RESOURCE-EFFICIENT EXPERIMENTAL DESIGNS FOR ON-FARM RESEARCH

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Farming systems research and extension, (FSR/E), seeks to identify limitations to food production capabilities in the context of farm family needs and resources. It is assumed (perhaps dangerously) that FSR/E involves the appropriate specialists, integrates the research objectives among these disciplines, and includes farmers both in the research process and in the evaluation of new technologies. Given these assumptions, this paper focuses on some specific tools needed for cropping systems trials on farms. We suggest experimental design criteria needed for on-farm crop research, summarize the utility of four designs commonly used in FSR/E, discuss the applicability of two relatively uncommon designs with potential for on-farm research, (OFR), and suggest some areas for future methodology development.

CRITERIA FOR ON-FARM EXPERIMENTAL DESIGNS

Gomez and Gomez (1984) provide a thorough review of considerations in OFR. This includes the types of data to be collected:

* Physical and biological environment of the farm
* Social and economic data
* Current farmer's practices and their productivity
* Productivity or yield measurements of new technologies
* Data that are expected to help explain the performance of each test factor

We will limit our discussion to experimental designs to optimize the latter two types of data collection.

The type of experimental design chosen should be dictated by the specified objectives of the research and the resources available. Cochran and Cox (1960) provide time-proven guidelines for clarifying the purpose of research prior to designing an experiment. The objectives usually fall into two categories: Treatment effect comparison and response estimation. Treatment effect comparison involves separating significantly different effects or identifying superior technologies, such as comparing the yield potential of a number of genotypes or the effect of various fertilizer amendments on soil test levels. Response estimation seeks to describe functional relationships or trends in response, such as the effect of increasing plant density on number of tillers in a small grain, or the relationship between yield and fertility level.

On-farm research may also be classified as "technology generation" or "pure research" vs. "verification" or "extension" (Gomez and Gomez, 1984; Barker, 1985). However, this distinction is largely a question of the nature of experimental objectives, specification of the level of farmer involment in field operations, how much direct technical supervision is necessary, and how readily transferable or "practical" are the results. A given design, e.g. a randomized complete block design (RCBD), may be utilized either in "research" or "verification" on farms.

There may, in fact, be a continuum of trials intermediate between pure research and pure extension. Given limited time and resources for research, it would be advisable to combine both research and extension objectives in a single trial and/or at a given site. The remainder of this paper considers experimental design objectives on the basis of "treatment effect comparison" vs. "response estimation" rather than "research" vs. "extension".

Given clearly specified research objectives, a second important consideration for OFR is the availability of suitable land and resources. Areas of uniform soil are often limited, particularly in marginal upland areas. Such areas also present transportation difficulties for the research personnel as well as for research supplies, samples for analysis, and communication of analytical results. For example, the Program on Environemtnal Science and Management (PESAM) of the University of the Philippines has outlying research stations in nine regions of the country where upland OFR is conducted. Several of these sites are on different islands, and on a given island, roads to the uplands are usually rough and subject to wash-outs following intense rains. Upland crop production sites, shifting cultivation fields in particular, tend to be small, irregular, and of non-uniform soil. Thus, experimental designs in support of FSR/E in many lesser developed countries must contend with limited land, inadequate transportation, and scarce research resources.

On-farm research in the U.S. and other more developed countries may share soil uniformity and transportation difficulties to some extent, but are more apt to be constrained by limited research funding. Given limited budgets, there is seldom support for on-farm trials comparable to that available for studies on research stations.

Thus, an experimental design for on-farm trials should address the objectives of the research, and consider the limitations in land availability and other experimental resources including supervision. In addition, involvement of farmers in the research process, both during design and assessment, should be emphasized. This is an area where agronomic methods have lagged behind the social and economic sciences in FSR/E, due partly to the difficulty in controlling experimental conditions or specifying farmer input into decision-making as a study factor. As Lightfoot (1983) noted, "Farmers' involvement in these experiments would usually extend only to the lending of land". Farmers' interaction with on-farm researchers is not only a practical means of direct extension of research results, farmers themselves are often very creative innovators. Thus, the criteria for on-farm experimental designs should include:

* Compactness and minimum numbers of observations (plots, experimental units) for meeting objectives
* Simplicity of design, field arrangement, data collection and analysis
* Flexibility in terms of farmer's input and aptness to farmers' conditions

COMMONLY USED EXPERIMENTAL DESIGNS

To date, on-farm cropping systems research has utilized experimental designs practically identical to those used on research stations, the main difference being restricted numbers of treatments and replications. We briefly evaluate four commonly used designs in terms of the criteria listed above. The reader should refer to Cochran and Cox (1960), Gomez and Gomez (1984) or other experimental design texts for full details.

Randomized complete block designs (RCBD) are used for many purposes, and are perhaps the most widespread type of field layout found in either research stations or on-farm trials. Depending upon the treatments specified, the RCBD may be used for either treatment differentiation or response estimation (e.g. a complete factorial arrangment of treatments). A simple RCBD may be quite compact and simple to design, implement, and analyze, and therefore appropriate for on-farm use. However, with increasing complexity of experimental objectives, the number of treatments and size of replications may increase beyond land availability and resource limitations. For example, a complete factorial to study three factors at three levels for response surface estimation would require 3^3, or 27 treatments per replication. If replicated a minimum of two times, one would need 54 plots -- a large number for many on-farm situations, especially if the farmer is expected to administer all treatments.

Split plot designs (SPD) are most useful where interactions between main treatments and sub-treatments are of primary interest. For intance, Barker and Sajise (1985) used a SPD with five cowpea (*Vigna unguiculata*) genotypes as main treatments, and sub-treatments of artificial inoculation vs. no inoculation to evaluate the interaction of the cowpea lines with inoculation in acid soil conditions in a shifting cultivation on-farm trial. Thus, the differentiation of treatment effects and interactions is the usual reason for using the SPD. It would be possible to use the SPD for response estimation since sub-treatments may be a given variable at several levels. However, it is seldom used for response estimation due to the unequal variances of means arising from different plot sizes required by the SPD. The SPD generally requires a more complex analysis than the RCBD.

Lattice designs (LD) facilitate the comparison of a large number of treatments which are assigned to incomplete blocks within replications. Cochran and Cox (1960) present numerous lattice designs, capable of handling up to 144 treatments in uniform blocks of 12 (a 12 x 12 quadruple lattice) as opposed to the 144 uniform experimental units per replication required for the RCBD. While the lattice and other incomplete block designs allow for "compactness" in terms of the area of uniform soil required for blocks, they still require the same total number of experimental units. In addition, they are considerably more complex to design, conduct, and analyze than the RCBD.

Fractional factorial designs (FFD) are used for exploratory estimation of responses and interactions, and are composed of smaller blocks than the full factorial arrangement of treatments in a RCBD. Like the lattice designs, the FFD is advantageous in terms of space saving per block, but still requires a large total number of experimental units. Furthermore, the FFD design and analysis is quite cumbersome, and likely too complex for routine on-farm use.

As the above comments suggest, there is much room for choice of experimental designs for on-farm cropping systems research which will improve their compactness and simplicity. To our knowledge, little statistical methodology development has been done specifically for on-farm cropping systems trials, except that of Gomez and Gomez (1984) which is a modification of the RCBD and complete factorial. Thus, the scientist is obliged to use one of the above designs, trimmed to as few observations as possible to address the research objectives. Two experimental designs which are relatively uncommon, neither of which were developed for OFR, may have utility in certain on-farm situations. A general presentation follows on the construction of augmented and central composite designs, with examples of their use and suggested application to OFR.

"UNUSUAL" DESIGNS WITH POTENTIAL ON-FARM APPLICATION

Augmented designs (AD) were developed by W.T. Federer (Federer, 1956; Federer and Raghavarao, 1975) for use in plant breeding experiments. The basis for this design is a "Standard design plus additional treatments...in the blocks or cells of the design" (Federer, 1956). As originally implemented, the main treatments of the "standard" design were advanced breeding lines or varieties with sufficient seed for replicated trials. The "additional" treatments within each block were breeding lines with sufficient material for only one observation or plot. Thus, an augmented RCBD might include several main treatments (lines) per replication which constitute the "standard" design, with a number of additional treatments (lines) unique to each replication. An example of an augmented RCBD from Federer (1961) is as follows:

Group 1	Group 2	Group 3	Group 4
A	A	A	A
B	B	B	B
C	C	C	C
D	D	D	D
e	h	k	n
f	i	l	o
g	j	m	

where upper case letters represent standard treatments, and lower case letters represent augmented treatments. The augmented design makes it possible to formally evaluate the non-replicated lines (e-o). Federer (1956) outlined the design and analysis of augmented RCBD and latin square designs, including the general analysis of variance and comparison of standard treatment means vs. augmented treatment means as well as comparisons among augmented treatment means. Later papers (Federer, 1961; Federer and Raghavarao, 1975) discuss additional augmented designs, and augmentation in incomplete blocks.

Barker (1985) proposed an on-farm trial using an augmented RCBD to evaluate the productiviy of several forage legumes overseeded into soybeans for fall/winter ground cover and spring green manure. This trial specifies six legume species as standard replicated treatments, and requires that additional legume species of the farmers' choosing be added as augmented treatments. Therein lies the unique contribution of augmented designs to on-farm cropping systems studies -- the flexibility to add farmer-chosen treatments to an on-farm experiment at a given site. The proposed on-farm study with soybean overseeding would be conducted at several sites, each having unique augmented treatments in addition to the standard "core" RCBD treatments. This approach could encompass many experimental objectives in on-farm research, such as tillage methods, fertility amendments, and weed control alternatives. In each case, the primary benefit would be that each cooperating farmer could add innovative treatments into a formal evaluation as part of that site's experiment. Alternatively, augmented treatments could allow rapid screening of additional researcher-specified treatments. The "standard" treatment analyses are readily combined over locations and seasons, and it should be possible to combine augmented treatment analyses over seasons. Thus, the augmented designs provide a unique opportunity to facilitate farmer input and rapid technology screening into on-farm cropping systems research. We suggest that this type of farmer involvement is critical to effective on-farm research with alternative cropping technologies.

Central composite designs (CCD) were developed by Box (1954) and Box and Hunter (1957) to reduce the number of treatment combinations required for response surface estimation. Hader et al. (1957) extended the CCD to agronomic studies, and these authors as well as Cochran and Cox (1960) and Barker (1984) provide more details on the design, layout, and analysis of the CCD. These compact designs facilitate response surface exploration and permit estimation of interaction effects, optimum points, and prediction equations.

The primary benefit of the CCD is in reducing the number of experimental units needed to estimate a second-order response surface polynomial. The estimation of a complex response surface is possible in a small area of uniform experimental material. For example, Barker (1984) used a CCD to study sweet potato and cowpea yield responses to N, P, and K on shifting cultivators' fields. The design required 20 plots, as opposed to 3^3 or 27 plots per replication in a full factorial RCBD. Thus, 108 plots are required for a complete factorial RCBD with four replications to provide the response surface estimation possible from 20 plots in a CCD. Cochran and Cox (1960) provide plans for additional CCD's, including up to six variables, and plans for CCD's in incomplete blocks. Like the lattice and fractional factorial designs, however, the CCD is relatively complex, and its complexity increases when incomplete blocks are utilized.

Compared to other experimental designs used for response estimation, the CCD offers considerable savings in the total number of experimental units required. It shold be possible to combine results of the CCD over locations and over years, but to date little work has been done with applications of the CCD or other response surface methodology designs to field crop studies. (Mead and Pike, 1975).

RESEARCH NEEDS

Currently available experimental designs do not fully meet OFR needs. However, the fact that two designs were identified "off the shelf" and applied to the on-farm setting suggests that practical experimental design development could lead to significant improvement of designs for on-farm research. We suggest methodology development is required in the following areas:

* New designs which better address soil and other variations among experimental units and among farmers, e.g. compact designs which perhaps easily facilitate analysis of covariance
* Response estimation designs which accomodate farmer innovations, such as the augmented design; perhaps an augmented central composite design
* Microcomputer software programs (such as Michigan State's MSTAT) specifically for on-farm situations and LDC applications: these would include:
  1. Software develoment to simplify analysis of presently available designs such as FFD and CCD
  2. Software development to facilitate analysis of results over locations and over years

In addition to the improvement of experimental designs for OFR , innovative approaches to studying cropping systems on farms which could help improve the simplicity, compactness, and farmer involvement in research and extension efforts merit further attention. These include:

* "Overlaying" of treatments on existing fields (Lightfoot, 1983)
* Data collection by farmers for survey/semi-structured field trials without direct researcher supervision (Barker, 1985)
* The efficiency of using various levels of replication depending upon experimental objectives (Gomez and Gomez, 1984, Chapter 16)
* Development of response curves to support computer models which lead to less dependence on complex trials over a large number of sites (Barker and Francis, 1985)
* Evaluation of yield stability and risk in cropping systems in addition to total yields and net returns
* Covariance of yields of two or more crops
* Comparison of cropping systems performance on the basis of total biomass production, total nutritive value, or other absolute criteria rather than relative yields from dissimilar crops
* Comparison of alternative cropping systems where components are dissimilar

CONCLUSIONS

As pointed out by Lightfoot (1983), field plot techniques for farming systems research have largely been "miniturized research station experiments" and have lagged behind socioeconomic methods, particularly in the direct involvement of farmers. While augmented and central composite designs do not completely fill the gaps in needs for on-farm experimental designs, they each provide at least one unique benefit which merits consideration. For treatment comparison trials, the augmented design permits flexibility in involving farmers directly in the definition of treatments. For response estimation experiments, the central composite design offers a dramatic reduction in the number of plots required and therefore a savings in scarce research resources and land suitable for field trials.

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