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SIMULATED YIELDS OF WHEAT AND RICE IN CURRENT WEATHER AND IN FUTURE WEATHER WHEN AMBIENT CO2 HAS DOUBLED

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ABSTRACT

The average grain yield and its variability is simulated for wheat and rice crops in 4 climates. The crops simulated are supplied with ample fertilizer and are without weeds, pests and diseases. Situations with continuously optimum water supply and with water shortage are both investigated. Yield predictions are made with 2 documented and evaluated models.

The simulations are repeated for future weather when the CO2 concentration has doubled. Temperature and precipitation will change, but solar radiation, windspeed and relative humidity remain constant. The impact of the higher CO2 concentration and of future weather on yield is computed. A third set of simulations deals with cultivars adapted to the future weather.

The increase in CO2 level permits potential crop yields to rise by 10-50%, but this rise is eroded by the higher temperatures. The results are different for each of the situations considered. Yield variability is low and not much affected in the tropics, but increases in cooler climates. The water use by the crops becomes much more efficient. This boosts water limited yields, except where precipitation falls. Variability remains then high or increases even further.

Implications for agricultural research, for breeders, for climatologists and for agricultural planners are discussed.

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INTRODUCTION

Crop yields are strongly influenced by weather. Therefore, changes in climates 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 is through systems analysis and simulation, as shown in this paper. For the simulations, we base ourselves on climate changes predicted by others, and deal only with the variability of yield per unit area for single crops. To extrapolate to yield variability at a national scale would require also an analysis of the shift in area used for these crops. This is not attempted.

The wheat and rice crop are chosen for this study because of their importance for the world food supply and because relatively good models are available for both. Yields and their variabilities are simulated in 4 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 rainfed crops: water-limited production). The simulations apply to relatively intensive agricultural systems where nutrients are supplied at an appropriate level. The variable reduction in yields due to diseases, pests, and weeds is not considered.

This paper summarizes a report by Van Diepen etal. (1987) in which more background and analysis of the results is provided.

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METHODS

General

Annual yields of wheat and rice are first simulated for series of 9-32 years in different climates. Subsequently, the weather data are modified to reflect climatic conditions under a doubled atmospheric CO2 level (680 vppm), which is expected to be reached in 70-100 years from now. To examine to what extent average yield and its variability changes, the same series of simulations is 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 is made about the characteristics that can be changed in the model to represent such new cultivars. Simulation with those crop properties provided a third set of average yields and yield variabilities.

Variability in yield between individual years is calculated as the coefficient of variation (CV).

Climates

The weather data used are daily values from standard meteorological stations: maximum and minimum temperature, total global radiation, average windspeed, precipitation and early morning water vapour pressure. Historical weather data from 4 different locations are used, representing a temperate region (Wageningen, The Netherlands), a Mediterranean region (Migda, Israel), a semi-arid tropical region with summer rainfall (Hyderabad, India) and a sub-humid tropical region (Los Banos, Philippines). The data for Wageningen (1954-1985) were obtained from the Department of Meteorology and Physics of the

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Agricultural University in Wageningen, those for Migda (1962-1982) from the Israeli Meteorological Service, those for Hyderabad (1975-1983) from the International Crops Research Institute for Semi-Arid Tropics (ICRISAT), and those for Los Banos (1959-1983) from the International Rice Research Institute (IRRI). Estimates about future weather conditions are based on Schlesinger and Mitchell (1985), and are presented in Table 1. We assume no changes in radiation, windspeed and relative air humidity. Future weather is 'created' by adding or subtracting the projected changes to both the mimimum and maximum temperatures; for precipitation the amount per wet day is changed by a fraction such that the average value given in Table 1 is obtained.

Crop models

The effect of an increased CO2 concentration on crop performance is obtained using relatively simple physiological assumptions. The light saturated maximum assimilation rate of individual leaves is supposed to have twice the present value (Goudriaan et al., 1985) whenever sink limitation is absent. The light use efficiency at the light compensation point increases by 25% (Goudriaan et al., 1984). The effect of high CO2 on leaf area development is more difficult to quantify. In agreement with Goudriaan and De Ruiter (1983), the specific leaf area under increased CO2 is assumed to be 35% lower than under present conditions.

Wheat The spring wheat model by van Keulen and Seligman (1987) is applied. It is a process-based model, executed with time steps of one day. Phenological development, dry matter accumulation and

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distribution, and organ formation are simulated in dependence of weather conditions and water and nitrogen supply. In the simulations for this paper, only parameters and functions characterizing the environment and the wheat cultivar are adapted. A fixed sowing date is assumed, specific for each location, irrespective of environmental conditions. For the irrigated crops a pre-sowing irrigation is applied in all cases to ensure proper germination. For the rainfed crops the onset of germination is determined by the rainfall pattern. If germination starts but the soil dries out before emergence is completed, crop failure occurs; the model does not allow for resowing.

Rice The model described by Wolf et al. (1986) and Rappoldt (1986) is applied to simulate the rice crop. It follows the same approach as the spring wheat model, but describes the growth processes and the soil water balance processes in a summary form and a more generalized manner. The simulations are executed for Los Banos and Hyderabad only, for the cultivar IR8 grown in the rainy season. The simulation starts with a successful transplanting into a wet soil on a fixed date. 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 is an upland paddy soil with a deep groundwater table and an effective rooting depth of 0.4 m.

Both models are explanatory: results can be fully explained on basis of physiological, (soil-)physical and micrometeorological processes.

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RESULTS

The current yield level and its variability

Wheat Average potential yields under the present weather conditions vary from about 3000 to 6700 kg ha-1 as a result of climatic differences, and are rather stable (CV around 10%). The average values are considerably lower (between about 1750 and 3250 kg ha-1), and the variability is usually much higher (CV up to 84%) in situations with limited water. Results of the simulations for the 4 locations are summarized in Tables 2 and 3.

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. (Such results, plotted as a yield-frequency-distribution-graph, show a S-shaped curve. This indicates that the coefficient of variation is an appropriate measure for variability.) Yield variability in this situation is due to 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.

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. There is a dramatic difference in variability between potential yield and water-limited yield in practically all situations, underlining the importance of water availability as a crucial constraint in crop production in many regions of the world. Because of the low and erratic rainfall at Migda, average yields are much lower and the variability is much larger: 84%. This computed

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variability is probably higher than in reality because of the assumed fixed sowing date and the absence of a possibility of resowing after an early crop failure. Still, it is obvious that variability is large indeed. The CV drops only to 68% if the years with total crop failure are excluded.

The reason for the low yields in Los Banos and Hyderabad is that the growth period is relatively short due to the prevailing high temperatures: on average 49 days between emergence and anthesis and 27 days for the grain filling period. The relative stability in Hyderabad is brought about by the fact that the crop relies entirely on stored soil moisture, combined with the assumption that the profile is at field capacity at sowing, irrespective of preceding rainfall.

The harvest index, the ratio of grain yield (economic yield) and total amount of biomass, is fairly constant when optimum moisture conditions are maintained throughout the season. If not, large fluctuations occur as a result of differences in the timing of moisture deficiency. The harvest indices and the range within which they usually fluctuate are presented in Figure 2.

Rice Average potential and water-limited rice yields and their variabilities under current weather conditions are presented in Table 2, and the corresponding transpiration coefficients in Table 3.

Potential yields 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

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temperatures during the rice growing season. Higher irradiation results in higher gross assimilation, and a lower temperature leads to a relatively lower maintenance respiration and to a longer growth duration (90 days in Hyderabad versus 85 days in Los Banos).

The range in water-limited yields is 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. Yield variability is mainly related to the rainfall pattern during the grain filling period. The higher rainfall in Los Banos leads to a lower variability in water-limited yields.

The total dry matter production in the rainfed situation never exceeds the total potential production. In some years, however, the water-limited production results 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 lower amount of vegetative dry matter at anthesis.

The future yield level and its variability

Future yields in optimal growth conditions are different from the current ones because the high CO2 level accelerates the rate of assimilation of crops and hence their rate of dry matter production. However, the higher temperatures lead also to increased rates of development and consequently to shorter growth durations. The overall effect can be positive or negative, as Table 2 shows.

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Wheat For Migda with the largest anticipated temperature rise is the effect of the shortened season by far the strongest: the potential yield decreases by almost 40%. The variability increases substantially to 22% because in more instances sink size is the limiting factor. At the other 3 locations is the effect on the growth rate the overriding factor, so that potential yields are higher. For Wageningen is this associated with a higher variability but not in Los Banos and Hyderabad. The future harvest index in Migda in optimal growth conditions is substantially lower than under present conditions and that for Hyderabad substantially higher, while the differences for Los Banos and Wageningen are small (Figure 2).

An outstanding feature at all locations is the large decrease of the transpiration coefficient. Contrary to the effect of other growth stimulating factors, assimilation goes up considerably without affecting transpiration (assuming a constant relative humidity of the air) at high CO_2. Yet, under rainfed conditions are the effects of expected weather changes more dramatic because the variability in precipitation plays 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.

Average rainfed yields in Wageningen are hardly affected. The more frequent occurrence of water deficiency during the growing season due to lower precipitation is compensated by higher growth rates under favourable conditions. The variability increases because the difference between dry and wet years is more pronounced. In Los Banos

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average yields under rainfed conditions increase by 30% to 2368 kg ha-1, but variability rises also. The combined effect of the higher assimilation rate and a more efficient water use result in more favourable growing conditions, though crop failures still occur. In Hyderabad average rainfed yields go up by 15%. As this crop grows entirely on stored soil moisture, the higher yields are due to the more efficient use of the available water.

Harvest indices in water limiting situations show little change, with exception of Migda where it rises substantially (Figure 2).

Rice Grain yields increase considerably at the high CO2 level. Without a change in temperature, yields would be 30-50% higher (Table 2). The relative increase in growth rate is not constant over the entire growth period. The greatest gain occurs when the canopy is fully closed. During the first month after transplanting the simulated growth is only very little above the simulated growth for the current CO2 concentration. This is the consequence of the assumption of a 35% decrease in specific leaf area.

The temperature increase of 2 C 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% in maintenance respiration. The resulting yield reduction amounts to 1100 kg ha-1 for Los Banos and 1400 kg ha-1 for Hyderabad. On balance, potential rice yields in future weather are 25-35% higher than current ones, while the variability remains almost the same.

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Adapted cultivars in future weather.

When the climate changes, adapted cultivars will probably be grown. Such adaptations are simulated by adjusting cultivar-specific characteristics. The effects of changes in many characteristics could have been explored with our models. We have limited ourselves to examine effects of different relations between temperature and development rate, which lead to different growth durations.

The overall effect on the average potential wheat yield is slightly positive compared to that for the unadapted cultivars, and much better in the Mediterranean climate. The potential yield is always higher than the current potential yield. For the water-limited production situations is the effect usually modest. The variability, however, remains almost unchanged by choosing other cultivars, although that was what we aimed for. The effect of our choice of better adapted rice cultivars has almost no effect (Table 2, 3).

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 on their variabilities. The results are influenced by the assumptions that, explicitly or implicitly, are incorporated in the models. Many of these are thoroughly evaluated. But some aspects that are important in this context may not have been simulated in sufficient detail. Models aiming specifically at analysing the effects of ambient CO2 concentration on crop performance could be developed further. More

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extensive basic data are also required, particularly on morphological and physiological characteristics.

Another important point is that the simulation results are not accurate under severe water shortage or heat stress. Yields and harvest indices should not be 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. This is a reflection of a constraint in the wheat model, sink size limitation, which is not included in the rice model. Though there is little doubt that this constraint is real, it is conceivable that this limitation can be avoided. The simulated increase in potential wheat yield may therefore be regarded as a pessimistic expectation, while that for rice represents an optimistic view.

The assumptions with respect to agronomic practice used in the models have also a distinct effect on the results. Using a flexible sowing date dependent on the rainfall regime for the rainfed wheat crops, an opportunistic strategy, would probably have resulted in a substantially lower variability in most cases. Also assumptions regarding fertilizer application in the rainfed wheat crop influence the final outcome.

The considerable effect of high CO2 on the transpiration coefficient is a major contribution to increased crop production under future weather conditions. Because of induction of stomatal closure by increased atmospheric CO2, transpiration rate on a leaf area basis will decrease. In the wheat crop is this reduction partially offset

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by increased leaf area formation. Both experimental (Jones et al., 1985) and theoretical studies (Goudriaan et al., 1985) confirm this effect for seasonal water use. The rice crop model yielded a slightly reduced leaf area. Much experimental evidence exists demonstrating the phenomenon of stomatal regulation, but it is still uncertain under what conditions it is effective. The difference in transpiration coefficient between wheat and rice at the same locations (Table 3) is considerable. It is due to different weather conditions because their growing periods are not identical, due to the occurence of growth rate reductions related to sink limitation without a feedback on transpiration in the wheat and not in the rice model, and due to different concepts in the computation of transpiration in both models.

Whenever a 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 CO2 concentrations may slightly improve the 'nutrient use efficiency', a large part of the favourable effects shown in this study will not express themselves under nutrient constraints. Models for the nutrient dynamics in soils and crops are still insufficiently developed, and more research is needed before such simulations are reliable.

CONCLUSIONS

General Some of the effects on wheat and rice crops computed for

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climates 70-100 years from now are quite large. They will start to emerge in the near future, such as increased water use efficiency of crops and higher potential yields.

The effect of an increasing CO2 concentration is positive for yield in the potential and water-limiting situations in all climates. The increase in temperature has a negative effect on growing season duration and hence on the total biomass produced, unless adapted cultivars can be used to counteract this effect. However, reduction of pre-anthesis growth of rice appears to be beneficial for its harvest index and grain yield. Taken together, average potential yields of wheat and rice will increase by 25-50% in the tropics under future weather conditions. For cooler climates is the effect smaller. For rainfed crops in the tropics increases yield also considerably. The gain appears small in a temperate climate, but large if precipitation increases. The variability, higher for water limited situations than for potential production, increases generally slightly or remains stable.

The effects on yield will probably be smaller for crops with a severe constraint in nutrient availability, but the extent to which is unknown. Two indicators of soil moisture are computed along with crop growth in the water-limiting situations: 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. They did not show much difference between the 3 sets of simulations made, and are not further discussed here. However, they should be considered again under nutrient stress. Crops might

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use then less water and soils may be wetter in average, making the need for fertilizers more explicit.

Physiological research A major component of the yield increase in future weather is the much more efficient use of water due to high CO2. However, a firm description of the conditions under which stomata respond is still lacking. The degree of regulation will affect water use efficiency, so that research in this field is necessary to improve predictions of future crop performance.

The potentially large yield increase under high CO2 concentrations in wheat and rice must be accommodated by an increase in sink size, i.e. more and/or larger grains per unit area. Research must quantify to what extent this will be achieved spontaneously in reponse to the improved carbohydrate supply of the plants, and how much must be achieved by plant breeding.

More experimental work is required to quantify the interactions between high CO2 level, assimilation rate and nutrient stress. In many current situations are crop yields fully determined by nutrient availability. The direct effect of CO2 and temperature is then probably small. But the indirect effect, a lower water use and hence more water in the soil, may be positive and stabilizing. It is uncertain to what extent yields under such conditions will be affected. The comparative advantages of legumes may be explored further, as their capacity to fix nitrogen will be reinforced by more assimilates.

To judge the effect of future weather on a geographic scale, experimental research and simulation should expand to other

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agricultural crops and to other plant types, such as trees and natural vegetation.

Plant breeding From the limited exploration of the effects of crop characteristics on yield in future weather is it somewhat speculative to derive recommendations for plant breeders. Results obtained suggest 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 specific cultivars.

The potential growth rate of C3 crops in the tropics, now considerably below that of C4 crops, is likely to catch up even without any genetic engineering with C4-characteristics. The positive effect of a high CO2 concentration on growth of C4 crops is expected to be smaller than on C3 crops, but the transpiration coefficient of C4 crops will probably also be reduced. Higher temperatures will shorten growing seasons and lower potential yields for existing cultivars.

Maintenance respiration takes an important and increasing share of the total assimilation at the expected higher temperatures, so that further research about cultivars with lower rates holds much promise.

Problems with high temperature stress will probably intensify slowly, particularly in C3 crops. Breeding will have to identify more tolerant cultivars. Adaptation for increased water stress is probably not often required.

Climatology For a more accurate description and prediction of the

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effects of climatic change on crop production a better prediction of the future weather conditions is indispensable. Particularly the eventual changes in radiation climate and air humidity are major factors involved in the response of crop performance to weather changes. Improvements in the General Circulation Models to take account of these factors are necessary.

Acknowledgement

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Table 1. Projected changes in temperature and precipitation at 4 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 standard deviation (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)

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Table 2. Predicted yields, in kg (dry matter) ha-1 of wheat and hulled rice, and their variabilities. 'Current' stands for simulation with actual weather data, 'future w.' for future weather, 'future a.' for future weather with adapted cultivars; + or - indicate future weather and highest and lowest estimate of precipitation from Table 1; 't0' stands for future weather with a CO2 concentration increase only.

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

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Table 3. The average transpiration coefficient of wheat and rice, in kg H2O kg-1 dry matter, and its variability (standard deviation). PP stands for potential production, WL for water limited production. For explanation of situations see Table 2.

		Wheat		Rice	
		PP	WL	PP	WL
Wageningen	current	279-46	250-113	-	-
	future w.	121-40	109-60	-	-
	future a.	126-44	108-42	-	-
Migda	current	336-40	322-162	-	-
	future w+	233-40	166-48	-	-
	future w-	233-40	154-72	-	-
	future a+	227-48	178-28	-	-
	future a-	227-48	149-38	-	-
Hyderabad	current	449-20	383-18	217-6	231-7
	future w.t0	-	-	146-4	142-5
	future w.	253-19	289-18	156-5	153-5
	future a.	262-19	279-20	152-6	149-5
Los Banos	current	360-26	339-40	218-13	217-12
	future w.t0	-	-	149- 9	145- 8
	future w.	166-24	160-22	155-10	153- 9
	future a.	175-24	165-20	149-10	147- 9

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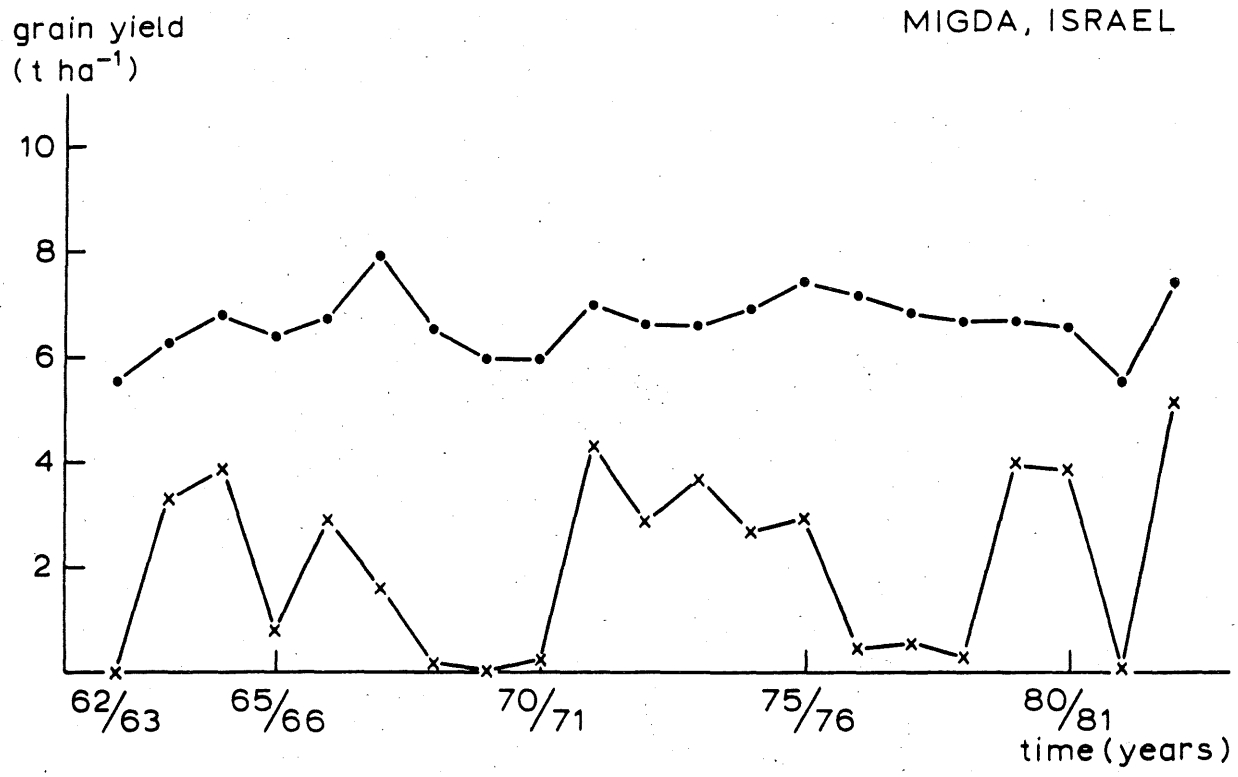

Figure 1. Yields of wheat in Migda, 1962-1982, for the potential growth situation (PP) and water limited growth (WL).

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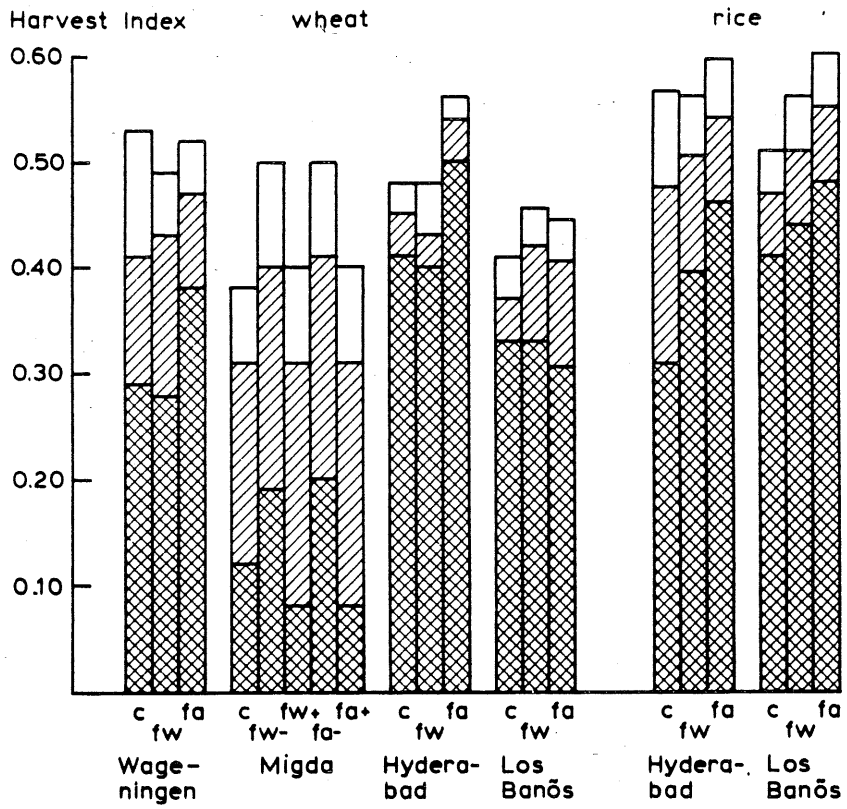

Figure 2. Histogram of harvest indices (kg grain per kg total above ground biomass) for wheat and rice, water limited production. The lower part of each bar reflects the harvest index reached or exceeded in 9 out of 10 years, the second part the harvest index reached or exceeded in 5 out of 10 years,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

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