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## Vegetable Cultivar Testing: Introduction to the Symposium

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Choice of the most appropriate cultivars is a key decision that vegetable growers face every growing season, and one on which the profitability of the crop depends. Evaluation of cultivars for adaptation to local growing conditions is therefore of crucial importance to extension and research personnel that serve the vegetable industry and the companies that are developing and releasing vegetable cultivars. The present-day climate of restricted budgets and pressure to move from applied to more basic research has forced experiment station and university personnel in North America to abandon or greatly reduce vegetable cultivar testing. The seed industry has traditionally relied on both public institutions and its own grower-cooperators to evaluate the merits of new lines. Increasingly, seed companies face requests for funding of these public trials, or are asked to pay entry fees to submit new cultivars for testing.

In Europe, cultivar testing has been more formally organized for many years, with separate government institutions responsible for testing and deciding which cultivars merit inclusion in official lists.

The considerable cost of these programs is also forcing changes in testing methodology at present. Although one can assume that good-quality seed of a large number of cultivars of most vegetable crops is available for purchase by growers in developed countries, cultivar testing in developing countries of the tropics requires much more concern with availability of good-quality seed of adapted cultivars after testing. Techniques of cultivar testing are often taken for granted, but may be major causes for meaningless results and wasted effort. This consequence is true not only in temperate areas but also in the tropics, where work with little-known species may require considerable preliminary experimentation to establish valid testing criteria.

The symposium authors address these and other major issues related to cultivar testing of vegetables and seek solutions to some of the questions posed below: a) How can vegetable cultivar testing be done more cheaply and efficiently? b) Who should be doing vegetable cultivar testing? c) Who should pay for vegetable cultivar testing, and how much does it cost? d) How can cultivar testing techniques be improved?

# Cultivar Testing: Public Point of View

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One of the most important decisions a grower makes when formulating plans for planting is what cultivar to select. The experienced grower has observed the evolution of cultivars and is intensely aware of the vast improvements that have been made through plant breeding. Much of the increase in crop productivity can be attributed to the disease resistance, environmental adaptability, and increased yield potential incorporated into cultivars by public and private plant breeders.

New cultivars of numerous vegetables are released each year that need to be screened, and the superior ones introduced to the industry as expeditiously as possible. Should public-funded institutions support cultivar testing programs from which cultivar recommendations can be derived or should cultivars find their position in the marketplace based on their performance and the reputation of the seed company?

## Background

The commercial seed industry is quite young, initiated only in the past 75 years. Prior to this time, growers generally saved their own seed, and cultivars were passed from generation to generation. Development of the seed industry initiated an arena of competition from which growers have the opportunity to select. Traditionally, land-grant universities in the United States have assumed the responsibility of evaluating the numerous cultivars of a particular crop under the unique climatic conditions and using cultural practices common to the state where the university is located. Often a university has several testing sites in order to assure that the unique climatic and/or edaphic conditions of various production areas are met. An effort is made to have growers observe these trials during the growing season and the results of these trials are the basis for making recommendations. Unlike pesticide evaluation, which is also done by public institutions, data collected from cultivar trials have little legal significance. There is no need for efficacy or residue data to be collected for product registration. Cultivar testing is justified on the assumption that it hastens getting superior cultivars to the growers and prevents economic losses to growers by planting unsuitable forms.

Each state administers these trials differently, but they are generally the responsibility of an individual who oversees them in conjunction with his/her research or extension program. Cultivar trials should not be considered basic research because they are not innovative or creative, even though they often provide information that is critical to plant breeders, plant nutritionists, or extension specialists. In addition, the results of such trials are not suitable for publication in a refereed journal, unless they are summaries of many years of trials on a crop or involve additional plant breeding work. It is unfortunate, but not unusual, for a young scientist with a research appointment to get so involved in conducting cultivar trials that a research program is not developed. Thus, at the time of review for tenure, the individual's publication record is less than desirable. Some successful extension specialists and researchers do oversee the cultivar trials that augment their programs, but it does demand major time and monetary commitments. Most public plant breeding programs compare leading commercial releases to their most advanced breeding lines or hybrids.

On the other hand, administrators in some states believe that the extensive field work that must go into cultivar trials is beyond the scope of most extension programs. Similarly, an extension specialist may be criticized if involvement in cultivar trials interferes with his/her fulfillment of other assigned responsibilities. Thus, cultivar testing is felt by most university researchers and extension specialists to be professionally unrewarding. Knowledge of cultivars is, however, highly important in communicating with growers and processors since it is so basic to the overall production system.

Today, seed companies have achieved a high degree of sophistication with extensive research, plant breeding, and cultivar testing and marketing segments. They have professional staffs whose reputation depends on the cultivars they develop. It is their responsibility to assure that their companies' materials are evaluated and introduced into the various vegetable production areas. This active program by private industry makes many public institutions question their need to conduct such trials.

## Cost of cultivar evaluations

Perhaps the biggest concern to university staffs and administrators today is the cost of doing cultivar testing. A reputable testing program is highly labor-intensive and thus becomes quite expensive. Even if we were to assume that the university would bear all overhead costs (i.e., land, equipment, fertilizers, pesticides, and supervisory personnel), a conservative cost per entry in a replicated cultivar trial would be \$128.00 (Table 1). The latter would cover those costs above and beyond those services provided by the research farm or grower-cooperator.

It is not surprising that university staffs and administrators question whether it is the best use of their resources to support cultivar trials. It is often suggested that such trials should be self-supporting and not a drain on state-appropriated funds. Seed companies have been reluctant to support these trials financially because they are so numerous, and they believe that they cannot afford to support every state's program. If some universities charge entry fees and neighboring states do not, the seed companies can enter their material in the trial with no entry fee and obtain the environmental adaptability data they require. It is also argued that a completely unbiased trial may not be possible when entries are limited to those for which an entry fee has been paid. This limitation concerns individuals at public institutions because they may not be able to include promising entries because the company does not wish to pay the fee.

## Where do growers get their cultivar recommendations?

There have been no scientific surveys, to our knowledge, of what influences grower selection of new cultivars, but certainly university recommendations are not the sole source of information. Based on experience and discussions with colleagues, it is thought that the seed company salesperson is the most influential advisor to the grower on cultivars, especially if the salesperson is well-established, respected, and has done business in a territory for a few years. These individuals put out trial plantings and distribute packets of new cultivars for growers to try. These salespersons are generally knowledgeable about vegetable crops and are aware that their reputation depends on giving accurate information to growers. An unprofessional salesperson who tries to take advantage of the growers does not last long in the business.

Table 1. Costs of conducting vegetable cultivar trials.\*

Technician (12-month appointment)	\$20,000
Seasonal labor (three individuals, 4 months)	9,000
Travel	1,000
Supplies	250
Computer charges	750
Publishing costs	1,000
	\$32,000
Cost/entry <sup>b</sup>	\$128.00

\*Overhead cost and supervisory personnel costs not included.

<sup>b</sup>Based on 10 crops  $\times$  25 entries/crop.



Perhaps the next most influential source of information is the processing company that contracts the raw product, or the broker engaged to sell the product on the fresh market. Processors, in particular, have extensive cultivar trials so that the raw product can be processed in their plants and the quality of the finished product evaluated. These trials are professionally conducted, statistically analyzed, and used extensively by the field department in deciding what cultivars to contract for culture and in what areas.

Another significant source of information on cultivars is observation of neighbors' fields and conversations among growers "in the coffee shop". As protective as some growers try to be, there are really no secrets in the produce industry. When a cultivar is performing well or has done poorly, word soon gets around. These observations are often not substantiated by accurate yield data or multiple years of observation, but are often remarkably profound.

It is often only after these other avenues are exhausted that the results of the public institution's cultivar trial are consulted. The massive amount of data and number of entries often cause confusion for the grower and are often ignored, unless they are summarized and highlighted by extension personnel. Official variety recommendations based on several years of testing are generally so conservative and late that they are ignored by the experienced grower. Conscientious growers often use university results to corroborate information from other sources and confirm their observations.

#### **Who does the public institution's cultivar trial benefit?**

Probably the greatest benefactors of cultivar trials are the seed companies. They are given the opportunity to see their material grown under a wide diversity of environmental conditions, and they receive a large amount of performance data. The data they receive are not only for their material, but their competitors' as well. These trial results are used by the seed companies' scientists in deciding what material should be kept and by the sales staffs to promote their material that performed well. Inclusion of material in university cultivar trials also gives their entries a great deal of exposure to potential customers.

Growers and processing companies benefit also, for they are provided open access to the university trials and can observe numerous cultivars under their cultural conditions. However, usually only a

small percentage of the growers and processors attend field tours or observe cultivar trials in progress, for they are extremely busy during the period when the trials should be observed.

Perhaps the public institutions' roles in cultivar testing are important because they aid the seed companies in making decisions on what lines to keep or drop. If so, it would seem appropriate for the companies to assist in defraying the cost of conducting them.

#### **Growers are backers of cultivar trials**

When asked to rate projects at a public institution's research and demonstration station, growers will generally put cultivar trials at the top of the list. They are aware that cultivars have had a profound influence on their industry, and they want to be the first in line when something new comes out. Also, when growers contribute to voluntary or mandatory check-off funds, cultivar trials are one of the items they want conducted with the money. It is never clear whether they sincerely believe cultivar trials are all that important or whether it is the traditional thing to fund. During discussions with growers, the conversation generally begins with the weather and cultivars, but inevitably passes quickly to matters of pest control, cultural practices, and marketing. Perhaps cultivars are just a method to get the conversation started.

#### **Conclusions**

Cultivar trials are necessary, but extremely expensive, time-consuming, and currently unrewarding professionally. It is anticipated, however, that cultivar trials will be imperative to evaluate the results of biotechnological developments under field conditions. In times of reduced research and extension budgets, public institutions are going to take a hard look at whether they can justify extensive cultivar evaluation programs. Commercial cultivars must be included in the evaluation of lines in a breeding program, and a few can be included in cultural practice experiments. Without outside support, large replicated trials are difficult to justify. Observation and grower trials will probably continue to play a major role in extension programs. Regional cooperative variety trials greatly increase the amount of information derived from a trial; however, the basic cost of conducting the trial is still borne by the researcher.

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## **Cultivar Testing, a Seed Industry Perspective**

**Paul Thomas**

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Cultivar testing is an essential part of cultivar development programs. The main purpose is to determine the regional environmental adaptability and market fit of the new cultivars or hybrids. It is essential to know whether the items to be tested have the required disease resistance for the areas, whether they meet the needs of the industry as far as type or quality is concerned, and whether they will perform well under the environment of the region. Private research stations may not be in the immediate vicinity of the area of intended use, but adequate testing in these untested areas is still essential prior to release of new cultivars.

Various approaches are used in cultivar testing by the different seed companies. Some seed companies evaluate new cultivars only through their own research departments. In this case, samples are sent to cooperators, both public and private, and decisions are based on results obtained from cooperator trial results and the results of the breeder's own trials. Other seed companies send samples of new cultivars for testing through their sales departments to public and private cooperators with possible visits of the trials during the growing season by sales personnel. Release decisions are based on the observations of these visits plus the results of their breeders' own trials.

Several companies today have established product development departments. Their responsibility is to place advanced experimental cultivars with public and private cooperators. They closely monitor the trials to determine the feasibility of releasing the experimental lines as finished products. Product development personnel are the liaison between the sales departments and research departments in recommending whether a cultivar is to be released, evaluated further, or dropped. Some companies use all of these avenues in evaluating new breeding lines from the research departments to be considered for release. Whatever the system used by a seed company, an honest and professional evaluation must be made regarding any given experimental cultivar tested. It is not to the company's or public's best interest to have cultivars promoted that do not fit the needs of the consumer, whether the consumer be a housewife, grower, shipper, processor, or home gardener.

One of the biggest problems we have as a private company is to be assured that the trial reports and evaluations are performed by qualified individuals. These people must know the markets and give accurate and complete information on performance and market fit for any new cultivar. Because our markets are so diverse, this is sometimes difficult to do. For example, when Petoseed sends out

samples of experimental tomatoes, they could be for the home garden, fresh market, or processing trade, all of which have different requirements. Will the evaluator always be capable or prepared to differentiate between these markets and evaluate each new cultivar accordingly? How can we as an industry be assured that these evaluators judge new cultivars correctly for the markets intended?

Over the years, Petoseed has relied heavily on public institutions for new cultivar testing, along with a limited number of private cooperators that were willing to participate in testing programs. Eventually, we found cooperators on whose evaluations we could rely. Recently, cultivar trials conducted by public institutions have been cut due to budget reductions, retirements, and academic trends to more basic research. In order to continue to evaluate new cultivars adequately, Petoseed has recently initiated a program through a Product Development Dept. to supplement our cultivar trials with those of the public institutions. Many times we use data from the public trials along with yield data obtained from growers, as well as processed product data supplied by processors and fresh product data from shippers to enable us to make the best decisions on cultivar releases. In other words, we use as much outside input as possible to estimate new cultivar performance from germination/emergence to disease reaction to final product performance. Programs of this depth and scope are costly to the company due to the many people involved and the travel required. As an average, we estimate a cost of \$75 per trial to evaluate one experimental cultivar off-station. This cost obviously varies with the crop being evaluated; processing tomato trials would be more expensive to test than fresh-market slicing cucumbers. On-station trials are estimated at \$150 per trial. This again would depend on the crop evaluated. Labor costs in harvesting and data collection of the experimental varieties are consistently the largest part of the expense incurred. Most of the overhead and all the farming costs and land costs are borne by the cooperator in the off-station trials. Growers will frequently also supply labor to harvest.

We try to cover a number of different species by regions. Petoseed does a good job of measuring performance in major production areas, but does not always have enough manpower or time to cover the more remote or less-profitable areas. In these instances, it is necessary to rely heavily on public research personnel or cooperating private customers.

Another changing aspect of the public institutions is that private companies are getting more requests for funding to help support public trial evaluations. This is difficult because I am sure none of us in private industry like to say "no" to a public servant. We have to evaluate the cooperator, as well as the benefits their support would provide to our company. We recognize the overall value of these programs, as we have contributed cultivars for testing for many years and still rely heavily on them to supplement our own testing programs. However, if we are going to spend money out of our own research budgets we need to be as certain as possible that we are going to get our money's worth. We are also asked to fund public research projects in addition to cultivar testing. This funding amounts from \$20,000 to \$30,000/year for our own company.

Public institutions may use these trials to teach students about vegetables, with students collecting all of the data. We receive impressive computer-generated reports with all types of data and analyses of variances. Many times the data and information do not really mean too much, as the numbers and statistics are irrelevant for the crop and specific market. Seldom does the report indicate the relative good as well as bad points of the different cultivars under some sort of analysis and conclusions section. This would indicate to me that the evaluator either does not know or prefers not to make a judgment on the merit of the entry. Data frequently do not tell the full story of a cultivar's performance. I have seen instances where varieties will receive high scores but are commercially unacceptable because of one major fault that cannot be adequately measured, such as firmness in tomatoes. In such instances, the evaluator must have sufficient industry knowledge to make this judgment.

I would like to see more cooperative trials, such as the Southern Cooperative Cucumber Trials or the Southern Tomato Exchange Program (STEP) Trials, etc., in which information is standardized.

The important characters to be evaluated are agreed upon by industry personnel, knowledgeable public horticulturists, and qualified personnel who then do the evaluation. These trials could serve as a teaching tool for students, but the head evaluator for each location would have the ultimate responsibility of making the decision on the merits and demerits of an experimental cultivar and concluding whether it would be advanced or dropped. Such cooperative trials would also be a drawing card for industry personnel to follow the performance in the various locations testing a given species and would serve the total industry. I believe that the seed industry would be more likely to financially support this type of program than many public trial testing programs now carried out. I realize that cooperative programs cannot be carried out in all species. However, it appears to me that for the major vegetable species, i.e., tomatoes, cucumbers, peppers, carrots, onions, melons, etc., in many production areas, this approach could work. I believe that from the industry standpoint we could get more for our money from this type of program and the public institutions would be more able to obtain financial support from the private sector. I cannot stress enough the success of any cultivar testing program being totally dependent on the knowledge, skill, and experience of the individual responsible for conducting it. Petoseed, as a company, would be highly reluctant to financially support a program if we did not receive direct benefits from it, because this money comes directly out of our research budgets.

I am against government agencies in the United States deciding what standard cultivars and hybrids are released and sold in U.S. markets. It is an accepted practice in some European and Middle Eastern countries for all new cultivars to be evaluated and judged through government-conducted trials prior to commercial sales. In some instances, these government trials are conducted poorly; in others, well. However, in most instances, the new cultivars have to pass government inspection and approval before being sold in the country. Sometimes it takes years for new cultivars to be accepted or approved, even if the advantages of new cultivars are obvious immediately. I do not believe our customers need this type of government protection, considering how well our present system has been working in the United States. Being in the seed business, we are well aware of the necessity for valid cultivar evaluations at the commercial agriculture level. Petoseed is willing to fund universities on the cultivar testing work they do, either on a per-cultivar basis or a long-term basis. However, the public sector must realize that we are in this industry as a business; if this expense becomes prohibitive, we can do this work more cheaply with our own co-operators.

One approach to consider for reducing public trial costs is to have county extension agents do the actual testing in cooperating growers' fields. A good example of this is the cultivar trials done by the extension agents in California with processing tomato growers. These trials give a good estimate of regional adaptability and are less expensive and more meaningful in total than research trials at the Univ. of California, Davis campus. The off-campus trials are grown in commercial fields of processing tomatoes using standard cultural practices. There are enough of these trials in each of the various counties that good replication is accomplished with different soil types, growing practices, and temperatures. It would be impossible to obtain such a wealth of information from a single location, such as the Univ. of California, Davis.

In years past, I have seen growers who would not plant a cultivar unless it was on the recommended list of the local university extension agent. This is changing with some crops, due to specific needs of certain industries that specify the cultivars to be produced by the farmer. Few growers will buy all the advertising "hype" of new cultivar releases from private companies. They normally will test them under their own environment and cultural practices for several years prior to committing to major acreages. We must remember that if a grower cannot make a profit using our hybrids and cultivars, he or she will not buy them. That is motivation enough for us in the private sector to make certain that new cultivar releases will be acceptable to the industry, but we also do not need inventories of unmarketable products.

The diverse and informal systems of cultivar testing in the United



States have generally been successful. However, due to budget constraints, we are now seeing many changes in the public sector that are in turn forcing changes in the private sector. There will be a

greater need for increased private funding of public cultivar trials in the future and private and public institutions will have to change their traditional roles to meet future industry needs.

## Vegetable Cultivar Evaluation in England and Wales: Developments and Economies

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The oversupply of agricultural commodities, including vegetables, in the United Kingdom has led the government to urge decreases in expenditures on the official cultivar testing program. At the same time, the submission of new lines by breeders into the test program continues unabated. In summarizing the vegetable cultivar assessment program, as carried out in England and Wales by the National Institute of Agricultural Botany (NIAB), both for the statutory National Listing requirements and for the production of Recommended Lists for vegetable growers, the emphasis therefore will be on the development of new techniques, particularly with a view to cost savings.

There are two separate aspects to cultivar testing in England and Wales. The first, which is a statutory function, is testing for National Listing and Plant Breeders' Rights. The other is testing for Recommended Lists (value for cultivation and use). The purposes of the two trial series are quite different, and different cultivar characteristics may be taken into account.

### NATIONAL LISTING AND PLANT BREEDERS' RIGHTS TESTS

As part of the European cultivar registration system, the United Kingdom adopts 2-year combined tests for Distinctness, Uniformity and Stability (DUS) for both National Listing and Plant Breeders' Rights (PBR). National Listing conforms with public law and is a requirement before marketing of seed is permitted. It gives a statutory obligation to ensure novelty, that synonyms are eliminated, and that seeds of a new cultivar being sold are true to type. On the other hand, the award of Plant Breeders' Rights is covered by private law, giving protection to the breeder over exploitation of his or her material, and allows the setting of royalties on seed sales that gives a return on the investment in breeding.

Vegetables differ from the testing of other crops in two important respects. First, there is no statutory requirement for performance assessment [i.e., Value for Cultivation and Use (VCU) measurements]. Second, once a cultivar is National Listed by an individual European Community (EC) state, there is little or no delay in its addition to the Common Catalogue, which is the compendium of all the National Lists from the EC. Once National Listed and then placed on the Common Catalogue, a cultivar can be marketed legally in all the EC states (Fig. 1). This reciprocal arrangement does not apply to PBR, which must be applied for separately in each of the EC states where it is wanted. Candidates submitted from outside the EC (e.g., from the United States) are treated in the same way as those from within (i.e., National Listing need only be sought in one country, but if PBR is wanted it must be applied for in each).

DUS testing is carried out for two successive years and, in the United Kingdom, about 150 new vegetable cultivars are assessed each year. A major problem is the high cost of the U.K. vegetable DUS tests due to the large number of cultivars that are already recognized. For example, there are 600 distinct cultivars of dwarf or snap bean (*Phaseolus vulgaris* L.) on the Common Catalogue. For testing a new bean cultivar, we have improved the selection of nearest neighbor controls by using 17 main discriminatory characters, which are computerized for the whole reference collection.

Selection of a reduced number of controls then depends on the adequacy of the description of the new cultivar provided by the breeder in the Technical Questionnaire.

For eight dwarf bean applications in 1986, the greatest numbers of controls thought to be necessary for one of these candidates was 77 out of the total collection of 600. We are moving toward the U.S. system, which gives more detailed distinctness information in the Technical Questionnaire but we are not yet in the position when only the computer is needed to compare the breeders' data against the stored reference collection data without any measurements by the testing authority in the field. In vegetables, assessment in the field is still considered essential to ensure the stability of the cultivar. Uniformity is also important for the grower.

Dwarf bean is a relatively inexpensive crop to evaluate. Being self-pollinated and with a number of good discontinuous characters, a one-row plot 10 m in length (150 plants) may be sufficient for the tests, which are essentially observational, but up to six rows may be needed when discrimination is difficult. Increased expense is incurred with the cross-pollinated species, e.g., onion (*Allium cepa* L.), whose plant-to-plant variability within a cultivar leads to problems in cultivar comparisons. Therefore, all plant characters on four 10-m rows must be laboriously measured, counted, or scored for the whole group of the relevant reference collection.

Methods that are now being introduced to improve the tests by reducing the variability between plants are: a) production of seedlings in plant cells for easier transplanting, and b) seedbed preparation of plots using a bed-system of tillage plus irrigation.

These procedures allow a 50% decrease in plants needed. New characters also are being used, such as the ratio of length/breadth of bulbs in onion, as this is a more discriminatory test than bulb length or bulb breadth used separately or the floral characters of the sprouted bulb. It is hoped that further economies will result from a) use of chemotaxonomic tests, e.g., the separation of *Faba* bean cultivars on seed tannin content; and the development of electrophoresis tests on seed, which could be used as an extra discrimination measure in addition to the internationally agreed characters. b) Intermittent testing of minor species, i.e., stop testing for 1 to 3

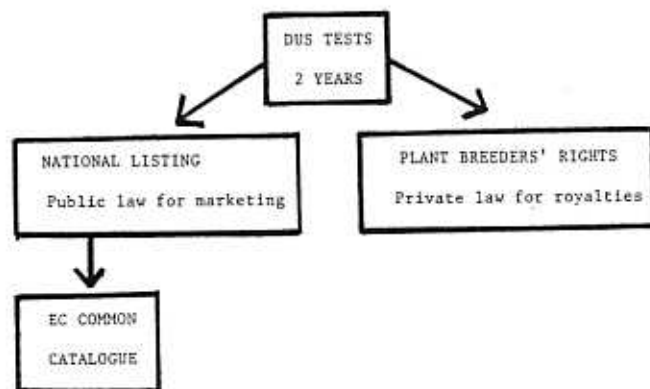


Fig. 1. EC system for Distinctness, Uniformity, and Stability (DUS) tests for new vegetable cultivars.

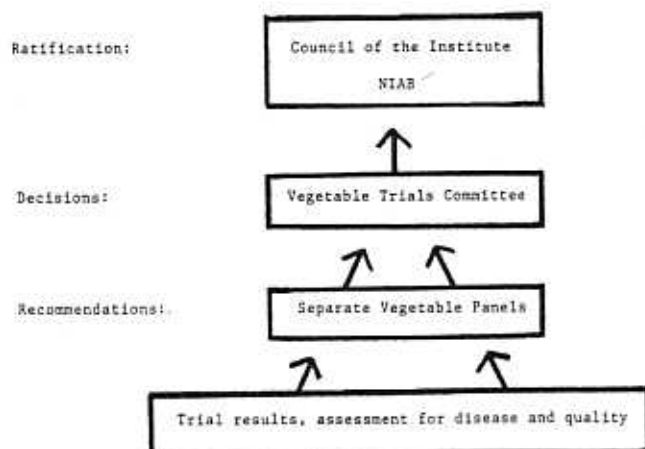


Fig. 2. Decision route for Recommended Lists.

years by holding up the candidate applications. c) Establishing bilateral testing agreements between EC countries so that economies can be achieved in the number of countries testing each species. There are now proposals for France, the Federal Republic of Germany, the Netherlands, and the United Kingdom to take on some 10 species each.

At NIAB, Cambridge, the DUS testing on vegetables is carried out by four systematic botany graduate staff, with five technical assistants. Twenty-two crops are covered at a total annual cost of \$280,000; this represents about \$2400 per candidate entered for 2 years of testing. At present, the U.K. government obtains about 25% recoupment from the fees charged, but is now planning to raise these fees to 50% of the total cost. This increase is why there is considerable demand from breeders to introduce economies and new procedures to reduce the costs of DUS testing; especially as it is more difficult for breeders of vegetables to obtain an adequate return in royalties as many of the species are not grown on large areas in Great Britain.

### RECOMMENDING VEGETABLE CULTIVARS TO GROWERS

Recommended Lists perform an essential role in crop improvement by the exploitation of new cultivars for commercial practice. Performance trials carried out by NIAB for growers in England and Wales normally use four sites over 3 years and with three replicates. Trials are located in the main growing areas for the crop concerned, either in growers' fields or at extension service stations. In order to reduce the number of candidates entering main trials, a preliminary screening trial is included for some crops (at two sites with two replicates), which then gives 4 years of testing in total.

Each year, decisions on the recommendations of new cultivars for growers are first considered by a panel of growers, technical experts, and consumers. The views of panel members on cultivars

are based on experience combined with the technical information provided on yield, field performance, disease resistance, storage, and marketability. Recommendations of all the crop panels are then presented to a Vegetable Committee, whose decisions are subsequently ratified by the Council of the Institute (Fig. 2).

For a candidate cultivar to be recommended, it must be of a standard that is "as good as the best" when compared with cultivars already recommended, taking all characteristics into account. Among the features that it is necessary to consider in vegetables are yield, disease resistance, and all the quality aspects demanded by the consumer, including uniformity. In brussels sprout (*Brassica oleracea* L. var. *bullata* subvar. *gemmifera* D.C.), for example, 14 characteristics are listed for each cultivar on the Recommended List; three for yield size grades, six for sprout characteristics (e.g., lodging, ease of deleafing), and a rating for resistance to powdery mildew (*Erysiphe cruciferarum* Junell). A new cultivar is first Provisionally Recommended before extra data confirms it for General Recommendation or for Special Use. When a Recommended cultivar is no longer "as good as the best", it will be removed from the List after due warning to the breeder, or it may be removed immediately if a serious defect appears. It is estimated that 90% of the vegetable cultivars grown commercially in the United Kingdom are on NIAB Recommended Lists. Over a 20-year period, the increase in yield alone attributable to new cultivars ranges from 10%, 25%, 30%, and 50% for cabbage (*Brassica oleracea* L. var. *capitata* L.), carrot (*Daucus carota* L.), lettuce (*Lactuca sativa* L.), and brussels sprout, respectively.

Feedback from the industry at each stage during decisionmaking is vital if confidence is to be maintained in our Recommended Lists by growers. Furthermore, the panels ensure that the correct priorities in testing are established for the requirements of the industry; this consultative process has greatly improved the relevance of our trial procedures. Our trials officers also ensure that the information breeders, growers, and processors actually require is received by devoting some 10% of their time in demonstrating trials, visiting breeders' plots, mounting vegetable conferences, and issuing relevant articles.

This activity makes a heavy workload nationally in the evaluation of vegetable cultivars for seven graduate staff and seven technical assistants. Due to a decline in funding, a rigorous assessment of our priorities in cultivar testing has been essential. The six highest-priority vegetable crops, based on value of output, i.e., cabbage, cauliflower [*Brassica oleracea* L. convar. *botrytis* (L.) Alef. var. *Botrytis*], carrot, lettuce, brussels sprout, and onion, are allocated 90% of the resources for performance trials (Table 1). Peas (*Pisum sativum* L.) for processing and for the green market and also dwarf bean were dropped from the NIAB testing program 6 years ago. This was not only due to the high cost of cultivar evaluation of these two crops, but it avoided duplication with processors' own trials and those of a processors' funded research organization (the Processors' and Growers' Research Organization). A longer list of minor crops, e.g., beetroot (*Beta vulgaris* L. var. *esculenta* L.), green sprouting broccoli (calabrese) [*Brassica oleracea* L. convar. *Botrytis* (L.) Alef var. *italica* Plenck.], zucchini (courgette) (*Cucur-*

Table 1. Field vegetables in the United Kingdom.

	Value of output, 1984-85 (\$10 <sup>6</sup> )	
Cabbage	92	Six Recommended Lists
Cauliflower	78	
Carrot	75	
Pea	75	
Lettuce	59	
Brussels sprout	47	
Onion	30	Descriptive List
Bean	26	
Leek	23	
Salad onion	20	
Beetroot	16	
Parsnip	13	
Other	111	
Total	665	

Table 2. Number of new carrot cultivars entering performance trials in England and Wales.

	Year					
	1980	1981	1982	1983	1984	1985
No. of cultivars	11	22	40	35	22	23

*bata pepo* L.), leek (*Allium porrum* L.), bunching onion, sweet corn (*Zea mays* L.), and parsnip (*Pastinaca sativa* L.), are now given much less attention (10% of resources) by the introduction of intermittent testing or a smaller trial input (two sites instead of four, or observation plots only) with the results being presented as a Descriptive List without full Recommendation.

The high rate of new cultivar development has meant that Recommended List trials have included as many as 600 entries. In the carrot crop, for example, a peak of 40 new cultivars was reached in 1982 (Table 2), from 28 breeders who now produce hybrids, and also due to the interest in the 'Nantes' type for cylinder stump carrots for the fresh market.

The cost of our performance trial program for the 600 cultivars in trial is \$600,000/year, which is an average of \$3600 for each candidate cultivar over its 3 or 4 years of testing. Continuous attempts have been made to find cost savings in this program by reducing it to the essentials required by the industry. These include: a) Reassessment of plot sizes and shape, e.g., using 30 to 40 plants for transplanted crops such as *Brassica* spp. and 100 to 200 plants for drilled crops such as carrot. b) Use of Vegetable Panels to prune by half cultivars that enter main trials after preliminary screening trials (especially needed for leek, carrot, and brussels sprout). c) Reducing the testing program for minor crops or those with declining interest; reduce their status to Descriptive List with a reduced number of test centers, also by intermittent testing depending on numbers of submissions. d) Computerization of data collection; data loggers now record cauliflower quality and yields of carrot and

cabbage. This can be a slower operation than using record sheets, as the characters for each crop are so different. However, overall savings may be achieved when software has been fully developed for data processing and the automatic production of 1-year results.

Demands by breeders, growers, and consumers for extra tests appropriate to new crops, changes in growing systems, and new market requirements suggest these topics for future developments: a) more trials on cultivars for plastic mulch (e.g., early carrot, lettuce, zucchini); b) shelf life evaluations under supermarket conditions (e.g., lettuce); c) consideration of taste panels for acceptability plus the development of sugar and acid analyses of produce; d) more work on new vegetables, which in the United Kingdom include green sprouting broccoli (calabrese), chicory (*Cichorium intybus* L.), Chinese cabbage [*Brassica pekinensis* (Lour.) Rupr.], and mooli or Japanese radish (*Raphanus sativus* L.); and e) assessment of cultivars with particularly well-developed disease resistance characters for use by organic growers.

With a continual emphasis today on achieving government savings targets, new areas of work can only be accommodated by discontinuing existing activities or identifying projects for a lower priority. Alternatively, more support now has to be obtained from all sectors of the industry itself to fund new development projects. Fortunately, cultivar evaluation will always rank as a high priority for breeders, the seed trade, and growers, if their businesses are to remain competitive. Extra sources of income from the industry itself will have to be obtained to ensure that reliable assessments of new vegetable cultivars can continue to be achieved.

## Vegetable Cultivar Testing in the Tropics

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Vegetable cultivar testing in the tropics is faced with fundamental problems that occur less frequently in the temperate areas. First, it must be decided what species of vegetables should be tested. Second, availability of planting materials, not only for the trial but also for the producer, can be a major limiting factor. Third, the methodology of testing is frequently different than in the temperate world, both in the cultural practices used and in the characteristics evaluated. Each of these points will be elaborated in the following paper, placing particular emphasis on the situation in Southeast Asia.

### Species to be tested

The choice of species selected for cultivar testing is usually based on which kinds of vegetables are grown in the area of interest to the experimenter. Thus, in temperate countries, the choice is readily made based on statistics of vegetable production or common knowledge. In many tropical countries, however, the number of vegetable species grown can be extremely large (8, 10), for they may include not only temperate species grown at high elevations or during cooler periods, but also warm temperature crops grown at low elevations. Within this range of crops, some are grown commercially on a relatively large scale, usually in monoculture, and others (or the same ones) in small garden plots (6, 16).

The commercially important crops may be classified into types that are commonly grown in developed countries and types that are primarily adapted to and important in the tropics. The former would include many temperate vegetables such as cauliflower, cabbage, snap beans, onion, garlic, pepper, eggplant, tomato, cucumber, lettuce, carrot, etc. In the latter class, in Southeast Asia, might be "kangkung" (*Ipomoea aquatica* Forsk.), *Amaranthus*, yard-long beans [*Vigna unguiculata* (sesquipedalis group) L. Walp.], bitter melon (*Momordica charantia* L.), and many others (8). A somewhat different list of locally important crops are found in other tropical areas, such as West Africa (11).

Cultivar evaluation of the commercial crops requires that the researcher choose a location and/or season of the year that provides a temperature and rainfall environment similar to that where the crop is being grown commercially. Locations for these trials may be difficult to find because of relative scarcity of research stations and personnel. Accessibility of such sites may be limited by poor roads or inadequate travel funds. Familiarity with common production techniques is also necessary to make sure that the testing methods are not exposing the cultivars to unrealistically high pressures of diseases and insects or, conversely, requiring a more complete control of pests than growers are able to obtain. The lack of inputs



Table 1. Bacterial wilt development and yield of 10 AVRDC lines in two successive trials at Bogor, Indonesia planted 50 days apart.

AVRDC lines	Plants wilting at 7 weeks (%)		Marketable yield (kg plant)	
	First	Second	First	Second
C1 143-0-10-3-0-1-10	3.3 ab <sup>2</sup>	30.0 ab	0.39 c	0.67 ab
C1 1131-0-0-43-8-1	0 a	20.0 ab	0.42 c	1.07 b
C1 1131-0-0-7-2-0-11	6.7 abc	36.7 ab	0.31 abc	0.42 a
C1 1131-0-0-13-0-6	10.0 abc	80.0 abc	0.28 abc	0.28 a
C1 1131-0-0-65-13-0-1	0 a	40.0 ab	0.36 bc	0.45 a
C1 5915-93D <sub>4</sub> -1-0	3.3 ab	0 a	0.32 abc	0.50 ab
C1 5915-153D <sub>4</sub> -3-3	76.7 d	100.0 d	---	---
C1 5915-153D <sub>4</sub> -3-4	46.7 cd	100.0 d	0.07 a	---
C1 5915-222D <sub>4</sub> -0-2	50.0 cd	96.7 cd	0.19 ab	---
C1 5915-229D <sub>4</sub> -1-4	63.3 cd	96.7 cd	0.14 a	---
Intan (Control)	6.7 abc	36.7 ab	0.45 c	0.51 ab

<sup>2</sup>Values in a column separated by HSD,  $P = 5\%$ .

such as pesticides, fertilizers, water, and land preparation equipment is a frequent limiting factor in vegetable production areas in developing countries, as is the lack of irrigation facilities.

With the wide range of environments possible in the tropics because of changes in elevation or location relative to mountains, etc., cultivar trials are frequently also adaptation trials that test whether particular vegetables can be grown in areas for which they were not originally developed. Thus, there is probably a greater need for preliminary, small-scale trials that precede fully replicated variety tests than in temperate areas.

#### Source of planting materials

One of the most frequently voiced constraints to vegetable production in the tropics is the lack of availability of good planting materials. In the Philippines, Ho (9) quotes estimates that 61% to 75% of the vegetable seed requirement of the Philippines is imported. A similar situation appears to exist in Malaysia (13) and Indonesia (9). In part this is because the countries may lack the cool weather conditions necessary to induce cold-requiring vegetables to flower. In addition, the specialized techniques of production for seed, harvesting, and processing to maintain high quality may be lacking. Finally, farmers find it difficult to produce seed as economically as can be supplied by countries like China (12) or the United States (11), where large-scale specialized seed produc-

tion is carried out.

As a result of this lack of local seed production, vegetable producers are forced to rely on seed merchants who may have very little control over quality and adaptation of the cultivars imported. Typically, the number of cultivars of any one crop available for sale is small.

In addition, seed viability may be low by the time of purchase. While most vegetable seed from major seed companies is shipped in moisture-proof containers, it usually must be divided into smaller lots for resale by the merchants. Seed of several vegetables rapidly loses both germination and vigor if repacked into paper packets and stored under ambient lowland tropical temperature and humidity (3). On the other hand, repacking into cellophane-aluminum-polyethylene-laminated packets can maintain high seed quality for more than 10 months under the same conditions, but this is seldom done at present.

There are several implications of these problems to persons conducting cultivar trials. Cultivars chosen to be included in trials should include those likely to be available to local growers. Any other cultivar should be chosen with some prior thought of how seeds showing superior performance would be made available to growers. It may be useful to conduct cultivar trials cooperatively with major seed distributors in a country, asking them to supply planting materials for the trials, and making sure that they see the trials at time of harvest.

Table 2. The fresh weight and number of pods of four "yard-long" bean cultivars grown on five different trellis.

Cultivar	Trellis type <sup>a</sup>	Pods/m <sup>2</sup> (no.)	Fresh wt /m <sup>2</sup> (g)	Change from control (A <sub>1</sub> , %)
1019	A <sub>1</sub>	41.0	498	---
	A <sub>2</sub>	36.9	471	-5.4
	A <sub>3</sub>	49.4	664*	+33.5
	A <sub>4</sub>	35.5	384	-22.8
	A <sub>5</sub>	31.1	340	-31.6
2830	A <sub>1</sub>	43.8	374	---
	A <sub>2</sub>	41.4	340	-8.9
	A <sub>3</sub>	79.5**	618**	+65.3
	A <sub>4</sub>	48.8	412	+10.1
	A <sub>5</sub>	52.4	314	-15.9
Darmaga	A <sub>1</sub>	28.5	321	---
	A <sub>2</sub>	26.1	286	-10.7
	A <sub>3</sub>	29.2	305	-5.0
	A <sub>4</sub>	22.0	233	-27.5
	A <sub>5</sub>	17.6	166*	-48.2
Cihideung	A <sub>1</sub>	26.0	349	---
	A <sub>2</sub>	31.1	439	+25.8
	A <sub>3</sub>	26.4	360	+3.3
	A <sub>4</sub>	32.2	446	+27.9
	A <sub>5</sub>	19.7	211	-39.6

<sup>a</sup>A<sub>1</sub> = control, bamboo poles 1.5 m high, A<sub>2</sub> = bamboo poles 2.5 m high, A<sub>3</sub> = raffia strings from horizontal poles, A<sub>4</sub> = plastic strings from horizontal poles, A<sub>5</sub> = corn stalk supports.

\*Significantly different from the control (treatment A<sub>1</sub>) at  $P = 5\%$  and  $1\%$ , respectively, using Dunnett's test.

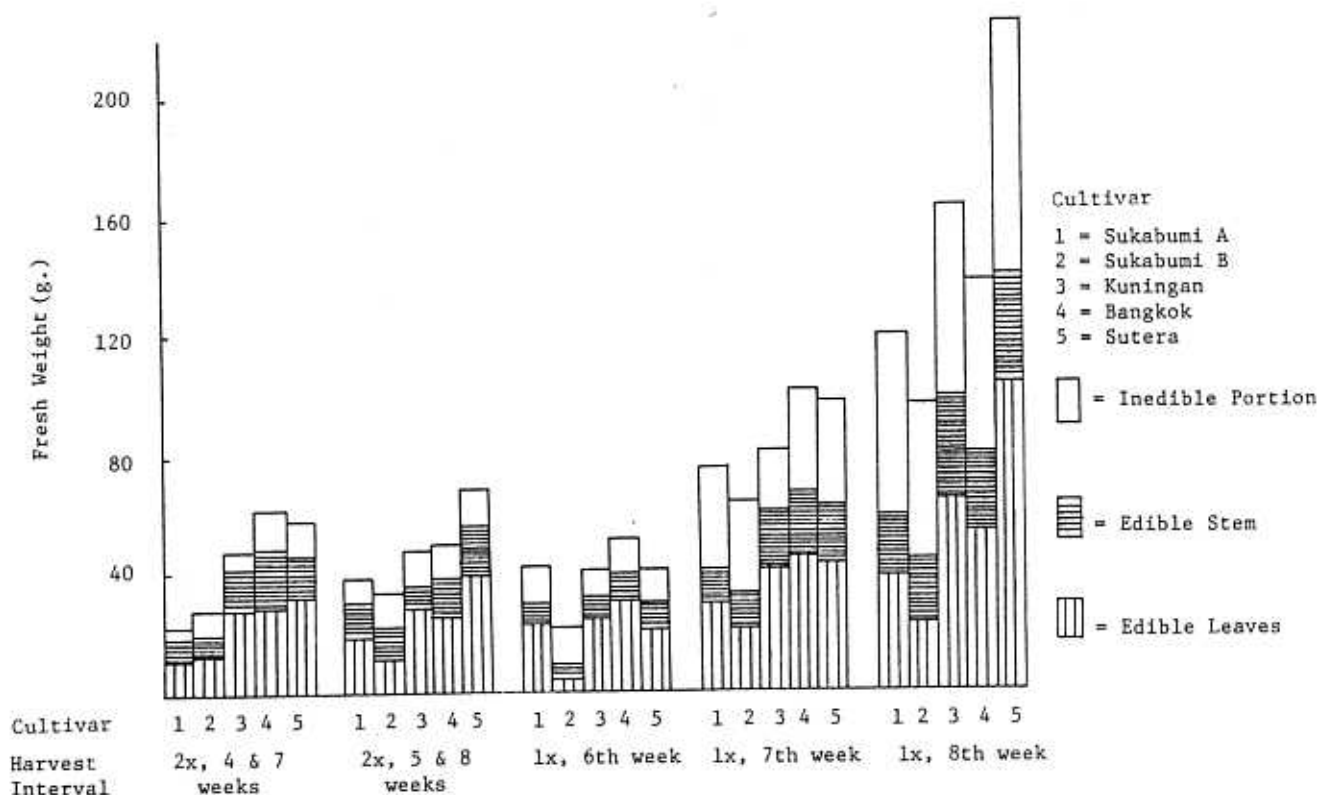


Fig. 1. Yield of edible and inedible portions of five cultivars of kangkung as influenced by timing and frequency of harvest.

Poor seed quality may be due to low germination, lack of seed purity, inclusion of foreign materials, broken seeds, etc. National seed testing and certification services designed to give growers an assurance of seed quality do not yet exist in many developing countries. Malaysia had plans in 1976 (4) to set up such a service. Such service in Indonesia is still focused on major food crops and not vegetables. Thus, local seed production enterprises, unless they voluntarily conform to guidelines of seed quality, potentially could produce lower-quality seed.

Production of high-quality vegetable seed already is practiced widely in Southeast Asia. Soo (11) describes the local production of okra seed in Malaysia. As labor wage rates increase in Japan and Taiwan, international seed companies are turning increasingly to other countries (such as Thailand and Philippines) for production of hybrid seed of tomatoes (ref. 13; B. Rowell, personal communication). In Indonesia, Sluis and Groot had cooperation with a local company to produce hybrid seed of vegetables and ornamentals for the European market. The mechanism and the experienced growers for seed production exist, but need to be harnessed to produce seed of adapted cultivars. Vegetable cultivar tests can play an important role in identifying cultivars that have adaptation and good yield in tropical environments.

Planting materials of vegetable crops commonly propagated vegetatively present special problems both to the person engaged in cultivar trials and to the grower. Because of quarantine regulations and fears of introducing diseases or insect pests, little planting stock

other than seeds is allowed to be imported into most countries. This lack of stock sharply limits the number of cultivars that are available for testing of vegetatively propagated crops such as garlic, kangkung, sweet potato, and many of the indigenous vegetable species such as *Moringa oleifera* Lam. (horse-radish tree, malunggay) and *Sauropus androgynus* Merr. Much more work is also needed to identify and distribute superior cultivars of these crops within countries.

For some crops, unavailability of seed of adapted hybrid cultivars has led to some innovative vegetative propagation techniques, for example, using tissue culture at the farm level (14). In the Dalat highlands of Vietnam, growers are currently propagating cabbage by tissue culture and by rooting of cuttings, since lack of foreign exchange has prevented seed importation.

#### Types of vegetable cultivar trials in Southeast Asia

As in many parts of North America, much of the vegetable cultivar testing in Southeast Asia is concentrated at experiment stations and agricultural colleges. There appears to be little coordinated testing. In the Philippines, however, a national cultivar testing program for vegetables was initiated in the late 1970s, and was coordinated by J. Deanon at Univ. of the Philippines, Los Baños (15, 16). In Indonesia, extensive cultivar testing is coordinated by the Directorate General of Food Crops Production and is conducted by extension agents throughout the country. Such multilocation tests are conducted by extension workers. At the Horticulture Experiment

Table 3. Shoot fresh weights of five *Amaranthus* species accumulated over three harvests (sample of six plants).

Species	Fresh wt (g)		
	Leaves and shoot	Stems	Inflorescence
<i>A. gracilis</i>	1097.0 b <sup>a</sup>	616.0 b	35.7 b
<i>A. tricolor</i> (green)	766.4 a	546.9 ab	21.7 ab
<i>A. tricolor</i> (red)	840.9 ab	418.1 ab	25.0 b
<i>A. caudatus</i>	633.4 a	275.4 a	0.0 a
<i>A. paniculatus</i>	772.4 a	395.0 ab	0.0 a
<i>A. dubius</i>	1679.9 c	1233.2 c	0.0 a

<sup>a</sup>Values in a column separated by HSD, *P* = 5%.

Station, newly introduced cultivars or lines are screened for adaptation to tropical conditions.

In their efforts to improve the yield, adaptation, and pest resistance of six vegetable crops (soybean, mungbean, tomato, Chinese cabbage, sweet potato), plant breeders at the Asian Vegetable Research and Development Center (AVRDC) conduct an extensive series of collaborative trials in a number of tropical countries, with heaviest emphasis on Southeast Asia. Typically, such trials compare the performance of several advanced breeding lines from AVRDC with local checks supplied by the cooperator. This may provide the local researcher with new cultivars with local adaptation and gives the breeders feedback on their cultivar development efforts.

As in the temperate areas of North America, the coordination of cultivar testing could probably be increased, with exchange of trial results and planting stocks of especially promising cultivars.

### Methodology of cultivar testing

Although seeds of vegetables from a number of international companies are sold in the tropics of Southeast Asia, there are frequently problems of adaptation and disease resistance of the cultivars sold. These problems are particularly true of tomatoes, for which fruit set at high temperatures and resistance to bacterial wilt are major limiting factors in the lowland tropics (15). Intensive breeding and selection programs to overcome these problems at AVRDC have resulted in a number of promising lines, which are being tested in Indonesia and elsewhere (1). Unfortunately, severity of bacterial wilt varies from one planting to the next, and is much influenced by weather conditions (17). In addition, there are several races of the pathogen. As a result, it is difficult to get consistent disease ratings, and extreme fluctuations occur in yield from one trial to the next (Table 1).

Yield trials with climbing vegetables present special problems, for the type and size of trellis used for plant support can have a significant influence on yield. Five trellising methods were compared in a cultivar test of four "yard-long" bean varieties. Trellis methods tested were: 1) bamboo 1.5 m high (control), 2) bamboo 2.5 m high, 3) "raffia" strings suspended from horizontal poles, 2 m high, 4) plastic string suspended from a 2-m height, and 5) corn stalks used as poles. As indicated in Table 2, there was an interaction between the cultivar and type of trellis used. 'Cihideung' performed better with other trellises as compared to the controls. Other cultivars, notably no. 1019, performed well with all trellis types. Thus, it may be necessary to precede cultivar trials of climbing vegetables with farm surveys to ascertain the types of trellises used by local growers and compare these to improved structures, as was done in this instance. Full-scale cultivar trials would then be conducted on those structures most often used or most promising for these growers.

For leafy vegetables of indeterminate growth habit, it must be determined when and how frequently the cultivars should be harvested to produce high yields of acceptable quality. A greenhouse study with upland kangkung (*Ipomoea aquatica* Forsk.) compared the effect of several harvest dates and harvest frequencies for four cultivars (7). The results show (Fig. 1) that cultivars differed in rate of early growth. Frequent harvesting generally reduced waste, even though total amounts harvested were lower. It is necessary in trials of this type to combine quality evaluation with an estimate of productivity.

In tropical environments, it is possible to grow certain vegetables either as short-lived or long-season plants. *Amaranthus* is frequently used as a vegetable—the leaves and young shoots are consumed

and are considered to have high nutritive value. Some amaranth species are slow to flower under tropical conditions, and therefore can be harvested by repeated picking of new shoots; others are quick to flower and are harvested only once, by uprooting the plants. *A. caudatus*, *A. paniculatus*, and *A. dubius* (Table 3) are of the first type. Other species, such as *A. gracilis* and *A. tricolor* (both red and green forms), can be grown only as short-season crops since they flower within 4 to 6 weeks after sowing.

While cultivar testing in the tropics is faced with problems, many of which are unique to the tropical environment, even a small amount of good cultivar evaluation can have enormous benefits to vegetable production and consumption. As we have tried to show, there is even greater need than in temperate areas to conduct cultivar trials in cooperation with seed producers and marketers to assure a supply of good quality seed for the growers, once superior cultivars have been identified. It is also necessary to conduct such trials with a recognition of the production systems and constraints of the vegetable growers. Such recognition would help guide the choice of an appropriate local control cultivars, and would indicate whether extensive cultivar testing should be preceded by cultural practice trials.

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# Efficient Methods for Testing Vegetable Cultivars

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Horticultural scientists often use field trials to determine the value of cultivars and experimental lines in specific production areas. Questions arise as to the most efficient methods for running such trials in order to gather as much information as possible with the least cost in both time and money.

For the purposes of this paper, I will define field trials as the small-scale production of a crop using many different experimental inbreds and hybrids, and commercial cultivars (collectively referred to as lines hereafter) in order to determine the relative value of each line for traits of importance to growers and researchers. Small-scale production implies testing of lines in either single-plant, unbordered hills; small, unbordered-row plots, or medium-sized, bordered-row plots. The plot size to be used depends on the type of information needed from the trial, and will be discussed later.

Testing is done in all phases of the development of new lines. Those can be divided into early, intermediate, and advanced stages as follows. In a breeding program, the early, segregating generations ( $F_2$  and  $F_3$ ) from a cross are often tested in single-plant hills for traits having a high narrow-sense heritability ( $>50\%$ ). Quantitative traits, such as yield, usually have a low heritability ( $<25\%$ ) and are tested in small plots in the more stabilized, later generations (for example, clones or  $F_4$  inbred lines) as part of the intermediate testing stage. Trials can have more replications and larger plots as the number of families is reduced, and the amount of seed or other propagules of each becomes more abundant. In those advanced stages, the lines might be sent to other researchers and growers for evaluation in large plots over many production areas. In this review, I concentrate on the intermediate and advanced stages of testing.

## TYPE OF TRIAL

Whether to evaluate lines as single-plant hills, small unbordered plots, or medium-size bordered plots can be determined by the information needed from the trial. Plant breeders in the intermediate stages of testing usually need information on many lines, but only as relative performance on a few basic traits. For them, hills or unbordered plots are usually sufficient.

Those in the final stages of testing of only a few lines, where much accurate information on many traits is needed, should consider medium-size or large plots, perhaps even with borders (multiple-row plots). The expected gain from selection can be used to determine the type of trial to run. Wehner (27) determined that intermediate stage trials with cucumbers (*Cucumis sativus* L.) should be run using small plots harvested once, rather than single-plant hills or multiple-harvested, large plots. It was also determined that two or three replications were more efficient than one; the additional information gained outweighing the additional space and effort required.

Garland and Fehr (6) reported hill plots to be as effective as row plots for yield trials in soybean [*Glycine max* (L.) Merr.]. The two methods had high phenotypic correlations and similar heritabilities. Others (7, 13, 17, 24) have evaluated different plots types in order to determine the optimum for trials in various crops.

Different testing methods can be compared using the ratio of the gain from selection as done for wheat (*Triticum aestivum* L.) by Kramer et al. (12). Eq. [1] is an example used for comparing a rapid (R) with a main (M) type of trial method:

$$\frac{CG}{G} = \frac{G_R \cdot b_{G(M) \cdot G(R)}}{G} = \frac{k_R \cdot h_R \cdot r_{G(M) \cdot G(R)}}{k \cdot h} = \frac{k_R \cdot r_{P(M) \cdot P(R)}}{k \cdot h^2} \quad [1]$$

where CG is the correlated gain from selection, G is the gain from selection,  $b_{G(M) \cdot G(R)}$  is the regression of main trial on rapid trial genotypes (lines in the trial), k is the selection intensity,  $h^2$  is the broad-sense heritability [ $\sigma_G^2 / (\sigma_G^2 + \sigma_E^2)$ ], h is the square root of the broad-sense heritability,  $r_{G(M) \cdot G(R)}$  is the correlation of main trial and rapid trial genotypes, and  $r_{P(M) \cdot P(R)}$  is the correlation of main trial and rapid trial phenotypes.

The last step in the equation is derived using the relationship shown in Eq. [2], which assumes a covariance of environments for the main trial and rapid trial ( $\sigma_{E(M) \cdot E(R)}$ ) of zero:

$$\begin{aligned} r_{P(M) \cdot P(R)} &= \frac{\sigma_{P(M) \cdot P(R)}}{\sigma_{P(M)} \cdot \sigma_{P(R)}} \\ &= \frac{\sigma_{G(M) \cdot G(R)}}{\sigma_{G(M)} \cdot \sigma_{G(R)}} \cdot \frac{\sigma_{G(M)} \cdot \sigma_{G(R)}}{\sigma_{P(M)} \cdot \sigma_{P(R)}} \\ &= r_{G(M) \cdot G(R)} \cdot h_R \cdot h_M \end{aligned} \quad [2]$$

In the equations,  $\sigma_G$  is the square root of the genotypic variance,  $\sigma_P$  is the square root of the phenotypic variance,  $\sigma_{G(M) \cdot G(R)}$  is the covariance of main trial and rapid trial genotypes,  $\sigma_{P(M) \cdot P(R)}$  is the covariance of main trial and rapid trial phenotypes, and other terms are as defined previously.

According to Eq. [1], the advantage of the rapid trial over the main trial can be calculated using the ratio of selection intensities for the two methods ( $k_R/k_M$ ) times the phenotypic correlation between the trials ( $r_{P(M) \cdot P(R)}$ ) divided by the broad-sense heritability for yield in the main trial. Correlations and heritability can be measured from field data where both types of trials are run. Selection intensity depends on the number of lines that can be evaluated using each trial method with the same resource inputs for all.

## EFFICIENT METHODS

**Plot shape.** During the intermediate and advanced stages of testing, lines usually are grown in plots. Therefore, the first method I will discuss for improving the efficiency of trials is optimum plot shape and size. Several decades ago there was much interest in optimum plot shape and size for field testing of various crops. It was determined that a rectangular plot shape was best, in many cases, for minimizing variability due to field environment. Christidis (3) reported that long, narrow plots were more likely than square plots to span irregularities in soil and slope in a field, and therefore would expose each plot to a more similar environment. Where there is no prior knowledge of field variability, rectangular plots generally will increase the variability within, and decrease the variability among, plots. That is the objective in most experiments where within-plot variability is not of any interest, but among-plot variability contributes to experimental error. In peas (*Pisum sativum* L.), plots consisting of  $3 \times 3$  units of the basic size had 27% larger cv for yield than those of the same size, but shaped as  $1 \times 9$  units (31).

In order to make replications or blocks (complete or incomplete) as uniform as possible, it is recommended that they be square. Square blocks will cover the smallest field area, thus reducing the heterogeneity of environment (soil, fertilizer, topography, rainfall). The use of small, square blocks will decrease variability within, and increase variability among, blocks. This is the ideal situation, since variability among blocks is removed from treatment effects during the analysis of variance.

If nothing is known about a particular field, then trials should have rectangular plots in square blocks for best control of environmental variability. If there is a known gradient of soil variability, moisture availability, or other environmental factor, then replica-

tions should be designed to take advantage of this. For example, rectangular blocks should be placed with their long axis perpendicular to the direction of the gradient.

**Plot size.** It is more difficult to generalize about optimum plot size than shape. However, Smith (18) developed an equation that has been useful in estimating optimum plot size. In a uniformity trial having plots of a basic size (the smallest definable unit), the variance of the plots would be  $V_1$ . The mean of a random sample of  $x$  units would therefore have a variance as shown in Eq. [3].

$$V_{\bar{x}} = V_1/x \quad [3]$$

If contiguous plots were combined, they would have variance as shown in Eq. [4].

$$V_{\bar{x}} = V_1/x^b \text{ for any } b \text{ from } 0 \text{ to } 1 \quad [4]$$

Taking logarithms of both sides, Eq. [4] becomes Eq. [5]:

$$\log(V_{\bar{x}}) = \log(V_1) - b \log(x) \quad [5]$$

Eq. [5] cannot be derived through mathematics, but has been shown useful for many different trials of various crops as summarized by Smith (18), and is known as "Smith's law".

Pearce (16) used computer modeling to show that Smith's law works for all practical sizes of agricultural field plots. Parameter "b" is an index of the degree of correlation between neighboring plots, and is known as "Smith's b". When there is much environmental heterogeneity, the correlation between neighboring plots usually will be small, making b large. However, b also can be large when a field is extremely uniform, since adjacent plots would not be correlated under such conditions (1). The slope of a regression of  $\log(V_{\bar{x}})$  on  $\log(x)$  provides a negative estimate of Smith's b ( $-b$ ).

Smith's b can be estimated using data from uniformity trials where all plots are the same size (usually the smallest reasonable unit) and are all planted with a single line. It is also possible to estimate optimum plot size from trials involving different treatments arranged in various experimental designs (randomized complete block, split plot, lattice, and others), providing a method that is easier than running a separate uniformity trial (8, 11). Methods of estimating b were reviewed by Swallow and Wehner (22).

Two problems arise in the analysis of data for optimum plot size, regardless of the method used: Smith's uniformity trial or Hatheway and Williams' general experiment. First, large plots are made up by combining adjacent small plots, so the variance among means of large plots is not as well estimated as for small plots. Second, because the same data are recombined in different ways to estimate variances of plots of different sizes, the points used to fit the line are not independent. Hatheway and Williams (8) reported a method to obtain the best linear unbiased estimate of b using generalized least squares.

In order to determine optimum plot size, an estimate of the cost is needed. Large plots provide more information per plot than small plots, but that advantage disappears when costs are considered. Costs per plot may be divided into:  $K_1$  = cost per plot for costs that do not depend on plot size; and  $K_2$  = cost per unit area for costs that increase with plot size. An example of costs per plot for cucumbers harvested once-over is given by Swallow and Wehner (22). Cost values then are combined in order to calculate a total cost (in worker-hours) as follows:

$$\text{Total cost per plot} = K_1 + K_2x \text{ for plots of size } x \text{ units.} \quad [6]$$

Optimum plot size can be estimated by combining Eqs. [4] and [6] as follows:

$$\begin{aligned} \text{Information} &= 1/\text{variance}^{-1} = 1/(V_1/x^b)^{-1} = x^b/(V_1)^{-1}, \\ \text{Cost per unit of information} &= (K_1 + K_2x)/(x^b/V_1)^{-1} \\ &= V_1(K_1 + K_2x)/(x^b)^{-1} \end{aligned} \quad [7]$$

Setting the derivative of equation G with respect to x equal to zero

and solving for optimum plot size ( $= x_{opt}$ ), we find:

$$x_{opt} = bK_1/[(1-b)K_2]^{-1}. \quad [8]$$

The value of  $x_{opt}$  is in multiples of the basic plot size (x).

**Plot borders.** Experiments and trials always should be surrounded by guard rows in order to provide competition to the plants on the outside plots of the field. Guards usually will consist of plots at the end of each row, rows on each side of the field, and a row on each side of rows inside the trial, which are left unplanted to permit spray equipment into the field. The guard rows also will take accidental abuse (uneven irrigation at the edge of the field and traffic that may accidentally run over plants near the edge), increasing the uniformity of the plots where data are collected.

However, the question arises as to whether borders should be used on each plot so that the line planted there will be surrounded by plants of the same line. Only the center row(s) is harvested in a bordered (three or more rows) plot, so the trial is a more realistic approximation of the monoculture production conditions of commercial production. The alternative is to have unbordered plots with different lines in adjacent rows. Trials run with unbordered plots take much less space, and are often the only choice in the early stages of cultivar development when supplies of seeds or other propagules are limited.

Unbordered (single-row) plots are acceptable if there is no interaction of line performance with border rows. Those interested in determining the necessity of using bordered plots should run trials for the crops and locations of interest. Experiments run using different lines in border rows show significant interaction in some cases. For example, wheat trials run using tall or dwarf lines only do not need bordered plots, whereas trials with both tall and dwarf wheats together should be run with borders (9). A similar result was found for tall and dwarf cucumber lines in multiple-harvest trials (28).

An additional question arises as to the necessity for using unharvested end-borders on each plot row. Often, plots are separated at each end by alleys to allow access for data collection or to make it easy to plant (changing lines in the planter while the machine is traveling through the part of the row designated as the alley). If plots do not touch others at each end, the yield of the plot is usually inflated by the lack of competition. The solution is to have unharvested plants at each end of the plot. However, plots without end-borders are easier to harvest and use less seed in a trial.

Plots without end-borders can be used if there is no interaction of line with border (i.e., all lines are inflated by about the same amount in yield when competition is reduced at the plot end). There was an interaction of end-border with line in soybean that was attributed to differences in maturity (30). Thus, in soybean trials, end-borders should be used on plots and should be removed by end trimming before harvesting. In cucumbers harvested once-over, there was no significant interaction of yield with end-border in the trials run in three environments in North Carolina (26).

If studies show that end-borders are needed for the crop and location of interest, an alternative method is to plant a different species at the ends of each plot that is easy to identify and to separate from the harvest area, but that still provides competition for the lines tested. R.L. Lower (personal communication) has used squash (*Cucurbita pepo* L.) end-borders for cucumber plots being tested for yield in the eastern U.S.

**Experiment size.** For those who run performance trials every year, it is useful to optimize the number of replications, locations, seasons (or planting dates), and years used to test the lines before making a decision. It is also useful to know the optimum experiment size when planning an experiment to gather information where resources are limited. A researcher interested in knowing the minimum number of replications to use in a trial where he or she would like to obtain significant differences among lines can use the formula for calculating Fisher's LSD:

$$\text{LSD} = t_{0.05, \text{error df}} \times (2 \times \text{EMS}/r)^{-0.5} \quad [9]$$

where LSD is Fisher's least significant difference,  $t$  is Student's  $t$ , EMS in the error mean square from a previous experiment, and  $r$



is the number of observations per treatment mean. The formula can be solved for  $r$  to determine the number of replications to use to obtain a particular LSD among lines in the trial:

$$r = t^2 \times 2 \times \text{EMS} \cdot (\text{LSD})^{-0.5} \quad [10]$$

A more interesting problem is to determine the optimum distribution of plots over years, seasons, locations, and replications. The optimum experiment size has been estimated for nested designs (14), as well as crossed designs using tobacco (10), cotton (15), maize (20), and peach (25). Generally, it has been found that it is better to distribute test units to extra years, followed by seasons (or planting dates) and locations, rather than to extra replications within an environment. Optimum distribution can be determined by growing one representative sample of lines in a trial over several years, seasons, locations, and replications. Variance then is partitioned into components due to genotypes, years, seasons, etc., as shown in Eq. 11:

$$V_{\bar{e}} = \frac{\sigma^2_{GY}}{y} + \frac{\sigma^2_{GS}}{s} + \frac{\sigma^2_{GL}}{l} + \frac{\sigma^2_{GYS}}{ys} + \frac{\sigma^2_{GYL}}{yl} + \frac{\sigma^2_{GSL}}{sl} + \frac{\sigma^2_{GYSL}}{ysl} + \frac{\sigma^2_{\epsilon}}{rysl} \quad [11]$$

where data are collected over  $y$  years,  $s$  seasons,  $l$  locations,  $r$  replications, and  $g$  genotypes (or lines). It is possible to determine the optimum distribution of experimental units by changing the number of years, seasons, locations, and replications using Eq. [11] and the variance estimates from the experiment. Wehner and Swallow (29) used a model consisting of 2 years, 2 seasons, 2 locations, and 2 replications (a total of 16 plots per line) for cucumber to determine the optimum distribution of plot units. For measurement of both fruit yield and quality, the best distribution made use of additional seasons, next in importance were years and locations, additional replications were least efficient.

A final consideration is the cost of distributing treatment units toward years, seasons, and locations and away from replications within environments. It can be expensive to make use of different test locations, and a breeding program can be delayed considerably by using several years for collecting trial data. Therefore, cost considerations can be used in determining optimum experiment size in the same way that they are used to determine optimum plot size. When that is done, information relative to cost is often maximized by using relatively many seasons and locations, and relatively few years and replications (23).

**Optimum test environment.** Some test environments show differences among lines in a performance trial better than others. Thus, it is often possible to identify location-season combinations that separate lines with the use of few replications relative to other environments. A measure of environmental value is the variation among lines for each environment. This can be measured using one set of lines in a test involving several years, seasons, locations, and replications. The best environments will have a large standard deviation of lines. Fasoulas (5) proposed an index to identify the environments that separate lines best. His index uses differences among lines in trials run in various environments to determine a differentiation index ( $D$ ), as in Eq. [12].

$$D = 200 \sum \{m[n(n-1)]^{-1}\} \quad [12]$$

In the equation,  $m$  is the number of means from which a particular line differs significantly and  $n$  is the number of lines in the trial.

Besides the capacity to determine significant differences among lines, test environments should have a high correlation with mean performance of lines over all environments. This relationship can be measured using a Pearson product-moment correlation, or by running a cluster analysis to determine which environments are clustered most closely with the environmental mean. Environments in which the lines remain in similar order and have similar performance to the environmental mean will be clustered together. The environment with the greatest standard deviation for lines then should be chosen from that cluster.

An alternative to the use of a standard deviation index is to use

regression of line performance at each environment on mean performance of lines over all environments (2). Thus, the slope of the regression curve for each environment indicates the ability to discriminate among lines. Environments would then be selected (one from each cluster of similar environments) that had the greatest slope (largest absolute value of  $b$ ).

## TRIAL MEASUREMENT

**Stability.** Certain traits are much more stable to measure than others. For example, yield in cucumber should be measured in once-over trials as fruit number rather than as weight or value (4) because fruit number is constant for a longer time than the other yield traits, so is less dependent on the date of harvest. Fruit number also has a higher heritability (0.17) than fruit weight (0.02), yet is highly correlated (genetic correlation = 0.87) with weight (19).

The stability of several traits that all estimate the same thing can be checked to determine which is best using measures such as the cv. The trait with the lowest cv in a series of trials should be used in place of other similar traits. Another quick check for usefulness is to calculate the range and Fisher's LSD over lines in a trial. Choose the trait with the lowest range per LSD, since it provides the greatest number of statistically significant differences among the lines.

**Subjectivity.** Subjective scores can be faster and easier to use than measured traits, but can be difficult to standardize among different observers. Subjective traits can be substituted where genetic correlation is high and the speed of data collection is fast compared to the measured trait. For example, a score of 1 to 9 can be used to rate cucumber fruit shape, or the number of cull fruits as a percentage of the total can be measured. Strefeler and Wehner (21) measured the genetic correlation between shape score and percentage of culls to be high in two of three cucumber populations, and shape score had a higher heritability and was faster and easier to measure than percentage of culls. Therefore, fruit quality can be improved more efficiently using the subjective trait than the measured trait.

Subjective scores can be translated into actual quantities by measuring a few plots that have been scored. However, if actual measurements are needed, or if several observers (especially if they are untrained) are rating the same trial, it may be better to take data using the measured trait.

Those who run trials annually will benefit from a consideration of efficient methods, since this will give them the most information per unit of resource spent. Efficient trials maximize one's ability to distinguish among the lines tested while minimizing the cost of running the trial.

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