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RISK AND UNCERTAINTY AS FACTORS IN CROP IMPROVEMENT RESEARCH[1]

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RISK AND UNCERTAINTY AS FACTORS IN CROP IMPROVEMENT RESEARCH

Much of the literature on risk and uncertainty in agriculture is focused principally on the behavior of farm producers in the light of the variability of natural and market events. This paper, in contrast, is concerned with the organization, operation, and productivity of a crop improvement system in the light of environmental variability. The word *environment* has come into common use in the last decade. Its misuse has also increased. Perhaps the most common misuse is equating environment with climate. For a general treatment of the "environmental complex," see Billings (1952). An abbreviated treatment of environmental elements appears in Herdt and Barker (1977).

Crop improvement activities respond to and partly determine the consequences of environmental uncertainty. That is, the degree of uncertainty in the natural environment and the response of producers to that uncertainty guide the research directed toward developing improved crop varieties and related agronomic and economic practices. And the existing technology partially determines the economic instability associated with variability in natural environmental factors. We briefly review the relevant concepts of environment, stability, and adaptability, and outline some economic principles for crop improvement and the implications of environmental variability for crop improvement in the light of the kinds of environmental variability that appear to exist. Finally, we review some techniques for evaluating multilocation genetic trials and present the results of some of our own efforts to evaluate recent international rice yield trials.

ENVIRONMENTAL FACTORS IN CROP IMPROVEMENT RESEARCH

Crop improvement activities would be immensely simplified if there were no *genotype-environment interactions*, which cause a genotype (or variety) to perform differently in different environments. *Genotype-environment interactions* could be termed phenotype-environment interactions. The crop's genotype is its true genetic attributes, while its phenotype is its revealed characteristics, which are affected by the environment. The genotype is by definition fixed. We use genotype here because it is possible to view the phenotype as the sum of genotype components, an environmental component, and an interaction effect.

Each genotype attains its maximum biological performance in a particular environment. As environmental elements depart from the state that is biologically optimal for a given genotype, negative genotype-environment

interactions reduce performance. Because the nature of this reduction in one genotype differs from that in another, it is possible to develop genotypes suited or "tailored" for different environments.

A new crop variety tailored for a given environment will be superior to existing crop varieties only over a limited range of similar *neighboring* environments. This range of neighboring environments will be quite narrow if few resources are directed toward crop improvement for neighboring environments, and will be broader if many resources are devoted to crop improvement for different environments.

Environments can most conveniently be defined in terms of their separate elements. Among the more important environmental elements are soil and topography, which are fixed within an area but highly variable between areas. From time to time, climatic and biotic elements vary both across areas and within areas. Economic and social elements affect the economic performance of genotypes; they vary among locations, seasons, and years. These various elements all affect the degree to which genotypes perform well over a range of environments.

One issue facing a crop improvement system is how to determine the optimal allocation of resources between tailoring genotypes to given environments and designing genotypes well adapted to a wide range of environments (wide adaptability). Environmental variability over time within a location is a problem that confronts producers, while environmental variability across locations does not cause risk or uncertainty to producers, but has implications for crop improvement research. One conceives the problem as being more complex when one recognizes that a crop improvement system comprises institutions at the international, regional, national, provincial, and even local level.

Tolerance, adaptability, and stability

The concept of tolerance used by plant geographers to explain plant movement and migration is relevant to the problem of developing well-adapted genotypes. Good's tolerance theory states that "each and every plant species is able to exist and reproduce successfully only within a definite range of environmental conditions" (Wilsie, 1962). Shelford's earlier general law of tolerance included observations on the relationship of plant performance to environmental variability (Wilsie, 1962). The concept of tolerance is schematically represented in Figure 1, where performance of alternative genotypes A, B, and C are related to one environmental factor, temperature. The figure shows that tolerance is not a constant trait, but a characteristic for which plant breeders can systematically search in their research programs.

In the modern literature, the concept of tolerance has been replaced by the related concepts of stability and adaptability. *Stability*, as used in this paper, refers to the performance of a genotype with respect to changing environmental factors over time within a given location. The more stable a variety, the less sensitive its performance is to environmental changes within a location. *Adaptability* refers to the performance of a genotype with respect to environmental factors that change across locations.

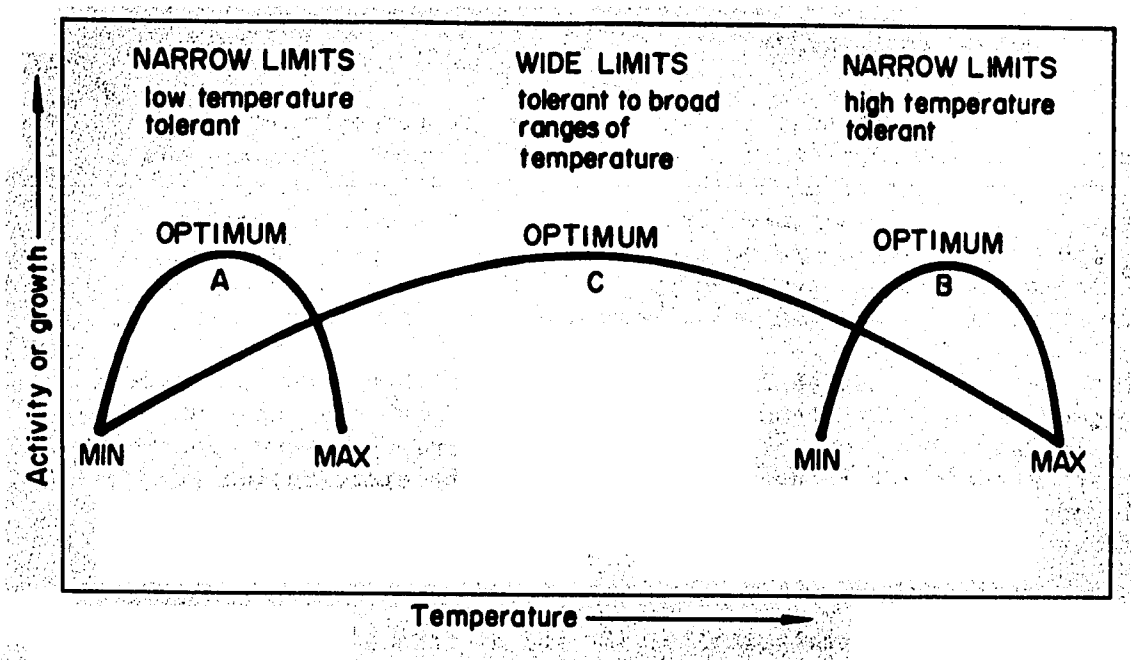

Fig. 1. Comparison of organisms with narrow limits to low and to high temperature with those having broad limits of tolerance. (Source: Wilsie, 1962.)

Existing literature on the measurement of stability and adaptability does not make a clear distinction between the two concepts (Finlay and Wilkenson, 1963; Eberhart and Russell, 1966; Goldsworthy, 1974; Laing and Fischer, 1973). In fact, there is a presumption in much of the literature that adaptability and stability are highly correlated. We provide some evidence that they may not be. This evidence is important to crop improvement strategies because these traits are subject to selection by plant breeders. The breeder can achieve higher stability or wider adaptability usually by sacrificing other traits. This selection process, then, is the primary means by which crop improvement programs respond to risk and uncertainty.

OPTIMIZING PRINCIPLES IN CROP IMPROVEMENT RESEARCH

Crop improvement research entails the improvement of genotypes, agronomic practices, and the economizing behavior of farmers. Genotype improvement can be accorded to a primary role since when new genotypes are developed, they provide scope for improvements in agronomic and economic or managerial practices. Accordingly, we give genotype improvement the primary focus of optimal crop improvement system organization vis-a-vis environmental factors.

We develop a conceptual framework that has implications for selection for genotype stability and adaptability to uncertain environmental changes affecting producers. Research to improve agronomic techniques and economizing techniques may be guided by similar considerations.

The search principle in research

Consider a set of research activities to improve the genotype of a particular crop in the context of a search model. Suppose the crop has only one important trait of economic value, say yield per hectare. Suppose that a group of plant breeders, with a given stock of genetic materials and a given set of methods and resources for screening and testing, attempt to produce new genotypes that are economically better than those existing. Also, initially assume only one environment.

The problem can then be set up as follows: the plant breeders search from a distribution of potential genotypes for genotypes that are superior to those existing. The stock of genetic materials and the known breeding and screening methods determine the parameters of the distribution of potential genotypes. The breeders determine the number of crosses and the volume of material screened. This now becomes a *statistics of extreme* problem.

To illustrate the problem analytically, let the distribution searched be the simple exponential, with mean θ,

$$F(x) = \lambda e^{-(x-\theta)}, \quad \theta < x \tag{1}$$

For this distribution, the expected value of the maximum x, denoted as Z, in a sample of n searches or observations is

$$E_n(Z) = \theta + \frac{1}{\lambda} \sum_{i=1}^{n} \frac{1}{i} \tag{2}$$

One can readily see that the expected value of x rises with n, but at a diminishing rate. That is, there are diminishing returns to search. This property of diminishing returns holds for virtually all distributional forms. Where that is not true, the Cauchy distributions represent distributional forms. Evenson and Kislev (1975) and Kislev and Rabiner (1976) discuss more completely the application of search models to research processes.

If the current technological level or best genotype is Y, the expected technological change ΔY, as a function of n is

$$E_n(\Delta Y) = \theta + \frac{1}{\lambda} \sum_{i=1}^{n} \frac{1}{i} - Y \tag{3}$$

$E_n(\Delta Y)$ increases (at a diminishing rate) as n increases, but decreases as Y increases. This can also be expressed as

$$E_n(\Delta Y) = \int_Y^{\theta} [1 - (F(Z)^n] \, dZ$$

where $F(Z)$ is the cumulative probability distribution of X.

Figure 2 illustrates the relationship between θ, Y, and ΔY for the exponential distribution. As Y shifts to the right, it becomes progressively more difficult to discover improvements, ΔY. The optimal n in any given time period is that n in which the (diminishing) marginal product of search is equal to the (rising) marginal cost of search.

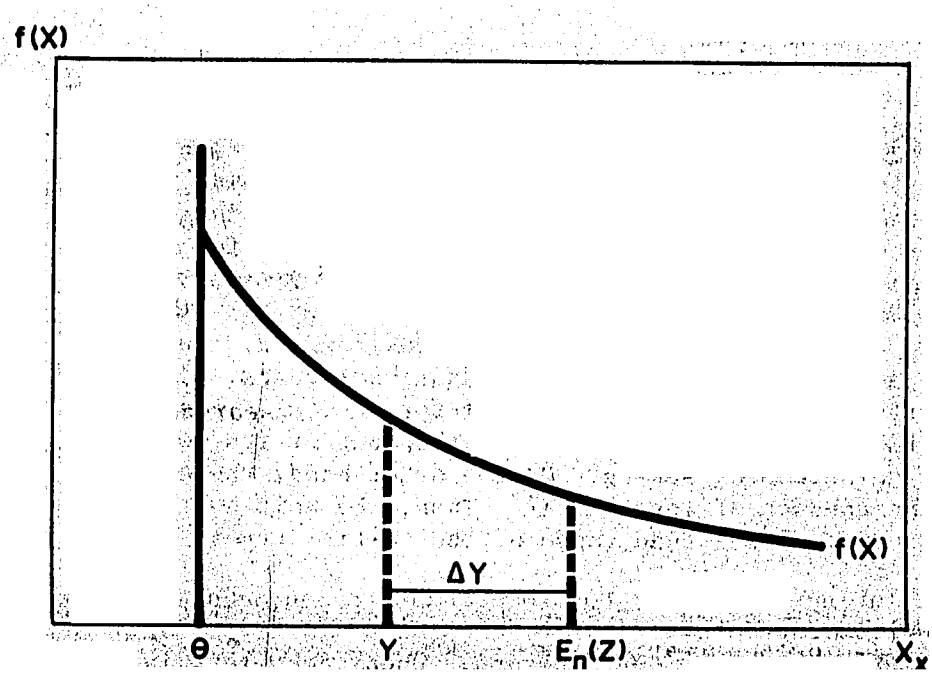

Fig. 2. The probability of discovering improved genotypes for a given distribution of potential genotypes.

This formulation indicates first that: the difficulty of finding better genotypes may be represented by $(Y - \theta)$, which is the gap between the best genotypes Y and the mean of the existing distribution (θ). The smaller the difference $(Y - \theta)$, the larger the technological gap and the more fruitful is search. Second, as search continues, Y is shifted to the right, the technological gap closes, and the scope for improvement decreases (the potential of the technology is exhausted). If the distribution searched is not altered, the marginal cost of research will eventually exceed its marginal return. Third, the greater the variance of the distribution of potential genotypes (holding the mean content), the higher the productivity of plant breeding research. Similarly, the higher the mean of the distribution of potential genotypes, the higher the productivity of plant breeding research.

One important implication from this model is obtained by considering how the mean and variance of the distribution of potential genotypes can be changed. That can be done by incorporating new genetic material into the research system, by developing more precise screening and testing procedures, and by developing new methods of research. As the model is expanded to consider several traits, such as disease and insect resistance,

fertilizer responsiveness, and response to photoperiod, the roles of such related sciences as entomology, physiology, and soil chemistry become clearer. Work in these areas changes the distribution of potential genotypes and therefore is productive even though it does not produce new genotypes directly.

Effect of environmental variation

We now introduce alternative crop production environments to deal with the basic issues of stability and adaptability. Suppose that the research system is producing genotypes for several locations, each of which may have several environmental states. Should the research system *target* its genotypes for one environment or for many environments; if for many, how many? If there were not added costs to producing more genotypes, the solution to the problem faced by the crop improvement system would be simple: to produce a genotype for every type of environment. But the number of genotypes cannot be expanded without additional costs. It costs more to organize a crossing and screening program for several types than for one type. Each type may require the development of its own kind of field trial and screening set-up. On the other hand, there are scale economies to the conduct of research.1/ Thus, the unit costs of additional genotypes may be lower than those of the initial types.

The benefits from tailoring technology to produce more types occur because negative genotype-environment interactions reduce the productivity of research outside its primary target environments. When technology is perfectly tailored to each environment, such negative interactions are minimized. But tailoring is unlikely to be optimal except in cases where the technology *potential* is almost completely *exhausted*.2/

Suppose that there are e discrete environments. Define a set of weights, W_e, to be the shares of total crop area in each environment. Then

$$V = \sum_{e=1}^{T} W_e E_n (\Delta Y_e) - C_n \quad (T) \qquad (4)$$

expresses the total expected value of the improved technology less the total costs (including social costs) during a particular period. The research system can attempt to maximize this expression by varying

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1/ In spite of scale economies, few research systems are capable of producing more than a few types. Even large systems would find it costly to produce, say, 15 types.

2/ This is due to the search process. The payoff to tailoring may be low relative to the payoff to improving on tailored material in the early stages of search. But as diminishing returns to this process set in, tailoring becomes more attractive. The history of sugarcane improvement shows a clearer pattern of just achieving basic gains, than of tailoring the high yielding material to environmental niches. Similarly, the high yielding rice and wheat varieties are now being tailored.

the intensity of research activity for a given type of environment, and T, the number of types of environments for which genotypes are targeted. More appropriately, the present value of a stream of V's over time should be maximized, and in each period, n and T should be chosen so that the present marginal value of the expected yield increase in each type should be equal to the present value of marginal costs for the entire system. These costs are a function of both n and T.

The choice of T, however, is not simple. One cannot handle the problem by saying that the research system should select the environments for which varieties are to be tailored on the basis of the weights. The importance of the environment is one factor, but a further consideration is required. As long as T is less than e, *spill-over* effects have to be considered and the fundamental research strategy will differ in that adaptability will become a valuable characteristic.

Spill-over and clustering principles. The spill-over effect is relate- to the genotype-environment interaction. An improvement in a genotype will have maximum value in one particular environment. But it may also represent an improvement for neighboring environments, that is, it may have a *spill-over*. Since there are many components to a technology, it is quite possible that the effects of environment interaction and, hence, the spill-over effects, will differ by component. Disease and insect resistance, for example, may represent components of technology with large spill-over effects. International centers and large national systems may be able to specialize in the production of these components, leaving local or branch stations the task of concentrating on the components with higher environment interaction effects.

In general, an optimal research system will include a grouping or clustering of environments into niches and a program directed to each niche. A program may specialize in improving only a subset of the components of the final technology. Other institutions and programs producing other components will also be organized according to a clustering of environments. Several layers of clustering may make sense, depending on the decomposability of technology and differing environmental effects.[3/]

Optimal clustering of environments could be based on statistical grouping concepts. Suppose that one formed T groups from e environments. The variance in environmental factors can be decomposed as: the sum of squared deviations from the group means and the sum of squared group mean deviations from the overall mean.

$$\sum_i \sum_j (e_{ij} - \bar{\bar{e}})^2 = \sum_i \sum_j (e_{ij} - \bar{e}_i)^2 + \sum_i (\bar{e}_i - \bar{\bar{e}})^2 \qquad (5)$$

[3/] Decomposability is itself an important factor in crop improvement research. With modern procedures for identifying traits and for screening, crop technology is probably more decomposable than it used to be.

By selection of groups to minimize within-group variance, the between-group variance and spill-over effects will be maximized. Now consider

$$\sum_e \sum_j (W_{ej} E_n (\Delta Y_{ej}) - \overline{E_n (\Delta Y)})^2 \qquad (6)$$

$$= \sum_e \sum_j (W_{ej} E_n (\Delta Y_{ej}) - \overline{W_e E_n (\Delta Y_j)})^2 + \sum_j (\overline{W_j E_n (\Delta Y_j)} - \overline{E_n (\Delta Y)})^2$$

To minimize within-group variance, groups will be so chosen as to equate the weighted-group variances.4/ The role of the weights can be seen in this case. The more economic activity there is in the environments, the more technology types will be produced for a given range of environments.

We can only approximate the optimizing principle here. We have not considered spill-over effects across groups and that may alter the picture. But, most importantly, we have not considered the effect of unstable environments over time.

Effect of variable environments. Once a grouping of environments is chosen, it will no longer be optimal to establish screening criteria and related research methods to produce technology tailored to a single environment within the group. Instead, it will be optimal to design or tailor a technology for the total group. This means that a trade-off will be made between genotypes with desirable chracteristics for one environment and high environment interaction effects, and genotypes that have less desirable characteristics for any single environment but are more widely adaptable. Figure 3 illustrates this proposition. The vertical axis measures the expected yield increment from alternative research programs. The horizontal axis measures a generalized environmental variable. Research programs 1, 2, 3, 4, and 5 produce expected yield increments represented by 11', 22' . . . . 55'. These technologies have high environment interaction effects, as depicted by the curvature, and thus are highly tailored to particular environments. The curve AA' reflects the expected yield increment from a program that selects for lower environment interaction effect, i.e., wider adaptability. Each of the highly tailored programs has a higher expected yield increment for its local environment while AA' has a higher yield increment over a broader range of environments.5/

4/ See Johnston (1960) for a discussion of clustering techniques.

5/ The trade-off between yielding ability and adaptability is part of the more general nature of crop characteristics. In the selection process, one cannot simply select for one trait and also obtain other characteristics. *Linkages* between traits can be broken through some breeding techniques but only incompletely. Thus, to get more of a desirable trait, one usually also obtains more of some undesirable traits and less of other desirable ones.

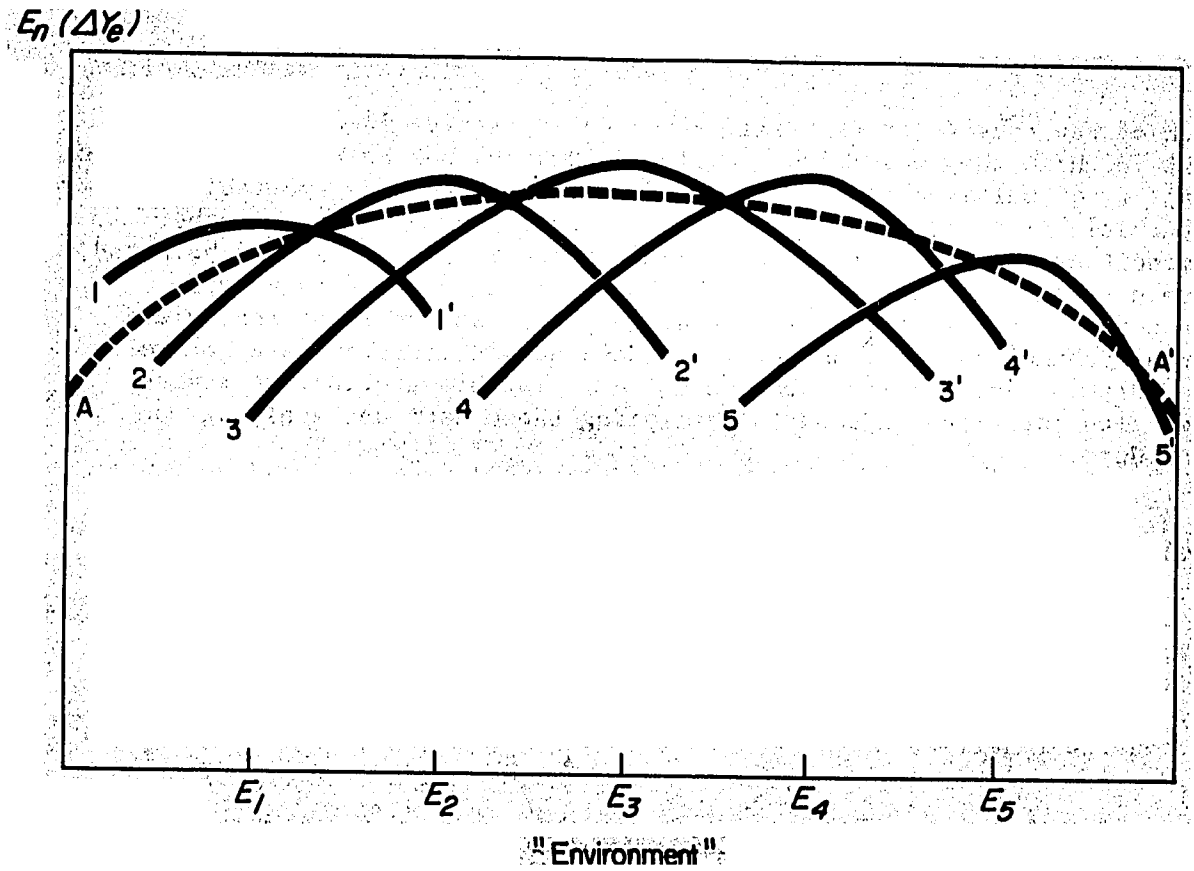

Fig. 3. Expected yield increments from alternative research programs.

If the range of environments, E_1 to E_5, represents a group, the optimal program will depend on the distribution of the crop by environment. If most of the production is concentrated around E_3, for example, the program producing 33' will be optimal. If production is evenly distributed from E_1 to E_5, the program producing AA' would clearly be superior.

Now suppose that in a certain location, the environment could range from E_1 to E_5 over time with a uniform probability distribution of occurrence of each environment. Under these circumstances, the wide adaptability program (AA') would be optimal for the location being considered.

But, if the distribution is not uniform across E_1 to E_5, then AA' may not be optimal and one of the tailored programs would be preferred. Clearly, the value of wide adaptability depends on whether variability in environmental conditions across locations is similar to variability in environments within locations. Not all environmental factors vary by location and the variance of, say, rainfall, across locations may not be highly correlated with the variance over time for some areas. Thus, it is likely that wide adaptability may not, in general, be optimal. We examine some empirical evidence related to this issue in the next section.

EVIDENCE ON STABILITY AND ADAPTABILITY

Much of the success of the semidwarf wheat varieties in areas outside that in which they were first developed (Mexico) has been attributed to the benefits of multilocation testing and the resulting wide adaptability. International yield trials have been conducted for a number of other commodities, including rice and maize. These trials, it should be noted, have not generally been utilized by breeders to identify phenotype characteristics, except yield. Average yields across locations, yield ranks within locations, and average ranks across locations are generally the only routinely calculated statistics. In this section, we review some alternative procedures for analyzing these data and applying one procedure.

Stability index concept and modifications

To characterize the yield stability of hybrids, Yates and Cochran (1938) suggested the regression of yield on an "environmental index" measured by the mean yield of all varieties in a particular environment. Finlay and Wilkinson (1963) used a logarithmic transformation of yield data and fitted the model:

$$\log (Y_{ij}) = a + b_i \log (X_{ij}) + u_{ij} \qquad (7)$$

where Y_{ij} = yield of variety i at site j, and X_j = mean yield of all tested varieties at site j. These authors paid the greatest attention to the biological interpretation of the stability parameters and its implication for a plant breeding program. The parameter b_i was used as an index of stability. This stability index was then plotted against variety mean yield. Their generalized interpretation is intuitively compelling (Fig. 4), especially when large numbers of diverse genetic materials are being categorized. Subsequently, Eberhart and Russell (1966), Laing and Fischer (1973), and Stroike and Johnson (1972) used similar models to estimate indices of "stability" for multilocation variety trials.

Recently, Matsuo et al. (1972) published an analysis of yields of 75 rice varieties grown at 45 locations, initially using the Finlay and Wilkinson method of analysis. Subsequent treatment of the data involved principal component analysis and orthogonal polynomial regression on environmental factors and utilization of Wricke's (1962) "ecovalance" concept.[6/]

Goldsworthy (1974) discussed an approach being developed (Mungomery et al., 1974) that is related to the concepts of groups discussed above in

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[6/] The reader may also refer to Wricke (1962) for discussions on the physiological and genetic basis of adaptability, and the implications of breeding for adaptability and productivity.

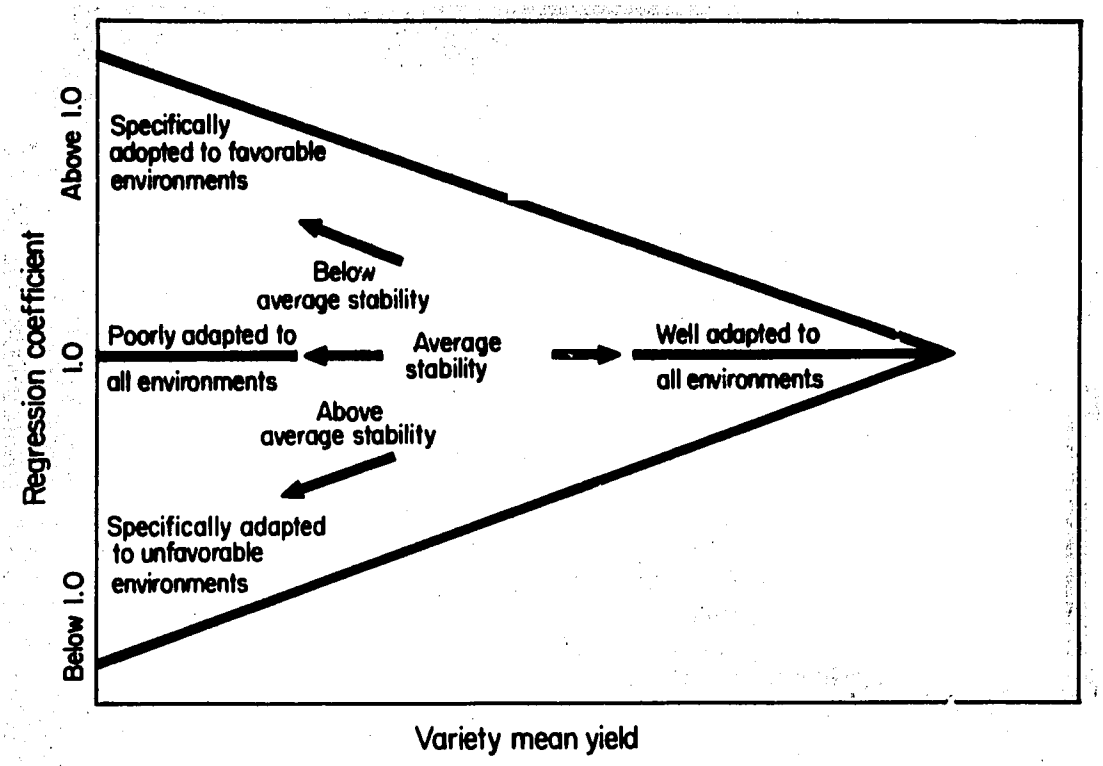

Fig. 4. Generalized interpretation of stability index versus variety mean yield over all environments. (Source: Finlay and Wilkinson, 1963.)

which "cluster" or "pattern" procedures reduce the complexity responses to environments. Initial testing of his procedures with wheat yield nursery data was superior to linear regression analysis.

Anderson (1974) has experimented with the use of stochastic dominance to evaluate data from international wheat improvement trials of CIMMYT. His technique gives primary weight to risk considerations so that varieties that have a very small frequency of poor performance are rejected in favor of varieties that may have a higher potential performance under appropriate environments.

Measurement of stability and adaptability

As the foregoing review indicates, most of the existing literature does not distinguish between adaptability and stability as this paper does. In this section, we report relatively simple measures of stability and adaptability for 22 rice varieties from the International Rice Yield Nursery (IRYN) trials for 3 years and similar trials conducted as part of the All India Coordinated Rice Improvement Program (AICRIP) in India for several years.

Our procedure is relatively simple. Each variety in the IRYN and the AICRIP set was planted in several locations (22 in the case of IRYN, and from 20 to 25 in the case of AICRIP) for 2 or more time periods. (In the case of IRYN, replications for each site were included in the analysis.)

The following models were fit:

$$Y_{jit} = a_1 + b^M{}_{it} + \sum_{t=2}^{m} d_{1i} L_i + e_{1jit} \quad (8)$$

$$Y_{jit} = a_2 + c^M{}_{it} + \sum_{t=2}^{p} d_{2t} T_t + e_{2jit} \quad (9)$$

The conceptual basis for these relationships is the standard analysis of covariance formulas. The variable M_{it} is an index of environment in each location i and time period t. Maximum yields (the average of the two highest yields at each location) are used as the index of environment. In expression 8, the yield of variety j in location i and time period t is regressed on the environment index for that location and period and on a set of location dummy variables. That removes systematic location effects and uses the within-location variance to estimate the parameters of the equation. The b coefficient is interpreted as a stability parameter measuring stability within a location across time.

Equation 9 includes time period dummy variables and the relationship is estimated using across-location variance. We interpret the estimated parameter c as an adaptability parameter measuring adaptability across locations.

We acknowledge that the error structure may not be fully consistent with this procedure and that alternatives exist (Binswanger, 1976). But we believe that these estimates will serve to at least initiate a more systematic investigation of these data.

Table 1 reports the estimates of the b and c parameters in the IRYN and AICRIP data. Figure 5 shows the relationship between the estimated stability and adaptability indices for the two sets of data. The results have important policy implications for the design of crop improvement research. They show that for the IRYN locations involved in these trials, adaptability and stability are not closely related. Breeders cannot rely on screening across these locations to select for stability. That raises some critical questions about the present crop improvement systems which, to some degree, are based on the presumption that adaptability and stability are closely related. The AICRIP locations however show positive correlation between adaptability and stability. The set of locations in the Indian program is apparently better suited to the joint selection for stability and adaptability than are the international locations. Thus, the Indian sites are perhaps a cluster, in the sense discussed in the previous section.

Both these results should, of course, be corroborated by other estimation procedures and by other data sets. One question that deserves explanation is the sensitivity of the results to the chosen locations. If it is possible to select it, a set of locations from within the IRYN

Table 1. Measures of stability and adaptability of yields.

	Stability coefficient Yield on maximum yield + location dummies		Adaptability coefficient Yield on maximum yield + time dummi	
	b′	SD	b′	SD
		1st, 2nd, and 3rd IRYN data		
1) PMI-6624-257-1	0.388	0.140*	0.894	0.041
2) RP4-14	0.688	0.108	0.496	0.048
3) BG 90-2	0.637	0.133	0.848	0.040
4) Chiang-Sen-Yu-6	0.639	0.179	0.673	0.053
5) C4-63	0.149	0.172	0.827	0.057
6) 841-36-2	0.190	0.151	0.764	0.052
7) IR630-27-1-1	1.671	0.146	0.678	0.058
8) IR578-95-1-3	1.250	0.151	0.670	0.059
9) BKN 6809-74-4	0.660	0.069	0.706	0.039
10) IR1529-680-3	0.930	0.100	0.743	0.042
11) IR26	0.099	0.150	0.485	0.055
12) Biplab	0.432	0.162	0.763	0.039
13) Jayanti	0.061	0.141	0.722	0.047
14) IET 2938	– 0.458	0.187	0.591	0.061
15) Pelita	– 1.288	0.350	0.848	0.085
16) Cica 4	1.181	0.099	0.423	0.057
17) SPR6726-134-2-26	0.408	0.147	1.052	0.044
18) KT 29	0.412	0.120	0.765	0.047
19) IR2071-588-6	0.783	0.165	0.621	0.063
20) IR8	– 1.598	0.174	0.622	0.049
21) IR2070-747-6	0.799	0.209	0.440	0.056
22) IR2061-213-2-17	0.271	0.202	0.987	0.063
		AICRIP data		
1) IR8	0.884	0.033	0.900	0.033
2) IR4-67-2-3	0.976	0.044	0.927	0.044
3) Chuvery	1.105	0.067	1.104	0.042
4) Hamsa	0.624	0.069	0.741	0.054
5) Jaya	0.758	0.046	0.899	0.042
6) Kaohsiung 68	0.730	0.056	0.934	0.053
7) Local Variety	0.557	0.040	0.681	0.041
8) Palma	0.621	0.065	0.938	0.045
9) Taiven 3	0.568	0.065	0.822	0.066
10) Vijaya	0.797	0.070	0.945	0.055
11) Taichung Native 1	0.807	0.046	0.916	0.045
12) IR8-64-3-1	0.863	0.046	0.890	0.041

*Standard deviation of the coefficient above it.

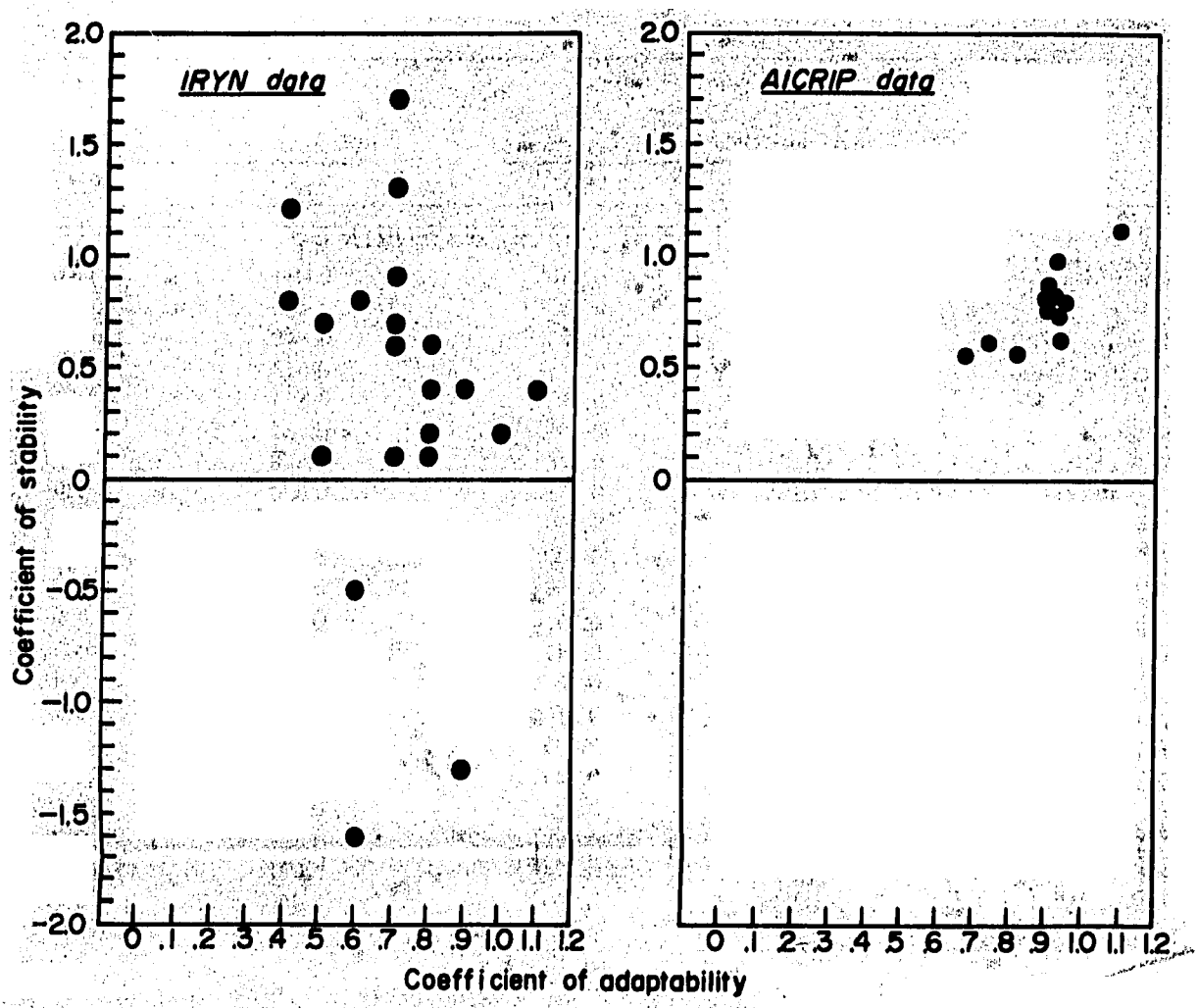

Fig. 5. Relationship of stability and adaptability.

data, where the correlation between the two measures is high, as it is in the AICRIP data, would be valuable to plant breeders.

Figure 6 shows the relationship between the stability and adaptability measures and the relative yielding ability of each variety. Since the performance of the variety in its best environment is most relevant, the figure shows stability and adaptability plotted against the average of the best two relative yields. There is little relationship between stability or adaptability and performance in the best two locations, suggesting that these traits may not be too costly in terms of yield performance.

Thus, we conclude that if no attention is paid to appropriate clustering, there is little support for the assumption that stability and adaptability are correlated. Adaptability may be correlated with stability within properly clustered locations, but clustering techniques were not investigated. High levels of stability and adaptability do not appear to reduce the performance of varieties in the locations where they are best adapted. All these conclusions are tentative, however, because the set of data supporting them is rather small.

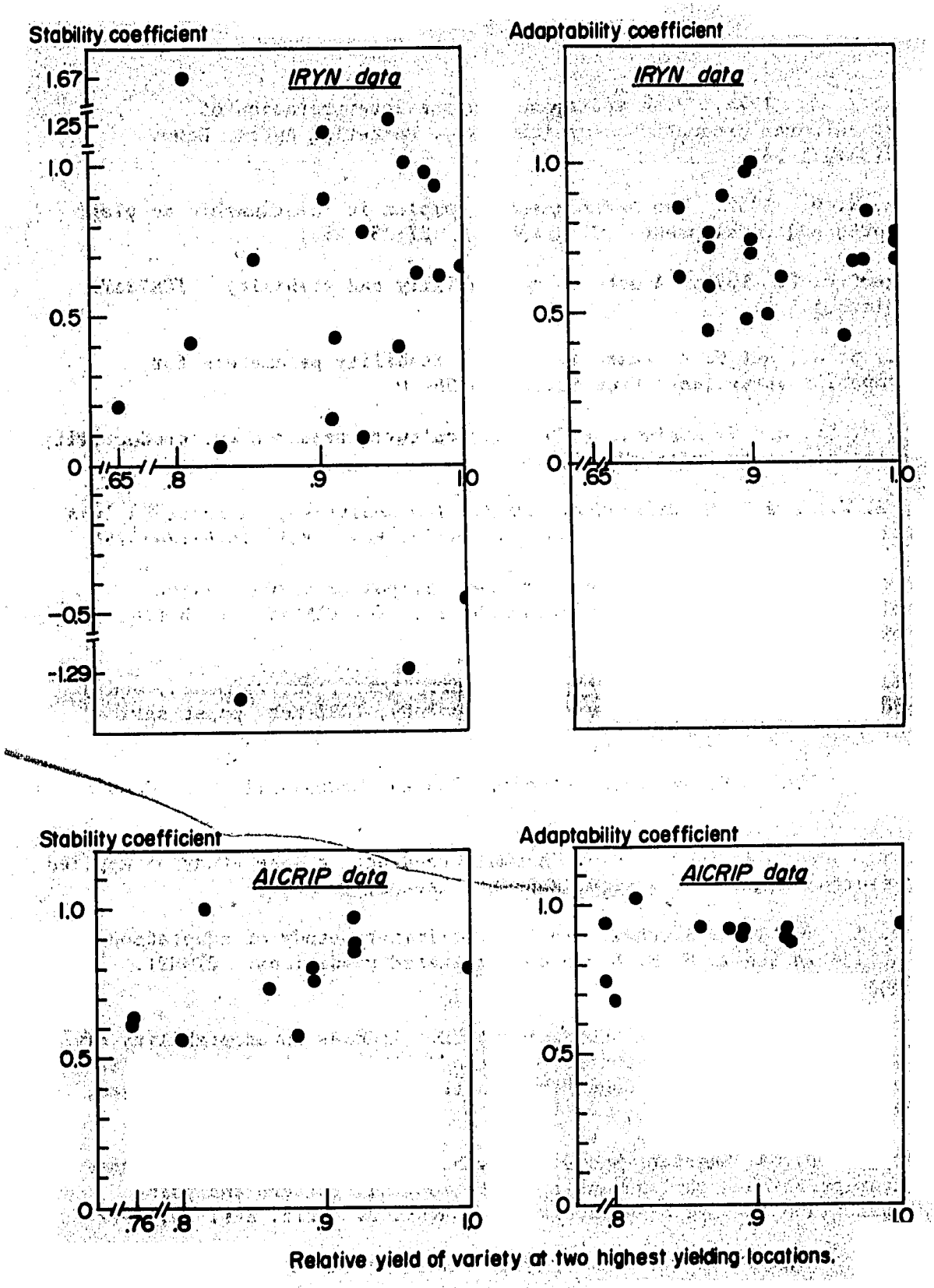

Fig. 6. Stability and adaptability coefficients of varieties plotted against yield of each variety at two best locations relative to all varieties at the same locations.

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