AGRONOMIC USES OF A MODEL OF WHEAT GROWTH, DEVELOPMENT AND WATER USE

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ABSTRACT

The use of a computer model of wheat growth, development and water use is demonstrated with simulations of the response of the crop to various changes in management, location and climate, including the "nuclear winter" and "greenhouse effect". Simulation of management changes, such as differing irrigation inputs and sowing dates, gave results similar to field observations. Simulation of changes of location indicated that yield decreased and maturity was advanced from South to North. A "nuclear winter" scenario predicted yield reductions of 10% in irrigated crops, but indicated a possible increase in the yield of unirrigated crops. Simulation of the influence of a "greenhouse effect" climate change indicated that Canterbury wheat yields could fall by 15 to 45%.

INTRODUCTION

Crop models are valuable research tools. They compel agronomists and physiologists to study crops in a structured and quantitative manner. They describe how crops function and interact with their environment, and lead to an improved understanding of the main processes which determine crop performance. Also, they help direct complementary experimental research in the most profitable directions by highlighting areas where knowledge is deficient.

Models have many applications. For example, they can be used to assess how crop performance is affected by altering various plant characters which are specified in the models by genotypic parameters. Thus, the most important characters can be identified and targeted for manipulation in plant breeding programmes. They can help identify crop management priorities by predicting the likely consequences of changing a crop's environment by varying its location or management.

We have developed a model which simulates the growth, development and water use of wheat. In this paper we describe it briefly, then illustrate its agronomic applications by predicting the effects on the performance of a typical winter wheat cultivar of varying irrigation management, sowing time, season and location. The model was used to assess the probable consequences of possible variation in climate — the "greenhouse effect" and "nuclear winter".

MODEL DESCRIPTION

A computer simulation model of crop growth is the mathematical expression of a set of rules about how a crop grows, and how various processes interact with the environment and with each other. The framework of the model used here is a simple statement about how yield is attained. The yield (Y) of the crop can be expressed in terms of the crop growth rate (C), the harvest index (HI) and time (t).

$$Y = HI \int_{\text{emergence}}^{\text{maturity}} C \, dt$$

Within this framework is a set of interacting submodels. The first three are a phenological submodel, to give the duration of growth, a growth rate submodel, and a partitioning submodel, giving HI. In addition to these, an evapotranspiration model calculates the water used by the crop and the status of soil water, and a water stress model calculates the influence of soil water status on growth processes. A brief description of the submodels follows.

1. Phenology

Intervals between defined events in the life of a cultivar are assumed to be constant on a thermal timescale that is corrected for photoperiod and vernalisation effects (Weir *et al.,* 1984). A cultivar is characterised by a set of genetic specific parameters which describe the number of degree days between such events as sowing, emergence, double ridge formation, terminal spikelet formation, anthesis and maturity. Once these numbers are known, the times of occurrence of the events can be calculated from the sowing date and weather data.

2. Crop Growth Rate

The crop growth rate (C) depends on the photosynthetically active radiation (PAR) intercepted by the crop, and hence on incident PAR, the leaf area index (LAI, a measure of canopy size), and the efficiency with which PAR is used to produce dry matter (Monteith, 1977). Incident PAR is calculated from solar radiation. Before anthesis, the increase in LAI is calculated from thermal time and the rate of change of daylength at emergence (Baker *et al.,* 1980); after anthesis, the decline in LAI is calculated from thermal time alone.

3. Dry Matter Partitioning

Until anthesis, all growth is considered to be vegetative, and after anthesis, is considered to be grain.

Some grain mass is also formed by translocation of dry matter from leaves and stems during grain growth (Jamieson and Wilson, 1988).

4. Water Stress

Water stress affects the crop growth rate in two ways. At moderate levels, PAR interception is affected because LAI either stops increasing or declines. At more severe levels, the radiation use efficiency declines. Water stress is quantified in terms of the soil moisture deficit (D), expressed as a proportion of the maximum available water content (AWC) and the amount of time since the last rain or irrigation.

The soil moisture deficit is calculated from a water budget. This uses irrigation and rainfall amounts and times, along with evapotranspiration calculated from separate transpiration (Ritchie, 1972), and soil evaporation (Tanner and Jury, 1976) models (Jamieson *et al.,* 1984).

SIMULATIONS

Simulations of the effects of management changes were based on weather data for the 1984/85 season at Lincoln and the cultivar Avalon. In this season water budgeting was used to schedule 3 irrigations totalling 150 mm in experiments with intensively managed wheat crops. Except where sowing date is varied, all simulations were for a crop planted on 4 May.

1. Variation in Irrigation Management

The effect of changes in irrigation management on yield was investigated by removing one or more of the scheduled irrigations, assuming a soil of 225 mm AWC. Results are given in Table 1. Included are water use efficiencies (WUE), calculated as the ratio of yield loss from the fully irrigated treatment to the amount of irrigation water withdrawn.

TABLE 1: Simulated Effect of Irrigation Management on the yield of Avalon Wheat.

Irrigations 17 Oct	30 Oct	5 Dec	Yield (t/ha)	WUE (kg/ha/mm)
30	60	60	9.81	—
—	60	60	8.61	40
30	—	60	7.22	43
30	60	—	9.05	13
30	—	—	6.57	27
—	60	—	7.85	22
—	—	60	6.86	33
—	—	—	6.22	24

The WUEs ranged from 0.13% to 0.44% of potential yield per mm of water, with a mean of 0.29% per mm, and are similar to values obtained from field data analysed by Baird and Gallagher (1986). The figures do suggest, contrary to their analysis, that sensitivity to water stress depends on when it occurs. Inspection of the table indicates that low WUEs were associated mainly with removal of the last irrigation. This is because the water could not all be used before maturity, partly because there was a substantial rainfall just one week after the last irrigation. It is also likely that some of the variation in WUE reflects inadequacies of the model.

2. Variation in Soil Type

The influence of soil type, as indicated by AWC, was investigated for rainfed crops by varying the amount of stored soil water available to the plants. This has the effect of bringing forward or delaying the onset of stress. AWC was varied from 90 mm, typical of a shallow loam over stones, such as a Lismore, to 270 mm, representing a deep clay loam such as a Wakanui. Results are shown in Figure 1. The lowest yield from the shallowest soil, at 5.2 t/ha, is

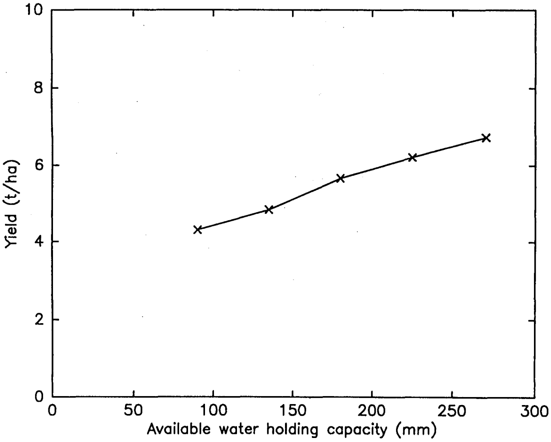

Figure 1: **Response of simulated yield of rainfed Avalon wheat to variation in soil available water holding capacity. The simulation used 1984 Lincoln weather data.**

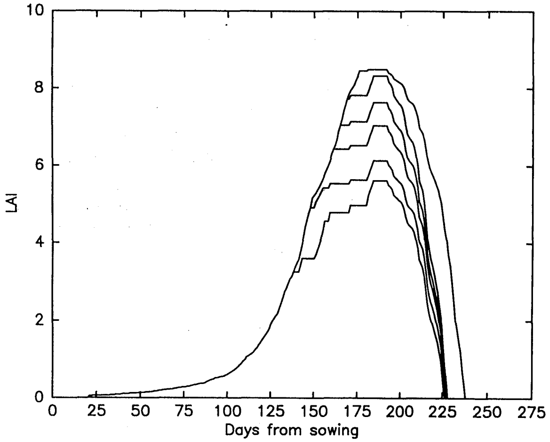

Figure 2: **LAI development and loss for the five simulations in figure 1. The outer envelope is for an unstressed crop; the maximum value of LAI in each other trace reduces as the yield.**

probably too high, and reflects some inadequacies in the way the model handles prolonged stress. The predictions of the variation of LAI with time are compared with predictions for an unstressed crop in Figure 2. Most of the yield decrease is associated with reductions in LAI, and hence PAR interception, during grain fill.

3. Variation in Sowing Date

The results of simulations with different sowing times are shown in Figure 3. The sowing times span a range from early May to the beginning of September, and were run with and without irrigation for a soil of 180 mm AWC. The overall decline in yield with delayed sowing is similar to that shown in field experiments (Drewitt, 1974).

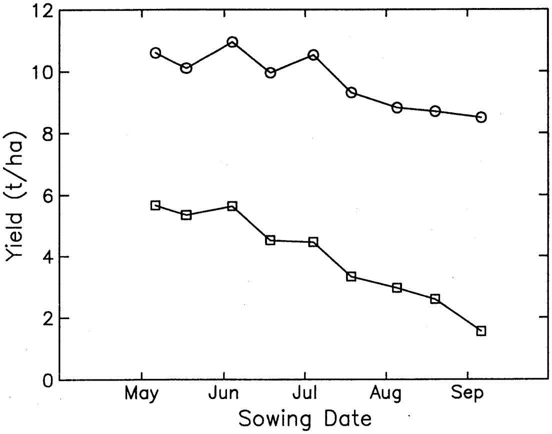

Figure 3: Variation of yield for irrigated (circles) and dryland (squares) for simulated crops of Avalon wheat using 1984 Lincoln weather data.

4. Change of Location

The effect of changing location was investigated by comparing simulations for Lincoln weather (latitude 43.6 °S) with simulations for weather conditions equivalent to those in the Waikato (about 2.5 °C warmer in summer, similar solar radiation receipts to Lincoln, latitude 37.8 °S), the Manawatu (2 °C warmer in summer, solar radiation about 90% of Lincoln's, latitude 40.4 °S) and Southland (2 °C cooler in summer, 83% of Lincoln's solar radiation, latitude 46.1 °S). AWC was chosen as 180 mm, and water was not a substantial limitation on yield. Simulation results are given in Table 2.

TABLE 2: Simulated Influence of Location on Crop Yield and Maturity.

Location	Maturity date	Yield
Waikato	13 Dec	5.88
Manawatu	19 Dec	6.26
Lincoln	4 Jan	8.23
Southland	31 Jan	9.71

Yield increases and the crops mature later with increasing latitude. The increase in yield from Lincoln to Southland is about 1.5 t/ha, despite the lower solar radiation receipts. This is because the delay of nearly a month in maturity provides more than enough opportunity to make up the loss by intercepting PAR for longer.

5. "Nuclear Winter"

Simulation of some kind is the only method available to assess the effects of some event like the 'nuclear winter' following a nuclear war. To investigate this a scenario put forward by Green *et al.* (1987) has been assumed. The relevant temporary climate changes are

*Spring −3 °C
*Summer −2 °C
*solar radiation −20%

The simulations were run with the 1984 data modified by these amounts, for a soil of 225 mm AWC. Temperature and solar radiation reductions resulted in a reduction in yield of about 10% in irrigated crops (9.81 to 8.85 t/ha), and an increased of about 20% in unirrigated crops (6.22 to 7.56 t/ha). Maturity was delayed by a month. The scenario gives a climate change slightly larger than a change in location from Lincoln to Southland, and the change is sufficient to cause a reduction rather than an increase in irrigated yield. Whether or not unirrigated yield increases or decreases will depend very much on the rainfall pattern of the particular season, and perhaps by the manner in which the climate changes this as well.

6. "Greenhouse Effect"

A scenario for climate change over the next 50 years is given by Maunder (1988). Taking a middle estimate from the range of predictions from global circulation models, the scenario was set 40 years hence, with temperatures 2-3 °C warmer, and CO_2 concentration at about 500 ppm, some 50% higher than now.

The scenario for simulations was the year 2030, assumed to have weather 3 °C hotter than 1984, but otherwise identical. In an attempt to account for CO_2 increase, simulations were run with the radiation use efficiency (A) unchanged, or increased by 25, 33 or 50%. The AWC of the soil was set at 225 mm, and irrigation applied as required. Results are summarised in Table 3.

TABLE 3: Effect of Climate Change on Wheat Yield and Maturity.

Year	A (g/MJ)	CO_2 (ppm)	Mature	Yield (t/ha)
1984	2.20	330	7 Jan	9.81
2030	2.20	500	7 Dec	5.42
2030	2.75	500	7 Dec	6.77
2030	2.93	500	7 Dec	7.22
2030	3.30	500	7 Dec	8.13

The increase in temperature brought forward the maturity date by a month, and A had to increase by an unlikely 50% or more to compensate. Chaudhuri *et al.* (1986) found yield increases of 60% and 55% in well watered and water deficient winter wheat grown in open topped containers when CO_2 was increased from 330 ppm to 825 ppm. This represents an increase in growth rate of around 60% for a increase in CO_2 concentration of 150%. If radiation use efficiency increases linearly with CO_2 concentration, then a 50% increase in CO_2 would give an increase in A of only about 20%.

Note that the climate change scenario suggests that Southland will have a climate similar to the current Canterbury climate. Hence wheat yields in Southland would be expected to be similar to current Canterbury yields.

AFTERWORD

The simulation model demonstrated in this paper is used primarily as a research tool with which hypotheses about processes can be tested in conjunction with field experiments. Nevertheless, the simulations outlined have shown that it can fulfil a useful role as a predictive and educative instrument. No model is complete, but the very incompleteness is useful in guiding future research.

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