

Water Use Efficiency of Wheat in a Mediterranean-type Environment. II* Some Limitations to Efficiency

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Abstract

Evidence is presented that water use efficiency and yield of wheat are reduced by insufficient leaf area and by inadequate content of nutrients in the top growth. Yields from field trials are compared with the potential yield, and a review is made of the limitations caused by weeds, the incidence of diseases and the harvest index.

The data highlight the need for field experiments to define the evaporation and transpiration components of water use in each environment. They also indicate the need for multi-factorial treatments to overcome all yield limitations and thereby attain the potential yield.

Introduction

In Part I (French and Schultz 1984), the relations between wheat yield and water use (evapotranspiration) were assessed at 61 sites in the South Australian wheat belt. Highest yield per mm of water use was 37 kg ha⁻¹ dry matter and 12.7 kg ha⁻¹ grain. More than 70% of the total water use occurred by anthesis. Highest-yielding crops gave a grain yield equal to 50% of the dry matter at anthesis.

The components of water use were assessed and the average loss of water by direct evaporation from soil and crop was estimated to be 110 mm (33% of total water use). A linear relation between yield and water transpired, gave a potential production per mm of 55 kg ha⁻¹ dry matter and 20 kg ha⁻¹ grain.

Production per mm water use and per mm of estimated transpiration was related to the daily average pan evaporation from sowing to maturity by the de Wit (1958) formula. The data could be fitted to this formula, but the value of the constant *m* varied with the percentage of the water use lost by direct evaporation. With this modification the formula was a useful index for estimating potential yield.

Only a small proportion of the crops gave yields approaching the potential for the environment. This paper evaluates some of the factors which limit the yield of wheat.

Materials and Methods

This paper examines the experimental data reported in detail in Part I but also introduces data sets from other experiments. In brief, in Part I measurements were made at 61 locations in a range of districts, soil types and growing seasons during the years 1964-1975. Weather variables were monitored at or near all sites. Soil moisture was measured at sowing and several times during the growing season.

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Plant dry matter production was recorded several times during the growing season, and grain yield was measured at maturity. The plant and grain samples were analysed for nitrogen, phosphorus and 11 other elements. Plant growth stages were recorded on the Feekes Scale (Large 1954), and soil and plant measurements were related to the actual growth stages at the time of sampling. Similar measurements were made on the data sets introduced for evaluation in this paper.

Results and Discussion

Evidence of Yield Limitations at District and Farm Level

While the climate determines the rate of development and potential yield of crops, the actual yield is determined by the management skills of the farmer.

District yield averages, in general, give a broad estimate of the state of the industry. In Fig. 1, the average wheat yields in 20 districts in South Australia from Western Eyre Peninsula to the Upper South East, are related to April–October rainfall for each of three different types of seasons. While it would have been desirable to relate yields to water use, few such measurements have been made.

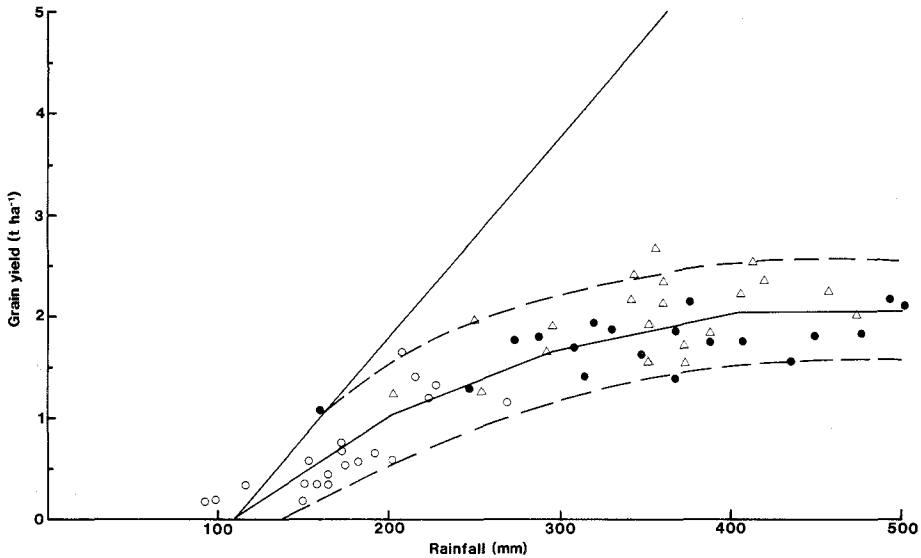


Fig. 1. The relation between the average grain yield of wheat for 20 districts in South Australia and April–October rainfall in three seasons: ○ 1977, drought year; ● 1978, good year; △ 1979, excellent year. The curved solid line is the mean yield derived by regression analysis of all data and the dashed lines define the standard deviation of the mean. The sloping line indicates the potential yield relation derived in Part 1.

However, in Part I, it was shown that, except where long fallowing added substantially to the subsoil moisture at sowing, there was a close correlation between water use and rainfall from April to October; hence rainfall during this period is used as an estimate of water use. Fig. 1 shows that the yield trend with rainfall is curvilinear, and the broken curves show the standard deviation about the mean yield. The maximum yield for any district in any year did not exceed 2.5 t ha⁻¹. The figure also shows the linear relation, established in Part I, between the potential grain yield and the amount of water transpired; the relation is 20 kg ha⁻¹ mm⁻¹. The figure illustrates the increasing deficit below the potential yield with higher rainfall.

Fig. 2 shows the same relation between grain yield and April–October rainfall obtained from experiments and measurements made in individual farmers' paddocks. The sites are from the experiments in Part I, from other published and unpublished experiments of our own and from published papers by other authors (cited later). There were a few sites with yields close to the potential, but most had yields below the potential with, again, a bigger deficit with higher rainfall. Some factors contributing to this variation in yield are examined.

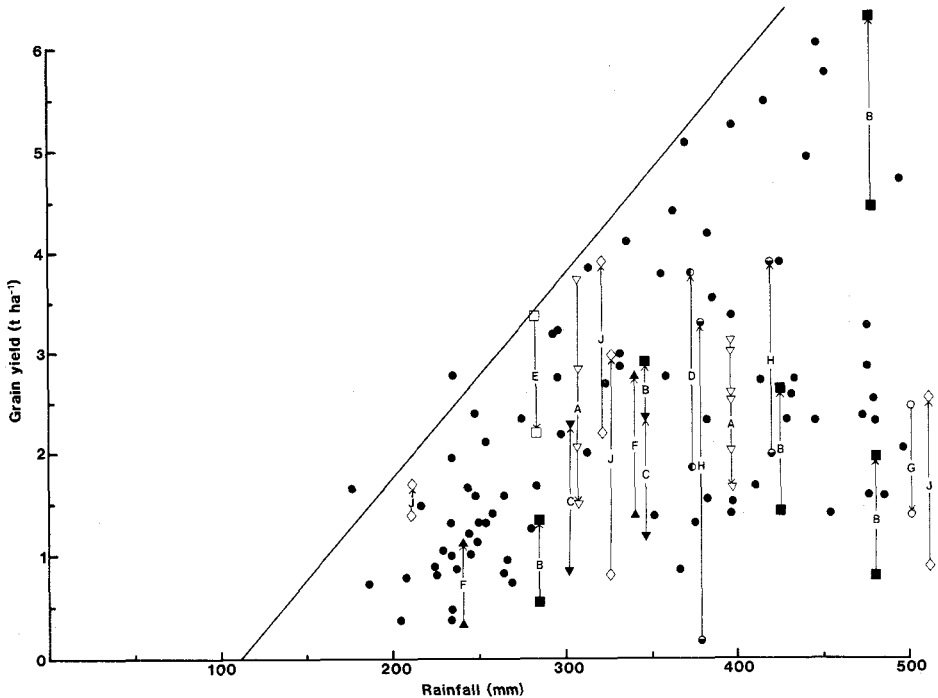


Fig. 2. The relation between the grain yield of wheat and April–October rainfall for experimental sites and farmers' paddocks. The sloping line indicates the potential yield relation (Part I). The responses to different treatments are shown by lettered lines linking points. Yield increases were obtained by the application of nitrogen (points linked by a B line), phosphorus (C line), copper (D line), control of eelworms (F line) and multi-factor research (J line). Yield reductions occurred because of delayed time of sowing (A line), effects of weeds (E line) and waterlogging (G line). Variation in yields in districts are shown by the H lines.

Factors Limiting the Yield of Wheat

Efficiency of conversion of radiant energy and leaf area index

Crop production is governed by the interception of radiant energy and the efficiency of converting this energy to dry matter. In the early growth stages, the interception is limited by the leaf canopy, and it is not until a leaf area index (LAI) of about 3 has been obtained that the crop starts producing dry matter efficiently. The main factors delaying the development of leaf area and hence dry matter, are temperature and water stress (Biscoe and Gallagher 1977).

At 16 sites LAI was measured several times up to anthesis and the arbitrary line fitting the relation between the LAI and dry matter of the highest yielding crops

could be described by the formula

$$\text{LAI} = 0.68 + 0.0015x - 0.12 \times 10^{-6}x^2 \quad (r^2 = 0.87),$$

where x is dry matter yield (kg ha^{-1}). From this equation, LAI 3 is equal to about 1800 kg ha^{-1} dry matter. Any factor that delays the attainment of this amount of dry matter thereby reduces the time the crop has for its maximum growth rate, and lower yields result. Our best crops reached the 1800 kg ha^{-1} dry matter in about 70 days from sowing, but the average production in 70 days was less than half this dry matter (Part I). The highest LAI obtained by anthesis was 5.4, when the dry matter was 6800 kg ha^{-1} . This value at anthesis is similar to the optimum dry matter proposed by Evans and Wardlaw (1976) and Fischer (1979).

Total solar radiation was measured from sowing to maturity at 12 sites and values ranged from 2200 to 3300 MJ m^{-2} . The efficiency of converting this radiation to dry matter and grain was calculated over the growing season. The average efficiency (based on 16.8 kJ g^{-1}) was 0.50% for dry matter and 0.14% for grain, while the efficiencies for the best crop were 0.77% and 0.29% respectively. These efficiencies were obtained with crop albedo values that ranged from 0.18 to 0.28 between tillering and anthesis, and declined to 0.12 by soft dough stage.

Table 1. Average content (kg ha^{-1}) of nutrients in top growth of wheat grown at 31 sites in South Australia during 1970–75 and the derived uptake of nutrients per mm water transpired to give maximum yield

The standard deviations of nutrient content varied from 30–60% of the mean

Nutrient	Content at anthesis (kg ha^{-1})	Maximum content	Content at maturity (kg ha^{-1})	Nutrients in grain	Uptake rate to give max. yield per mm water transpired ($\text{kg ha}^{-1} \text{ mm}^{-1}$)
Nitrogen	72.0	90.2	80.3	48.4	0.65
Phosphorus	9.4	10.8	9.4	5.9	0.07
Potassium	102.0	119.9 ^A	65.1	9.1	0.90
Sulfur	9.3	11.0	9.5	3.6	0.07
Calcium	9.1	10.6	8.7	1.0	0.07
Magnesium	9.5	11.6	10.0	3.2	0.08
Sodium	5.7	8.9	7.8	0.7	0.07
Chlorine	43.2	50.5 ^A	29.0	2.3	0.40
Silicon	106.7	138.7	116.1	3.1	0.90
Copper	0.049	0.068	0.047	0.014	0.0006
Zinc	0.074	0.091	0.079	0.041	0.0007
Manganese	0.258	0.340	0.298	0.089	0.0025
Dry matter (kg ha^{-1})	6140	7890	7280	2210	
Water use (mm) from sowing	246	311	343	343	

^A Maximum content before anthesis.

During the most productive growth interval, viz. tillering to anthesis, the average efficiency of conversion of radiant energy to dry matter was 1.1%; the best crop converted 2.1%, which produced $140 \text{ kg ha}^{-1} \text{ day}^{-1}$, a value similar to that obtained in Queensland (Angus *et al.* 1980). These compare with up to 2.35% conversion and $200 \text{ kg ha}^{-1} \text{ day}^{-1}$ recorded at Tamworth (Doyle and Fischer 1979),

and 155–178 kg ha⁻¹ day⁻¹ at Rutherglen (Connor 1975). As discussed in Part I, the production in this interval is probably limited by the amount of water (2.2 mm day⁻¹) available for transpiration.

The effect of nutrient availability on water use efficiency

Moisture is not the only factor limiting production in low rainfall areas; a shortage of nutrients may be just as critical (van Keulen 1975), as nutrient-deficient plants use water at about the same rate as a well-balanced plant (Leggett 1959).

In Table 1, the average values for nutrient content of plant tops at different stages of growth are listed for 31 sites. The maximum content of nutrient (except for potassium and chlorine) occurs close to the soft dough stage and the nutrient content at maturity is generally lower. Of the nutrient content at maturity, more than 60% of the nitrogen and phosphorus is removed in the grain, together with 50% of the zinc, and 30–40% of the sulfur, magnesium, copper and manganese.

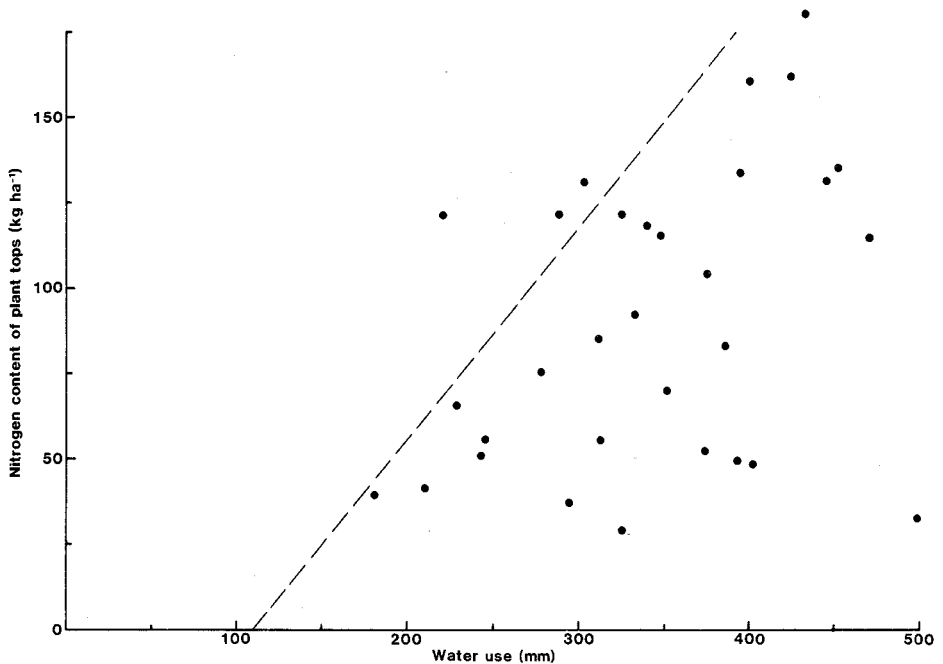


Fig. 3. The relationship between maximum nitrogen content of the plant top growth and water use by wheat.

In Fig. 3, maximum nitrogen content is related to water use. Again the data are scattered, but, by using the technique as described in Part I and drawing arbitrarily a line through the most efficient sites, it can be seen that, after the soil evaporation value of 110 mm, the efficient crops take up 0.65 kg ha⁻¹ nitrogen for each mm of water transpired. Similar assessments were carried out for the other nutrients, and the rates of accumulation of nutrients in the top growth to give maximum yield of dry matter per mm water transpired are shown in Table 1. Thus to produce the potential yield of 55 kg ha⁻¹ dry matter (and 20 kg ha⁻¹ grain) per mm water transpired, the crop needs to take up either by mass flow or diffusion, 0.65 kg ha⁻¹

nitrogen and 0.07 kg ha^{-1} phosphorus for each mm water transpired. These criteria are similar to those of Kassam (1981). The values in Table 1 suggest that the average maximum content of nitrogen (N) and phosphorus (P) in the top growth is below the optimum required to give the highest yield for the 233 mm (343 - 110) water transpired. Similarly, Novoa and Loomis (1981) maintained that for maximum yield of grain, the maturing biomass should contain a nitrogen concentration of 1.4-1.6% N. The average concentration in our data was 1.14% and only 9 of the 31 sites had values within the range of 1.4-1.6%.

A further measure of nutrient effect on water use efficiency is the index used by Fischer (1981), viz. the ratio of kg grain to kg nutrient uptake. With our data, for maximum efficiency of water transpired, the nitrogen index for grain production is $20 \text{ kg ha}^{-1} \text{ grain} / 0.65 \text{ kg ha}^{-1} \text{ N} = 31$, i.e. for each kg N in the top growth, the potential yield of grain is 31 kg ha^{-1} . Similarly, for P, the index is $20 \text{ kg ha}^{-1} \text{ grain} / 0.07 \text{ kg ha}^{-1} \text{ P} = 280$.

Thus to produce 1 t of grain with the maximum efficient use of water transpired, a crop has to take up 32.5 kg N and 3.5 kg P . The ratio of N : P is therefore 9.3 : 1; our average value calculated from Table 1 is 8.4 : 1.

This index may be linked with other criteria to assess fertilizer needs. Russell (1963) indicated that a wheat crop had adequate nitrogen when the grain nitrogen concentration exceeded 2.3%. Ten out of our 31 sites had grain nitrogen concentrations equal to or greater than this value, and for these the nitrogen index ranged between 20 and 30 : 1, and the N : P ratio was greater than 8 : 1. These values are close to the optimum values calculated above. In eight other sites where the grain nitrogen content was low (1.6-1.9%), the nitrogen index ranged between 30 and 60 : 1 and the N : P ratio was less than 7 : 1. Similar assessments were made for phosphorus. Ten sites had a low grain phosphorus concentration (less than 0.20%) and for these sites, the phosphorus index was greater than 280 : 1. Where phosphorus contents were above 0.27%, the index value was less than 280 : 1.

Table 2. Crops with a large decline in dry matter and/or nitrogen content of top growth between maximum values and maturity

Site	Year	Dry matter (kg ha^{-1})		% decline	Nitrogen in tops (kg ha^{-1})		% decline	Nitrogen in grain (kg ha^{-1})
		Max.	Maturity		Max.	Maturity		
Jamestown	1974	9 800	7 210	36	105	55	48	28
Manoora	1973	9 940	9 630	3	136	85	38	41
Two Wells	1971	6 500	6 500	0	122	71	42	44
Turretfield	1973a	12 740	11 140	14	181	146	19	55
Turretfield	1973b	11 110	9 800	13	161	117	27	39
Turretfield	1973c	9 050	7 750	17	135	102	24	27

The average decline in dry matter and nitrogen between the stage of maximum content and maturity was 8% and 11% respectively (Table 1). However, at several sites, the decline in one or both of these measurements was much greater (Table 2). In general these bigger losses of nitrogen were independent of the dry matter decline and occurred where there was a high content of nitrogen in the plant, but only a relatively small amount of nitrogen (less than 50 kg ha^{-1}) in the grain. These large losses of nitrogen between maximum content and maturity range from 0.6 to

2.0 kg ha⁻¹ day⁻¹. The losses compare with 1.2 kg ha⁻¹ day⁻¹ reported by Kassam (1981), a 20% loss during the 3 weeks before maturity (Wetselaar and Farquhar 1980), also equal to 1.2 kg ha⁻¹ day⁻¹, and the loss of 40–50 kg ha⁻¹ (20–30%) reported by Barley and Naidu (1964). Storrier (1962) also found a marked decline in nitrogen after anthesis in crops grown on soils with a high mineral nitrogen content.

The effect of weeds, diseases and pests

Very few crops in our experiments had obvious weed infestations except the site at Two Wells 1971. Here, the yield of weeds (barley grass, ryegrass, brome grass and soursobs) reached 2420 kg ha⁻¹ at the heading stage of wheat which had produced 5810 kg ha⁻¹ dry matter. Weed dry matter declined thereafter, and the crop produced 6500 kg ha⁻¹ dry matter and 2180 kg ha⁻¹ grain. Total water use was 280 mm. The potential yield for this water use, defined from the de Wit formula as described in Part I, is 3480 kg ha⁻¹ grain (i.e. 60% higher), but the difference could not be ascribed specifically to weed growth alone. The effect of the weed infestation in decreasing water use efficiency is shown by the *E* line in Fig. 2.

Other experiments have shown specific yield losses from weed infestations. Thus Kohn *et al.* (1966) showed a yield reduction of 0.36 kg grain per kg weed growth, and Mears (1968) and Lumb (1973) recorded grain losses of 1.0–1.3 t ha⁻¹ due to weeds. However, the size of the reductions also depends on the crop yield; Paterson (1976) showed that a yield of 1000 kg ha⁻¹ wheat was reduced by 200 kg ha⁻¹ when infested with wild oats at a density of 50 plants m⁻², and by 600 kg ha⁻¹ with a wild oats density of 400 plants m⁻². However, when the crop yielded only 400 kg ha⁻¹, the reduction due to wild oats was not significant.

Experiments have also shown that yield of wheat can be greatly reduced by cereal cyst nematodes (*Heterodera avenae*), and the root diseases 'take-all' (*Gaeumannomyces graminis*) and root rot, *Rhizoctani solanii*. Thus, Rovira *et al.* (1981) recorded significant yield increases at seven of their eleven sites by controlling eelworms with nematicides, applied at sowing. The highest yield increase, 0.9 t ha⁻¹ above the untreated yield of 0.23 t ha⁻¹, is shown in Fig. 2 by the *F* line at 248 mm rainfall. In another experiment on calcareous sandy loam, the incidence of 'take-all' was reduced by growing medic pasture or grain legumes in the year before wheat, and yield increases of up to 0.8 t ha⁻¹ were obtained.

In our experiments, no assessment was made of the incidence of eelworms or root diseases, but it is probable that these factors contributed to the reduction of yield below the potential at a number of the sites. Another pest which can lower yields is the cereal circlio (*Desiantha caudata* Pasc.), which Grierson and Allen (1976) found reduced yields from 3.55 to 2.30 t ha⁻¹.

Several of our experiments in 1973 and 1974 were affected by rust, and, although the effect on dry matter was small, the loss of grain was much higher. Thus at Turretfield 1973, the harvest index was only 0.21. If an average value of 0.35 had been obtained, grain yield would have increased from the measured yield of 2520 to 4120 kg ha⁻¹.

Waterlogging

In some winters waterlogging is a problem. In our experiments, two sites only were obviously affected by waterlogging. One was at Saddleworth 1971 where only

2.8 kg ha⁻¹ of grain were produced from each of the 503 mm water used, and yield was over 1 t ha⁻¹ less than that of a surrounding area unaffected by waterlogging. The effect of waterlogging on water use efficiency is shown in Fig. 2 by the G line. The other site was at Northfield 1971, where the application of 30 kg ha⁻¹ N increased the yield from 550 to 2120 kg ha⁻¹.

The effect of changes in harvest index

In Part I, it was shown that the highest yielding group of crops had a harvest index (the ratio of grain to total dry matter) of 0.35 compared with 0.29 in the average group. Crops with the higher index were sown early and completed anthesis before the onset of the stress date. Lower indices can be caused by high nitrogen application, water deficits during anthesis and grain filling (French 1978; Passioura 1981) and by high plant density (Kirby 1967). Harvest index also varied with varieties. During the course of these experiments, and others conducted separately, the harvest index ranged from 0.30 for Gabo and Halberd, to 0.33 for Eagle, to 0.36 for Kite, to a mean \pm s.e. of 0.43 ± 0.04 for Condor over a range of drought and favourable seasons.

In many experiments, higher grain yields over the years have been attributed largely to the progressive increase in harvest index (Syme 1970; Donald and Hamblin 1976; Austin 1978; Austin *et al.* 1980; Bremner 1980; Davidson and Birch 1980), for there is often little difference in the amounts of crop dry matter produced per unit of water (Richardson 1923; Fischer and Turner 1978; Fischer 1979; Bremner 1980). In the United Kingdom, the harvest index has increased from 0.34 to 0.50 over the last 50 years, without much change in the total dry matter (Austin *et al.* 1980). A key to greater water use efficiency is a high harvest index.

Future Needs

Crop yield is a function of the interaction between weather, soil and management. Our two papers indicate that there is ample scope for increasing water use efficiency on most farms and thereby increasing yield.

Data presented highlight the need for a simple field measurement to separate the amount of water lost by direct evaporation from that used for transpiration. The evaporation loss varies with rainfall patterns in the growing season, soil type and cultivation practices and therefore influences both the amount of water available for transpiration and the potential yield. Estimates of transpiration by using refinements of techniques such as the silicon content (Hutton and Norrish 1974; Schultz and French 1976) would be valuable, and would enable more accurate calculations of the size of the deficits between actual and potential yield.

The deficits due to some of the limitations to crop growth are illustrated in Fig. 2. For example at 380 mm rainfall, the range of yields measured along a transect of 14 farms north of Adelaide is shown by the length of the H line. Yields varied from 0.16 to 3.3 t ha⁻¹ (Simon and Rovira 1982), and the lower yields were attributed to the high infestations of cereal eelworm and variable effects of the root diseases rhizoctonia and 'take all'. At 425 mm rainfall another H line shows the variation of yields obtained at another location in the Mid-North in different paddocks on the one farm; the yields ranged from 2.0 to 3.9 t ha⁻¹.

The decline in yield from delayed times of sowing (see Part I) are represented by an A line linking ∇ ; the A line at 307 mm rainfall is from Turretfield in 1972; the other A line at 397 mm is from Kimba in 1974.

Responses to the application of nitrogen fertilizer are represented by the B lines. At about 480 mm rainfall there are two examples. One experiment increased the yield from 0.8 to 1.8 t ha⁻¹; the other at a different site increased the yield from 4.4 to 6.3 t ha⁻¹. While the first experiment gave a significant yield increase, the research must be seen as inadequate because there is still a deficit of over 4 t ha⁻¹ below the potential which could be obtained with the rainfall. It would be more informative if the results described the experiment as increasing yields from 13% to 29% of the potential yield.

The nitrogen responses at the second site approached the potential yield. This is the only one of our experiments in which a single factor responses has approached the potential. Two other responses to nitrogen rates (B lines) are shown at 280 mm and 430 mm rainfall. The four sets of data could be evaluated by regression analysis, but because of the variable deficit below the potential, it is doubtful whether there is much to be gained from this type of analysis in defining factors that prevent the attainment of the potential yield.

Other responses to fertilizer applications are shown for phosphorus (C lines) and for copper (King and Alston 1975) by the D line. It is apparent, however, that rarely do single-factor experiments give yields that approach the potential yield. If this yield is to be achieved, then it is first necessary to identify all the limitations to yield and to then overcome them with multi-factor treatment research, an approach strongly recommended by Cooke (1982).

Examples of the success of such multi-factor research are shown in Fig. 2. Thus at 320 mm, a J line shows the range of yields obtained by King (1984) in a field study in the Upper South-East of South Australia. Limitations to yield were identified as nitrogen deficiency, weeds and the incidence of root diseases. By progressively combining treatments in both the year before the crop and in the crop year to overcome these limitations, wheat yields were increased from 2.2 to 3.9 t ha⁻¹, i.e. the yields were increased from 54% to 95% of the potential yield for the rainfall.

The other example is from A.D. Rovira (personal communication) — J line 325 mm — who combined conventional and direct drill cultivation with the effect of cereal crop, grain legume crop and pasture in the year before the wheat; yields increased from 0.8 to 3.0 t ha⁻¹. Even so, there is still a deficit below the potential, emphasizing the need to identify all the limitations in the field. This point is further demonstrated by the other J line at just over 500 mm, where yields were increased by a series of rotations but the maximum was still below the potential.

Future field research should aim at measuring more precisely the amount of water lost by direct evaporation. Potential yield can then be defined from the amount of water available for transpiration. Deficits between actual and potential yield can be resolved by multifactor treatment research that removes the limitations.

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