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Chapter 13

Research Methods for Multiple Cropping

Anne M. Parkhurst
Charles A. Francis

Multiple cropping is both a means of subsistence and a way of life for many limited-resource farmers. Research has been limited to date on the many and complex systems or patterns we call multiple cropping. Experiments have employed classical statistical methodology and time-honored, well-tested experimental designs (Parkhurst and Francis, 1984a). Researchers have tended to use simple designs as in monoculture (Mead and Stern, 1980). Although many underlying biological and mathematical assumptions are likely to apply to more complex systems, the sheer number of factors and interactions make analysis, interpretations, and setting priorities for research much more difficult. This chapter explores the magnitude of the complexity of research questions, and how it is possible to quantify production constraints. Once this is accomplished, priorities must be established in a research program. Some methods are proposed for doing this in a systematic way.

Although it is difficult to manipulate single components of a cropping pattern without affecting many others, an efficient methodology is needed to control most factors in order to study each component of a system. This technology must be evaluated on the farm. Only if the end user is given an opportunity to view and try new alternatives can this research and development cycle be com-

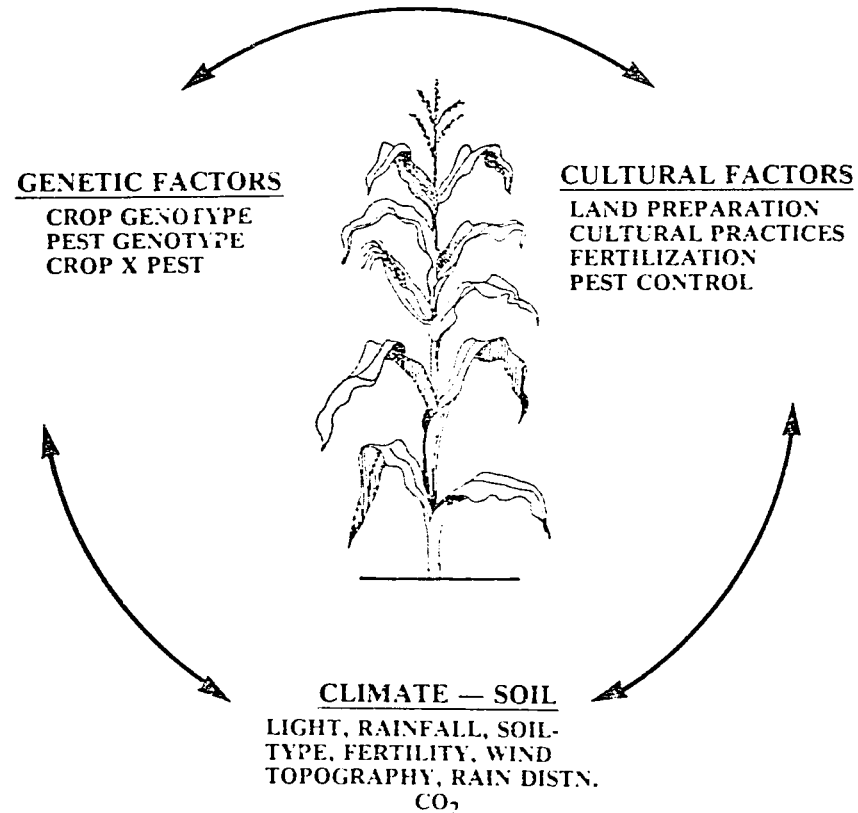
plete. This methodology complements Chap. 14 by Mead, providing a broad framework into which the analyses may be expected to fit.

Central to the theme of the chapter is the assumption that the research job is not finished if the results are not published or put together in some form that will reach the farmer and affect farming success. Whether to increase production, to reduce costs or inputs, or to improve the stability of the cropping pattern, the ultimate objective of research is to improve production practices and produce results that will effect some change on the farm. More specific objectives of research may be appropriate for basic studies or work in other areas of science, but research for complex systems needs to be carefully directed toward solving immediate food production problems and the sustainability of production systems while attempting to improve or regenerate the production resources available to the farmer.

COMPLEXITY OF RESEARCH QUESTIONS

Complex cropping systems that intensify the use of land are important in the agriculture of developing countries. Multiple cropping may take the form of sequential double or triple cropping, or may involve some degree of intercropping, where two or more species are found in the field at the same time. The former, an intensification in time only, is similar to traditional monoculture and presents no unusual design or statistical challenges that cannot be handled with traditional research methodology. Intercropping, on the other hand, represents a degree of complexity that is difficult to handle with the usual application of our current techniques.

This cropping pattern complexity is illustrated in Figs. 13.1 to 13.3, where some of the many possible interactions involved in a two-crop pattern and a three-crop pattern are compared to the better understood monoculture system (adapted from Francis, 1981a). Climatic and soil factors are relatively unaffected in the short run by intercropping, compared to monoculture. There are no doubt some microclimatic changes in humidity, wind speed, and amount of light reaching the soil surface, but these have not been quantified in convincing detail. There may also be longer-term effects on soil organic matter and structure due to the species variety and cropping intensity of intercrop patterns. More apparent differences are found in cultural practices required for these intensive systems and used by farmers, and in the genetic factors which involve not only crop genotypes but also the insects and pathogens that attack each crop. Considering Fig. 13.1, there are 15 major factors listed for the monocrop situation, and thus 105 combinations of two factors that may interact. In Fig. 13.2, a two-crop pattern and simplest of all possible intercrops, the 26 factors (15 from Fig. 13.1 plus an additional 11 factors) listed could combine in 325 possible pairs of factors. Figure 13.3 shows a three-crop pattern with 39 single factors and the resulting 741 possible two-way interactions. The increasing number of possible interactions as the number of single factors increases is illustrated in Fig. 13.4.

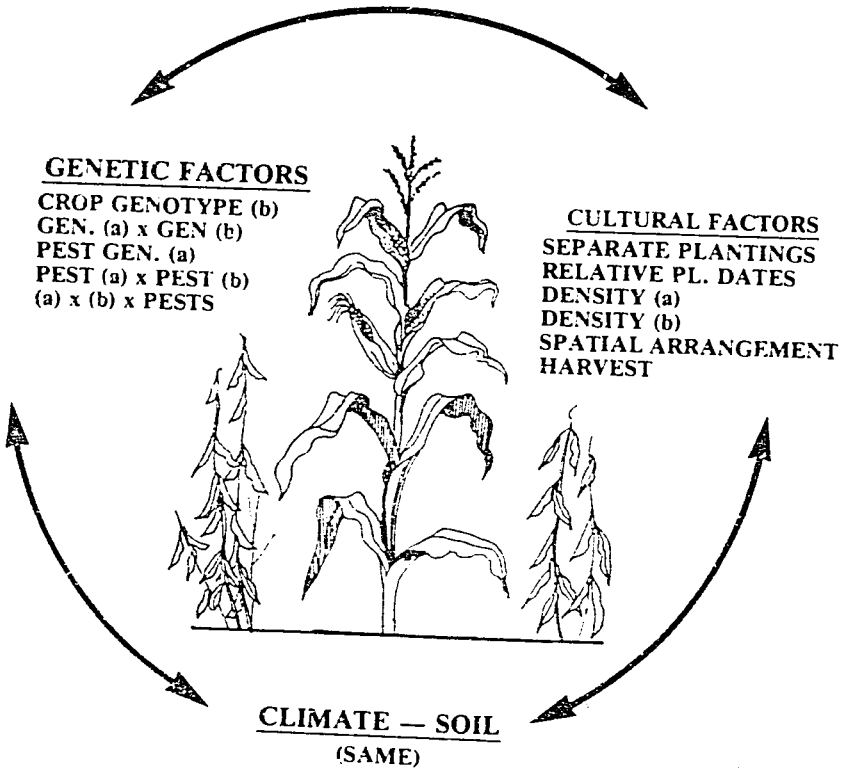


Crop = maize
Total factors = 15
Possible two-way interactions = 105

Figure 13.1 Interactions in a model monoculture cropping system. (Reprinted by permission from *Plant Breeding II*, Kenneth J. Frey, ed., © 1981 by the Iowa State University Press, 2121 South State Ave., Ames, IA 50010.

Although this oversimplifies the comparison between monoculture and intercropping, the figures attempt to quantify to some degree the complexity that must be dealt with in research of these systems.

There is a further degree of complexity found with intercropping patterns when we consider the economic and social situation in which farmers use these systems. Often found on small farms with limited resources, intercrop patterns are used to fill a series of needs for the farmer: food, income, and security. The criteria that the farmer uses to evaluate success or failure also may be different from the purely commercial/economic yardstick used for large farms. Thus, family nutrition, a range of food crops and animal species, stability and distri-



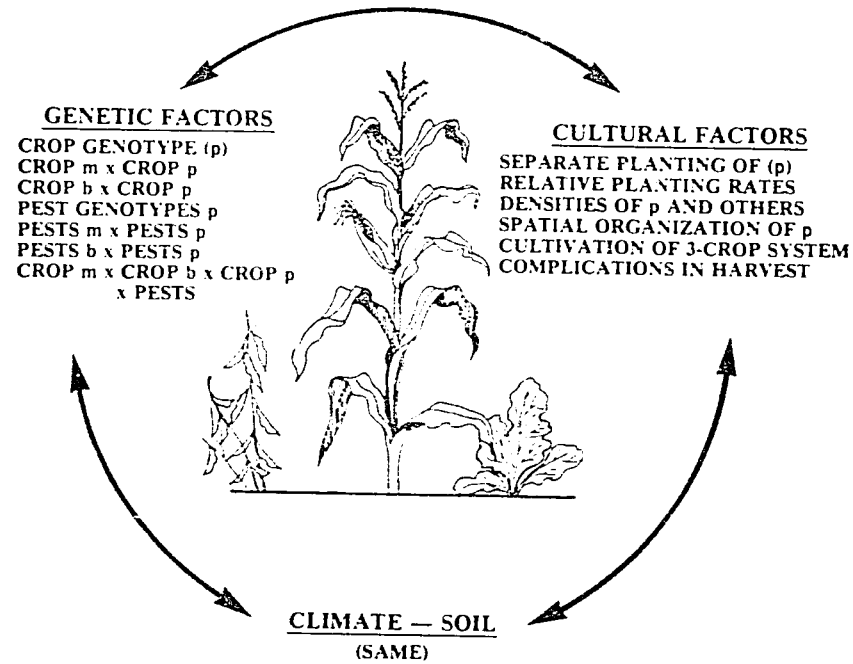
Crop a = maize
Crop b = bean
Total factors = 26
Possible two-way interactions = 325

Figure 13.2 Interactions in a model two-crop pattern, giving those factors in addition to those presented in monocrop in Fig. 13.1. (Reprinted by permission from *Plant Breeding II*, Kenneth J. Frey, ed., © 1981 by the Iowa State University Press, 2121 South State Ave., Ames, IA 50010.)

bution of production through the year, and minimizing risk may all be more important to the farmer than economic return, which is used to evaluate most commercial monocultures (Francis, 1981b; Willey, 1979a, 1979b).

EVALUATION OF CONSTRAINTS TO PRODUCTION

In production research on complex cropping systems, it is particularly difficult to evaluate what factors most constrain production in a given region (Parkhurst and Francis, 1984b). A number of factors complicate this evaluation. It may be



Crop m = maize
Crop b = bean
Crop p = potato
Total factors = 39
Two-way interactions = 741

Figure 13.3 Interactions in a model three-crop pattern, giving those factors in addition to those presented in monocrop (Fig. 13.1) and intercrop (Fig. 13.2).

difficult to examine a crop growing in a mixture with other species and determine immediately if deficiency symptoms or lack of vigor are due to a soil-related problem, shortage of water, or some other type of competition inherent in the system. Since relatively little is known about crop species interactions in these systems, and since most technical agronomists are trained to observe, describe, and research monoculture systems, even the initial evaluation of limitations to production is difficult.

Further complicating the activity is a lack of understanding of the farmer's objectives in growing crops in complex mixtures. The agronomist may be thinking in terms of maximum production, optimum economic return, or how to mechanize a farm to save labor. On the other hand, the farmer may be more concerned about food production for the family, stability of production through the year, how to minimize risk of failure, or how to most profitably employ the family in this enterprise. A specialist who is trained to examine biological,

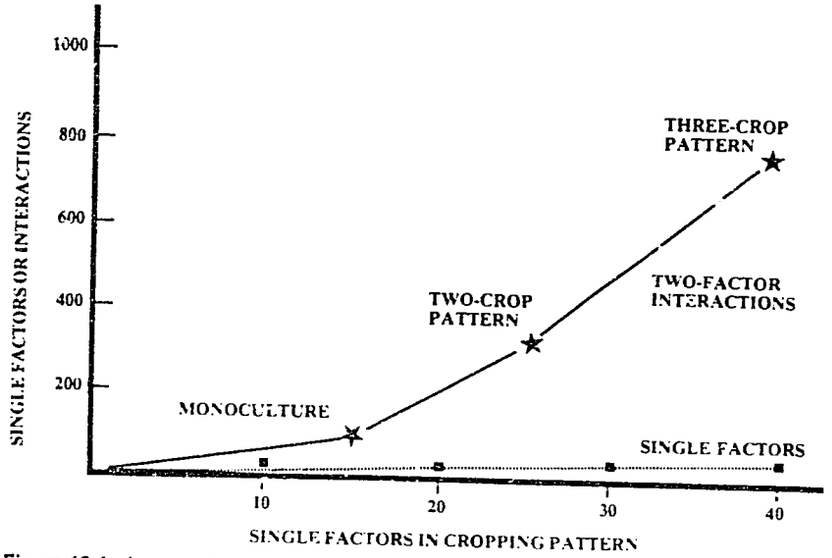


Figure 13.4 Increase in two-factor interactions as a function of increasing number of factors which may vary in cropping patterns.

climatic, or economic constraints in commercial monoculture may be unprepared to use the appropriate yardstick to evaluate an intercrop system. A frequent recommendation by specialists has been to eliminate intercropping completely, and to plant soybeans or maize as a commercial monocrop. This illustrates a lack of understanding by researchers of the farmer's goals and the critical role the complex cropping system plays in the family's survival (Parkhurst and Francis, 1984b).

Problem identification can be as simple as talking to a few established experts in the area and using this conventional wisdom to embark on a research program, or as complex as spending several years talking to farmers and using detailed questionnaires to quantify constraints. Between these two extremes are some alternatives that should be useful to the researcher.

Conventional Wisdom Approach

A method frequently employed to evaluate constraints is the collection of conventional wisdom on what is going on in prevalent cultural systems on the farm. In a semiarid zone, "Everyone knows that water is the most limiting problem!" Therefore, a program is designed to develop drought-tolerant cultivars. Minimum tillage is included in the package to reduce moisture loss and lower crop densities are recommended to make best use of available water. This is illustrated by monoculture sorghum (*Sorghum bicolor*) grown in the western part of Nebraska, an area where rainfall is marginal for sorghum.

Another example is the maize (*Zea mays*)/bean (*Phaseolus vulgaris*) intercrop found in the Andean zone. Conventional wisdom among researchers who

are trained to research and extend monoculture technology may be that pure stands of soybeans (*Glycine max*) are more economically rational than the intercrop system of the farmer. Replicated experiments show that net income is greater from soybeans on the research station than the farmers appear to gain from their intercrop with low inputs. Although counter-intuitive to those who have worked in multiple crop systems, this approach to research may in fact be successful if the problems are the correct ones, and the choice of solutions is appropriate to the problems and to the farmers they are designed to help.

The approach may be to talk to researchers with extensive experience in the zone, to read the literature (if any exists), or to meet with a few key informants who farm or who are familiar with cropping in the area. The limitations of this approach are obvious: the information base is limited to those consulted, and to their biases about what is actually happening in the zone.

The range of options that is suggested to improve current systems also may be limited, since these same sources will have some conventional wisdom ideas about how to solve production constraints. In the sorghum program in Mali, local and international researchers have assumed that water was limiting in a zone where rainfall was between 400 and 700 mm per year. A recent study by a Dutch team showed that nitrogen is often the most limiting factor in any zone with a good distribution of at least 300 mm of rainfall on those soils (Art Onken, personal communication). Thus, research programs designed around moisture as the most limiting factor may have ignored or at least deemphasized the importance of nitrogen in this area. In summary, we cannot afford to ignore ideas of those with experience in a region. It is equally risky to depend on this as the only source of information.

Research and Literature Evaluation

A more comprehensive approach to evaluation of limiting factors includes the above collection of conventional wisdom plus the careful study of research results in the literature of the region and of areas with similar climate and crops. This information may be available in local libraries, in annual reports, in summaries of research that do not have wide circulation, or in the files of other researchers who are active in the area. Although we need to take into account these results and build any new research program on past results rather than start from zero, we must keep in mind that this prior research may have suffered from the same problems outlined above. It is both difficult and necessary to evaluate not only the results but the research questions they were designed to answer and the conclusions that were drawn. What has been the impact of this past research? What were the farmer's reactions to the results, or have results reached the farmer? To the extent possible, the conditions under which research was conducted must be evaluated, and the creditability of the results needs to be considered.

In many situations where intercropping is important, there is a dearth of information from the research stations. Since most emphasis has been placed on plantation crops for export and on commercial monocultures, there may be little

that is helpful on multiple cropping. Nevertheless, there will be data and recommendations on monoculture on some of the same crops that are or might be included in the intercrop, and these data need to be evaluated. For example, genetic resistance to a specific pathogen that causes stalk rot in maize will work equally well in monoculture or in an intensive cropping pattern, even though the incidence and relative importance of stalk rot may be different between the two systems. On the other hand, a specific fertility recommendation for a cereal crop in monoculture may have to be modified drastically to make that recommendation appropriate to a system that mixes the cereal with one or more legume species. These pieces of information have to be sorted out to improve the knowledge base for intercropping.

Observational Experiments on Farms

Another approach to learning about constraints is to plant observational trials. These preliminary experiments both on the experiment station and on the farm can combine careful study of farmer's systems with the introduction and observation of some types of improved technology. This may include some changes in cultural practices identified by either the researcher or the farmer, new crop varieties, some new inputs, or a combination of these (Parkhurst and Francis, 1984b). These types of observational plots bring the researcher into close communication with the farmer, and help to build an appreciation of the farming systems in the area. This approach is being developed under the general umbrella of "farming systems research," although the total activity of FSR is more complex than what is suggested here. Recent publications that detail some of the work done in this area include those by Garrity et al. (1979) and Harwood (1979). The recent book by Gomez and Gomez (1983) and the methodology published by Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) (Byerlee and Collinson, 1980; Perrin et al., 1979) on planning technologies both developed this theme of using farm-generated results for making recommendations.

Detailed Limiting-Factor Surveys

Detailed surveys of crop production on specific crops or on cropping systems can lead to precise definition of constraints, although the cost both in time and resources may be prohibitive. A survey may be as simple as a mail questionnaire, such as that used to evaluate the incidence of the downy mildew disease in the Philippines on maize (Francis, 1967). The results from this survey showed quantitatively that the incidence of the disease was greater in the rainy than in the dry season, and that there was a heavy occurrence in four centers in the country. The data were used to locate screening trials to select for resistance.

A more complex study was done on the factors limiting bean production in three departments in Colombia (Gutierrez et al., 1975). This consisted of visits by trained agronomists to more than 150 farmers during the growing season, with at least three visits to each farm per season. A detailed questionnaire, completed during each visit, gave information on farm size, level of technology, and sociological aspects of the farm environment. It detailed land preparation, planting, protection practices, irrigation (if any), fertilization, other cultural details during the season, harvest and yield data, and disposition of the crop. The analysis of these questionnaires gave a broad look at the problems in bean production in these departments, and provided the basis for evaluation of different research strategies directed toward solving these constraints. Given the costs for doing research, the value of crops harvested, and the financial advantage of controlling one specific problem (e.g., resistance to rust disease), the basis was given for a cost-benefit analysis of different research strategies.

This type of approach is rarely feasible before embarking on a research project. In addition, the evaluation of a multiple cropping system is far more complex than that for a single crop species. Nevertheless, there are some questions and a part of this methodology that could be very useful in an attempt to quantify problems in a multiple cropping system.

These approaches to identification of constraints are not mutually exclusive. There is a need to spend some resources and some time on this evaluation, and a need to bring from each of these approaches any information that can be useful. The time spent on this part of a project usually is minimal, and it would be advisable to err on the side of more time spent evaluating constraints than to follow the time-honored path of conventional wisdom.

ESTABLISHING RESEARCH PRIORITIES

Priorities in research may be established after the constraints outlined above have been carefully and comprehensively evaluated. More often, some abbreviated process is used to quickly arrive at a set of objectives, and the researcher is off at full speed with the program. This is illustrated by the development projects that put a plant breeder and a soil fertility expert in the field to work in their discipline-specific areas, since "everyone knows that new varieties and good fertility recommendations are needed before progress can be made." Several years later, an agronomist and agricultural economist may be called upon to evaluate the results of the work, and may in fact find that neither genetic potential nor soil fertility were and are the most limiting factors. Thus, some careful consideration given to choice of research priorities and design of a research program is essential to ensure that this program will in fact have a payoff in the future.

Some of the factors that need to be integrated into this decision include a comprehensive knowledge of the crops grown and the constraints to their production, the probabilities of solving these problems through research, the chance of adoption of new solutions once they are available, the costs in time and resources of reaching these recommendations, and the total cultural and economic milieu into which the recommendations are to be made. What is the chance for adoption? Do these solutions provide an alternative to solve some problem which is actually perceived by the farmer as a limitation to production? What is the cost of adoption, and what risk is involved? And if the new technology is adopted on a wide scale what will be the effect on total production in the region and on

product prices? These questions are rarely contemplated during the design of a research program.

Priorities often are set according to one or several criteria. Usually they are set by crops, since most research programs in the world are organized by crops and not by cropping systems. This immediately hampers the solution of problems that are complex and involve more than one species. This is both an institutional constraint, since departments, research projects, and budgets are organized along crop and discipline lines, and a barrier confronted by the individual researcher who has been trained to look at one crop at a time. In addition to the focus on single crops, the priorities may be set by geographic area, or areas that are defined by some political boundary such as a state, department, province, or country. These boundaries rarely correspond to any climatic or cropping system region. Priorities may be set by farm size, where large farmers have the economic influence and interest in research to stimulate scale-specific research that is more useful to the large than to the small farm. Research plans frequently are drawn up by one academic discipline, since the departments and budgets are organized this way and since we have learned to communicate best with those who speak the same specific dialect in the technical community. Most of these approaches to setting priorities ignore the need to study several crop species at once, the need to look at integration of disciplines, and the importance of a holistic approach to solving production problems in complex systems. Infrequently, there will be a team or a rare individual who looks at the entire farm and evaluates the limiting factors to production on that farm and how alternative strategies might help the farmer to improve production, food balance for the family, or total income and distribution of that income through the year.

One approach that can be used to quantify priorities is a process that puts the available information into a matrix of (1) limiting factors, (2) probabilities of solving those limitations, (3) importance of each factor vis-à-vis the others, (4) probability of adoption of new technology, and (5) some composite of these data to give a ranking of research priorities. This approach is illustrated with two examples, one for monoculture sorghum (*Sorghum bicolor*) in Nebraska, and another for a maize/bean intercrop in the Andean zone.

Monocrop Example

The simplest case is illustrated with a monoculture crop in the temperate zone. This is done to explain the method by using a crop that has a relatively well-known set of constraints, on which considerable research has been done, and where the probabilities of success of alternative approaches to increase production have been established. An example for sorghum in Nebraska is given in Table 13.1 (adapted from lecture notes of second author). Eight limiting constraints to sorghum production are listed, along with their relative importance in limiting yields of the crop. Next, alternative solutions are presented that appear to be feasible either through plant breeding or agronomy or a combination of the two. In the case of drought, either tolerant hybrids or irrigation could help solve this constraint. The probability of developing more tolerant hybrids is relatively low

Table 13.1 Stepwise Method of Calculating Research Priorities for Sorghum in Nebraska
Numbers Based on Survey of Active Research Workers in State

Limiting factor	Importance of factor,[a] X	Potential solution	Probability of solution, Y[b]	Probability of adoption, Z[c]	Index of priority, XYZ[d]	Order of priority
Drought	9	Tolerant hybrids	0.3	0.9	2.43	2
		Irrigation	1.0	0.1	0.90	10
High temperature	3	Tolerant hybrids	0.4	0.9	1.08	9
		Planting date	0.2	0.3	0.18	14
Low temperature	2	Tolerant hybrids	0.8	0.7	1.12	8
		Planting date	0.5	0.6	0.60	12
Greenbug	6	Chemical treatments	1.0	0.2	1.20	6
		Resistant hybrids	0.8	1.0	4.80	1
Stalk rot	4	Rotation/management	0.7	0.6	1.68	5
		Chemical treatment	0.1	0.1	0.04	16
Fertilizer cost	7	More efficient hybrids	0.3	0.9	1.89	4
		Rotate legumes	0.8	0.4	2.24	3
Chinch bug	3	Resistant hybrids	0.2	0.8	0.48	13
		Chemical treatment	0.8	0.5	1.20	6
Stalk borer	2	Resistant hybrids	0.5	0.6	0.60	11
		Chemical treatment	0.4	0.2	0.16	15

[a]10 = most important, 1 = least important.
[b]Probability based on prior research on this crop and experience with other crops.
[c]Chance of wide adoption of new technology in state.
[d]Product of these three items, to give a weighted priority for each factor.

based on research to date, while the probability of correcting this deficiency with irrigation is high.

The next column lists these probabilities of finding solutions through research. Some types of technology have been successful on this crop or another cereal, and are given a high chance of success. Greenbug (*Schizaphis graminum*) resistance has been found before, and no doubt will be found for new races that emerge. Chemical treatment, if applied in a timely way, can control greenbugs with complete success, just as irrigation can solve the drought problem. At the other extreme, tolerance to high temperature, efficiency of fertilizer use, and resistance to chinch bugs have been difficult research problems and these solutions are less likely

Once these solutions are available, if the research is successful, there is a question of adoption. Any factor that can be incorporated into the seed as a genetic trait, such as greenbug resistance or more efficient use of nitrogen by the crop, has a high probability of success if the farmer in fact perceives this constraint and is willing to buy a hybrid with that characteristic. On the other hand, use of irrigation on a traditionally dryland crop such as sorghum or use of chemicals to control greenbug at a prohibitive cost would have a low probability of adoption.

If these three factors are multiplied,

$$\text{Importance } X \times \text{ probability of solution } Y \times \text{ probability of adoption } Z = \text{ index of priority } XYZ$$

the resulting index of priority gives a quantitative measure of where research emphasis should be placed. Needless to say, the results of this exercise are only as good as the information that is used and the assumptions that go into the determination of probabilities. This is a way to quantify conventional wisdom, or to further process data that comes out of a limiting-factor survey of the type described above for beans.

Intercrop Example

A parallel analysis of priorities for an intercrop situation is presented for a maize/bean cropping pattern in the intermediate elevation in Colombia in the Andean zone. This exercise is more complicated for a number of reasons. First, one needs to deal with two crop species and their associated disease and insect problems. These pest problems not only affect each crop, but the intercrop pattern may influence the severity of each problem and their relative importance may be different between this pattern and the better-studied monoculture. It is more difficult to assess the relative importance of each factor, since these will depend on specific rainfall patterns in the area, number of potential crops per year, and the objectives of the farmer. Even within the same cropping pattern, these objectives may vary depending on the need for maize and for beans, and the orientation toward sale of some excess production of each. Probabilities of solution of the problems can be extrapolated from monoculture experience on

each crop and from past research on this important intercrop pattern, but the probabilities of adoption are less confident.

Table 13.2 lists several constraints that may limit maize/bean production in the area, along with some potential solutions to these problems. Some of the solutions that are obvious to those who have worked in developed countries in the temperate zone (irrigation to avoid drought stress, chemical control of anthracnose disease, purchased chemical fertilizers) are either very expensive or not available to the farmer with limited resources. A number of problems might be solved by use of new varieties or hybrids with disease resistance or different morphology. This is an excellent solution for the farmer who cannot adopt more expensive alternatives, but as shown later this approach does not have the high probability of adoption that the genetic package enjoys in a developed country. The management solutions to several of these constraints are designed to be minimal in cost, but their adoption will depend on how the farmer perceives both the problem and the potential solution, and whether this solution appears to meet one of the objectives of the farmer.

This information is used to calculate a priority index. The importance assigned to each factor is a general value for this intermediate elevation cropping region (1500 to 2200 m above sea level), and the number will vary with specific location, elevation, soil type and fertility, current cropping systems practiced by farmers, varieties, and the level of technology. Probabilities of solution are based on experience with monoculture on the same crops, or on research that has been conducted in the zone (see Parkhurst and Francis, 1984a, 1984b, for references to this research). The adoption probabilities are scale-specific to small and medium sized farms in this area, which are most likely to use the intercrop pattern of maize and beans.

Based on this analysis, the highest priority should be given to breeding for anthracnose resistance in beans. Anthracnose disease is a large problem with the currently used varieties of beans but is likely to be solved by research. The adoption level is high because it is easy to demonstrate the difference between resistant and traditional susceptible varieties in the field, and after a one-time purchase or trade for seed, the farmer can save seed for the next planting.

The next priority is use of manure or compost on maize. The practice would employ materials that are available locally to the farmer and involve family labor, while the other solution, using chemical fertilizer, would be difficult to implement in spite of its high probability of success.

The third priority is to breed maize with a stronger stalk to resist lodging when planted with the beans. This type of goal has been reached before by maize breeders, and the adoption of a new variety or hybrid based on visual comparisons by the farmer should have a high success rate. Lower priority is placed on such changes in technology as irrigation of the intercrop for obvious reasons, and complicated changes in management that require fine tuning a system when the results are not obvious.

This exercise is only as useful as the assumptions made in generating the priority index. Some of the estimates of importance are based on observations

Table 13.2 Stepwise Calculation of Research Priorities for Maize/Bean Cropping Pattern in the Andean Zone at Medium Elevation

Limiting factor	Importance of factor, X	Potential solution	Probability of solution, Y	Probability of adoption, Z	Index of priority, XYZ
Anthracnose (in beans)	9	Resistant variety	0.7	0.8	5.04
		Chemical treatment	1.0	0.1	0.90
Lodging in maize	7	New variety	0.9	0.6	3.78
		Less aggressive bean	0.5	0.2	0.70
Competition in maize	5	Taller variety	0.7	0.5	1.75
		Changed management	0.4	0.3	0.60
Rust (in maize)	3	Resistant variety	0.9	0.3	0.81
		Chemical treatment	0.8	0.1	0.24
Water stress	6	Irrigation	1.0	0	0
		Reduced densities	0.7	0.4	1.68
Fertility (for maize)	8	Chemical fertilizer	1.0	0.2	1.60
		Compost/manure	0.7	0.8	4.48

Note: See Table 13.1 for explanation of numbers.
Source: Data from Parkhurst and Francis, 1984b.

and discussions with farmers, plus experience in research in the zone. Others are based on conventional wisdom. The better the farmers' systems are known, the better these estimates will be. Probabilities of solution of constraints by research are well established, based on previous research on these crops and others in the zone. The probabilities of adoption are less secure, since there is little experience in extension work with intercrop patterns, and it is difficult to extrapolate from experience with large farmers to those with limited land and resources. More important than the absolute numbers given in the example is the approach. With these priorities set for the pattern or patterns of interest, it is possible to proceed with design of research to reach solutions to limiting constraints.

METHODOLOGY FOR COMPONENT RESEARCH

Given the complexity of the questions to be resolved in the experimental search for new components of technology for multiple cropping, a careful evaluation must be made of the methodology available for research. Treatment designs available for this work range from the simplest of single-factor experiments with several levels or varieties, to the most complex complete or incomplete factorial designs (Parkhurst and Francis, 1984b). There is a need for balance between unreplicated observational plantings (to get general ideas about combinations of practices and to bracket treatments of interest) and more detailed and replicated experiments (from which careful analyses can be made of main effects and interactions). The complexity of research and design questions was addressed in a recent paper (Francis, 1983) in which some of the alternative designs were evaluated in a qualitative way. Huxley and Maingu (1978) and Mead and Stern (1980) have proposed use of systematic designs. These options are further described by Mead in Chap. 14.

First, it is necessary to consider the numerous interactions outlined in the figures. The two-crop pattern illustrated in Fig. 13.2 is used as an example. Although there are 325 possible two-way interactions between pairs of factors, some of these are much more likely to occur than others. For example, genotype of bean is more likely to interact with the morphological plant types of associated maize than with topography. Relative planting dates of maize and beans are more apt to interact with weed growth and success of different herbicide mixtures than with the type of land preparation practiced. It is possible to predict from prior experience with monoculture and from limited research on intercrops which of these interactions are most likely to be important, and which are unlikely to affect results. This exercise can greatly simplify the process of experimentation, since the researcher can focus on those main effects and interactions that are most likely to be important in the design of components of new technology. Another useful focus is to concentrate on those factors over which the farmer can exercise some control.

If rainfall is limited in a region, there is little the farmer can do to increase the supply of water to crops if irrigation is impossible. It may be possible for

the farmer to adjust the planting date to take advantage of available rainfall, to choose different crop species or varieties that are more tolerant to drought conditions or that mature more rapidly and thus avoid drought. Thus, the potential adoption of new technology is considered from the very beginning as the researcher evaluates what factors are important in the system and which constraints should be addressed through research.

An Intercrop Example

In this context, a consideration of important interactions is a crucial step. An example of these interactions for a two-crop pattern is given in Fig. 13.5. The eight main effects are described briefly to show why these were chosen out of the 26 factors given in Figs. 13.1 and 13.2, because of their importance as main effects or because of the predicted interactions between pairs or among more of these factors in the intercrop system.

Maize Variety and Bean Variety Choice of crop variety is under direct control of the farmer, and limited-resource farmers often save their own seed from one harvest to the next planting. Conventional wisdom in the international centers and in many national programs is that introduction of new crop varieties can be one of the most cost-effective ways to increase production potential in agriculture. For this reason, there has been an emphasis on plant breeding in the centers. Tolerance to insects and pathogens, drought and other stress conditions, and better nutritional quality can all be built into the genetic package, and this component is one in which research can make a substantial contribution.

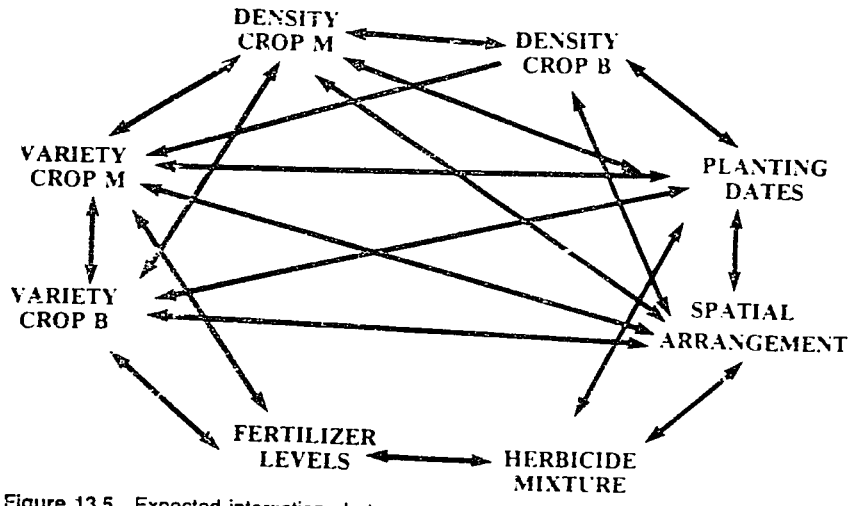


Figure 13.5 Expected interactions between pairs of factors in a two-crop pattern, maize (M) and bean (B).

Fertilizer Levels Fertility often is limiting where intensive cropping is practiced, and a strong emphasis has been placed on fertility trials over the past several decades. The use of soil tests and recommendation of chemical fertilizers has been central to the contributions of the agricultural research establishment. The principal constraint to the farmer of limited resources in adopting this technology has been its cost and the availability of fertilizers in the immediate farm environment.

Herbicide Mixtures Use of chemical weed control in multiple species combinations is both difficult, due to the potential phytotoxicity of compounds on one or more crops, and exciting, in the potentials this offers to the farmer whose crops are reduced in yield by competitive weed growth.

Spatial Arrangement The physical organization of crops in multiple species systems is under direct control of the farmer, and can drastically affect the relative performances of component crops. As new varieties are developed for testing in cropping patterns, alternative arrangements of these crops need to be studied, and these options need to be consistent with the farmer's objectives in planting two or more species in the field.

Planting Dates Relative dates of planting can be varied to favor one component or the other, and to shift both the competitive advantages and the eventual growth and productivity of the crops.

Bean and Maize Density Also important to the relative production levels of the component crops are the densities at which they are planted. This factor also is important in relation to the amount of rainfall available, the types of crops in a mixture, the relative competitiveness of the crops, and the objectives of the farmer.

Choice of these eight factors in the example does not imply that other factors cannot be manipulated by the farmer in the design and choice of a cropping pattern and production strategy. Factors in Fig. 13.5 represent those that have shown importance in experiments and on the farm, and those which have been shown to interact with each other in past experiments. The relative magnitude of these interactions is important to evaluate before considering choice of an experimental design. Again, based on monoculture experience and some research results, these can be compared.

Since it is not feasible to study all interactions simultaneously, it is useful to build a priority index in the manner described above for prioritizing constraints. To get a priority index for interactions, PI_i, each interaction is assigned a probability of existence, $PROB_i$, and rank, RK, according to influence from least (1) to most important (9). The priority index is

$$PI_i = (PROB_i)(RK)$$

Table 13.3 illustrates which of the factors are likely to interact with which other factors ($PROB_e$), and a ranking (RK) is given to the expected importance of the interaction. As shown in Table 13.3, interactions are predicted to be highest between varieties of the two cultivars and bean variety with maize density (rating = 9). Bean variety is expected to interact with relative planting dates and bean density, and maize variety with maize density (rating = 8). Other important though less critical interactions are predicted between varieties and several cultural practices, and between pairs of these cultural practices (ratings = 4 to 7). Other interactions (ratings = 3 or less) are expected to be nonexistent or small enough to be ignored in the research process. This identification of most-probable significant interactions allows the design of an experiment or series of experiments that can explore effectively the main effects of these factors and the interactions that need to be known to design new technology for the farmer.

Research on these factors and their manipulation can confirm the initial predictions and identify which factors are sensitive to changes in cropping pattern and which ones are not. For example, experience and results may show that the

Table 13.3 Probability of Two-Way Interactions, Importance of Interactions, and Priority Indices for Two-Way Interactions for Maize/Bean Intercrop Pattern in the Andean Zone

Factors	Bean var.	Maize var.	Fert. level	Herb. mix	Spatial arrange.	Planting dates	Bean density	Bean density
Bean variety		0.8[a] 9[c]	0.2 3	0.2 5	0.6 4	0.4 8	0.7 8	0.6 9
Maize variety	7.2[c]		0.3 6	0.2 4	0.4 3	0.3 6	0.5 5	0.6 8
Fertility level	0.6	1.8		0.1 5	0.2 3	0.1 2	0.4 4	0.6 4
Herbicide mix	1.0	0.8	0.5		0.5 4	0.6 3	0.3 2	0.4 3
Spatial arrangement	2.4	1.2	0.6	2.0		0.7 7	0.5 6	0.6 4
Planting dates	3.2	1.8	0.2	1.8	4.9		0.6 5	0.7 3
Bean density	5.6	2.5	1.6	0.6	3.0	3.0		0.9 6
Maize density	5.4	4.8	2.4	1.2	2.4	2.1	5.4	

[a]Probability that two-way interaction exists.
[b]Influence ranking: Importance of interaction in intercrop success.
[c]Priority indices for two-way interactions.
Source: Data from Parkhurst and Francis, 1984b.

bean/maize cropping pattern performance is strongly dependent on the plant type of the taller maize component, and thus any new maize suggested for the system must be tested carefully in conjunction with other components of technology to avoid those types that would provide extreme competition for the lower story bean crop. On the other hand, any bean variety will be shaded to some degree by the maize, and if all bean varieties are reduced equally in yield (e.g., no bean variety by cropping pattern interaction) there is limited need to test new bean varieties in combinations with other components. The bean component of the mixture can be changed with a minimum amount of testing. The upper story crop (maize) may be relatively unaffected by weed competition, and thus not interact significantly with herbicide treatment, while the lower story bean crop may be drastically influenced by weed growth and the ability of different herbicide mixtures to control unwanted weeds in the cropping pattern. These types of information will result from the testing of component technology, and will lead to the most efficient possible testing scheme.

In order to design efficient experiments to evaluate these main effects and interactions, the importance of higher-order interactions must be evaluated. If there are three-way, four-way, or other interactions that have been shown in the past to be important, their activity in the field will confound or obscure the main effects or two-way interactions that might be expected to have importance in this bean/maize intercrop pattern (Fig. 13.5). The probability of each three-way interaction and its predicted importance shown in Table 13.4 is multiplied to determine the priority index for research on each factor. The same was done for a few important four-way interactions (Table 13.5). Higher-order interactions were ignored because of the difficulties in visualizing their effects in a practical field setting. Of the 56 possible three-way interactions, there were 11 that had a research priority greater than 1. Of these, 7 included the effect of maize variety, an overriding factor due to differences in plant height and the dominance of this factor in the system. Of the 70 possible four-way interactions, only 6 had a research priority equal to or greater than 1. All these included maize or bean variety, maize or bean density, or both. These interactions are most likely to influence results of studies of main effects and lower-order interactions, and are the ones most logical to include in the first cycle of research.

What are the design options? There is an on-going debate between those who advocate large complex multifactor designs (Mead and Riley, 1981; Mead, Chap. 14) and those who insist on simplicity and designs that study one to three factors at a time (Francis, 1983). In general, the approach using larger complete or incomplete factorial designs may be the appropriate one when there are many interactions of interest and the researcher is anxious to get as much information as efficiently as possible on both main effects and interactions.

To compare three of these options, Table 13.6 shows a situation where eight factors are to be tested: (1) four bean varieties, (2) three maize varieties, (3) six bean density levels, (4) eight maize density levels, (5) three herbicide mixtures (including checks), (6) three fertilizer treatments, (7) four alternative spatial arrangements of the two crops, and (8) three relative planting dates of

Table 13.4 Probability of Three-Way Interactions, Importance of Interactions, and Priority Indices for Three-Way Interaction for Maize/Bean Intercrop Pattern in the Andean Zone

	Var M	Fert.	Herb	Spat.	Pl.Dt.	Dns B	Dns M
Var B × Var M		0.2[a]/2[b]	0.1/3	0.6/5	0.4/5	0.3/4	0.4/5
Var B × Fert	0.4[c]		0.1/1	0.2/2	0.1/3	0.2/2	0.2/2
Var B × Herb	0.3	0.1		0.2/3	0.2/3	0.1/2	0.2/2
Var B × Spat	3.0	0.4	0.6		0.3/2	0.2/3	0.4/3
Var B × Pl.Dt	2.0	0.3	0.6	0.6		0.2/4	0.2/4
Var B × Dns B	1.2	0.4	0.2	0.6	0.8		0.3/3
Var B × Dns M	2.0	0.4	0.4	1.2	0.8	0.9	
Var M × Fert			0.1/3	0.1/3	0.1/2	0.2/3	0.3/4
Var M × Herb		0.3		0.3/3	0.2/3	0.2/2	0.3/3
Var M × Spat		0.3	0.9		0.4/4	0.2/2	0.3/3
Var M × Pl.Dt.		0.2	0.6	1.6		0.2/3	0.3/4
Var M × Dns B		0.6	0.4	0.8	0.6		0.2/3
Var M × Dns M		1.2	0.9	0.9	1.2	0.6	
Fert × Herb				0.1/3	0.2/3	0.2/2	0.2/2
Fert × Spat			0.3		0.3/2	0.2/2	0.2/2
Fert × Pl.Dt			0.6	0.6		0.3/3	0.3/3
Fert × Dns B			0.4	0.4	0.9		0.4/4
Fert × Dns M			0.4	0.4	0.9	1.6	
Herb × Spat					0.3/3	0.2/2	0.2/2
Herb × Pl.Dt.				0.9		0.2/2	0.3/2
Herb × Dns B				0.4	0.4		0.4/3
Herb × Dns M				0.4	0.6	1.2	
Spat × Pl.Dt.						0.2/3	0.3/3
Spat × Dns B					0.6		0.4/3
Spat × Dns M					0.9	1.2	
Pl.Dt. × Dns B							0.3/3
Pl.Dt. × Dns M						0.9	

[a]Probability that three-way interaction exists.
[b]Influence ranking: importance of intersection in intercrop success.
[c]Priority indices for three-way interactions.

Table 13.5 Probability of Four-Way Interactions, Importance of Interactions, and Priority Indices for Four-Way Interaction for Maize/Bean Intercrop Pattern in the Andean Zone

Interaction	Probability of occurrence	Influence ranking	Priority index
Var B × Var M × Dns B × Dns M	0.3	5	1.5
Var B × Var M × Pl.Dt. × Dns M	0.2	5	1.0
Var B × Var M × Spat Arr × Dns M	0.2	5	1.0
Var B × Spat Arr × Pl.Dt. × Dns B	0.3	4	1.2
Var B × Spat Arr × Dns B × Dns M	0.4	3	1.2
Spat Arr × Pl.Dt. × Dns B × Dns M	0.5	2	1.0

Table 13.6 Comparison of Three Designs for Several Levels of Eight Factors in Maize/Bean Intercrop Pattern

Factor	Levels	Factor	Levels
Bean varieties	4	Bean densities	6
Maize varieties	3	Maize densities	8
Fertility levels	3	Spatial arrangement	4
Herbicide mixtures	3	Planting dates	3

Option I: Complete factorial (4 × 3 × 3 × 3 × 6 × 8 × 4 × 3), 2 replications
Treatment combinations: 62,208
Size of experiment: 684,288 m² or 68 ha

Option II: Fractional replication (3^8 factorial, $\frac{1}{3}$ replicate)
Treatment combinations: 6561
Size of experiment: 72,171 m² or 7 ha

Option III: Eight small experiments

1. Maize (2) bean (2) varieties and maize (2) bean (2) densities split-plot with maize variety/density as whole plot treatment combinations and bean variety/density as subplots with whole plots in randomized complete blocks (2 replications), RCB.
   Treatment combinations: 16
2. Bean varieties (2), spatial arrangement (4) and maize (2) bean (2) densities. Factorial treatment design in RCB.
   Treatment combinations: 32
3. Bean varieties (2), densities (3), spatial arrangements (4), and planting dates (3).
   Factorial treatment design in RCB.
   Treatment combinations: 72
4. Maize varieties (2), spatial arrangements (4), and planting dates (3).
   Factorial treatment design in RCB.
   Treatment combinations: 24
5. Maize (3) bean (3) densities and fertility (3), split split plot in RCB with fertilizer as whole plot, maize density as subplot.
   Treatment combinations: 27
6. Variety trial for maize (8) and bean (6), split plot in RCB with maize variety as whole plot and bean variety as subplot.
   Treatment combinations: 48
7. Spatial arrangement (4) and herbicides (3). Factorial treatment combinations in RCB.
   Treatment combinations: 12
8. Maize density (3) and planting date (3). Factorial treatment combinations in RCB.
   Treatment combinations: 9

Total treatment combinations: 240

Size of experiments: 3120 m² or $\frac{1}{3}$ ha with 30 percent borders

Note: Minimum replications: 2. Minimum plot size is 5 m² plus 10 percent borders; option III has 30 percent borders.
Source: Adapted from Parkhurst and Francis, 1984b.

the two components. In option I, when eight factors with these levels are placed in a complete factorial with all combinations, there are 62,208 combinations or 124,416 plots in a two-replication experiment; using 5 m^2 per plot requires an area of 684,228 m^2 including an additional 10 percent for borders. This one experiment covers more than 68 ha, clearly an unmanageable monster of a trial. Option I allows evaluation of all main effects and all interactions.

In option II, a factorial replication with only three levels of each factor reduces treatment combinations to 6561 and total size of a two-replication experiment to about 7 ha. This is still a large experiment; it does allow evaluation of all main effects and interactions, although all specific combinations of varieties are not present. Other types of incomplete factorial designs could be utilized, and each would incur loss of some information. Finally, option III illustrates the use of eight small experiments concentrating on varieties of maize with varieties of bean (number 6), interactions of densities of both crops with varieties (number 1), herbicide mixtures with spatial arrangements (number 7), planting dates with spatial arrangements (number 4), fertilizers with both crop densities (number 5), and other factors that would give information on main effects and the most important interactions, but not all the interactions studied in options I and II. Even with two replications of these experiments, the number of plots is reduced to 240 and the size of the experimental area is only 3120 m^2 with 30 percent added for borders. These are the types of practical trade-offs that the researcher is forced to make.

There are obvious advantages both to the large and to the small experiments. Practical experience in the field has shown that a larger number of small experiments is easier to handle than one or two larger factorial treatment designs. Since operations at planting, data collection time, and harvest are complicated, it is more expeditious to handle each experiment as a unit and complete the field operations in 1 day when possible, then move on to another experiment.

Field Organization

Additional details on the organization of the trials in split-plot designs in the field may be helpful. The typical and logical hierarchy of split-plot assignments is to put the factor of greatest interest in the smallest subplot. For example, a trial may include bean densities, maize densities, bean varieties, and maize varieties, and the researcher attaches the following priorities to these factors: (1) maize densities, (2) bean varieties, (3) maize varieties, and (4) bean densities. The theoretical design approach would place bean densities in main plots, maize varieties in split plots, bean varieties in split split plots, and maize densities in the smallest subunits. The most replication, greatest number of degrees of freedom, and most powerful testing would be directed at maize densities and bean varieties.

In the practical reality of intercropping and field research, there are other concerns that strongly influence organization of treatments. The dominant nature of the maize overstory crop and competitive influence of both maize variety and maize density strongly suggest that these factors be placed in as large a plot as possible. Since the competitive effect of maize variety or density is so much greater than bean variety or density, many plots of the latter can be placed in large plots of the former with a minimal need for border rows. When plot size and border area can be minimized, a given number of treatment combinations can be fit into a smaller experimental area and this is more likely to be uniform with fewer large variations in soil fertility. A number of experiments on bean varieties with maize have been conducted with single row bean plots, since the principal competition is from the maize and there is limited influence of one bean row on the neighboring bean rows.

In the above example, a logical order for the field organization might be (1) maize variety in main plots, (2) maize densities, (3) bean densities, and (4) bean varieties in the smallest subplots. Although the precision of specific comparisons may differ from what was intended by the researcher at the outset, the overall quality of information from the experiment will be higher and the logical arrangements of treatments make this a smaller, more manageable, and more valuable experiment. Other practical considerations on borders needed to separate planting dates or spatial treatments, and minimal plot size needed for fertilizer or herbicide applications, can also influence the field use of designs (Davis et al., 1981). Of interest to the plant breeder is the testing of large numbers of new materials coming from a crossing program. It generally is much more useful to test twice as many new crosses in plots half as large, then to use larger plots (e.g., one-row versus two-row plots), if this plot size is consistant with the levels of differences one wants to detect. These are practical conclusions based on dozens of field experiments on these types of genetic and management factors.

Use of Multiple Environments

In order to move confidently from this first cycle into more refined experiments with fewer factors under study and more precise levels of factors, such as density or fertility, the researcher could make use of either multiple locations or multiple seasons in a single location. If the range of rainfall and temperature fluctuation from one year to another can be approximated by using different locations within a region, it is more time-efficient to work across locations to get information as quickly as possible and move on to subsequent cycles of research and testing on the farm. There are some important trade-offs between years, locations, and replications in experiments. These were evaluated in recent studies on sorghum (Saeed et al., 1984) and on maize (Brakke et al., 1983). Figure 13.6 shows the expected standard error of a sorghum genotype mean when a series of cultivars is tested over a range in environments and over 1, 2, or 3 years (from Saeed et al., 1984). About five environments in 1 year would give the same degree of precision in measuring a genotype mean as 2 years' testing in two environments, and about eight environments give the same precision as 3 years' testing in two environments. Economics of research may dictate multiple years of testing in one site, but the cost is a delay in getting credible results for moving on to another cycle, or a delay in getting results out to farmers. Figure 13.7 shows the improved precision as a result of increasing replications vs. testing over more

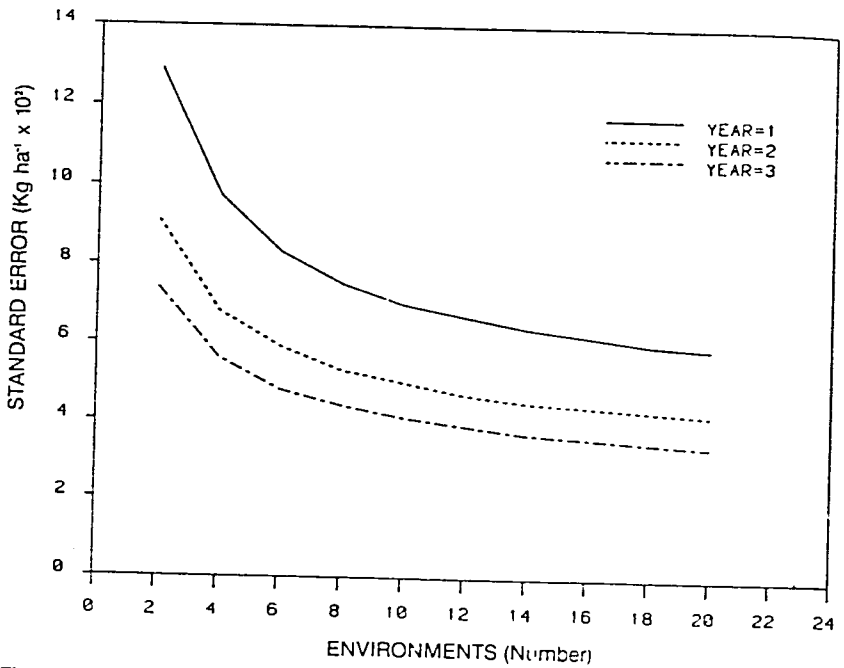


Figure 13.6 Expected standard error of a genotype mean yield for various assumed numbers of years and environments within years when replications = 2. (From Saeed et al., *Agron. J.*, vol. 76, 1984, pp. 55–58. Reprinted by permission of the American Society of Agronomy.)

locations. It is obvious that two replications are desirable to increase precision, allow valid statistical comparison of cultivars, and provide a low-cost method of producing more valid results. However, more than two replications are of limited value, and the advantages of additional locations are clear from the figure. The maize data (from Brakke et al., 1983) demonstrated similar trends. Commercial hybrid maize and sorghum breeders follow a methodology of minimal replication and maximum number of field locations.

Before proceeding to the next cycle, it is assumed that the trials in the first cycle have been run in at least two seasons or years, or that two or more locations have been used as a proxy for seasons to gain reliable results. A minimum of three locations is desirable, since this gives a better measure of treatment by location interaction, and gives an indication of most important trends if at least two of the three locations agree in results. More than two locations provides insurance, since loss of one location would not hold back the program for a season. This information leads to conclusions about interactions and main effects from the experiments outlined above, and lays the foundation for succeeding cycles of experiments.

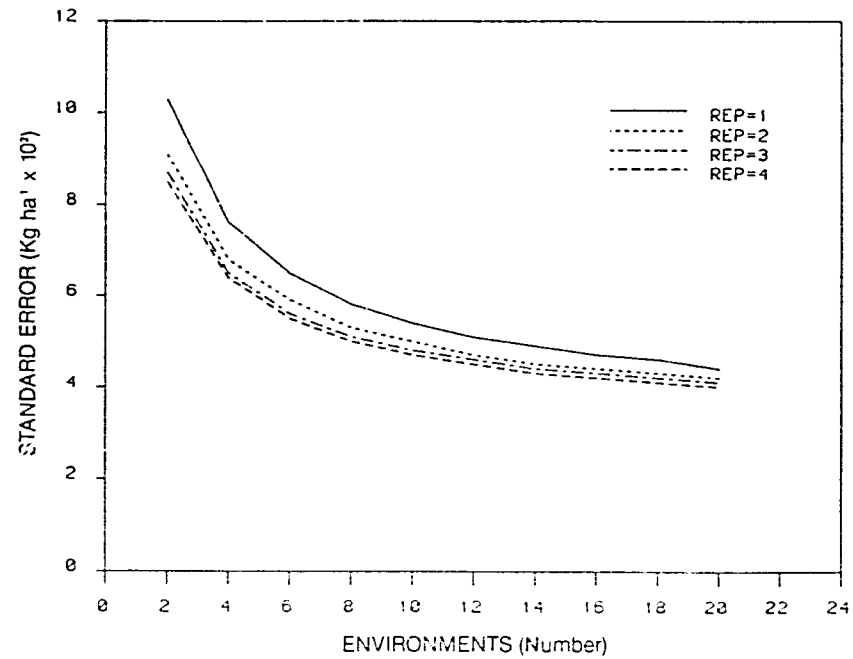


Figure 13.7 Expected standard error of a genotype mean yield for various assumed numbers of replications and environments when years = 2. (From Saeed et al., *Agron J.*, vol. 76, 1984, pp. 55–58. Reprinted by permission of the American Society of Agronomy.)

Large Factorial Designs

More complex designs are recommended by Mead and Stern (1980) to improve efficiency of research. There is no question about the theoretical validity of this approach, and many convincing arguments are presented in Chap. 14. The complications of large factorial designs can be illustrated with two examples from tropical crops research provided by Francis (unpublished data). An experiment in CATIE in Costa Rica was designed to study the main effects and interactions among five crop species and four levels of management. Rice (*Oryza sativa*), dry beans, maize, cassava (*Manihot esculenta*), and sweet potato (*Ipomoea* sp.) were planted in monoculture, in all combinations of two crops, in all combinations of three crops, in all combinations of four crops, and in the five-crop intensive intercrop pattern. Main plots were divided into four levels of management: traditional farmer treatment, use of fertilizer, use of weed control, and use of both fertilizer and weed control. Although only two replications were used, this experiment covered 12 ha (about 30 acres). Obviously, many other cultural practices were held constant to attempt to understand the effects of species, mixture, and management of weeds and fertility.

This massive undertaking was continued over several years, and a few of

the component systems were evaluated, and results were published as graduate student thesis/dissertation studies. The majority of this valuable information has not been published. The magnitude of the experiment, the variability that is introduced by planting over such a large area, and many significant interactions that result in the analysis all make this type of experiment difficult to manage and the data difficult to interpret.

A second example of the massive experiment was a maize study on the north coast of Colombia that was carried out in 1971 and 1972 (Francis, unpublished data). The objective was to assess the potential impact of new technology on maize production by introducing one or more components of a new package for farmers of limited resources. Four levels of fertility, weed control (farmer practice versus herbicide), insect control (none versus insecticide), land preparation (farmer practice versus complete tillage), and maize cultivar (farmer variety versus commercial hybrid) were the five factors included in the study. These were included in all combinations in a factorial treatment design and in a split-plot field design with tillage practices as the main plots and the maize cultivars as the smallest subplots. With the five factors, four replications, and four-row plots that were 10 m long, this experiment occupied about 1 ha in each site. Six agronomists in training with CIAT carried out these experiments on six different farmers' fields, and the results were assembled for analysis in the central facility.

The most positive result of the experiments was the interaction of agronomist with farmer, as both learned about maize through the implementation of the experiment and data collection in the field. The least productive part of the exercise was the analysis and interpretation of the data. Three of the experiments produced insufficient data for useful analysis, and the other three had coefficients of variation that were higher than normally acceptable in maize research. In the analysis, most of the interactions in these three experiments were significant, making any interpretation of the main effects difficult. There was further difficulty in the interpretation of any interaction more complex than the two-way between two factors.

The end result was frustration by the young agronomists over the complexity of the experiments and disbelief by the farmers over the magnitude of the trial and why those young agronomists were so excited about putting so many pretty flags and little white stakes in their fields. It was also a learning experience for those who designed the trials about the value of complexity in farmers' field trials. Our conclusion was that large experiments are not useful for meeting this type of objective. In later trials, we invariably concentrated on two or three factors at the most in order to better understand the complexity of these components as they function in tropical cropping patterns.

Criteria for Evaluation

When analyzing the results of an experiment, decisions must be based on evaluation criteria defined by the farmers' objectives. There are several ways to evaluate cropping systems: by yields of individual component crops, comparisons

to monoculture such as equivalent yields, relative yields, and LER. Examination of these criteria may lead to different conclusions (Parkhurst and Francis, 1984b).

Consider the experiments conducted on maize/bean intercropping systems in Colombia (Francis et al., 1982a, 1982b). Two varieties of beans, bush and climbing, were grown at three common bean densities and intercropped with eight maize densities. The experiments were conducted as split plots with maize density as the whole plot and bean density as the subplot. There were four replications of each whole plot.

Analysis of variance and appropriate F tests were performed for the individual yields, total equivalent yields, and relative yields of maize and beans, as well as for LER. A bivariate analysis (Dear and Mead, 1983) was calculated but discounted, since the correlation between maize and bean yields was inconsistent over treatments. The test of homogeneity of covariance between bush and climbing bean data indicated the two experiments should be analyzed separately.

The effect of maize density was significant in both experiments for all criteria (Table 13.7). The effect of bean density and the maize/bean density interaction was another story. Bean yield and relative bean yield gave results different from the other criteria. For bush beans, there was significant variation in bean densities; for climbers, the maize/bean interaction was significant. Bivariate plots of the yield confirmed the information provided by these criteria.

The important point is that total system yield shows a remarkable compensation in the system. The taller maize crop dominates and tends to offset the effects of the bean crop. This is one facet of the system. However, if the objective is to improve the individual components (a plant breeder's point of view), to ignore individual yields is to miss important information. For this range of bean densities, bean yield increases with increasing density. It is essential to examine the data from all angles of interest in order to reach an understanding of how a multiple cropping system works.

Table 13.7 Probability of Greater F Value from Analysis of Variance of Yield for Maize/Bean Cropping System in Colombia

Source of variation	df	Maize yield	Bean yield	Total equivalent yield	Relative maize yield	Relative bean yield	LER
Bush bean experiment:							
Maize density	6	0.001	0.001	0.001	0.001	0.001	0.001
Bean density	4	0.215	0.001	0.685	0.215	0.001	0.685
Maize × bean density	24	0.928	0.083	0.950	0.928	0.083	0.950
Climbing bean experiment:							
Maize density	6	0.002	0.001	0.010	0.002	0.001	0.010
Bean density	4	0.674	0.831	0.819	0.674	0.831	0.819
Maize × bean density	24	0.326	0.013	0.107	0.326	0.013	0.107

Source. Adapted from Francis et al., 1982a, 1982b.

Even more important to the success of a program is the correspondence of the evaluation criteria in these experiments to the criteria used by farmers to decide whether or not to adopt the new technology. If the researcher is fine-tuning LERs or equivalent yields, while the farmer is more interested in reducing risk, producing a range of crops for the family, or looking at stability of food and income, there is a need for better communication to bring these criteria together (Francis, 1981b). The farming systems approach that involves the farmer from the identification of constraints through the research process to the recommendation of new technologies appears to offer many advantages.

FARM TESTING AND VALIDATION OF TECHNOLOGY

Agricultural research traditionally has been conducted on the experiment station, with a second step of validation or demonstration on the farm. Where conditions on the experiment station—resource base, land quality, soil fertility, type of cropping system, and level of technology—are similar to those on farmers fields, this scheme of testing will produce credible results for farmers. This pattern of research has prevailed in temperate and developed countries, and has proven successful there. When there is a large difference between conditions on the farm and on the station, as commonly found in developing countries, this system may break down. If the experiment station research is conducted under mechanized, irrigated, pest-protected conditions, this may be very different from farms nearby where hand labor is used for tillage, farmers depend on natural rainfall, and pest problems (including weeds, insects, and plant pathogens) are severe. Under these conditions, it is important to question the conventional wisdom of doing a large amount of research and testing on the station before moving out to farmers' fields.

This concern has led researchers to greater emphasis on testing under farmers' conditions. There have been methodologies proposed by CIMMYT in Mexico and in Kenya on using research station data to make recommendations to farmers (Perrin et al., 1979; Byerlee and Collinson, 1980). Their training program has emphasized the use of on-farm trials to test components of technology under real-world conditions so that new practices will have a realistic test before any firm recommendations are organized for the farmer. These trials have assumed different forms, with some organized and carried out entirely by researchers, some done entirely by farmers, and others executed in a cooperative way. This last approach has been called the participatory model, and is being widely used in some projects and labeled "farming systems research" (Gilbert et al., 1980). Important applications have been developed and tested in Guatemala (Hildebrand, 1979).

The farming systems approach to research involves farmers in the identification of problems, the design of potential solutions, and the research carried out on farm to test alternatives and evaluate their potential to increase production. Exciting applications of this methodology are taking place in Botswana (Norman et al., 1983). This process is attractive because of the direct involvement of the farmer in all stages of the research process, and because it will help the researcher to anticipate potential problems with the adoption of new technology once it is ready. This process is a cyclical one, starting with the identification of limiting factors to production, and the design of research to solve those problems. Research may be conducted either on station or on farm or both, and the results are discussed with the farmer to determine their potential applications. Validation of results on the farm is conducted in a cooperative way, and if the package or component is successful, there is no difficulty in extension of results in that immediate area. After the new practice or package of practices is introduced into the system, an evaluation is made of the impact of this new technology, and new constraints are identified for further research. This collaborative model with farmer participation is becoming more popular in developing country research projects.

The analysis of data is complicated when research is conducted on farmers' fields under a wide range of conditions. One approach has been to use unreplicated observational plots on each farm, and to analyze these across farms confounding farm (location) with replication. Although this is valid statistically, there often are so many confounded factors with location and the error terms are so large that it is difficult to interpret data and distinguish between treatment effects. For this reason, a joint approach with some station trials including replication and researcher control and some on-farm counterpart trials for study of applications can be an efficient method. It is important to decide which of the many possible treatments of interest have potential to solve production-limiting constraints before moving to the farm. Otherwise, it would be physically impossible to conduct meaningful observational trials on the farm. The intermediate approach, using replicated trials on farms with some participation of the farmer, is another way to get both real world conditions for the trial and enough control to get meaningful data. There is yet much to be done in designing and implementing meaningful research that relates work on the stations to real problems on the farm.

There is concern in the research community that the job is not finished until results have reached the farm and there is some evaluation of what has happened as a result of the introduction of new technology. In order to measure impact of a change in technology, it is necessary to know current production levels or income before the introduction of something new. If there is a careful survey of farming practices and problems in the current production systems, as outlined in the section on problem identification and priorities for research, this will help to establish a baseline for a given region, crop, or production system. If only conventional wisdom is used to determine what problems should have priority in research, there is less chance that this baseline will be available. Again, the farmer can participate in the process of identifying current production levels and problems. This is the best way to involve the primary producer in the total effort, and will help to ensure that research is correctly oriented to real problems in the zone.

The setting of baseline levels for production also ensures that there will be

something against which to measure the impact of the new technology. An important part of this process is to correctly identify the objectives of the farmer. The commonly accepted goals of maximum production and net profit that are used in most developed countries may not apply to farmers with limited resources. Among the criteria that a small farmer may use to evaluate success in the system are production of a range of crop and animal products for consumption by the family, stability of production and income, distribution of this production and income through the year, minimal costs of inputs to adopt the new technology, and minimal risk associated with a conversion from traditional practices to the new methods (Francis, 1981b). These factors are difficult to measure, and are outside the competence and appreciation of most scientists trained in agriculture, especially agronomy and animal science.

The creation of interdisciplinary teams for this type of assessment is becoming more commonplace. The inclusion of rural sociologists and agricultural economists on teams that formerly were made up entirely of agronomists is a welcome step in the right direction. With the correct training and orientation in the field, this type of biological/social science team can make considerable progress identifying the cultural and social aspects of a farming system as well as the biological constraints to production. Some of these factors can be quantified, and some have to be evaluated on a more qualitative basis. The input of social sciences to agricultural development as part of this complex evaluation of impact is important in measuring the effects of new technology, and in the design of research systems for solving further constraints to production (see Chap. 12).

The view for the future looks promising. On-farm research in an untapped area with limited prior work. As information systems and agricultural computer networks become more commonplace, it will become possible to have a network of on-farm experiments augmented by experiment station research. In addition more thought needs to be given to the trade-offs between replicating results over years vs. locations. Simulations based on environmental parameters tempered with records of time-series data can provide insight into this problem.

Another area of great potential is the application of multiobjective programming techniques to multiple cropping research methodology. A hierarchy of research objectives, such as economic, technical, and social goals, can be formulated along with associated resource requirements (growing degree days, energy, rainfall limitations). A "best" strategy can be identified and limiting conditions under which the strategy will remain best can be established. Researchers would then have a systematic way of controlling the decision-making process.

REFERENCES

Brakke, J. P., Francis, C. A., Saeed, M., Youngquist, W. C., and Nelson, L. A. 1983. Efficiency of testing maize in different environments and cultural systems. *Agron. Abstr.*, 1983, p. 42.

Byerlee, D., and Collinson, M. 1980. *Planning Technologies Appropriate to Farmers: Concepts and Procedures*. CIMMYT Economics Program, Mexico.

Davis, J. H. C., Amezquita, M. C., and Muñoz, J. E. 1981. Border effects and optimum plot sizes for climbing beans (*Phaseolus vulgaris*) and maize in association and monoculture. *Exp. Agric.* 17:127–135.

Dear, K. B. G., and Mead, R. 1983. The use of bivariate analysis techniques for the presentation, analysis and interpretation of data. *Statistics in Intercropping*. Tech. Rep. 1, Dep. Applied Statistics, University of Reading, Reading, U.K.

Francis, C. A. 1967. *Downey Mildew Disease of Maize in the Philippines*. M.S. thesis, Cornell University, Ithaca, New York.

———. 1981a. Development of plant genotypes for multiple cropping systems, in: *Plant Breeding Symposium II*, Chap. 7, (K. J. Frey, ed.). Iowa State University Press, Ames, Iowa.

———. 1981b. Rationality of farming systems practiced by small farmers, in: *KSU Symposium on Small Farms in a Changing World—Prospects for the Eighties*. Kansas State University, Manhattan, Kansas.

———. 1983. Research methodology for intercropping experiments. *Agron. Abstr.*, 1983, p. 44.

———. 1985. Variety development for multiple cropping systems, in: *CRC Critical Reviews in Plant Science*. CRC Press, Boca Raton, Florida, 3:133–168.

Francis, C. A., Prager, M., and Tejada, G. 1982a. Density interactions in tropical intercropping. I. Maize (*Zea mays* L.) and climbing beans (*Phaseolus vulgaris* L.). *Field Crops Res.* 5:163–176.

———. 1982b. Density interactions in tropical intercropping. II. Maize (*Zea mays* L.) and bush beans (*Phaseolus vulgaris* L.). *Field Crops Res.* 5:253–264.

Garrity, D. P., Harwood, R. R., Zandstra, H. G., and Price, E. C. 1979. *Determining Superior Cropping Patterns for Small Farms in a Dryland Rice Environment: Test of a Methodology*. International Rice Research Institute (IRRI), Los Baños, Philippines.

Gilbert, E. H., Norman, D. W., and Winch, F. E. 1980. Farming systems research: a critical appraisal. *MSU Rural Devel. Papers* 6.

Gomez, A. A., and Gomez, K. A. 1983. *Multiple Cropping in the Humid Tropics of Asia*. IDRC, Ottawa, Canada, IDRC-176e.

Gutierrez, U., Infante, M., and Pinchinat, A. 1975. *Situación del cultivo de frijol en America Latina*, in: Boletín Informe ES-19, Centro International de Agricultura Tropical (CIAT), Cali, Colombia.

Harwood, R. R. 1979. *Small Farm Development: Understanding and Improving Farming Systems in the Humid Tropics*. Westview Press, Boulder, Colorado.

Hildebrand, P. E. 1979. Generating technology for traditional farmers—the Guatemalan experience. *Symposium on Socio-Economic Constraints to Crop Protection*. IX Intl. Congress of Plant Protection, Washington, D.C.

Huxley, P. A., and Maingu, Z. 1978. Use of a systematic spacing design as an aid to the study of intercropping: Some general considerations. *Exp. Agric.* 14:49–56.

Mead, R., and Riley, J. 1981. A review of statistical ideas relevant to intercropping research. *J. Roy. Stat. Soc. A* 144:462–509.

Mead, R., and Stern, R. D. 1980. Designing experiments for intercropping research. *Exp. Agric.* 16:329–341.

Norman, D. W., Modiakgotla, E., Seibert, J., and Tjirongo, M. 1983. Helping the limited resource farmer through the farming systems approach to research. *Culture Agric.* 19:1–8.

Parkhurst, A. M., and Francis, C. A. 1984a. Time-honored experimental designs and complex cropping systems, in: *Proc. 144th Ann. Meeting Amer. Stat. Assoc.*, Philadelphia, Pennsylvania, p. 81.

———. 1984b. Research methodology and analysis for complex cropping systems, in: *Proc. Int. Biometrics Conf.*, Tokyo, pp. 100–109.

Perrin, R. K., Winkleman, D. L. Moscardi, E. R., and Anderson, J. R. 1979. *From Agronomic Data to Farmer Recommendations: an Economics Training Manual*, CIMMYT Information Bull. 27, Mexico City, Mexico.

Saeed, M., Francis, C. A., and Rajewski, J. F. 1984. Maturity effects on genotype x environment interactions in grain sorghum, *Agron. J.* 76:55–58.

Willey, R. 1979a. Intercropping—its importance and research needs. Part 1. Competition and yield advantages, *Field Crop Abstr.* 32:1–10.

———. 1979b. Intercropping—its importance and research needs. Part 2. Agronomy and research approaches, *Field Crop Abstr.* 32:73–85.

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