ANALYSIS OF RESPONSES OF FIELD PEAS TO IRRIGATION AND SOWING DATE

2. MODELS OF GROWTH AND WATER USE

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ABSTRACT

Four simple models were used to help explain how 3 sowing times and 6 irrigation treatments caused growth and water use to vary in a field pea experiment, and to analyse the transpiration efficiency and response of drought to peas.

A water use model which estimates transpiration and soil evaporation separately described the evapotranspiration of the crops as measured by the water balance method. However, evapotranspiration rates were similar for all treatments because regular rainfall occurred. Differences among treatments in ground cover, the main crop factor usually affected by water deficit, were small.

Analyses with a growth model showed that the treatments caused yield variations mainly by affecting the duration of growth, and therefore the amounts of photosynthetically active radiation (PAR) intercepted by the crops. Water deficit reduced yields by curtailing the seed-fill period; this resulted in reduced harvest indices. Yields varied among sowing times mainly because of different opportunities to intercept PAR. There were also less significant effects of changed PAR utilisation efficiencies and harvest indices.

Transpiration efficiency was reasonably stable if the daytime vapour pressure deficit was taken into account. This means that yield cannot be increased without using more water in transpiration; the conditions required to achieve maximum yields are the same as for maximum water use.

A drought response model accurately described the seed yield response to water deficit, relative to the potential yields in fully irrigated conditions. We conclude that this model is the most useful because it allows irrigation to be subjected to accurate cost-benefit analysis.

Analysis of the experimental results using the four models helped explain how the treatments caused variations in crop performance and provided insights into how crop growth and water use interacted with the environment. Therefore it was possible to draw conclusions which should apply in other circumstances.

Additional Key Words: Evapotranspiration, photosynthetically active radiation, drought response model, water use, seed yield

INTRODUCTION

Conventional methods of analysis in agronomic research usually produce results specific to the sites and seasons in which experiments were conducted (Wilson *et al.,* 1984b). Response functions characterising crop performance, separated from site and season variability, are seldom defined with the result that extrapolation to predict likely responses in other circumstances is difficult. A major reason is that site and season characteristics are either not reported or are not used to aid interpretation of results. Therefore, the results provide few insights into the causes of crop responses to agronomic treatments.

The traditional approach to overcome this problem is to repeat experiments at several sites and/or in several seasons to obtain measures of the variation caused by environmental effects relative to the variation caused by the treatments being studied. Even then, the treatment effects are seldom established quantitatively and the scientific problem is to understand the effects of various variables, individually and collectively (McAneny and Kerr, 1984).

These deficiencies are well recognised, and the need for changes in agronomic research procedures was discussed at a symposium on "Approaches to Agronomic Research" held at the Agronomy Society of New Zealand Conference in 1980. Progress towards solving the problems has been made by the establishment of the concept of minimum data sets for agronomic experiments (Hackett *et al.,* 1979; Cossens, 1980; Nix, 1980; McAneny and Kerr, 1984). These provide the necessary data to make more meaningful interpretations. Although this is important, in our view it is the rational interpretation of climatic and biological data, rather than its collection, which presents the greater challenge.

Our approach to agronomic research is to use simple models with sound physical and physiological bases to analyse and interpret the results of experiments. The objective is to analyse results in such a manner that crop responses to management variables can be separated quantitatively from variable site and seasonal factors. With this quantitative understanding, it becomes possible to use the results to predict likely responses in other, untested circumstances. Experiments are designed in the context of the models, and these determine which parameters should be measured. The models thus have two purposes: first, to help explain experimental results, and second, to help predict responses in other circumstances.

In this paper we illustrate our approach by using four models to analyse the results of the field pea experiment described in the companion paper (Wilson *et al.,* 1984b).

The objectives were to:

1. analyse the water use of field peas and explain how it was affected by agronomic treatments.
2. analyse the growth of field peas, identify the crop characteristics which caused it to vary, and explain how agronomic treatments affected those characteristics.
3. characterise the water use efficiency of field peas.
4. define a relationship between yield and drought.

DESCRIPTION OF THE MODELS

Crop Water Use

It is necessary to describe the soil water deficits in order to quantify crop responses to irrigation. This can be done by constructing a water budget as follows:

Soil water deficit = soil water content at field capacity
+ rainfall + irrigation
− evapotranspiration − runoff
− drainage

Evapotranspiration (E) was estimated using the simple model proposed by Ritchie (1972) in which transpiration (E_t) and soil evapotranspiration (E_s) are calculated separately:

$$E = E_t + E_s \qquad (1)$$

The upper limit of E_t was taken as the maximum evapotranspiration rate (E_p) estimated using the Penman (1948) equation. In cases where the soil is drying and/or crop cover is incomplete, E_t is calculated from E_p as follows:

$$E_t = E_p (1 - \tau) F \qquad (2)$$

where τ is the ratio of net radiation measured at the soil surface to that measured above the crop and F is a function of the soil water deficit (S):

$$F = 1 \quad \text{for } S \leqslant S_l \text{ or after rain or irrigation} \qquad (3a)$$

$$F = 1 - a(S - S_l) \text{ for } S > S_l \qquad (3b)$$

where S_l is a limiting deficit, and a is a constant. F varies between 1 at field capacity and 0 when all available soil water is exhausted. When a rain event of more than 3 mm or an irrigation occurs, the applied water is assumed to be freely available and is used at the potential rate until exhausted. The values of S_l and a were assumed to be 110 mm and 0.0064/mm, respectively. We had no data for peas, so the above values were obtained by fitting E data from barley (Jamieson, 1982) to the model.

E_s is assumed to proceed at the potential rate when the soil surface is wet, and to enter a falling rate phase as the soil dries. Thus E_s was taken as the smaller of two calculated rates:

1. Limited by the energy available at the soil surface:

$$E_s = \tau E_p \qquad (4)$$

2. Limited by the rate of water vapour diffusion to the surface of the drying soil (Black *et al.*, 1969; Ritchie, 1972; Tanner and Jury, 1976):

$$E_s = b\,t^{1/2} \qquad (5)$$

The value of b (8 mm/day$^{1/2}$) was obtained from Bowen ratio measurements of E_s from a drying soil at Lincoln (P.D. Jamieson, unpublished).

Crop Growth

Seed yield (Y) is analysed as the integral of the growth rate with time, multiplied by the harvest index (HI) (Monteith, 1977):

$$Y = HI \int C\,dt \qquad (6)$$

The daily growth rate (C) is analysed as the product of the energy available for growth and the efficiency with which it is used. According to the model, the growth of crops with adequate water and nutrients, and free from weeds, pests and diseases is related linearly to the amount of photosynthetically active radiation (PAR) which they intercept:

$$C = A\,Q \qquad (7)$$

where A is the efficiency with which a crop uses PAR to produce dry matter and Q is the amount of PAR intercepted by the crop canopy. Q is calculated from:

$$Q = Q_o (1 - \tau) \qquad (8)$$

where Q_o is the daily incident PAR. We assumed that the extinction of net radiation and PAR in the canopy is identical.

Water Use Efficiency

We analysed water use efficiency using a model in which dry matter production is related linearly to the ratio of E_t and the daytime vapour pressure deficit (Bierhuizen and Slatyer, 1965):

$$\text{Transpiration efficiency} = C / E_t = k / (e^* - e) \qquad (9)$$

where k is an empirical constant with the dimensions of pressure and $(e^* - e)$ is the daytime vapour pressure deficit.

Tanner and Sinclair (1983) used theoretical arguments and published values of C, E_t and $(e^* - e)$ for several crops to estimate values of k. They concluded that k is a stable parameter which characterises the transpiration efficiency of a crop.

Response to Drought

A simple model proposed by Penman (1971) was used to analyse the response of seed yield to drought. The model defines drought in terms of "potential soil moisture deficit" (D), the difference between E_p, initial soil water deficit, and inputs of rain and irrigation, integrated over the season. E_p was calculated using the Penman (1948) equation with an adjustment for ground cover similar to that used by French and Legg (1979). When ground cover in the fully irrigated crop is less than 50%, E is calculated as the mean of E_p and E_s; for ground cover of more than 50%, E is taken as E_p. This method was used in preference to the above E model because it is very simple, requires few measurements and can be applied where ground cover is assessed visually.

When D is small, seed yield is maximum. When a critical deficit (D_c) is exceeded, a yield reduction occurs. According to the model, the reduction is directly proportional to the difference between the maximum D (D_m) experienced by the crop during growth and D_c. The model can be expressed as two equations:

$$Y = Y_o \qquad D_m \leqslant D_c \qquad (10a)$$

$$Y = Y_o\,[1 - c(D_m - D_c)] \qquad D_m > D_c \qquad (10b)$$

where Y is seed yield, Y_o the yield of a fully irrigated crop and c is an empirical coefficient which describes the yield response to drought. The yield reference of the model is the yield achieved in fully irrigated conditions which contrasts with the conventional approach where the reference is usually the yield of an unirrigated "control". Consequently the model's response function is independent of variable seasonal rainfall.

The major assumptions of the model are that crop growth is not inhibited by weeds, pests and diseases or catastrophic climatic events and that there are no significant effects of temperature on crop growth. Growth is assumed to stop or slow substantially when D_c is exceeded or all applied water is exhausted.

MATERIALS AND METHODS

The models were used to analyse results of the experiment described by Wilson *et al.* (1984b). Several measurements were made in addition to those described in that paper.

Crop ground cover was estimated in all plots at regular intervals during growth from measurements of PAR above and below the canopies with a 1 metre line quantum sensor. It was assumed that errors resulting from the difference in extinction coefficients between photosynthetic photon flux density, PAR, and R_n would be small, and the results were used to calculate values of τ (equations (2), (4) and (8)) for the calculations of E_t, E_s and Q. Daily Q_o values were obtained from a weather station about 300 m from the experiment site.

Crop growth was measured at fortnightly intervals by harvesting 0.5 m² samples of above ground dry matter from each plot, drying and weighing. HI was calculated as the ratio of seed yield to maximum total dry matter. The number of harvests varied among sowing time treatments because the duration of growth varied.

To test the E model, crop water use was estimated using the water balance method from fortnightly measurements of volumetric soil moisture content to a depth of 1.2 m with a neutron probe. An access tube was installed in each of two plots of the unirrigated (NI) and fully irrigated (WB1) treatments of each sowing date. There was no runoff and drainage errors are discussed in the results section. Soil moisture in the upper 0.2 m was measured gravimetrically.

Daily daytime vapour pressure deficit data for use in the transpiration efficiency model calculations were obtained from the weather station.

RESULTS AND DISCUSSION

Crop Water Use

Estimates of E calculated from the water use model were compared with the water balance estimates for each neutron probe access tube (Figure 1). The water balance calculations accounted for rainfall and irrigation but neglected drainage.

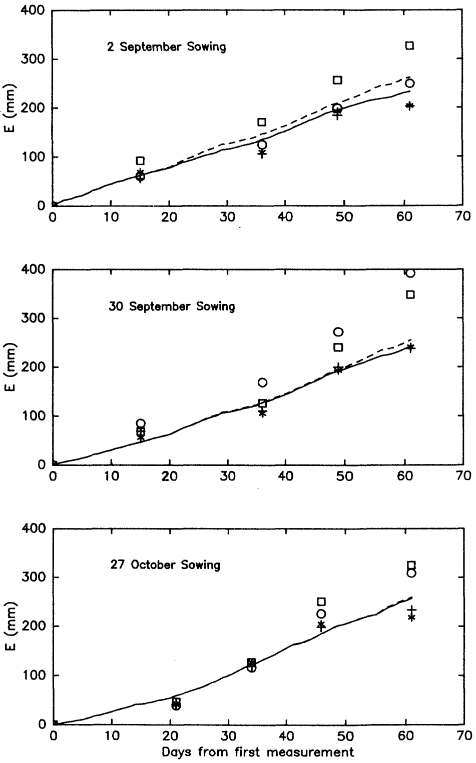

Figure 1: Model and water balance estimates of cumulative evapotranspiration (E). Solid lines represent model estimates for the unirrigated treatments, and broken lines are the same for the irrigated treatments. The symbols + and * are measured values for each access tube in unirrigated plots, and ○ and □ are the same for unirrigated plots.

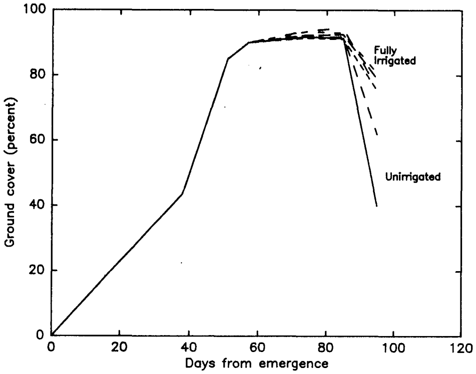

Figure 2: Effect of irrigation treatments on ground cover in the 2 September sowing.

According to the model, there was little difference in E between the NI (non-irrigated) and WB1 (fully irrigated) treatments. This occurred because soil water deficits did not become substantial in the NI treatment and because there were no significant differences in ground cover between treatments until late in the season (Figure 2).

In the NI treatments, there was good agreement both between tubes and between the model and water balance estimates. However, in the WB1 treatments the water balance estimates of E disagreed between tubes and were substantially larger than those from the model.

The discrepancies between the tubes in the WB1 treatments suggest variable infiltration patterns, and substantial drainage below the profiles. The cumulative difference of 77 mm between the two tubes in the 2 September sowing could not be explained by differences in ground cover between the replicates. The discrepancies between the model and water balance estimates of E must also be caused by drainage because they occurred during the period of full ground cover when E was unlikely to be greater than the maximum rate (E_p).

The last water balance estimates of E in the NI treatments in the 2 September and 27 October sowings are lower than the model estimates. There are two possible reasons: first, when the crop was senescing green ground cover may have been overestimated, and second, the effect of soil water deficit on E_t may have been more severe than assumed.

Having established the model's utility, and assuming the discrepancies were mainly due to drainage, we used it to estimate total E and E_t for all treatments (Table 1). Differences were small, mainly because of high rainfall in December and January, and similar durations of growth for all sowing times. The calculated values of E_t were used in the water use efficiency analyses.

TABLE 1: Calculated cumulative evapotranspiration (E) and transpiration (E_t). See Wilson *et al.* (1984b) for details of irrigation treatments.

Treatments Sowing date	Irrigation	Water applied (mm)	E (mm)	E_t (mm)
2 September	NI	0	344	225
	WB1	105	371	258
	WB2	50	368	259
	FL	50	368	259
	PF	55	357	242
	FLPF	105	373	263
30 September	NI	0	341	222
	WB1	155	366	275
	WB2	100	357	253
	FL	50	352	250
	PF	55	354	248
	FLPF	105	363	269
27 October*	NI	0	320	249
	WB1	105	327	263
	WB2	50	323	255
	FL	55	324	257
	PF	50	324	257
	FLPF	105	328	265

*Until 31 January, because of failure of solarimeter

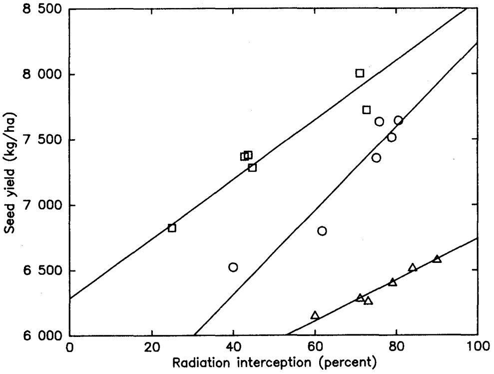

Figure 3: Relationships between seed yield and a single measurement of radiation interception during late seed fill. Measurements were made on 29 December, 13 January and 30 January for the 3 sowings. Symbols are: 2 September (○, r^2 = 0.90); 30 September (□, r^2 = 0.91**); 27 October (△, r^2 = 0.96***).**

Crop Growth

The main effect of irrigation on growth was to delay senescence slightly. The pattern was similar for all sowings and is shown for the first sowing in Figure 2. Irrigated plots intercepted more radiation during seed fill, the period when seed yield is very dependent on radiation interception (Figure 3). Therefore, although the irrigation treatments did not improve maximum total dry matter production, they significantly increased HI and seed yield (Table 2). Irrigation had no effect on the development of ground cover or PAR conversion efficiency, probably because severe soil water deficits did not occur early in the

TABLE 2: **Effect of irrigation and sowing time on maximum total dry matter, seed yield and harvest index. See Wilson *et al.* (1984b) for details of irrigation treatments.**

Treatment	Maximum dry matter (kg/ha)	Seed yield (kg/ha)	Harvest index	Harvest Date
Sowing date				
2 September	11330	7250	0.64	23 January
30 September	13130	7470	0.58	2 February
27 October	12100	6360	0.54	13 February
LSD 5%	750	210	0.04	
LSD 1%	1000	280	0.05	
Irrigation				
NI	12600	6500	0.53	
WB1	12300	7290	0.60	
WB2	12070	7100	0.60	
FL	11680	7150	0.61	
PF	11660	6820	0.60	
FLPF	12790	7310	0.57	
LSD 5%	1060	290	0.05	
LSD 1%	1410	390	0.07	

unirrigated treatment. In previous experiments (Wilson *et al.,* 1984a), the main effect of drought was to reduce ground cover development, although Zain *et al.* (1983) also found a substantial influence of drought on PAR conversion efficiency.

Changing the sowing time significantly affected both total dry matter production and seed yield (Table 2). The 30 September sowing produced the highest yields. The duration of growth from emergence to complete senescence was 99 days, PAR conversion efficiency was 2.6 g/MJ (Figure 4), and the HI was 0.58 (Table 2). These are intermediate values for the sowing time treatments. However, the total amount of radiation intercepted by this treatment was highest because the crop was actively growing for longer in January when radiation was greatest. The lowest yields were obtained from the 27 October sowing, which had a 94 day growth duration, PAR conversion efficiency of 2.3 g/MJ and an HI of 0.54. These factors outweighed the advantage of high incident radiation in January. The 2 September sowing did not produce the highest yields, even though it had a 103 day growth duration, PAR conversion efficiency of 3.1 g/MJ and HI of 0.64. Most of its growth occurred early in the season when radiation was low and it senesced before the period of highest radiation in January.

We cannot explain in terms of the model why growth duration, PAR conversion efficiency, and HI varied among the sowing time treatments. However, we suggest two likely reasons for the variations. First, the later-sown crops had shorter growth durations because plant development is a function of thermal time. The main consequences were reduced HI's caused by shorter seed fill periods later in the season when temperatures were high. Second, the probable cause of the reduced PAR conversion efficiency with later sowing was that the canopies were light saturated for longer periods by the higher PAR levels later in the season.

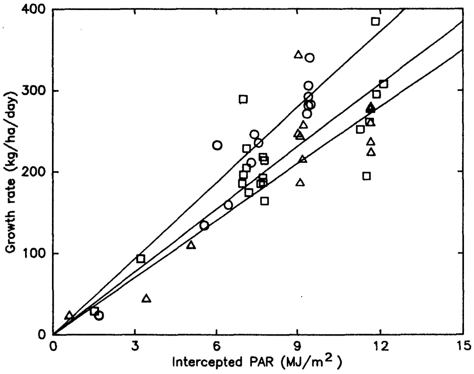

Figure 4: **Relationships between mean daily growth rate and intercepted PAR between successive harvests. The slopes of the regression lines are 3.1 ± 0.1 g/MJ (r^2 = 0.90***) for 2 September (○); 2.6 ± 0.1 g/MJ (r^2 = 0.79***) for 30 September (□); 2.3 ± 0.1 g/MJ (r^2 = 0.89***) for 27 October (△). The slopes of the regression lines, which were forced through the origin, are significantly different at the 0.1% level.**

When crop growth and yield were analysed using the growth model, it was possible to establish the causes of yield variation. The treatments affected yield mainly by changing the opportunity for the canopies to intercept radiation, especially during seed fill. This caused HI to vary. There were also less important changes in the PAR conversion efficiency.

Water Use Efficiency

The analyses with the transpiration efficiency model showed a stable relationship between dry matter production and water use. The mean value of $k = 0.041 \pm 0.001$ mb was within the range for C3 crops (0.040 to 0.065 mb) given by Tanner and Sinclair (1983). Irrigation had no effect on k but there were statistically significant differences among sowing times (Figure 5). However, the differences were small and of little practical significance.

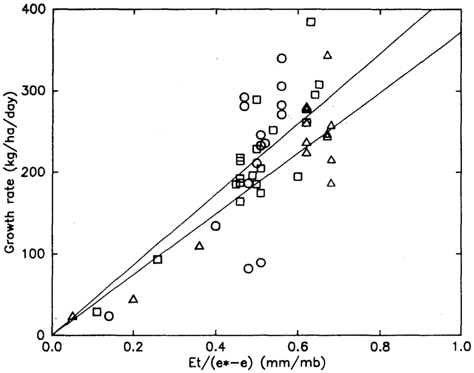

Figure 5: Relationships between mean daily growth rate and the mean ratio of transpiration to vapour pressure deficit [$E_t/(e^* - e)$] between successive harvests. Slopes of the regression lines, which were forced through the origin, give values for k of 0.043 ± 0.002 mb (r^2 = 0.81*) for 2 September (○) and 30 September (□), and 0.037 ± 0.001 mb (r^2 = 0.91***) for 27 October (△).**

The results mean that dry matter production cannot be increased without using more water in E_t. The conditions required to achieve maximum yields are the same as for maximum water use. Consequently the main prospect for improving crop water use efficiency lies in improved management to increase E_t as a fraction of E. However, there are limits to such improvements; the water use efficiency can only approach transpiration efficiency as the upper limit (Tanner and Sinclair, 1983). Transpiration efficiency could also be increased by growing crops in humid climates where $(e^* - e)$ is small.

Response to Drought

The response of seed yields to drought was fitted to the model outlined in equations (10). Our procedure was to locate the approximate value of D_c by inspection, and then to fit yield data corresponding to D_m values greater than this by least squares. This produced values and standard errors for D_c and c.

The results from this experiment alone were insufficient to allow precise definition of the critical potential soil moisture deficit (D_c), so data from experiments in previous years were included (Wilson *et al.*, 1984a). The slope of the yield response to drought (Figure 6) means that 0.20 ± 0.02% of the potential yield is lost for each mm of D_m beyond D_c. The value of D_c for peas in this soil was 88 ± 2 mm. Thus, for example, an irrigation (or rain) of 50 mm applied when $D = D_c$, will return 600 kg/ha in a crop with a potential yield of 6000 kg/ha.

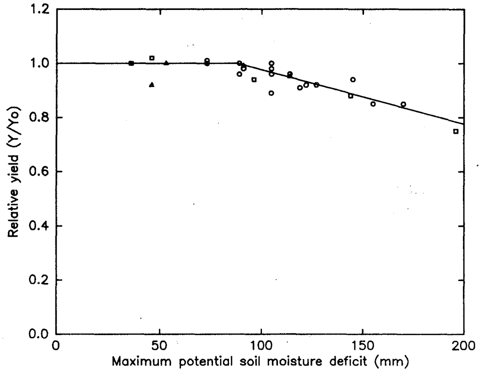

Figure 6: The ratio (Y/Y_0) of seed yield to that of a fully irrigated crop, versus the maximum potential soil moisture deficit that occurred between emergence and maturity. The slope of the line beyond the critical potential soil moisture deficit (88 ± 2 mm) is −0.0020 ± 0.0002 mm^1 (r^2 = 0.89*). Data from this experiment are represented by the symbol ○. [Adapted from Wilson *et al.*, 1984a].**

The results have important implications for irrigation management. First, the yield response to irrigation is proportional to potential yield, so that crops with high yield potential should have priority for irrigation. Second, the response function allows a value to be placed on water so that an accurate cost-benefit analysis can be carried out.

There was no evidence that peas were particularly sensitive to drought at flowering and pod fill. The maximum potential soil moisture deficit occurred at different times in different treatments but none caused a deviation from the yield response function. However, severe deficits did not occur in any treatments, and none were subjected to deficits exceeding D_c before flowering.

CONCLUSIONS

In this experiment the analyses with the models led to the following general conclusions:

1. Drought caused premature senescence during seed fill. However, severe drought earlier in the season would probably have had additional effects on crop growth.
2. Varying the sowing time changed the amount of PAR intercepted by the crops and the PAR conversion efficiency. These changes caused variations of growth and water use.
3. Transpiration efficiency was stable for peas provided that the daytime vapour pressure deficit was taken into account. Water use efficiency can be improved only by maximising the transpiration component of total water use.
4. Yield loss caused by drought was directly proportional to the maximum difference between the supply and demand for water during growth.

5. Field peas were no more sensitive to water deficit at flowering and pod fill than at any other time. However, the range of conditions tested was limited.

The models helped explain how the agronomic treatments caused variations in crop performance, and provided insights into how crop growth and water use interacted with the environment. Hence it was possible to draw conclusions which should apply in other circumstances. In contrast, conventional statistical analyses of results of the same experiment (Wilson *et al.,* 1984b) showed merely that yield depended on sowing time and irrigation, a conclusion already well established.

This paper is presented as an inital step toward making the results of agronomic experiments more transportable between sites and seasons. Our results do not answer all the questions about the growth, water use and drought response of peas, mainly because the experiment was conducted in a wet season. We do not claim that the models presented are the only suitable options available for analysing the results of agronomic experiments. However, they are a useful framework for rational analyses of biological data which allow interpretations of crop responses independent of the specific circumstances of an experiment.

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