Paper 5

NEW APPROACHES TO UNDERSTANDING THE GROWTH AND YIELD OF PEA CROPS

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INTRODUCTION

Pea crops exhibit poor stability of yield compared with other crops, particularly cereals. Consequently, their average yield over a range of growing conditions is relatively low, even though they can produce high yields in favourable conditions. Reduction of instability to improve the average yield is therefore an important objective of research in agronomy, crop physiology and plant breeding.

The first step towards growing high yielding pea crops is to apply the best available advice for crop management and cultivar selection. In general, this information is already available. There have been many studies in New Zealand of the effects on pea yields of factors such as time of sowing, plant population, cultivar, weed and disease control, and irrigation and fertiliser requirements. Jermyn (1984) published a pea management and cultivar guide which summarises the main requirements for growing good pea crops.

Research has solved many practical problems associated with growing arable crops, and has produced cultivars adapted to New Zealand conditions. However, it has done little to solve the problem of, or explain the reasons for, yield variations among crops. As Gallagher *et al.* (1983) pointed out, the influence of site and season on crop growth and yield is usually much greater than the effects of management treatments on each crop. This is especially true for peas. Therefore, a primary research objective should be to establish why pea yields vary so markedly among sites and seasons. This can only be achieved by improved understanding of the processes which contribute to the growth and yield of pea crops, the way they vary among genotypes, and the effects on them of environmental conditions which are mainly responsible for yield variability.

To achieve these aims, new approaches are needed to studying the growth and yield of pea crops. The purpose of this paper is to review traditional and alternative approaches, with the aim of assessing the suitability of each for identifying the causes of yield variability among crops. Successful approaches should suggest new management and breeding strategies to improve yield stability. First, the traditional method of analysing the components of seed yield is considered. Deficiencies of the method are

Table 1. Seed yield and yield components of peas (from Stoker, 1975).

Irrigation	Plant population (no. m^{-2})	Seed yield (kg ha^{-1})	Pods per plant	Peas per pod	1000 seed weight (g)
None	38	1440	2.8	4.5	266
	71	2440	2.6	4.4	262
	95	2080	2.2	3.4	253
	125	2190	1.9	3.2	243
	148	2070	1.8	2.8	241
	195	1650	1.5	2.2	237
3 irrigations	42	2670	4.6	5.1	230
	80	3560	3.5	5.1	219
	104	3740	3.0	4.8	213
	138	4120	2.6	5.0	206
	155	3430	2.1	4.4	208
	211	3360	1.7	4.0	204

identified, and alternatives are discussed which use quantitative approaches to analyse the growth and yield of crops. An approach is described which analyses crop growth and yield in terms of available energy and the efficiency with which it is used. The importance for yield stability of growth duration, dependent on the rate of crop development, and harvest index are also discussed.

Apart from diseases, water supply is usually the main environmental factor responsible for yield variability among crops. The final section therefore describes the practical implications for irrigation management of recent new approaches to studying the water requirements and responses to water deficit of pea crops.

ANALYSIS OF YIELD COMPONENTS

In agronomic research, the yields of pea crops are usually analysed in terms of four so-called components of yield whose product is the seed yield per unit area (Y):

$$Y = A \times B \times C \times D$$

where A is the number of plants per unit area, B is the mean number of pods per plant, C is the mean number of peas per pod, and D is the mean seed weight. The components are mutually inter-dependent, and crop management aims to maximise yield by achieving a balance whereby each component is maximised.

The grower can control A directly by changing the seeding rate, and the effect on yield of varying A has been examined in many experiments. Most results reflect the inter-dependence among the four yield components, which is often called "plasticity". As the plant population is increased there is a corresponding progressive decrease of all the other components. The results in Table 1 from Stoker (1975) illustrate this point. The consequence is that yield increases with increasing population until an optimum is reached, then declines thereafter. The optimum population varies among cultivars and growing conditions. It is usually about 100 plants/m^2 for non-branching cultivars and 70/m^2 for branching cultivars, and is generally higher in more favourable growing conditions (Table 1).

Some control can be exercised over the other three yield components (B, C and D) through choice of appropriate cultivars, because genotypes vary in their propensity to produce pods per plant and peas per pod, and in their mean seed weights. Breeders have aimed to produce higher yielding cultivars by exploiting this variation. However, differences among cultivars are generally smaller than variations caused by changing plant populations or other management practices and, especially, differences among sites and seasons.

Apart from being used to examine the effects of different plant populations and cultivars, the yield component approach has also been used frequently to describe the effects on yield of many other treatments, such as sowing time, weed control, fertilisers and irrigation. In all results the dominant theme has been the plasticity among the components. As one component responds directly to a treatment, the others exhibit a great capacity to compensate by either increasing or decreasing so that yield changes caused by the treatment are often relatively small.

Despite its common use, the yield component approach has the major deficiency that it does not explain yield variations; it merely documents them by describing the structure of seed yield per unit area. The results of an experiment are always specific to the site and season in which it was conducted, and variability among sites and seasons is usually much greater than among the treatments in each experiment (Gallagher *et al.,* 1983), so extrapolation of experimental results to predict likely responses to the same treatments in other conditions is not possible. Since the deficiency cannot be overcome by the traditional approach, which is to repeat experiments at several sites and/or in several seasons, alternative methods of yield analysis are needed which take account of environmental effects to produce results with more general applicability.

ANALYSES OF CROP GROWTH AND DEVELOPMENT

The alternative approaches aim to develop quantitative relationships between crop performance parameters and environmental factors, by using simple models with physical and physiological bases to analyse and interpret the results of experiments. The objective of the analyses is to achieve a better understanding of the causes of yield variations, by separating crop responses to treatments from variable site and seasonal factors. The approaches produce general principles which make it possible to predict likely crop responses in other, untested circumstances, and to explain the causes of yield variations, both among agronomic treatments and different sites and seasons.

Considerable progress has been made in the use of models to analyse the growth, development and yield of cereal crops. Peas have received much less attention, but recently attempts have been made to apply to peas some of the principles developed for cereals.

Crop growth and yield

An approach which is becoming generally accepted is to analyse seed yield per unit area (Y) as the integral of the growth rate with time, multiplied by the harvest index (Monteith, 1977):

$$Y = HI \int C \, dt$$

where HI is the harvest index and C is the daily rate of above-ground dry matter production. C is analysed as the product of the energy available for growth and the efficiency with which it is used. The hypothesis is that 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) they intercept during active growth:

$$C = E\,Q$$

where E 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. Therefore, growth and yield variations can be interpreted in terms of changes in four parameters: HI, E, Q and the duration of growth.

The model embodied in equations (2) and (3) has been used successfully to describe the growth of several other crops (Monteith, 1977; Biscoe and Gallagher, 1977; Gallagher and Biscoe, 1978; Charles-Edwards, 1982), but until recently there were no analyses of peas. In two recent papers (Jamieson *et al.,* 1984; Wilson *et al.,* 1985) we have shown that this model satisfactorily described the growth of pea crops in a range of conditions, even though yields varied considerably among seasons, cultivars, sowing times and irrigation treatments. The main conclusions were:

- Yield variations were associated with changes in all four parameters.
- The value of E was consistent, except for variations among irrigation treatments in one experiment. Usually, about 2.4 g of dry matter were produced per MJ of PAR intercepted (Fig. 1).
- HI differed among treatments, although the variations were relatively small. However, they were sufficiently large to invalidate the assumption commonly made for cereal crops that HI within a cultivar is fairly constant. The significance of varying HI for yield instability among pea crops is discussed later.
- Total dry matter yield differences were mainly caused by variations in the duration of growth, which meant that crops intercepted different amounts of PAR (Q) (Fig. 1).

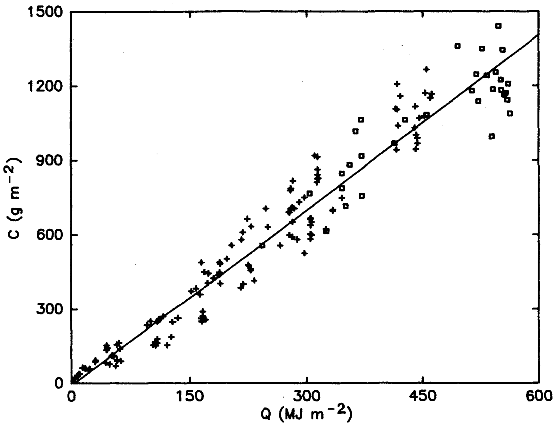

Figure 1. Relation between cumulative total dry matter production (C) from successive harvests, and intercepted PAR (Q) for field peas in five experiments in four seasons, with different cultivars, sowing times, and irrigation treatments. The maximum value for each treatment has a square symbol, and the slope of the regression line is 2.36 ± 0.03 g MJ^{-1}(r^2 = 0.97*). (from Wilson *et al.,* 1985).**

These results suggest that to produce high total dry matter yields, crop management should aim to maximise the duration of growth and hence the opportunity to intercept PAR. There are many possible strategies to achieve this, such as sowing early with adequate plant populations to achieve early canopy expansion and ground cover, choosing late maturing cultivars to maximise the duration of PAR interception, or using irrigation to avoid water deficit and prevent premature senescence. However, these strategies may not always be appropriate for producing high seed yields, because changing HI was the other main cause of yield variations. To maximise HI and seed yield, it is especially important to ensure that the duration of the seed-fill period is not restricted. For example, seed fill may cease prematurely if water is deficient or if high temperatures accelerate the rate of crop development to maturity.

The advantage of this approach to yield analysis is that it allows the causes of yield variations to be identified, both within experiments and between different sites and seasons, in terms of meaningful crop and environmental parameters. Therefore, it provides a useful framework for interpreting crop responses to treatments independent of the specific circumstances of an experiment.

Crop development

Pea yields are very dependent on the duration of growth. This in turn depends on the rate of crop development, which differs considerably among cultivars. Knowledge of the rate is a vital aspect of matching a cultivar's characteristics to the most suitable management and environments for it. If the matching is incorrect, crop growth and yield will be adversely affected. For example, in drought-prone environments cultivars with rapid development rates have the best chance of growing to maturity during periods of adequate rainfall and soil water availability. On the other hand, cultivars with slow development rates will have longer growth durations and therefore more opportunity to intercept incident PAR and produce high yields in well-watered conditions. Consequently an understanding of crop development, and the genotypic and environmental factors which affect it, is important.

There are two distinct aspects of crop development; phenological and canopy development. The former, which refers to the rate of progress through the growth stages, depends on temperature and photoperiod, and is mainly independent of crop management. Canopy development, which determines the rate of canopy formation, its duration, and its senescence, depends mainly on temperature. However, it is also very sensitive to environmental stresses and crop management. Most effects on yield of pests or diseases, nutrient or water deficiencies, or weather factors can be interpreted in terms of changes in canopy development, and hence the ability of crops to intercept incident PAR during growth.

Harvest index

Unlike cereals, variable HI is an important contributor to yield instability among pea crops. Not only is HI sensitive to crop management and environmental factors, but its stability also differs substantially among genotypes. In cereals, it is generally recognised that the major contribution of plant breeding to improved yields has been through increased HI. The challenge to pea breeders is similarly to identify genotypes with stable, high HIs.

Ambrose and Hedley (1984) and Hedley and Ambrose (1981) investigated reasons for the variation of HI stability among pea genotypes by examining the performance of individual plants in crops. They found that the variability of HI among plants differs substantially between pea genotypes. In populations of all genotypes they examined, some plants had HIs as high as 70% while others produced no seed (i.e. their HIs were zero). The distribution of individual plant HIs between the extremes of 0% and 70%, and the proportion of barren plants, determined the overall crop HI of a cultivar. The examples in Figure 2 illustrate the different distributions of individual plant HIs for two contrasting field pea cultivars.

These observations have important implications for pea breeding and selection procedures. Traditionally, 'desirable' plant types are selected by breeders for their superior performance as single plants, and usually those chosen are competitive, dominant types. However, Ambrose and Hedley (1984) hypothesised that when these are grown in crop communities they have the most variation of HI from plant-to-plant, the lowest overall crop HI, and therefore poor seed yields. Most of the seed is produced by a few dominant plants, while most other plants produce very little. To produce large seed yields, the individual plants making up a crop should be weak competitors, with poor performance as single plants. Therefore, the selection of vigorous and productive plants in early generations may work against selection in later generations on the basis of plot yield.

This hypothesis is supported by Donald and Hamblin (1976, 1984) who advanced a similar argument for wheat, although Hedley and Ambrose (1985) provided evidence that the variance of HI between plants is less in cereals than for peas. Moreover, Evans (1981) argued that the hypothesis is supported by physiological analyses of historical improvements in yield potential. The major practical problem, in view of the enormous genetic diversity in peas, is to define the plant types or characters associated with good ability to produce consistent HIs in crop communities. Early indications from Ambrose and Hedley's research are that the ideal plant could prove to be a non-competitive semi-leafless type with poor performance as a single plant.

WATER REQUIREMENTS OF PEA CROPS

Water supply is usually the main environmental factor responsible for yield variability among pea crops. It is clear from the previous discussion that water deficits lower yields mainly by reducing PAR interception by shortening the growth duration of crops and by affecting canopy development. The nature and extent of the yield reductions depend on the timing, duration and severity of deficits during growth.

Knowledge of the water requirements of crops and of their responses to water deficit is important for answering practical questions faced by growers concerned with scheduling irrigations efficiently:

- When does a crop need irrigating?
- How much water should be applied?
- What is the likely yield benefit from an irrigation, or the likely yield penalty if irrigation is delayed?

Responses to irrigation by pea crops have been studied in many trials, but the results have not provided adequate

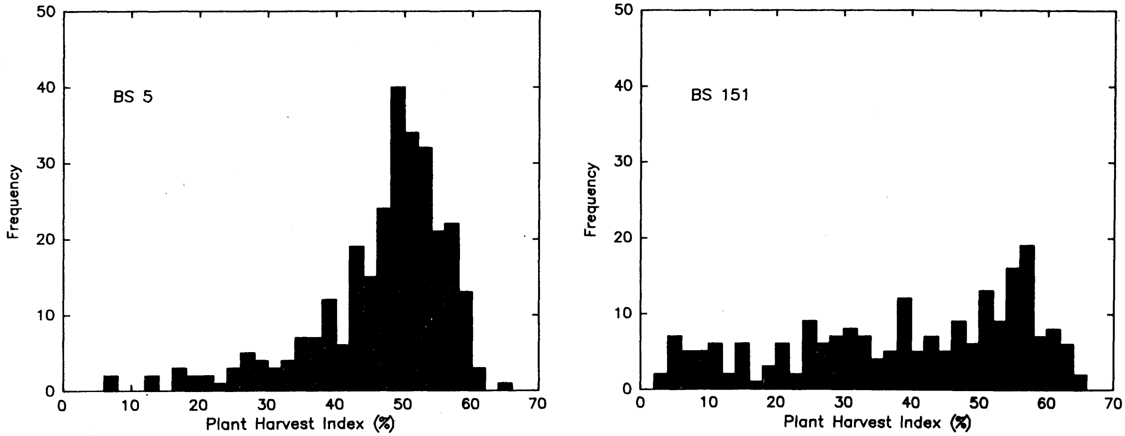

Figure 2. **Plant harvest index frequency distributions for two contrasting field pea genotypes grown at 123 plants per m^2. Barren plants (2.1% for BS 5 and 30.2% for BS 151) were excluded. Crop harvest indices were 48% for BS 5 and 38% for BS 151. (from Ambrose and Hedley, 1984).**

answers to these questions because most results are specific to the time and location of the trials. Results range from yield depressions caused by irrigation in wet seasons or locations, to large yield increases in dry conditions. Despite the variable results, the general recommendation has evolved that pea crops should be irrigated during flowering and pod fill, unless rainfall is appreciably above average.

This recommendation takes little account of water availability to crops during growth, so irrigation scheduling is not based on crop water need. Crop growth, water use and drought stress during a season depend mainly on weather conditions, especially evapotranspiration (E) rates and rainfall, and these factors should be considered when making irrigation scheduling decisions. We have used new approaches to examine these factors in relation to the water requirements and yield responses of pea crops. Our results are described in detail in two other papers (Jamieson *et al.*, 1984; Wilson *et al.,* 1985), and the main practical implications for management of crop water supplies are summarised below.

- Water use (E) rates by well-watered crops with complete leaf canopies are governed by meteorological conditions, mainly radiant energy and air humidity. The E rate is reduced by soil water deficit or when leaf canopies are incomplete because, like growth, E is very dependent on the amount of radiation intercepted.
- Crop yields cannot be increased without using more water, because there is a very close relationship between crop growth and E rates. Therefore, to produce maximum yields management should aim to maximise water use, because anything which restricts the E rate will limit yield potential by also restricting the growth rate.
- Knowledge of the E rate and the amount of rainfall received is necessary to determine when to irrigate a crop, and how much water to apply. Crops should be irrigated according to the results of water budget estimations of soil moisture deficits.
- The amount of yield reduction below the potential yield for the conditions depends on the severity of water deficits experienced by a crop during growth (Figure 3). No reduction occurs if the critical deficit (Dc) for the crop/soil combination, about 50% of the plant-available water in the top 1 metre of soil, is never exceeded during the growth of a crop. However, a yield reduction is caused whenever the critical deficit is exceeded. The reduction is directly proportional to the difference between the maximum deficit (Dm) experienced by a crop during the season, and Dc. The result for field peas in Figure 3 means that the seed yield decreases by about 0.22% for every mm of D below the critical deficit. Thus, for example, a typical irrigation of 50 mm applied when Dc is exceeded will produce a yield increase of 660 kg ha^{-1} in a crop with a yield potential of 6000 kg ha^{-1}.

  It is important to note that the yield reduction is proportional to the potential yield in well-watered conditions. This means that crops with high yield potential suffer the greatest yield losses if water deficient conditions are allowed to persist. On the other hand, the same crops will produce the greatest yield benefits when irrigated. Therefore, in practice, the best crops should receive priority for limited water supplies, because they will produce the greatest yield return per mm of water used.

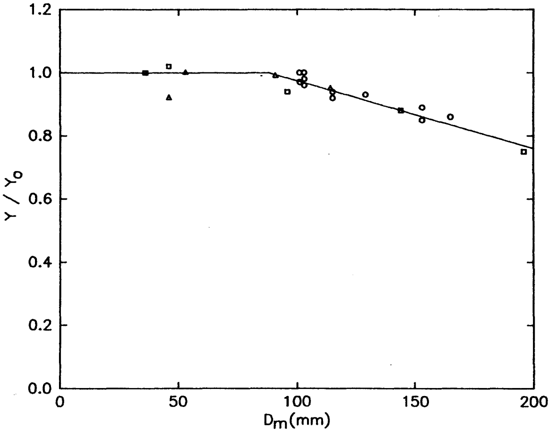

Figure 3. The ratio (Y/Yo) of the seed yield of unirrigated or partially irrigated field peas to that of a fully irrigated crop versus the maximum potential soil moisture deficit (Dm) that occurred between emergence and maturity in three experiments. The slope of the line above the critical potential soil moisture deficit (88 ± 2 mm) is -0.0022 ± 0.0002 mm^{-1} (r^2 = 0.89*). (from Wilson *et al.,* 1985).**

- Our results suggest that no stages of crop development are more sensitive to water deficit than others. This contrasts with the usual recommendation that pea crops are especially sensitive during flowering and pod-fill. By coincidence, however, in many seasons water budget calculations show that crops commonly require irrigating at these times. However, it is not a good general rule for all seasons and locations. Crops should be irrigated when they need water.

CONCLUSIONS

Research on peas must aim to find ways to improve yield stability. This brief review has suggested some new approaches which could be used to determine the main causes of yield variation.

In most agronomic research, pea yields have been analysed using the yield component approach. However, the main principles required to produce high-yielding crops are well established. To increase the average yield, the aim should be to encourage application of these principles. Further significant advances from traditional agronomic research are unlikely. The conventional, empirical approach has successfully solved many practical problems, but further trials are only likely to produce fine-tuning of established practices.

Future progress is more likely from studies of the effects on yield of environmental and genotypic factors, and their interactions. The new approaches help to identify the main parameters of crop growth and development which react to environmental factors to affect yield, and which vary among genotypes. These intepretations lead to explanations of the most likely causes of yield instability, and to the possibility of better matching of cultivars to management and environments to maximise yield.

Variations of HI and duration of growth are the main genotypic factors responsible for yield variations. Improved stability of HI is most likely through breeding, and strategies to achieve this were suggested. No consistent variations of HI caused by management and environmental factors have been established. Most yield differences are caused by variations in growth duration, and therefore opportunity for crops to intercept PAR. Therefore, crop management should aim to maximise the duration. More information is needed about the development characteristics of pea cultivars so they can be chosen rationally to best exploit prevailing environmental and management conditions.

Water supply is the main environmental factor causing yield variability among pea crops. Variability can be minimised by correctly matching cultivars to the most suitable environments for them, and managing them to use available water supplies efficiently. The yield stability of irrigated crops can be improved by applying irrigation management principles based on knowledge of the water requirements of crops and their responses to water deficit.

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