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CENTENARY REVIEW

Past developments and future opportunities in the design and analysis of crop experiments

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SUMMARY

A review of papers on the statistical design and analysis of experiments published in the *Journal of Agricultural Science, Cambridge*, over the last 100 years is presented. The development of significant ideas in the practical design of field experiments is reviewed. Some possible future developments in the design of spatial field trials and computer-aided design of experiments are discussed.

INTRODUCTION

The early part of the last century saw the development of many new and important ideas in statistical methodology including the seminal publication by Gosset (1908) on the distribution theory of small samples from a normal distribution. This theory became the basis of the famous Student's *t*-test and had a profound effect on the development of statistical methodology in agriculture. Gosset was well aware of the importance of his work and in one of his illustrative examples suggested that 'cases where the tables will be useful are not uncommon in agricultural work, and they would be more numerous if the advantages of being able to apply statistical reasoning were borne in mind when planning the experiments'. The *Journal of Agricultural Science, Cambridge*, founded in 1905, was well placed to help develop these advantages and during the following 100 years, the publication of new statistical methodology in the journal has helped revolutionize the way that agricultural experiments are planned and executed.

In this paper, some of the important developments in the statistical design and analysis of experiments associated with the *Journal of Agricultural Science, Cambridge*, will be outlined. The main developments have been in the area of field crop experiments and the focus of the paper will be on work in this area. The aim of the review will be to cover the general principles of the design and analysis of experiments and specialized areas such as genotype × environment interaction studies, competition designs, diallel cross designs and other special purpose designs will not be covered. It is not intended to produce a comprehensive bibliography of all design and analysis papers published in JAS over the last 100 years and only a selection of relevant papers will be discussed.

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SOME EARLY DEVELOPMENTS

The first important paper on statistical methodology published in the *Journal of Agricultural Science, Cambridge*, was by Wood & Stratton (1910) and was concerned with the interpretation of experimental results using the probable error of a mean based on large sample theory. The authors discussed the numbers of observations required for a given level of precision and discussed the power of an experiment to solve a proposed problem. They investigated field trials using both uniformity data and data from published trials with duplicated plots and concluded that it was useless to compare single plots 'whatever their size'. For small treatment differences, the number of plots must be increased either by 'duplication several times in the same experiment, or by repetition of the experiment at several stations, or for several seasons'.

The next major statistical paper was by Mercer & Hall (1911) and was devoted to a study of the experimental error of field trials. They collected uniformity data from a large number of small plots of wheat and mangolds and compared the statistical properties of plots of different sizes obtained by amalgamating yields of neighbouring plots in different ways. They showed that the standard deviation of plots of increasing size decreased more slowly than expected on the assumption of independent yields from neighbouring plots. This showed that 'some considerable correlation exists between the yields of adjacent plots'. They then showed that by amalgamating yields from plots 'scattered systematically' across the whole trial, the standard deviation of plots could be reduced more in accordance with the assumption of independent yields. They recommended that in field experiments, each unit of comparison should be replicated up to five times using plots 'systematically distributed within the experimental area'.

There then followed an important period of development during the 1920s that led to some key ideas in the theory of experimental design. These included the ideas that experimental plots should be arranged at random in replicated blocks to provide unbiased estimates of error and that treatment factors of interest should be examined in factorial treatment combinations rather than individually (Fisher 1926). During this early period, the *Journal of Agricultural Science, Cambridge*, published a substantive series of important papers on the topic of Studies in Crop Variation largely inspired by R. A. Fisher's statistical work at the Rothamsted Experimental Station. Paper IV in the series (Eden & Fisher 1927) exemplified many of the key ideas of blocking, randomization and factorial experimentation.

COMPLEX DESIGNS IN THE 1930s AND 1940s

Following the initial development of blocked experiments, researchers soon found that large replicate blocks of treatments in field experiments were very heterogeneous and that smaller, more complex block designs were needed for precise comparison of treatments. Eden & Fisher (1929) discussed a range of block designs and, remarkably, introduced the idea of reducing block size by confounding certain unimportant factorial contrasts between blocks. Their description of the example design was inadequate but their key idea of reducing block size by confounding unimportant treatment contrasts was undoubtedly correct.

The first major paper in the *Journal of Agricultural Science, Cambridge*, to deal with the subject of complex blocking and confounding was by Yates (1933), in which he discussed the design and analysis of a range of blocked and confounded factorial treatment experiments. His paper covered the principles of main effects confounding in split-plot experiments and also gave a fully valid account of the method of reducing block size by confounding unimportant treatment contrasts between blocks. Yates (1935) then gave an important paper on complex experiments at a discussion meeting of the Royal Statistical Society where much of the modern theory and practice of factorial experiments and confounded block designs was outlined. An unfortunate aspect of that paper was that Yates 'condemned' a general class of designs called semi-Latin square designs because of 'biased error'. Although a number of discussants were clearly uncomfortable about this 'condemnation', researchers were deterred from using these useful and effective designs for many years.

In the following year, Yates (1936*a*) discussed a class of incomplete Latin square designs obtained by omitting a single row or column from a Latin square and showed that these designs had useful practical properties. Also in that year, Yates (1936*b*) developed the highly important class of designs now called lattice designs. These designs were originally called pseudo-factor designs and were intended to provide efficient incomplete block designs for unstructured treatment sets by imposing an artificial pseudo-factor structure on the treatments and then confounding pseudo-factor contrasts between blocks in as efficient a way as possible. This collection of papers by Yates, together with a paper by Yates on balanced incomplete block designs published elsewhere (Yates 1936*c*), laid the foundations of modern block design theory.

In 1938 Fairfield Smith published an empirical law (Smith 1938) that described the relationship between plot size and plot variability. This law was very influential, for a time, in studies on the choice of plot sizes for experiments.

By the early 1940s, factorial treatment designs were widely used in many areas of research and were of proven value. However, one major practical problem remained. As the number of factors in an experiment increased, the number of factorial combinations needed for a complete factorial treatment design became very large, especially for factors with more than two levels. Consequently, factorial trials with many treatment factors involved large numbers of treatment combinations and were often impracticable. This problem was solved for a large class of factorial designs by Finney in two influential publications on fractionation, one in the *Journal of Agricultural Science, Cambridge* (Finney 1946) and one elsewhere (Finney 1945). Although much of the theory of fractionation has been developed elsewhere (see, for example, Edmondson 1994), fractionation has found many practical applications in agricultural research and has allowed agricultural experiments with numerous factors to be carried out at a reasonable cost. See for example Chinloy *et al.* (1953).

Finally, at the end of this period, Pearce & Taylor (1948) discussed the changing of treatments in long-term trials using ideas from the theory of confounded block designs.

MODERN DESIGN WORK

Following the rapid developments of the 1930s and 1940s, there was a long period during the 1950s when, possibly due to the appearance of specialized journals such as Biometrics, little of relevance to our review was published in the *Journal of Agricultural Science, Cambridge*. However, beginning in the 1960s and especially during the 1970s and later, new areas of work in the design of experiments began to emerge in the journal.

First, Patterson & Ross (1963) undertook an examination of the effects of long narrow cereal plots on the efficiency of block designs. These plots had been introduced to accommodate the new technique of combine harvesting and it was important to know whether they affected the efficiency of variety trials using lattice designs. Patterson & Ross examined the relationship between error variance and block size using data from 454 cereal trials and concluded that the gain in efficiency from using small blocks in cereal trials was as great for the long narrow plots as it had been for the wide short plots used previously.

Next, Patterson (1965) published an influential paper in the *Journal of Agricultural Science, Cambridge*, on the construction of fractional factorial treatment designs for rotation experiments. This paper used the idea of a *design key* to identify factorial treatment contrasts with individual pseudo-factorial plot contrasts and provided a systematic method for constructing blocked and fractionated factorial designs. Later, the method was used to develop an algorithm for an early computer program for the design of factorial experiments called DSIGN, which is full described elsewhere in Patterson (1976).

Then, from the late 1970s onwards, perhaps due to the increasing power and availability of computers, there was an upsurge of interest in the development of block designs for various purposes. Patterson *et al.* (1978) introduced a new class of cyclically generated lattice designs called alpha designs, which greatly extended the class of lattice block designs then currently available for variety trials. Fielding & Killick (1983) reported favourably on the use of alpha lattice designs in a small sample of potato variety trials and Patterson & Hunter (1983) later published a substantial examination of alpha lattice design efficiency based on an analysis of 240 cereal variety trials in the UK. They concluded that the designs improved cereal trial efficiency under UK conditions by about 42% relative to randomized block designs. A description of the algorithm used to design alpha designs was given by Paterson *et al.* (1988).

Finally, Yau (1997) examined the efficiency of alpha lattice designs in 714 international cereal yield trials and concluded that alpha lattice designs gave worthwhile improvements in efficiency relative to randomized block designs, although not such marked improvements as those reported by Patterson & Hunter (1983). As there was no additional cost in implementing the new designs, he recommended the use of alpha lattice designs in international and regional field trials rather than conventional complete randomized block designs.

Row-and-column designs can be particularly useful for trials with small plots and the efficiency of two-dimensional alpha lattice type designs was investigated for small plot barley trials by Robinson *et al.* (1988) using 129 spring barley trials. Gains in efficiency similar to those reported by Patterson & Hunter (1983) were obtained and the two-dimension alpha designs were reported to be equally as useful as the one-dimensional designs. Patterson & Robinson (1989) then published a series of efficient row-and-column designs for variety trials with two replicates.

In a related but separate area of work, Edmondson (1998) developed a class of balanced row-and-column designs obtained by omitting a main row or a main column from a special class of semi-Latin squares called Trojan squares. These designs are natural generalization of the incomplete Latin squares of Yates (1936*a*) and would probably have been developed much earlier had it not been for the Yates (1935) 'condemnation' of semi-Latin squares. Ironically, Yates himself, as early as 1937, (Yates 1937, Section 16i and 16j) used Graeco-Latin and hyper-Graeco-Latin squares to construct row-and-column designs that were identical with the class of designs we now know as Trojan squares!

DEVELOPMENTS IN SPATIAL METHODS

The designs and analysis discussed so far have all been based on block designs with the assumption of fixed or random block effects. However, even from the very early days of randomized block designs, research papers in the *Journal of Agricultural Science, Cambridge*, have shown a continuing interest in the use of spatial methods for the analysis of field trials. An early study by Sanders (1930) examined a regression of annual crop plot yields on the yields of the same plots from previous years while Eden (1931) carried out a similar study for a perennial crop by regressing tea bush yields on the yields of the same bushes from previous years. Sanders found little advantage in the method but Eden reported very substantial improvements in precision. Interestingly, the method of covariance regression on plot position (see Federer & Schlottfeldt 1954) was not discussed by either author and did not occur in the Fourth Edition of Statistical Methods for Research Workers (1932) by R. A. Fisher, although the method did appear in later Editions (Fisher 1973, Section 48) and had, apparently, appeared by at least the 10th Edition published in 1946 (Federer & Schlottfeldt 1954).

A different approach to spatial analysis in field trials was suggested by Papadakis (1937), who discussed a method for eliminating trend effects by fitting a regression of the yields of individual plots onto the

Table 1. *Some recent papers on spatial aspects of the design and analysis of experiments using nearest neighbour* (*NN*) *methods*

Paper	Topic	Comment
Dyke & Shelley (1976)	Computer design of NN serially balanced designs for 36 plots.	Constructed linear designs balanced for negative interference between neighbours in disease trials.
Kempton (1982)	Adjustment for NN competition between rows in sugar beet breeding trials involving small, single-row plots.	Found negative correlations with bias of up to 40 % in some trials. Discussed models for competition effects and serially balanced designs for NN effects.
Kempton & Lockwood (1984)	Analysis of inter-plot competition for field bean varieties using NN serially balanced designs.	Found differential competition effects between varieties in adjacent rows with yields altered by up to 20 % for some neighbouring varieties.
Lill *et al*. (1988)	Simulation study of a nearest neighbour method of analysis.	Study suggested NN methods might be 6–18 % more efficient than an incomplete block analysis
Cullis & Gleeson (1989)	Re-analysis of 1019 variety trials in Australia including 219 lattice designs. For the lattice designs, NN analysis was compared with incomplete block analysis.	Found average NN efficiency of the designs in incomplete blocks was 1·77 compared with an average efficiency of 1·50 for the incomplete block analysis. Authors recommended NN analysis for small-plot field experiments such as variety trials.
Kempton *et al*. (1994)	Analysis of yield variation in 224 UK cereal variety trials including comparison of both one and two-dimensional NN analysis versus incomplete block analysis.	Found one-dimensional NN analysis gave variances 10–20 % smaller than corresponding block analysis but a two-dimensional NN analysis with mean efficiency 1·59, gave little extra efficiency compared with a two-dimensional block analysis with mean efficiency 1·53.
Talbot *et al*. (1995)	Re-analysis of more than 600 UK crop variety trials for assessment of inter-plot competition between varieties.	Found bias due to NN competition that suggested yields of some varieties were biased by as much as 4 %. Suggested minimizing interference in variety trials by restricted randomization to ensure that certain phenotypes were never neighbours.
Ainsley *et al*. (1995)	Simulation study of interference effects between neighbours in field trials.	Found that NN methods may not adjust treatment effects towards their true values in the presence of neighbour interference. Suggested that their results 'cast doubt on the application on NN methods to the analysis of field trial data, at least routinely'.
David *et al*. (1996)	Construction of designs for controlling bias due to inter-plot competition.	Designs constructed by restricted randomizations of alpha lattice type block designs so that adjacent varieties showed similar competition effects.
Solórzano *et al*. (1997)	Examination of the suitability of various designs for disease trials.	Developed designs for reducing inter-plot interference effects in trials involving airborne diseases.
Pearce (1998)	Simulation study of Papadakis method of NN adjustment for fertility effects using randomized designs.	Found the method generally effective but problems occurred with interference and edge effects. Thought that the consequences of interference effects were especially serious when using NN methods.
Watson (2000)	Study of spatial dependence in herbage grass variety trials.	Fitted semi-variograms and used the spatial information to assess optimal incomplete block design sizes and likely efficiency of alpha designs.
Durban *et al*. (2001)	Combined model for adjustment of fertility trend and NN inter-plot competition effects simultaneously using 70 sugar beet variety trials.	Found competition occurred almost as frequently as trend and the combined model resulted in a change to the top yielding variety in 20 of the 70 trials. Ignoring NN effects could 'lead to results that were both biased and inefficient'.
Sarker *et al*. (2001)	Re-analysis of 53 variety trials on lentil comparing a range of incomplete block and NN methods for lattice designs.	Found that a combined lattice and NN analysis gave at least a 1·4 gain in efficiency compared with a 1·2 gain for a lattice block analysis alone. Recommended that 'spatial methods should augment but not replace block design methods'.
Dyke *et al*. (2002)	Comparison of serially balanced and fully systematic designs for disease effects.	Reported that their serially balanced designs were probably optimal for analysis of disease effects.

yield residuals of neighbouring plots. He thought this model more appropriate for spatial effects in a field trial than a randomized blocks model and advocated the use of a systematic rather than a randomized layout. Bartlett (1938) made a theoretical study of the method using data from two completely randomized designs and found that the gain in efficiency could be considerable if there was much correlation between plots and reported that the method 'should be approximately valid and sometimes useful'. However, he thought the method would 'hardly, as Papadakis suggests, affect the design of experiments of the randomized block type'.

A major drawback of spatial methods has always been the computational labour involved in the analysis of the data but the advent of modern computing has effectively removed this obstacle and since about the early 1970s, there has been a considerable upsurge of interest in spatial methods in the *Journal of Agricultural Science*, *Cambridge*. Table 1 shows a summary of all relevant papers concerned with spatial analysis of field trials that have been published in JAS from about 1970 onwards. The issues raised by spatial analysis are complex and controversial and cannot be discussed in detail here but a few comments have been inserted into Table 1 to provide a brief indication of the content of each paper. For a full understanding of the issues involved, the reader should refer directly to the relevant papers.

FUTURE DEVELOPMENTS

Objective statistical methods have been at the heart of effective agricultural research for almost a century and despite the development of powerful new research technologies in agriculture and biology, look set to remain at the heart of crop and field experimentation for the foreseeable future. The design of field experiments is a well-developed technology but one of the few remaining areas not yet, perhaps, fully developed is the use of computer intensive methods at the design stage of experiments. The following suggestions are for areas of research where modern computing power might be used more intensively.

Agricultural experiments are expensive, complicated and difficult to interpret and may run for many years. Under these circumstances, the need for efficient and reliable experimental design is paramount. Modern computing power now makes it possible to carry out computer intensive studies at the design stage of an experiment and it seems likely that there will be much more emphasis in the future on the power of a design to provide required solutions under various assumptions about the plot and treatment models. It seems likely, therefore, that formal power studies of designs will become much more important in the future than they have been in the past.

Although past experience has shown that classical block designs work well in practice, considerable evidence now exists to show that spatial methods can be used to improve the efficiency of crop experiments. It seems likely, therefore, that there will be more emphasis in the future on choosing designs that are spatially efficient. One approach might be to use an efficient incomplete block design but to restrict the randomization to maximize the expected information from a spatial analysis. Development of efficient design for spatial information seems likely to continue in the future but it would be unwise to depart too far from the principle of the blocked and randomized field trial that has worked so well for the last 80 years.

In the past, computer software for design of experiments has usually been licensed and has often required highly specialized programming skills and training. This has meant that much of the complex design theory developed in the past has been unavailable to non-specialists and has been little used. In the future, web-based software to provide expert virtual advice systems on the construction of experimental designs could be used to solve this problem. Such systems would utilize the complex algorithms needed to construct the complex designs needed for efficient experiments but would provide advice through a non-technical interface. Although it is still unclear how best to develop such software, a web-based resource that embodies some of these ideas is currently under development and can be found at: http://biometrics.hri.ac.uk/

Further development of appropriate computer virtual advice software could substantially improve the future application of powerful and efficient experimental designs in crop research.

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