgegevens over meer dan 20 jaar beschikbaar waren, was een belangrijke beperkende factor in dit onderzoek. Een temperatuurverhoging van 3 °C leidde, op alle lokaties, tot een opbrengstverlaging van de potentiële produktie, als gevolg van het korter worden van het groeiseizoen. Een verdubbeling van de CO_2-concentratie leidde tot een opbrengstverhoging van 40 %, als gevolg van een toename van de fotosynthesesnelheden. De combinatie van temperatuurstijging van 3 °C en een verdubbeling van het CO_2-gehalte leidde tot een opbrengststijging van 1-2 ton ha^{-1}. Voor de water-beperkte produktie waren de gevolgen anders: een temperatuurverhoging leidde tot een kleinere opbrengstderving en tot een afname van de opbrengstvariabiliteit; een verdubbeling van de CO_2-concentratie had een grotere opbrengstverhoging tot gevolg door een efficiënter gebruik van water door het gewas. De combinatie van beide resulteerde in een opbrengstverhoging van 3 ton ha^{-1}.

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Curriculum vitae

Sanderine Nonhebel werd geboren op 17 september 1960 in Rijswijk (Z.H.). In juni 1978 behaalde ze het atheneum-B diploma aan Het Rhedens Lyceum te Rozendaal. In dat jaar begon ze aan de studie planteziektenkunde aan de Landbouwhogeschool te Wageningen. Het doctoraal examen werd in 1986 afgelegd met de vakken: fytopathologie, theoretische teeltkunde en meteorologie. Aansluitend aan haar studie werd ze aangesteld als toegevoegd onderzoeker bij de vakgroep Fysische Geografie en Bodemkunde van de Rijksuniversiteit Groningen. Er werd m.b.v. simulatiemodellen onderzoek gedaan naar het waterverbruik van bossen in Nederland. Van 1987 tot 1992 was ze aangesteld als toegevoegd onderzoeker bij de vakgroep Theoretische Produktie Ecologie van de Landbouwuniversiteit Wageningen en verrichtte het in dit proefschrift beschreven onderzoek.