Simulated variability of wheat and rice yields in current weather conditions and in future weather when ambient CO_2 has doubled

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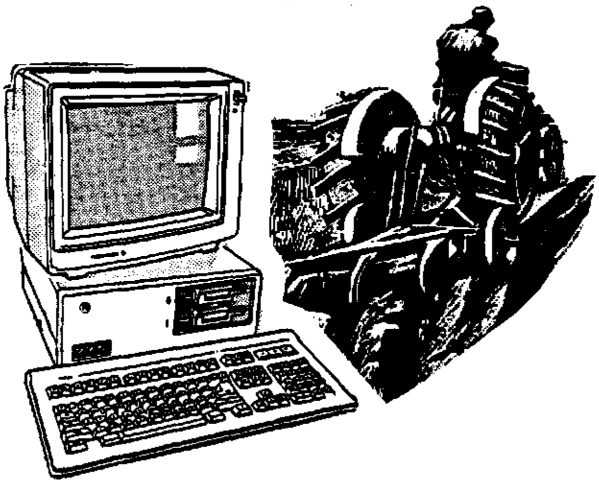

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SIMULATED VARIABILITY OF WHEAT AND RICE YIELDS IN CURRENT WEATHER CONDITIONS AND IN FUTURE WEATHER WHEN AMBIENT CO_2 HAS DOUBLED

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Abstract

The average grain yield and its variability were simulated for wheat and rice crops in four different climates: temperate, mediterranean, sub-humid tropical and dry tropical. The climates were characterized by sets of measured daily weather data covering periods of 9-32 years at typical sites. Crop growth was simulated for conditions with ample nutrient supply and without weeds, pests and diseases. Situations with continuously optimum water supply and with water supply as dictated by the precipitation regime were both investigated. Yields were predicted with two documented and evaluated simulation models. Variability was expressed as the variation coefficient of the average yield.

The simulations were repeated for future weather conditions for the same crops on the same locations. From a recently published study estimates were obtained of the changes in temperature and precipitation in the regions concerned at the time that the ambient CO_2 concentration has doubled (in 70-100 years from now). Solar radiation, wind speed and relative humidity were supposed not to change. The impact of these changes in weather on yield over the series of years was computed, and the variability derived. A third set of simulations dealt with cultivars that were better adapted to the future weather pattern.

The increase in CO_2 level permitted potential crop yields to rise by 10-50 percent, but this rise was eroded by the higher temperatures. The results were different for each of the situations considered. Variability in potential yield was low and it was not much affected by the climatic changes in the tropics. The variability increased in cooler climates. The water use by crops became more efficient. This boosted water-limited yields, except where precipitation dropped. Variability then remained high or even increased.

In this report implications are presented for agricultural planning and research, for physiologists, breeders, and climatologists.

1 INTRODUCTION

Yield variability is an important aspect of agricultural production, with consequences for the behaviour of individual farmers, for food policies of individual countries and for international trade. Hazell (1986) recently presented an extended review and analysis of yield variability and of possible changes in its value. Yield variability appears to be a complex notion. It consists of at least two components: year-to-year variability in yield per unit area due to fluctuating weather and varying biological constraints, and year-to-year variations in the cultivated area. Variability in yield is often superimposed on a positive trend in yields per hectare, due to technological improvements. The latter also cause an increasing uniformity of species and cultivars, which probably leads to increases in variability at a national level. A wide geographic distribution of a crop can reduce variability. Those aspects, of particular importance at the national level, are not discussed here. We dealt only with the variability of yield per unit area for single crops. Yield variability is generally around 10 percent under favourable conditions with grain yields of 4000-8000 kg ha^{-1}, but may be as high as 100 percent under unfavourable conditions with average yields of 1000-3000 kg ha^{-1}.

Crop yields are strongly influenced by weather. Therefore, changes in climate, or rather in weather, may have important impacts on agriculture in general and on yields and their variability in particular. Experimentation to establish effects of expected climate changes on yield and variability is very laborious, expensive and slow. An alternative method to examine the effects of anticipated climatic changes on yield and yield variability is through systems analysis and simulation. For these simulations, we based ourselves on climate changes predicted by others and dealt only with the variability of yield per unit area for single crops. To extrapolate from these results to yield variability at a national scale would require also an analysis of the shift in area used for these crops. This was not attempted.

The wheat and rice crop were chosen for this study because of their importance for the world food supply and because relatively good models were available for both. Yields were simulated and their variabilities calculated for four geographic regions, characterized by different climatic conditions, for situations with optimum soil water (irrigated crops: potential production) and for situations where soil water availability is dictated by precipitation and soil physical properties (purely rain-fed crops: water-limited production). The simulations apply to relatively intensive agricultural systems, where nutrients are supplied at an appropriate level. Reductions in yield due to diseases, pests and weeds were not considered.

A summary version of this report was presented by Penning de Vries et al. (1987) at the International Symposium on Climate and Food Security, New Delhi, February 1987.

2 METHODS

2.1 General

Annual yields of wheat and rice were simulated for different locations with the use of series of 9-32 years of actual weather data. Subsequently, the weather data were modified to reflect conditions under a doubled atmospheric CO_2 level (680 cm^3 m^{-3}), which is expected to be reached in 70-100 years from now. In order to examine to what extent average yield and its variability may change, the same series of simulations was repeated for future weather conditions. As those conditions are rather different from the present ones, it can be anticipated that new cultivars of wheat and rice will be used. An educated guess was made about the characteristics that can be changed in the model to represent such new cultivars. Simulation with those crop properties provided the third set of average yields and yield variabilities.

The potential 'greenhouse' effect of trace gases such as O_3, NH_4, NO_2, and CFH's is equivalent to that of CO_2 in terms of climatic change, but no direct effect on crop growth was taken into account.

Variability in yield between individual years was calculated as the coefficient of variation (CV), because relative variations are more important than absolute ones. If necessary, higher moments of the statistics can be extracted from the cumulative frequency distributions that result from these computations, but they will not be discussed here. There was no trend in yield over many years in this simulation study.

2.2 Weather data

The weather data used were daily values from standard meteorological stations: maximum and minimum air temperature, total global radiation, average wind speed, precipitation and early morning vapour pressure. Historical weather data from four different locations were used, representing a temperate region (Wageningen, Netherlands, 52°00' N 5°40' E), a Mediterranean region (Migda, Israel, 31°20' N 43°40' E), a semi-arid tropical region with summer rainfall (Hyderabad, India, 17°27' N 78°28' E) and a sub-humid tropical region (Los Banos, Philippines, 14°12' N 121°15' E). The data for Wageningen (1954-1985) were obtained from the Department of Meteorology and Physics of the Agricultural University in Wageningen, those for Migda (1962-1982) from the Israeli Meteorological Service, those for Hyderabad (1975-1984) from the

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), and those for Los Banos (1959-1983) from the International Rice Research Institute (IRRI).

Estimates of future weather conditions were based on expected changes in climatic conditions (Table 1), given by Schlesinger and Mitchell (1985), who compared the results of three different general circulation models (GCM's). The results of all three models agree in that in response to increased ambient CO_2 concentrations air temperatures will increase, at higher latitudes more strongly than in the tropics. At a global scale the hydrological cycle will be intensified and many regions will receive more precipitation. However, the results of the models differ considerably with respect to the geographic distributions of the predicted climate changes. We considered these differences as an indication of the uncertainty of the expected changes. Not all climatic factors are simulated in these GCM's, and most notably the expected changes in the radiation climate are absent. As a zero-order approximation, we assumed no changes in radiation, wind speed and relative air humidity. A constant relative humidity is considered more likely in GCM studies than a constant absolute humidity and this is in accordance with the predicted intensification of the hydrological cycle. It was assumed that no changes in cross correlation between weather parameters occur.

Future temperatures for the simulations were 'created' by applying the projected changes to the daily values of both the mimimum and maximum temperatures. The change in rainfall over the growing season was calculated as the change in average rainfall per day (Table 1) times the length of the growing season. Dividing this amount by the historic average rainfall over the same growing period gives the proportional change in rainfall. Multiplying the historic daily rainfall figures by this fraction gives the future rainfall data. This procedure leaves the number of rainy days unchanged. Both adjustments are straightforward and transparent and allow direct comparison of results between individual years. The current correlations between weather variables are retained.

2.3 Crop models

The wheat and rice models used for this study belong to the SUCROS family of summary crop growth simulation models, that have been developed over the past 15 years in Wageningen at the Department of Theoretical Production Ecology (TPE, formerly TT) of the Agricultural University, the Centre for Agrobiological Research (CABO) and the Centre for World Food Studies (SOW). The models simulate seasonal crop growth in time steps of one day. Daily growth is calculated as the result of the physiological, agro-hydrological and micrometeorological processes. The rates of these processes depend on the crop's momentary state and on the prevailing environmental conditions, particularly weather and soil. Such process-based models are explanatory, which allows their use for predicting crop performance under altered environmental conditions.

The effect of an increased CO_2 concentration on crop performance was described with the use of relatively simple physiological assumptions. The value of the light-saturated maximum assimilation rate of individual leaves was supposed to have twice its present value (Goudriaan et al., 1985) whenever sink size limitation was absent. The light use efficiency at the light compensation point increased by 25 percent (Goudriaan et al., 1984). The effect of increased CO_2 concentration on leaf area development is more difficult to quantify. It has been observed that the increased assimilate availability is partly expressed in thicker leaves, rather than in increased leaf area growth (Goudriaan and de Ruiter, 1983). In agreement with these observations the specific leaf area under increased CO_2 was assumed to be 35 percent lower than under present conditions.

2.3.1 The spring wheat model

The spring wheat model by van Keulen and Seligman (1987) was applied. In this model phenological development, dry matter accumulation and distribution, and organ formation of a spring wheat crop are simulated in dependence of weather conditions and water and nitrogen availability. Weeds, pests and diseases are assumed to have no influence.

Phenological development is calculated on the basis of cultivar-specific linear relations between air temperature and development rate that differ for the pre-anthesis and post-anthesis growth stages. Relevant phenological stages are defined on a scale from 0 (emergence), to 1 (dead ripe), with anthesis at 0.5.

The basis for dry matter accumulation is canopy gross assimilation, calculated from the photosynthesis-light response curve of individual leaves, the green area index of the canopy and the prevailing irradiation conditions. The light-saturated maximum assimilation rate of the leaves is a linear function of the nitrogen concentration in the leaf blades. Maintenance respiration is calculated from the dry weight of the various organs, by taking into account the effects of temperature and nitrogen concentration. The partitioning of primary assimilates over the various organs, leaf blades, stems and sheaths, roots, a pool of reserve carbohydrates and grains is described by partitioning functions in dependence of development stage. The instantaneous partitioning pattern is influenced by the water status and the nitrogen status of the vegetation. The conversion efficiency of primary assimilates into structural plant material is a function of the chemical composition of the material formed.

The number of tillers, ears, spikelets, florets and grains is simulated. The rate of organ formation at any relevant phenological stage depends on the rate of carbohydrate flow to the meristematic tissue and a cultivar-specific minimum carbohydrate flow needed to initiate a viable organ. That minimum value is also dependent on the development rate of the crop, expressing the notion that an organ requires a minimum size to be viable. Effects of water shortage or nitrogen shortage on organ formation are mediated through their effects on carbohydrate availability.

The soil water balance is calculated, taking into account infiltration, transpiration, soil surface evaporation and leaching, and provides current available soil water in the rooted zone. Canopy transpiration follows from the potential value, determined by the evaporative demand of the atmosphere, and the current water availability. Insufficient water in the rooted zone or limited capacity of the root system for water uptake results in partial stomatal closure, with consequently a reduction in transpiration. Gross assimilation is then reduced in proportion to the reduction in transpiration.

Performance of the model was evaluated with data sets from Israel, Australia and Syria. The results of these validations showed that if the required cultivar characteristics can be estimated with sufficient accuracy, the model can give an adequate description of the effects of environmental conditions, water supply and nitrogen supply on growth, yield and water use of spring wheat.

Choice of simulation parameters for wheat

In the simulations for this paper, only parameters and functions characterizing the environment and the wheat cultivar were adapted. A fixed sowing date was assumed, specific for each location, irrespective of the prevailing environmental conditions. For the irrigated crops a pre-sowing irrigation was applied in all cases to ensure proper germination. For the rain-fed crops the onset of germination is determined by the rainfall pattern. The consequence is that the onset of germination and the moment of emergence depend on rainfall distribution. Moreover, if germination starts and the soil dries out before emergence is completed, crop failure occurs and the model does not allow for resowing. This assumption may have resulted in lower average yields and higher variability than under an opportunistic strategy where sowing date is dependent on the rainfall regime.

For Migda simulations started on October 1, the initial soil water being dictated by rainfall conditions in the preceding season, i.e. in some cases residual moisture was present in the profile. Sowing was assumed on November 15, resulting in emergence for the rain-fed crop between November 22 and February 18. Complete crop failure occurred in five out of the 21 years. The 'standard' wheat cultivar used had the same properties as the one defined for optimum conditions by van Keulen and Seligman (1987).

For Wageningen simulations started on March 1. It was assumed that at that date the profile is at field capacity as a result of the precipitation excess in winter time. April 1 was assumed as sowing date, resulting in emergence for the rain-fed crops between April 8 and June 29. In that situation crop failure occurred in 5 out of 32 years. The wheat cultivar for these conditions was assumed to have a pre-anthesis development rate 1.2 times that of the 'standard' wheat defined for Migda. This assumption was necessary to obtain phenological development in accordance with published data (Spiertz et al., 1971).

For Los Banos simulations started on November 1. It was assumed that the soil profile is at field capacity at that date as a result of the high precipitation in the preceding months. Sowing was assumed to take place on November 15, resulting in emergence between November 22 and December 8. Crop failure due to interrupted germination occurred once in the 24 years. The wheat cultivar for these conditions was one having a pre-anthesis development rate 0.9 times that of the 'standard' wheat. This gave reasonable agreement with observed phenological data (Aggarwal et al., 1987).

For Hyderabad a somewhat different approach had to be taken. Simulations started on September 1, again with the profile at field capacity following the high precipitation in the preceding months. Sowing cannot take place before November 1 due to very high temperatures (Tandon, 1985). At that time, however, the top soil is dried out and germination fails in all cases. As a relatively intensive agricultural practice was assumed it was also postulated that for the rain-fed crops a pre-sowing irrigation is applied to ensure proper germination. The result was that wheat in Hyderabad emerged between November 8 and 11 for all years. The cultivar was identical to the one defined for Los Banos.

2.3.2 The rice model

The WOFOST model described by Wolf et al. (1986) and Rappoldt (1986) was applied to simulate the growth of a rice crop. It follows the same approach as the spring wheat model, but describes the growth processes and the soil water balance in a more summarized form. In this model the partitioning of assimilates is fixed and specified as a function of development stage only. The nitrogen concentration in the plant organs is invariate and the effect of possible nitrogen shortage on assimilate partitioning cannot be simulated. In addition, this model does not take into account the possible effects of sink limitation, implicitly assuming that sink capacity is always sufficient to utilize the available assimilates.

Choice of simulation parameters for rice

The simulations for the rice crop were executed for 25 years at Los Banos (1959-1983) and for 10 years at Hyderabad (1975-1984) for the cultivar IR8, grown in the rainy season. The simulation starts with a successful transplanting on a fixed date. The selected dates are 'normal' for the main rain-fed rice crop at both locations: August 1 at Los Banos and July 16 at Hyderabad. In current and future weather situations the same initial weight of the crop at transplanting was used (200 kg ha^{-1} dry matter of which 75 kg ha^{-1} is leaf). For the water-limited production it was assumed that the whole rooting zone is saturated at the time of transplanting, so that crop failure due to drought cannot occur during the early growth stages. Yield reductions due to temporary drought can only result from water deficiency during the mid and late growing season.

The soil used in water-limiting conditions was an upland paddy soil with a deep groundwater table, an effective rooting depth of 0.4 m, and a maximum percolation rate of 0.005 m d^{-1}. This is not a prime rice soil, but is well-suited to serve as an indicator of drought risk in rice cropping during the rainy season.

3 RESULTS

Results of the simulations are summarized in Tables 2 and 3. Average potential and water-limited yields and their variabilities for the two crops and the four locations under present and future weather conditions are presented in Table 2, and the corresponding harvest indices, transpiration coefficients and some characteristics of the soil water balance in Table 3.

3.1 Current yield levels and their variability

3.1.1 Current potential and rain-fed wheat yields

Average potential yields under the present weather conditions varied from about 3000 to about 6700 kg ha^{-1} (expressed in dry matter). This large range in potential yield levels reflects the climatic differences between the four locations. For each location separately the yield level was rather stable (CV around 10 percent) as a result of the smaller variability in weather conditions.

In situations with limited water the average values were considerably lower (between about 1750 and 3250 kg ha^{-1}), and the variability was usually much higher (CV up to 84 percent).

Simulated grain yields of irrigated wheat in Migda over a sequence of 21 years are presented in Figure 1, as an example of the results. The average yield is 6636 kg ha^{-1} and its variability amounts to 9 percent. Such results plotted as a yield-frequency-distribution graph show an S-shaped curve (Figure 2), indicating that the coefficient of variation is an appropriate measure for variability. In this situation yield variability is the result of the combined effect of irradiation and temperature on the various yield-determining processes. These include assimilation and respiration on the source side and rates and length of period of organ formation on the sink side. No detailed analysis of the individual effects has been attempted here.

Figure 1 also presents the yields of wheat at the same location and under identical weather conditions, but with precipitation as the only source of water. In almost all situations the variability in potential and water-limited yields differed enormously. This underlines the importance of water availability as a crucial constraint in crop production. Because of the low and erratic rainfall in Migda (highest value observed in this period 424 mm, lowest value observed 78 mm), average yield was much lower (2070 kg ha^{-1}) and the variability was much larger: 84 percent. This computed variability is probably higher than in reality because of the assumed fixed sowing date and the absence

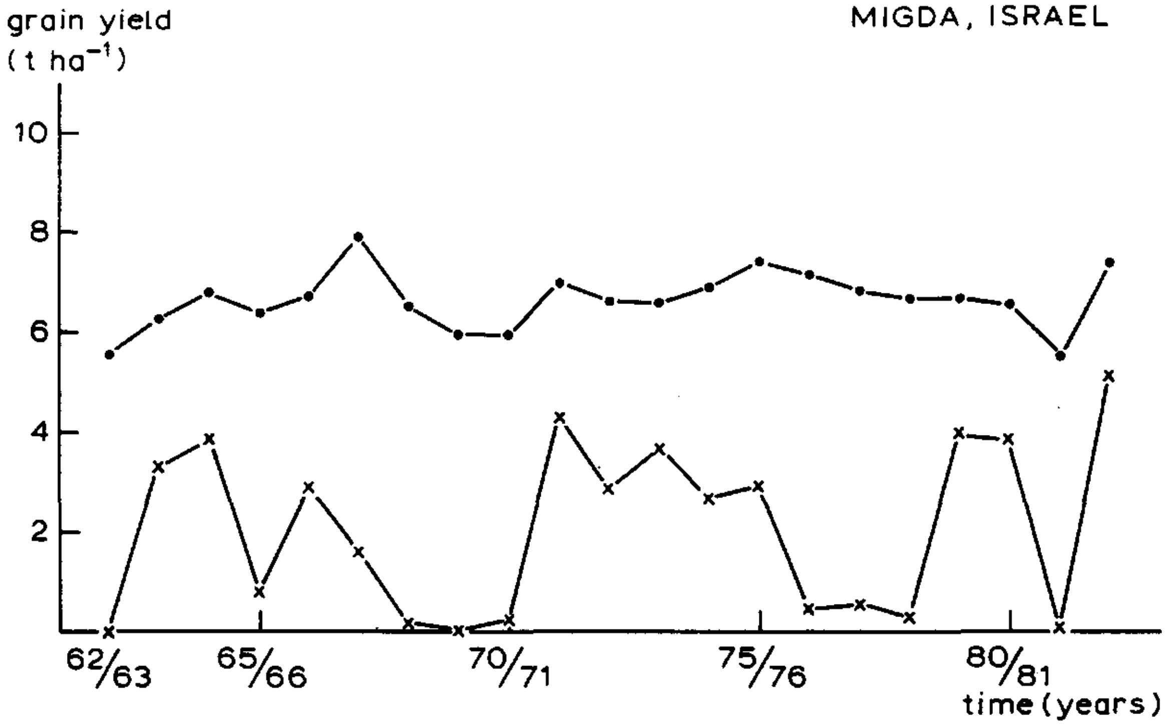

Figure 1. Yield of wheat in Migda in 1962-1982 for the potential growth situation (upper curve) and precipitation-limited growth. For the average yield and the corresponding CV, see Table 2.

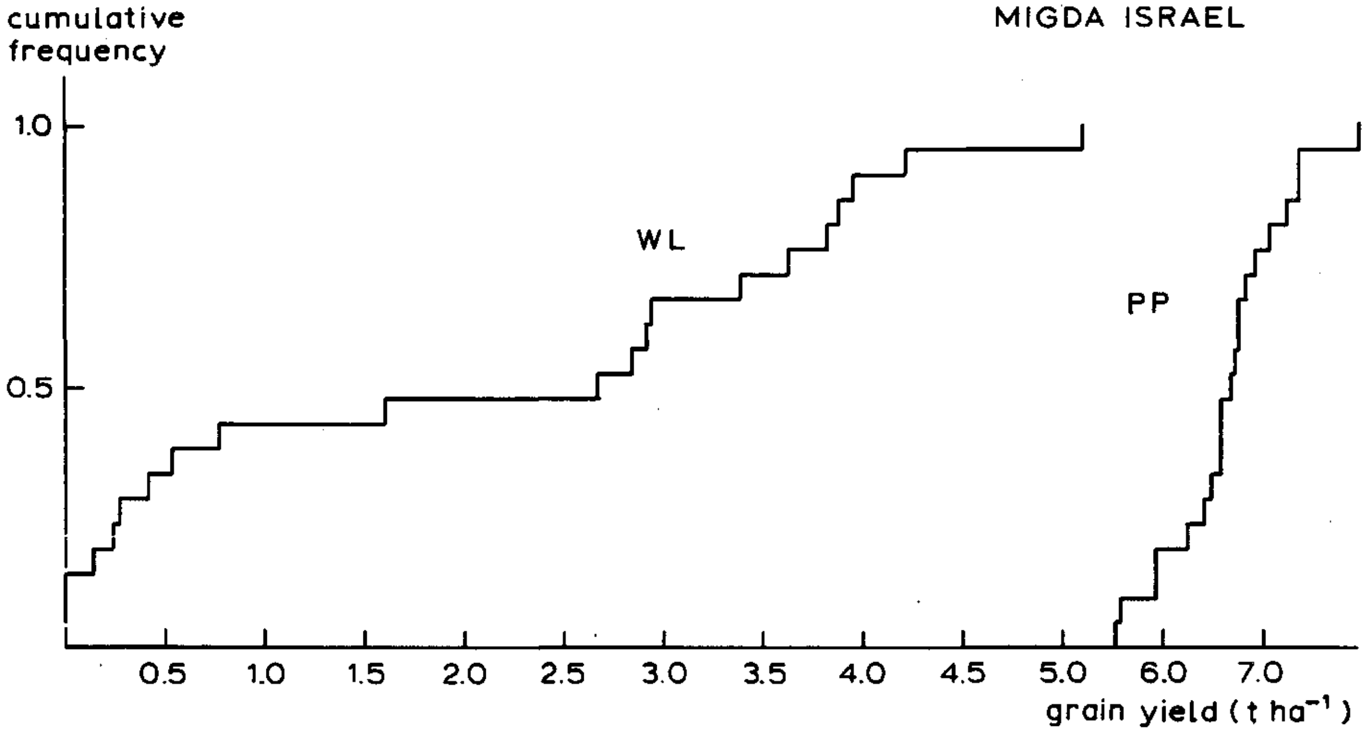

Figure 2. Cumulative frequency distribution of wheat yields in Migda with optimal water (PP) and water from precipitation only (WL).

of a possibility of resowing after early crop failure. Still, it is obvious that variability is large indeed. The CV drops only to 68 percent if the years with total crop failure are excluded. The yield-frequency-distribution graph for this situation, also presented in Figure 2, confirms that the coefficient of variation is a fair measure of variability.

For Wageningen the water-limited yield level was about half the potential level and variability was as high as 61 percent due to crop failure in 5 years and limited moisture availability during the growing season for most of the years. The soil used for this simulation experiment was a fairly heavy soil with a limited storage capacity and a deep groundwater table, so more drought-prone than most Dutch wheat-producing soils.

Potential wheat yields for Los Banos for the 24 year period varied between 2000 and almost 4000 kg ha^{-1} and were on average less than half the values found for Migda and Wageningen. The CV was 12 percent. The reason for the low yield is that, even for a cultivar with a lower pre-anthesis development rate than for the previous locations, the growth period was relatively short due to the prevailing higher temperatures: on average 49 days between emergence and anthesis and 27 days for the grain-filling period. Under rain-fed conditions the average yield was only 1852 kg ha^{-1}, with a variability of 40 percent. The average value agrees well with recent experimental evidence (Aggarwal et al., 1987).

For Hyderabad potential grain yield averaged 4167 kg ha^{-1}, with a variability of only 8 percent, for crops emerging around November 10, i.e. after the rainy season and when temperatures have dropped somewhat. This relatively low average yield is again due to the fact that the growing period was relatively short due to the high temperatures. Under rain-fed conditions average grain yield was 1766 kg ha^{-1} with a CV of 10 percent. This relative stability is brought about by the fact that in all years the crop relies entirely on stored soil moisture, combined with the assumption that the profile is at field capacity at the start of the simulations on September 1, irrespective of preceding rainfall.

The harvest index, the ratio of grain yield (economic yield) and total biomass, was fairly constant when optimum moisture conditions were maintained throughout the season. If not, large fluctuations occurred as a result of differences in the timing of moisture deficiency. This is shown in Figure 3, which presents the mean harvest indices and the range within which they usually fluctuated (harvest index in Table 3 is average plus standard deviation).

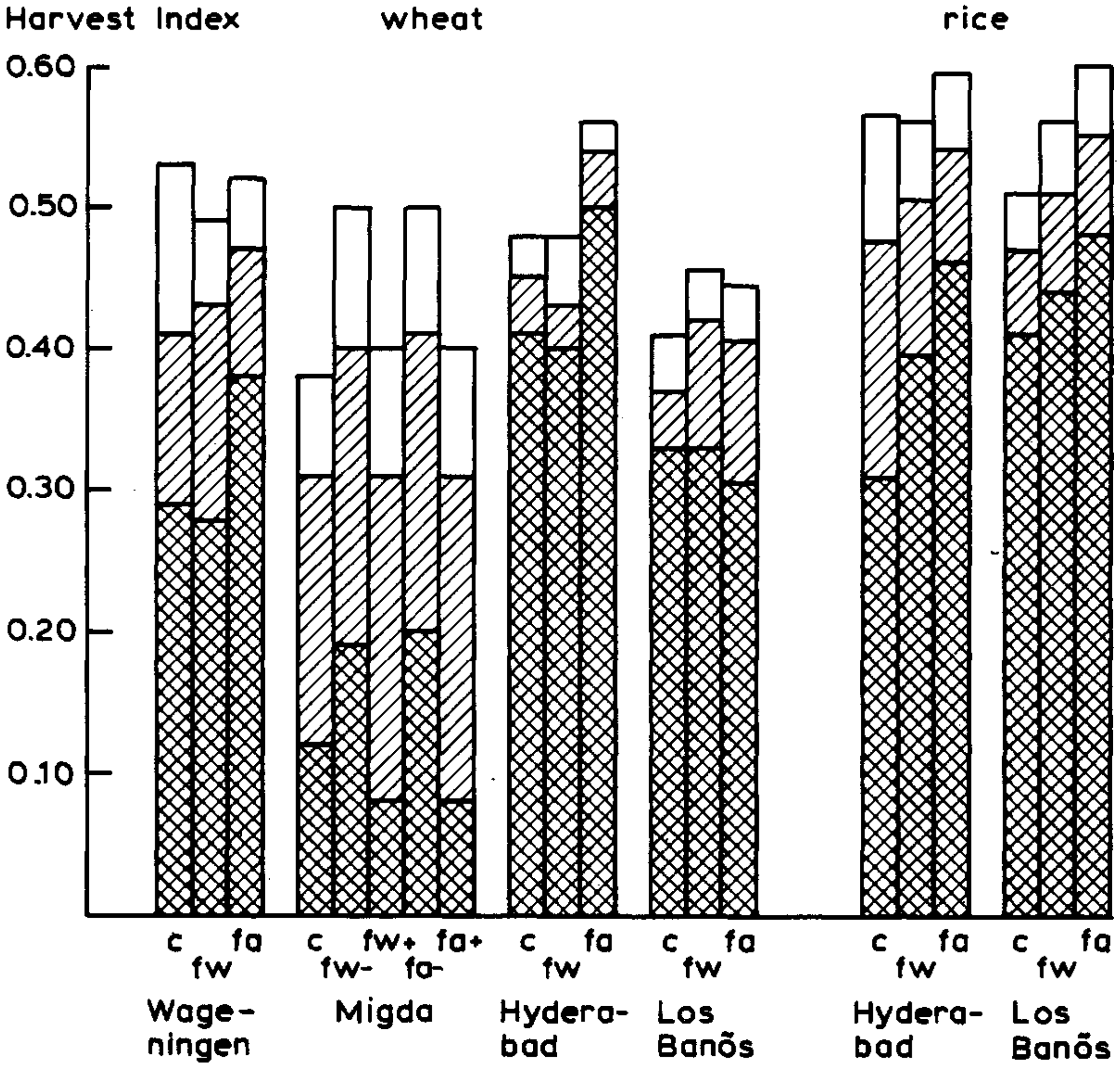

Figure 3. Histogram of harvest indices (kg grain per kg total aboveground biomass) for wheat and rice, water-limited production. The lower part of each bar reflects the harvest index reached or exceeded in 9 out of 10 years, the second part the harvest index reached or exceeded in 5 out of 10 years, and the upper part the harvest index reached or exceeded in 1 out of 10 years. For explanation of abbreviations: see Table 2.

3.1.2 Current potential rice yields

Potential yields (expressed in dry matter) varied from 5100 to 7600 kg ha^{-1} for Los Banos and from 7200 to 8500 kg ha^{-1} for Hyderabad. Yield variability is related to the temperature and irradiation regimes, which show stronger fluctuations in Los Banos than in Hyderabad. The higher potential yield in Hyderabad is related to higher irradiation and lower average temperatures during the rice-growing season. Higher irradiation results in higher gross assimilation, and a lower temperature in a relatively lower maintenance respiration and a longer growth duration (90 days in Hyderabad versus 85 days in Los Banos).

The yield-determining components of potential rice production under current weather conditions are quantified in Table 4. The difference of about 1400 kg ha^{-1} in grain yield between Hyderabad and Los Banos can be attributed largely to the higher gross assimilation rate in Hyderabad, resulting in a difference in average potential growth rate of 33 kg ha^{-1} d^{-1}. Over a grain-filling period of 31 days this difference amounts to 1023 kg ha^{-1}. The one day longer duration of this period in Hyderabad, resulting from a 1 °C lower mean temperature add another 200 kg ha^{-1} to the difference, while already at the beginning of the grain-filling period a greater amount of reserves formed shortly before anthesis is available for translocation to the grains, resulting in another 200 kg ha^{-1} more grain yield.

A considerable fraction of gross assimilation is required for maintenance respiration. The absolute amount required depends on the living biomass, its distribution over plant organs, and a temperature dependent proportionality factor. This factor doubles for each 10 degrees temperature increase, corresponding with an increase of 7 percent per centigrade.

During the grain-filling period the living biomass was 14 percent larger in Hyderabad than in Los Banos, but as a result of lower mean temperature the respiration requirement per unit biomass was 7 percent lower. Consequently, the respiration losses were 7 percent higher in Hyderabad. However, the 'net' assimilation rate was still higher in Hyderabad than in Los Banos, in absolute amount as well as relative to gross assimilation. The fraction of gross assimilation used by the crop for its maintenance respiration was 44 percent in Hyderabad and 47 percent in Los Banos.

There were important differences in variability between the yield determining components. At both locations the daily gross assimilation rate, expressed in CH_2O, fluctuated within the range of 240 to 600 kg ha^{-1} d^{-1}, be it that the average was lower in Los Banos. The maintenance respiration rate remained in general within 10 percent of its average value of 210 kg ha^{-1} d^{-1}.

The balance between assimilation and maintenance respiration, which is the substrate for crop growth, varied from 0 to 400 kg ha^{-1} d^{-1} and was characterized by a strong variability, which can be related to variations in cloudiness. The greater variability in potential yield level in Los Banos must be attributed to the more frequent, but irregular, occurrence of cloudy skies.

3.1.3 Current water-limited rice yields

The range in water-limited yields was 3900 to 7600 kg ha^{-1} for Los Banos and 3600 to 8600 kg ha^{-1} for Hyderabad, with transplanting dates of August 1 and July 16, respectively. These yields should be considered only as indicative, because they depend to a large extent on the rather arbitrarily choosen maximum percolation rate of the soil. If better paddy soils with a lower percolation rate were simulated, yield reductions due to drought would be smaller. In comparison to the potential production the water-limited production was on the average 5 percent lower in Los Banos and 18 percent in Hyderabad. The greater yield reduction under water-limited conditions in Hyderabad is due to the lower rainfall. The average rainfall during the period covered by the simulations was 590 (± 170) mm in Hyderabad and 703 (± 266) mm in Los Banos. Yield reductions due to drought did not occur as an annual phenomenon. In Los Banos there was no reduction at all in 14 years out of 25, and in Hyderabad this was the case in 3 of the 10 years. The greatest calculated yield reduction in a single year was 35 percent in Los Banos and slightly more than 50 percent in Hyderabad. These reductions in part of the years changed the yield variability from 9.2 percent for the potential to 14.8 percent for the water-limited production situation in Los Banos, and from 5.4 to 26.6 percent in Hyderabad (Table 2). Yield variability is mainly related to the rainfall pattern during the grain-filling period.

Total dry matter production in the rain-fed situation never exceeded total potential production. In some years, however, the temporary water shortage resulted in a higher harvest index or even a higher grain yield than without water limitation. This phenomenon occurs when drought stress during the pre-anthesis phase results in a lower standing biomass at anthesis. As the harvest index is defined as the ratio of grain yield to total aboveground biomass, a lower leaf biomass leads directly to a higher harvest index provided that the leaf biomass present is still capable of intercepting (practically) all the light, so that assimilation rate is not affected. A higher absolute grain yield results in still higher harvest indices. This occurs if during the post-anthesis period still sufficient green material is present to intercept all the incoming radiation and to sustain high assimilation rates, while the lower maintenance requirements of the vegetative material allow a higher grain growth rate. This implies that the crop in the potential growth situation produces more vegetative material than needed for maximum assimilation. A leaf area index exceeding 7.5 is often found, while a value of 5 is already sufficient for almost complete radiation interception.

3.2 Future yield levels and their variability

Future yields under optimum growth conditions are different from the current ones because the high CO_2 level accelerates the rate of assimilation of crops and hence their rate of dry matter production. However, the higher temperatures lead also to increased maintenance respiration losses and to increased rates of development, resulting in shorter growth durations. The overall effect can be positive or negative (Table 2).

3.2.1 Future potential wheat yields

For Migda with the largest anticipated temperature rise during the growing season (Table 1) the effect of the shorter growth duration was much stronger than that of increased assimilation rates: the potential yield decreased by almost 40 percent when the same cultivar was used. The decrease is associated with the sink size limitation during the grain-filling period i.e. the number of grains is not sufficient to accumulate all the assimilates formed. This results in mature crops with relatively high reserve levels in the straw due to incomplete translocation to the grains. The variability increased substantially to 22 percent, because in more instances sink size is the limiting factor, i.e. the variation is now more strongly related to the interannual variability in both temperature and irradiation.

At the other three locations the effect on the growth rate was the overriding factor, so that average potential yields were higher. For Wageningen this was associated with a higher variability. This is due to the same reasons as for Migda, i.e. in some years sink size is the limiting factor, resulting in relatively low yields. For Los Banos and Hyderabad the variability did not change under future weather conditions, because sink size limitation did not occur, as the number of grains was always sufficient to take up the flow of assimilates.

The future harvest index in Migda under optimal growth conditions was substantially lower than under present conditions and that for Hyderabad was substantially higher, while the differences for Los Banos and Wageningen were small (Table 3). The decrease in Migda follows directly from the lower grain yield due to sink size limitation. For Hyderabad the higher growth rates resulted in a more vigorous assimilatory apparatus at anthesis and hence led to an increased source strength during grain filling. For Los Banos the increase in grain yield was nearly proportional to the increase in total dry matter production, hence the harvest index remained constant; for Wageningen sink size limitations did occur in some years, leading to a somewhat lower harvest index with a slightly higher variability.

An outstanding feature at all locations is the large decrease in the transpiration coefficient (Table 5). This is the result of the assumption that the stomatal resistance is actively regulated by the crop, such that with high CO_2 concentrations assimilation increases considerably without affecting transpiration (assuming no change in relative humidity of the air in the future). This point will be treated further in the discussion.

3.2.2 Future water-limited wheat yields

Under rain-fed conditions the effects of expected weather changes were more dramatic because the changes in precipitation played an important role. For Migda, we used both extreme values of expected changes in precipitation (Table 1), to investigate the sensitivity for this uncertainty in climate prediction. The expected change of 0.5 mm d^{-1} on average corresponds to a change of about 25 percent in average annual precipitation. If precipitation in Migda decreased, average yield decreased by about 10 percent to a level of 1925 kg ha^{-1}. If precipitation increased the average yield rose by 80 percent to 3638 kg ha^{-1}. Variability increased with decreasing average yield level, as expected. The harvest index increased under both assumptions and its variability decreased with increasing harvest index (Figure 3). Under the growing conditions of the Mediterranean climate, moisture deficiency during grain filling is a common phenomenon that has an increasing impact at lower precipitation levels.

Average rain-fed yields in Wageningen were hardly affected. The more frequent occurrence of water deficiency during the growing season due to lower precipitation was compensated by higher growth rates under favourable conditions. The variability increased because the difference between dry and wet years is more pronounced. The harvest index increased somewhat, because the length of the pre-anthesis phase is relatively stronger reduced than that of the post-anthesis phase.

In Los Banos average yields under rain-fed conditions increased by 30 percent to 2368 kg ha^{-1}, but variability also increased from 40 to 51 percent. The combined effect of the higher assimilation rate and the more efficient water use (transpiration coefficient less than half under future weather conditions) resulted in more favourable growing conditions, despite the shorter growing period and the lower precipitation. Although crop failures still occurred, the harvest index was more favourable and the variability was not affected.

In Hyderabad average rain-fed yields went up by 15 percent to 2036 kg ha^{-1}. As this crop grows entirely on stored soil moisture, the effect of a difference in precipitation perse was absent, hence the higher yields were due to a more efficient use of the available water: a decrease of about 25 percent in the transpiration coefficient (Table 3).

The soil moisture indicators, average volumetric water content in the 20-30 cm soil layer from emergence till maturity, and total soil water in the potential rooting zone at the end of the growing season, were only affected to a limited extent. At Migda total soil moisture at maturity was substantially higher in all future weather scenarios, either as a result of more rainfall or of a shorter growing period. The quantities are, however, not large enough to allow cultivation of a second crop. The changes in soil water content were only marginal at all other locations.

3.2.3 Future potential rice yields

Differences in current and future potential yields are due to the combined effects of CO_2 and temperature increase. An explanation of the simulation results requires a separate treatment of these effects. The simulations have been repeated therefore for a doubled CO_2 concentration without and with the expected temperature change (Table 1). The results are given in Tables 2 and 3.

The CO_2 effect

Grain yields increased considerably as a result of the high CO_2 level. Without a change in temperature, mean potential yields would be nearly 50 percent higher (Table 2). The calculated yield increase for individual years varied from 40 to 50 percent, depending on the irradiation regime, and was higher for sunny than for cloudy years. The relative increase in growth rate was not constant over the entire growth period. The greatest gain in production occurred when the canopy was fully closed. But in particular during the first month after transplanting, the simulated growth rate under high CO_2 hardly exceeded that for the current CO_2 concentration. This is the consequence of the assumption of a 35 percent decrease in specific leaf area, which means that 1.54 times more dry matter must be invested in the leaves to obtain the same leaf area. This leads to a slower evolution of leaf area during the early growth stage, so that the crop intercepts less radiation than under current conditions. In addition, the maintenance respiration requirements per unit leaf area increase. As a result the effect of the increased assimilation rate per unit leaf area is virtually neutralized during the early growth stage. But as soon as leaf area no longer limits the light interception the gross assimilation rate increases substantially above current levels, resulting in an increased rate of dry matter accumulation. For a fully closed canopy the increase in gross assimilation rate varies from about 50 percent on clear days to 30 percent on overcast days. Moreover, the slow initial growth is advantageous for grain filling in rice, because a relatively smaller vegetative apparatus requires less maintenance and that has a positive influence on the harvest index.

The combination of all these CO_2 effects adds up to a somewhat stronger proportional increase in grain yield than in total aboveground biomass, and consequently to a slightly higher harvest index.

Table 5 presents a quantified picture of the contribution of the major growth determining processes to the yield formation. In comparison with the current yield level the grain yield is 51 percent higher in Hyderabad and 44 percent in Los Banos. The differences in response to the higher CO_2 concentration are related to differences in radiation and temperature conditions influencing gross assimilation and respiration processes. The higher average irradiation level in Hyderabad allows an increase of 43 percent in gross assimilation rate to 730 kg ha^{-1} d^{-1}, while the day-to-day fluctuations are in the range of 320 to 900 kg ha^{-1} d^{-1}. The maintenance respiration rate increases with 33 percent to 300 kg ha^{-1} due to the higher plant weight, but that comprises a smaller proportion of gross assimilation than under current conditions. In Los Banos the average gross assimilation rate goes up by 40 percent to 630 kg ha^{-1} d^{-1} and the maintenance respiration rate with 40 percent to 285 kg ha^{-1} d^{-1}. The difference between the two locations in daily growth rate during grain filling increases from 33 kg ha^{-1} d^{-1} under current weather conditions to 62 kg ha^{-1} d^{-1} under the influence of the higher CO_2 concentration.

The temperature effect

The temperature effect is discussed here for the situation that CO_2 has doubled. A temperature increase of 2 °C (Table 1) results in a shortening of the total growth cycle from transplanting to maturity by 6 days, of which 2 days at the expense of the grain-filling period. Another consequence is an intensification of 15 percent in maintenance respiration. This relative respiration increase is almost counterbalanced by a decrease of 14 percent in biomass. This balancing, however, is not as close as these numbers suggest because the trade-off between biomass and respiration may be non-linear. The average relative maintenance respiration rate of a crop is influenced not only by the total living biomass but also by the repartition of this biomass over its constituent plant organs, which vary in chemical composition. Both total weight and weight repartition are varying in the course of the growth cycle, and consequently the relative maintenance respiration rate varies. The lower biomass production during the vegetative period is due to the combined effect of the shorter time available for the formation of productive capacity in the form of green leaf area, the relatively greater respiration losses and the shorter time available for the accumulation of dry matter.

The yield formation process is summarized in Table 6. During the grain-filling period the gross assimilation rate is slightly lower than in the situation without temperature change, due to the less complete light interception by the canopy with a lower leaf area index. The average maintenance respiration rate is somewhat higher due to a relatively more leafy vegetative biomass. This relative abundance of leaves is the result of their formation during the earliest growth stage, when the respiration losses are still small. Overall potential rice yields in future weather are expected to be 25-35 percent higher than the current ones, while the variability remains almost constant. The yield reduction resulting from the temperature increase amounts to 1100 kg ha^{-1} for Los Banos and 1400 kg ha^{-1} for Hyderabad. Comparison of Tables 5 and 6 shows that this yield reduction is composed of 300 kg ha^{-1} less reserves available at anthesis, 300 to 600 kg ha^{-1} yield loss due to the lower growth rate, and 600 kg ha^{-1} due to the shorter grain-filling period.

3.2.4 Future water-limited rice yields

The future water-limited yield levels of rice in Los Banos and Hyderabad are influenced by the higher potential growth rates, the higher temperature and the higher rainfall (Table 1). In spite of the higher growth rates, the water requirements hardly change. On a day by day basis the crop's future water requirements are approximately the same as under current conditions, but due to the shortening of the crop's growth cycle by 6 days the seasonal requirements are slightly lower, and a given drought period occurs at a slightly shifted crop development stage. The crop is somewhat more sensitive to drought periods in the middle of the growth cycle, but is less affected by droughts at the end of the season.

The increase in rainfall is higher in Hyderabad than in Los Banos (Table 1). The increase of 1 mm per day in Hyderabad corresponds with a proportional increase of 15 percent over the growing season and the increase of 0.5 mm per day in Los Banos with 6 percent, proportionally. The total increase in rainfall over the crop growth cycle is less than these percentages indicate, because of the shortening of this period with 6 days.

In Los Banos the average future yield reduction due to drought was some 4 percent. On a year by year basis these reductions followed the same pattern as under current weather conditions. In comparison with the current water-limited yields the increase was 29 percent, comparable to the increase in potential yield.

In Hyderabad the larger increase in rainfall caused the yield reductions due to drought to become relatively smaller. The water-limited yields increased therefore more strongly than the potential yields and the variability in water-limited yields decreased from 27 percent in current to 22 percent in future conditions.

3.3 Adapted cultivars in future weather

When the climate changes, other cultivars will probably be grown that are better adapted to the modified weather conditions. Such adaptations are simulated by adjusting cultivar-specific characteristics. It is possible to explore the effects of changes in many characteristics with the models. We have limited ourselves to the examination of effects of different relations between temperature and development rate, which lead to different growth durations.

The overall effect on average potential wheat yields was slightly positive and much better in the Mediterranean climate. The potential yield was usually higher than the current potential yield. For the water-limited production situations the effect was usually modest. The variability, however, remained almost unchanged by choosing other cultivars, although we aimed for a decrease in yield variability. The effect of our choice of better adapted rice cultivars was almost negligeable (Tables 2,3).

3.3.1 Adapted wheat cultivars

At Migda for the irrigated crop a cultivar was defined having a pre-anthesis development rate that was, at all temperatures, 0.85 times that of the 'standard' cultivar of the previous runs. Consequently, the pre-anthesis phase lasted longer, and the average potential yield increased by more than 50 percent. The slower phenological development has two effects: the time period for leaf formation is longer, hence the leaf area index at anthesis is higher (source strength increases), and the period for formation of the reproductive organs is longer, so that grain density is higher (increased sink strength). The combined effects brought the average yield to within 5 percent of the value under present weather conditions, be it that the variability had more than doubled.

For the rain-fed crop under expected higher rainfall the same cultivar was used as for the irrigated crop. Obviously, the effect is less dramatic in this case, as water deficiency is still a major limitation, but a yield increase of 15 percent compared to the standard cultivar can be achieved. For the expected lower precipitation situation a cultivar was 'selected' having a pre-anthesis development rate a factor 1.15 faster than the standard, in an attempt to complete the growth cycle earlier to avoid late season water stress. The effect, however, was only marginal. It could well be that for these conditions a cultivar would have to be selected that combines a greater sink strength, more grains per unit area, with a faster development. That possibility has not been explored in the present study.

At Los Banos, where the higher future temperatures decrease the length of the growth cycle by about 5 days, the adapted cultivar has a pre-anthesis development rate and a post-anthesis development rate both a factor 0.9 times the standard, for both the irrigated and the rain-fed crops. The effects of the use of this cultivar were only modest, giving yield increases of about 10 percent for both situations, thus enhancing the favourable effect of future weather conditions on yield potential in Los Banos.

At Hyderabad the adapted cultivar was identical to the one used at Los Banos. The performance of this cultivar was only marginally better under irrigated conditions, despite its longer growth duration. The main reason is that sink size remains a major problem in a number of years. Under rain-fed conditions the effect was much stronger mainly due to the more favourable harvest index reached by this cultivar (0.55 versus 0.44). Since the genetic variability in growth duration among spring wheat genotypes covers about the range assumed here, the negative effects of future weather conditions on yields of spring wheat can almost completely be remedied by the use of appropriate cultivars.

3.3.2 Adapted rice cultivars

The most likely adaptation of cultivars to future weather consists in modifying the pre-anthesis growth duration. Without adaptation the rice crop will have a shorter growth duration in the future due to higher temperatures. A longer pre-anthesis growth duration seems a logical answer to compensate this effect. However, this results in lower yields, because the present cultivars develop sufficient vegetative material under future weather conditions. Hence, shortening of the pre-anthesis growth duration may have a positive effect on grain yield, at least as long as the source strength is sufficient to sustain maximum growth during grain filling. A shortening of the pre-anthesis growth period results in a reduction in the formation of vegetative biomass and hence in respiration needs. The effect on grain yield depends on the balance between decreases in assimilation and respiration rates. In the simulations a 10 percent shortening of the pre-anthesis growth period had almost no effect on grain yield and its variability, but increased the harvest index by 10 percent.

An even stronger response to a shortening of the pre-anthesis growth duration is found in simulations of such an adapted rice cultivar under current weather conditions. The adaptation should therefore not be considered as typically needed for future weather conditions. The simulation results indicate that even a modern rice variety as used in this study builds up more green leaf area than strictly needed for maximum grain production. On the other hand the abundance of leaves provides the crop a certain buffer against leaf eating organisms, which are not considered in the model. Shortening of the vegetative growth period could also have a negative effect on the number of grains, thus reducing the sink size, but that aspect is not included in the rice model.

Another adaptation that would have a yield increasing effect is a lengthening of the grain-filling period. Such an adaptation is more speculative, and also not typical for the future weather conditions only. Its effect has not been evaluated in the present study.

4 DISCUSSION

The results of these simulation experiments should be considered indicative for the effects of anticipated changes in climate on average yields of wheat and rice and their variabilities. The results are influenced by the assumptions that, explicitly or implicitly, are incorporated in the models, both with respect to crop characteristics and management practices. Many of these assumptions are thoroughly evaluated. But as the models were not developed specifically for the purpose for which they have been used in these experiments, some aspects that are important in this context may not have been simulated in sufficient detail. The effect of ambient CO_2 concentration on stomatal behaviour and hence on assimilation and transpiration is represented in a simplistic way. Models aiming specifically at analysing the effects of increasing ambient CO_2 concentration on crop performance should be developed further to incorporate these effects in more detail. More extensive basic data are then also required, particularly on the effects of CO_2 on morphological and physiological characteristics. More knowledge is needed about the effect of higher CO_2 concentrations and assimilation rates on the specific leaf area.

In the present study the influence of increased atmospheric CO_2 on leaf area development is defined by the assumption of a fixed increase in leaf thickness. This results in differences in leaf area development in the crop growth simulations for current and future conditions. These differences are reinforced through the mechanism of positive feedback between leaf area and assimilation rate. An alternative assumption could be to make the leaf area development independent of the ambient CO_2 concentration by introducing leaf area development under current CO_2 conditions as a forcing function in the simulation of future conditions. Leaf thickness then becomes a state variable dependent on the net assimilation rate.

Another important point is that the model results are not very accurate under severe water shortage or heat stress. The quantitative insights on the border between production physiology and survival physiology are not very well developed and therefore simulated in a simple and preliminary manner. Yields and harvest indices should not be extrapolated to exceptionally unfavourable years by using the CV's presented.

The computed response of rice yields to future weather is larger than that for wheat. That is partly caused by effects of sink size, that are taken into account in the wheat model, but not in the rice model. There is little doubt that sink size can limit grain yield, but it is quite conceivable that this limitation can be removed through expansion of sink size. The simulated increase in potential wheat yield may therefore be regarded as a pessimistic expectation, while that of rice represents an optimistic view.

The assumptions with respect to agronomic practice used in the models also have a distinct effect on the results. Using a flexible sowing date dependent on the rainfall regime for the rain-fed wheat crops, an opportunistic strategy, would probably have resulted in a substantially lower variability in most cases. Also the assumptions regarding fertilizer application in the rain-fed wheat crops influence the final outcome. A 'reasonable' amount of fertilizer was applied on a fixed date in the growing season, irrespective of the weather conditions or the condition of the crop at that moment. A more judicious behaviour could have resulted in lower variability, especially under dryland conditions, where ample nitrogen availability in a drought-like situation may lead to luxurious vegetative growth with its associated water use at the expense of grain yield.

The considerable effect of high CO_2 on the transpiration coefficient is a major contribution to increased crop production under future weather conditions. The effect depends on the type of regulation of stomatal closure. In the rice and wheat models it is assumed that induction of stomatal closure by increased atmospheric CO_2 does not exist, so that the calculated transpiration rate on a leaf area basis will not change. The reduction in transpiration coefficient is therefore mainly the result of the increased assimilation rates. In the wheat crop model this reduction is partially offset by increased leaf area formation. In the rice model maximum leaf area was slightly lower under future weather conditions. The difference in transpiration coefficient between wheat and rice at the same locations (Table 3) is considerable. That is partly due to different weather conditions because their growing periods are not identical, partly to the occurrence of growth rate reductions related to sink size limitation without a feedback on transpiration in the wheat and not in the rice model, and partly to different concepts in the computation of transpiration in both models.

Both experimental (Jones et al., 1984; 1985) and theoretical studies (Goudriaan et al., 1985) confirm the effect of high CO_2 on seasonal water use. In general, increased CO_2 results in a strong increase in water use efficiency, largely due to increased growth rate, and only to a limited extent due to decreased crop transpiration. Much experimental evidence exists demonstrating the phenomenon of a stomatal regulation mechanism in many C3 crops whereby a constant ratio is maintained between the CO_2 concentrations in the plant and in the air, but it is still uncertain under exactly what conditions it is effective, and under what conditions it is absent. Further research to substantiate this important phenomenon is required.

Whenever serious shortage of nitrogen or minerals occurs during the growing season, as is common in many agricultural systems, the effects of weather on yield and yield variability are more difficult to predict. More efficient water use may then lead to situations where more often nutrients become the major limitation to crop production. Although higher CO_2 concentrations may slightly improve the 'nutrient use efficiency', most of the favourable effects shown in this study will not express themselves under nutrient constraints. Models for the nutrient dynamics in soils are still insufficiently developed, and more research is required before simulations of nutrient-limited yields are reliable.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 General

Despite the cautionary remarks in the previous chapter some general conclusions can be drawn. Some of the effects associated with weather that can be expected in 70-100 years from now, such as increased water use efficiencies of crops and higher potential yields, are considerable.

The effect of increased CO_2 concentration is positive on yields in the potential and water-limiting situations. The increase in temperature has a negative effect on the length of the growth cycle and hence on yield, unless adapted cultivars are used to counteract this effect. It may be expected that average potential yields of wheat and rice will increase by 10-50 percent in most cases under future weather conditions, provided that adapted cultivars are available. This effect is clear both for the potential and water-limited situations. The magnitude of the increase, however, varies among locations. The variability increases generally slightly or remains stable. The effects on yield will probably be smaller for crops grown under severe nutrient deficiency, but the extent to which is unknown. The soil moisture indicators, average moisture content in the soil profile during the growing season, and total soil moisture at the end of the growing season are only marginally affected. Hence, no strong effect is expected on water availability for crops receiving ample fertilizer. More water might become available under nutrient stress, making the need for fertilizers more explicit.

This study also reveals some knowledge gaps with implications for crop physiologic research, plant breeding, and climatology.

5.2 Physiological research

A major component of the yield increase under future weather conditions is the much more efficient use of water under high ambient CO_2 concentrations. However, knowledge of the conditions under which CO2-induced regulation of stomata is operative is still lacking. The presence of such a regulation and the degree of regulation will affect water use efficiency, so that explanatory research in this field is necessary to improve the predictions of crop performance under future weather conditions.

The potentially large increase in yield of wheat and rice under high CO_2 concentrations must be accomodated by an increase in sink size, i.e. more and/or larger grains per unit area. Research should clarify to what extent this will happen spontaneously as a result of the improved carbohydrate supply of the plants, and to what extent it must be accompanied by selection of stronger tillering cultivars.

More experimental work is required to quantify the interactions between high CO_2 level, assimilation rate and nutrient stress. In many situations at present crop yields are fully determined by nutrient availability. The direct effect of CO_2 and temperature is then probably small. But the indirect effect, a lower water use, may be positive and stabilizing. It is uncertain to what extent yields under such conditions will be affected. The comparative advantages of legumes should be explored further, as their capacity to fix nitrogen could increase because of a greater supply of assimilates.

To evaluate the effect of future weather conditions on a geographic scale, experimental research and simulation should be directed to other agricultural crops and to other plant types, such as trees and natural vegetation.

5.3 Plant breeding

From the limited exploration of the effects of crop characteristics on yield under future weather conditions it is somewhat speculative to derive recommendations for plant breeders. The results from this study suggest that there is a need for a wide spectrum of cultivars with respect to growth duration to exploit the relative advantages of the various environments. More explanatory research on genotype x environment interaction is necessary to formulate recommendations for the use of specific cultivars.

Because of differences in stomatal regulation between C3 and C4 crops it may be that the potential growth rate of C3 crops in the tropics, now considerably below that of C4 crops, will catch up under the influence of an increased CO_2 concentration, even without any genetic engineering with C4 characteristics.

Maintenance respiration takes a major and increasing share of the total assimilate supply at higher temperatures, so that further research on cultivars with lower maintenance requirements holds much promise.

Problems of high temperature stress will probably intensify, particularly in C3 crops. Screening will have to identify more tolerant cultivars, but the problem does not seem to be urgent. Adaptation to increased water stress is probably not often required.

5.4 Climatology

For a more accurate description and prediction of the effects of climatic change on crop production a better prediction of future weather conditions is indispensable. Particularly the possible changes in radiation climate and air humidity are major factors involved in the response of crop performance to weather changes. It is necessary to improve in the General Circulation Models to take these factors into account.

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Table 1. Projected changes in temperature and precipitation at four locations, based on Schlesinger and Mitchell (1985) Figures 4.38, 4.39, 4.41 and 4.42. The numbers represent the average increase or decrease in the periods indicated; precipitation change is expressed per day, counting 30 days per month. The range given (in parentheses) is an indication of the uncertainty.

Temperature change (°C)	December-February	June-August
Netherlands	+6 (2)	+3 (1)
Israel	+4 (1)	+3 (1)
India	+3 (1)	+2 (1)
Philippines	+2 (1)	+2 (1)
Precipitation change (mm d^{-1})	December-February	June-August
Netherlands	+0.5 (0.5)	-0.5 (0.5)
Israel	0.0 (0.5)	-0.5 (0.5)
India	+0.5 (1)	+1.0 (3)
Philippines	-0.5 (1)	+0.5 (1)

Table 2. Predicted grain yields and their variabilities. Yields are in kg (dry matter) ha^{-1} of wheat and hulled rice. 'Current' stands for actual weather data, 'fut w.' stands for future weather data without changes in crop characteristics, 'fut a.' stands for future weather with adapted crop cultivars; the + or - for Migda indicate future weather and highest and lowest estimate of precipitation from Table 1, respectively. The amendment 't0' for rice in Hyderabad and Los Banos stands for future weather with a CO$_2$ concentration increase only.

		wheat				rice			
		potential production		water-limited		potential production		water-limited	
Wageningen	current	6202	11%	3266	61%	0		0	
	fut w.	6818	26%	3233	89%	0		0	
	fut a.	7409	22%	3353	95%	0		0	
Migda	current	6636	9%	2070	84%	0		0	
	fut w.+	4092	22%	3683	68%	0		0	
	fut w.-	4092	22%	1925	113%	0		0	
	fut a.+	6453	19%	4164	65%	0		0	
	fut a.-	6453	19%	2097	112%	0		0	
Hyderabad	current	4167	8%	1766	10%	7827	5%	6404	27%
	fut w.t0	0		0		11632	7%	9858	22%
	fut w.	5754	8%	2036	11%	10238	7%	8619	22%
	fut a.	5936	9%	2590	10%	10286	6%	8632	23%
Los Banos	current	3067	12%	1852	40%	6394	9%	6061	15%
	fut w.t0	0		0		9307	11%	8278	16%
	fut w.	3819	10%	2368	51%	8128	11%	7830	18%
	fut a.	4035	11%	2519	52%	8266	12%	7808	20%

Table 3. Some characteristics of wheat and rice production in the conditions considered; the first number is the average, the second its variability (standard deviation) expressed in absolute values. PP stands for potential production, WL for water-limited production. The transpiration coefficient is the total transpiration by the crop divided by the total aboveground dry matter (kg H_2O kg^{-1} dry matter); W5AV is the average soil moisture content (m^3 m^{-3}) from emergence till maturity in the soil layer 20-30 cm deep (wilting point at 0.075 for Migda, 0.18 for Wageningen, 0.31 for Los Banos, 0.27 for Hyderabad; field capacity at 0.23 for Migda, 0.32 for Wageningen, 0.445 for Los Banos, 0.44 for Hyderabad); WTOT: total soil moisture in the potential rooting zone at maturity (mm).

	harvest index		transp. coeff.		W5AV	WTOT
	PP	WL	PP	WL	WL	WL
Wheat						
Wageningen						
current	0.45-0.03	0.41-0.09	279-46	250-113	0.24-0.06	290-55
fut w.	0.42-0.06	0.40-0.12	121-40	109-60	0.24-0.05	286-70
fut a.	0.43-0.08	0.44-0.10	126-44	108-42	0.22-0.05	292-54
Migda						
current	0.44-0.02	0.28-0.10	336-40	322-162	0.13-0.03	156-21
fut w+	0.33-0.04	0.37-0.11	233-40	166-48	0.16-0.03	198-44
fut w-	0.33-0.04	0.27-0.13	233-40	154-72	0.11-0.04	169-35
fut a+	0.39-0.04	0.37-0.11	227-48	178-28	0.16-0.03	186-41
fut a-	0.39-0.04	0.26-0.14	227-48	149-38	0.11-0.04	166-31
Hyderabad						
current	0.40-0.02	0.45-0.02	449-20	383-18	0.31-0.01	342-4
fut w.	0.46-0.03	0.44-0.02	253-19	289-18	0.34-0.01	355-9
fut a.	0.46-0.03	0.54-0.02	262-19	279-20	0.34-0.02	353-8
Los Banos						
current	0.42-0.04	0.36-0.05	360-26	339-40	0.37-0.04	459-46
fut w.	0.42-0.02	0.41-0.05	166-24	160-22	0.36-0.07	492-40
fut a.	0.41-0.02	0.39-0.05	175-24	165-20	0.37-0.07	480-39

Table 3 (continued)

	harvest index		transp. coeff.		W5AV	WTOT
	PP	WL	PP	WL	WL	WL
Rice						
Hyderabad						
current	0.48-0.02	0.48-0.02	217-6	213-7		
fut w.t0	0.51-0.02	0.49-0.07	146-4	142-5		
fut w.	0.51-0.03	0.50-0.06	156-5	153-5		
fut a.	0.56-0.03	0.53-0.05	152-6	149-5		
Los Banos						
current	0.46-0.04	0.48-0.05	218-13	217-12		
fut w.t0	0.49-0.04	0.50-0.05	149- 9	145- 8		
fut w.	0.49-0.05	0.51-0.05	155-10	153- 9		
fut a.	0.53-0.04	0.54-0.05	149-10	147- 9		

Table 4. Yield-determining components of simulated potential rice production in Hyderabad and Los Banos under current weather conditions.

	Hyderabad	Los Banos	
At anthesis			
leaves and stems	8500	7400	kg ha^{-1}
reserves for grain	1140	1000	kg ha^{-1}
From anthesis to maturity			
average temperature	25	26	°C
average daily rates of processes			
gross assimilation (CH_2O)	510	450	kg ha^{-1} d^{-1}
maintenance respiration (CH_2O)	225	210	kg ha^{-1} d^{-1}
	---- -	---- -	
net assimilation (CH_2O)	285	240	kg ha^{-1} d^{-1}
growth efficiency of grains	0.73	0.73	kg kg-1
	---- x	---- x	
grain growth	208	175	kg ha^{-1} d^{-1}
duration	32	31	d
	---- x	---- x	
post-anthesis grain production	6660	5425	kg ha^{-1}
At maturity			
total straw	8500	7400	kg ha^{-1}
total grain	7800	6425	kg ha^{-1}
	----- +	----- +	
total aboveground dry matter	16300	13825	kg ha^{-1}
harvest index	0.48	0.46	

Table 5. Yield-determining components of simulated potential rice production in Hyderabad and Los Banos under double ambient CO_2 concentration without temperature increase.

	Hyderabad	Los Banos	
At anthesis			
leaves and stems	11370	9900	kg ha^{-1}
reserves for grain	1600	1500	kg ha^{-1}
From anthesis to maturity			
average temperature	25	26	°C
average daily rates of processes			
gross assimilation	730	630	kg ha^{-1} d^{-1}
maintenance respiration	300	285	kg ha^{-1} d^{-1}
	--- -	---- -	
net assimilation	430	345	kg ha^{-1} d^{-1}
growth efficiency of grains	0.73	0.73	kg kg-1
	---- x	---- x	
grain growth	314	252	kg ha^{-1} d^{-1}
duration	32	31	d
	---- x	---- x	
post-anthesis grain production	10048	7800	kg ha^{-1}
At maturity			
total straw	11370	9900	kg ha^{-1}
total grain	11650	9300	kg ha^{-1}
	----- +	----- +	
total aboveground dry matter	23000	19200	kg ha^{-1}
harvest index	0.51	0.49	

Table 6. Yield-determining components of simulated potential rice production in Hyderabad and Los Banos under double ambient CO_2 concentration and 2 °C temperature increase.

	Hyderabad	Los Banos	
At anthesis			
leaves and stems	9650	8510	kg ha^{-1}
reserves for grain	1300	1200	kg ha^{-1}
From anthesis to maturity			
average temperature	27	28	°C
average daily rates of processes			
gross assimilation	720	625	kg ha^{-1} d^{-1}
maintenance respiration	315	295	kg ha^{-1} d^{-1}
	---- -	---- -	
net assimilation	405	330	kg ha^{-1} d^{-1}
growth efficiency of grains	0.73	0.73	kg kg-1
	---- x	---- x	
grain growth	295	241	kg ha^{-1} d^{-1}
duration	30	29	d
	---- x	---- x	
post-anthesis grain production	8850	6990	kg ha^{-1}
At maturity			
total straw	9650	8510	kg ha^{-1}
total grain	10150	8190	kg ha^{-1}
	----- +	----- +	
total aboveground dry matter	19900	16700	kg ha^{-1}
harvest index	0.51	0.49	

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