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There are several potential sources of information for purposes of forecasting crop yields. One is eye estimates or appraisals made either by farmers or trained observers. Such observations may be taken at specified times during the growing season. Then, after several years' data have been accumulated, appropriate models may be established which can be used currently for converting the appraisals into yield forecasts. In the past, forecasts of crop yields in the United States have been based primarily on appraisals made by farmers. Forecasts based on historical yield and weather data are another possibility. Much research has been done to find a reliable basis for forecasting yield from current year weather data. But, in our experience, results have been far from encouraging.

In the search for more objective and more precise methods, our efforts for several years have been focused on the possibilities of forecasting yields from plant measurements. The results have been promising and, as a matter of fact, operating programs for making forecasts from plant measurements have been implemented for four leading crops, cotton, maize, wheat, and soybeans, and for several tree crops, walnuts, oranges, pecans, peaches, and filberts.

Before discussing yield forecasting and estimation from plant measurement, a brief indication of how the sample of fields and plots within fields are selected will be given. Each June a probability area sample survey is conducted which provides information on acreages planted to various crops and on livestock and other items. In this survey all fields in each sampling unit are delineated on aerial photographs and the kind of crop and acreage in each field ascertained. For each crop a subsample of fields is then selected with probabilities proportional to acreage. Within each sample field two small plots are selected, essentially by use of random co-ordinates. These plots are marked by small stakes so the same plots may be visited from time to time during the growing season to obtain the data needed for making forecasts. The plots are harvested as soon as the crop is mature for purposes of estimating yield. Immediately after harvest, the fields are again visited, using another sample of plots, in order to measure harvesting losses, that is, the amount left in the field.

The Statistical Reporting Service had in operation for the 1965 crop season a program of preharvest sampling for winter wheat, maize, cotton, and soybeans, as summarized in Table 1. Measurements for forecasting were taken on 1 May, 1 June and 1 July for winter wheat and on 1 August, 1 September and 1 October for the spring planted crops, maize, cotton, and soybeans.

For tree crops there is a major interest in forecasts several weeks prior to harvest. Preharvest sampling is not being done as this appears to offer little advantage over waiting for estimates based on growers' reports on amounts harvested, especially when the total crop is harvested within a short period. Incidentally, the amount of some crops left unpicked as a result of selective harvesting may vary considerably from year to year.

In the development of statistical models, three time periods might be considered because each presents a different kind of problem. The first is the short period just prior to harvest when the problem is limited to developing appropriate sampling and

TABLE 1. – PREHARVEST SAMPLING IN 1965

Crop	Number of sample fields	Approximate size of plots in acres[1]	Approximate size of population		Standard error of estimated yield per acre
			Acres in millions	Percent of U.S. total	
Winter wheat	2 300	0.0001	31.4	91	0.25 bu
Maize	3 000	0.0023	54.5	95	0.70 bu
Soybeans	1 700	0.0004	27.2	95	0.30 bu
Cotton	2 600	0.0015	13.9	97	7.50 lb

[1] Two plots are selected in each field.

estimation techniques as forecasting is not involved. Many are familiar with preharvest sampling, a technique that has quite generally been called crop cutting. All fields may not mature at the same time, so the dates for this short preharvest period can vary from field to field, which requires advance knowledge about when each sample field is likely to be harvested. This is known from the observations taken during the growing season and from contacts with the farmers.

The second time period might be called late season. It begins with the date when all fruit[1] has been set or the time when, if any additional fruit is set, the probability of it contributing to the yield is zero for practical purposes. Hence, for the second period as just defined, the problem can be stated as that of predicting the survival of the fruit and predicting what the average size of fruit will be at the time of harvest.

The third period is the time after the plant has developed foliage, but preceding the date when all fruit has been set.

Preharvest estimates

As already indicated, the problem of preharvest estimates is essentially one of sampling and estimation, not forecasting. A minimum of about three years should be allowed to develop and implement an operating program of yield estimates for a crop from preharvest observations. In fact, if the goal is to have a successful preharvest survey on an operational basis during the third year, a well-planned, intensive effort by experienced mathematical statisticians in this line of work is needed.

Typically, the first year's effort would be limited to a very small number of fields to obtain preliminary measures of variability for establishing size of plots and other aspects of sample design, and to develop operating instructions for a pilot survey the next year. Alternative techniques of measuring the yield on small plots would be tried. This would include consideration of various means of locating sample plots objectively and ascertaining the advantages of alternative instruments or equipment. Potential sources of error or bias would be identified and means of control considered. In addition, for developing means of estimating harvesting losses, sample plots should be gleaned after harvest. Thus the goal of the first year's effort is to develop, as fully as possible for trial the following year, sound, detailed [illegible] training plans [illegible] ensuring the quality [illegible]

The second year's effort could be regarded as an intensive and extensive pilot operation using a sample that might be one fifth or one fourth the size anticipated for a fully operational program. From the second year's experience much better information should become available on variance components and time requirements for various parts of the job so the sample design can be optimized. Quality checks on the field work should provide a basis for improvement of field procedures which must be rigorous and tightly controlled.

Experience has indicated that preharvest yield estimates (adjusted for harvesting losses) may be on a different level than estimates derived from reports from farmers. Which is correct, if either? Since potential biases are inherent in the procedures, it is important that provision be made for ascertaining the validity of the preharvest sampling and estimating techniques. The probability of selection of each plot is very small, so an unusual amount of attention must be given to avoidance of nonrandom errors. Field workers may not be completely objective in the process of locating sample plots. Or, if plots are subsampled for certain characteristics, there may be opportunity for bias in the techniques of subsampling. Also, instances may occur where the definition of the fruit to be harvested is replaced by a worker's own personal definition or interpretation.

There are various ways of getting a valid independent check, depending upon the crop. Take maize as an example. Farmers generally do not have weight measurements of the amount harvested and often have only approximate measures on a volume basis. To obtain a good independent check, special arrangements might be made with a small number of selected farmers for getting the total weight and other relevant measurements for the entire crop harvested from particular fields. Sample plots in these fields should be selected and harvested using procedures identical to those used in the survey. The number of plots would need to be large enough to give estimates having low sampling error so that any appreciable bias can be detected. Adjustments may be necessary for such factors as differences in moisture percentage at the time of the preharvest sampling and the time of harvest. Also, when comparing yield estimates and actual yield from the entire harvested field, one should be on the alert for inconsistencies in concepts of acreage. One of the problems arises from the possible difference between the actual land area of the field from which sample plots are selected and what a farmer reports as the acreage in a field.

For purposes of sampling, it is often useful to treat yield as the product of factors such as yield per plant and number of plants per acre, or, in the case of cotton, for example, as the product of weight per boll, the number of bolls per plant, and the

[1] In this paper "fruit" is used in a botanical sense and includes buds, blooms, or other developing parts that have potential for contributing to the fruitage, that is, the product for harvest.

number of plants per acre. Some factors are simple and inexpensive to measure, while others may be time consuming or difficult to measure accurately. A good example is the counting of cotton plants in contrast to picking cotton or counting the fruit on a cotton plant. An optimum sampling plan considering time and variance components may call for counting of all plants in a two-row plot 20 feet long, whereas observations such as detailed fruit counts might be limited to only a few plants in a plot.

Matters of sampling design could be discussed at length; being stressed, however, is the importance of a balanced effort giving rigorous, tightly controlled procedures regarding all important sources of error. Experience has indicated that inherent biases can be eliminated or controlled effectively by intensive training of the field staff, close supervision, quality checks, and providing clear, concise, well-defined field procedures; but astute observation is essential for the identification and control of factors affecting the quality of results.

Some advantages of preharvest sampling

Estimates derived from preharvest sampling are available earlier than estimates from postharvest farmers' reports. Prior to harvest, a farmer can report only his appraisal of the crop prospects. On the other hand, estimates based on preharvest sampling must be based on average harvesting losses or delayed until such time as harvesting losses can be determined from gleaning sample plots after harvest.

In addition to the advantage of objectivity, preharvest sampling provides a means of getting much valuable information that cannot otherwise be easily obtained. By means of laboratory analysis of samples taken from fields, information on various attributes of crop quality can be made available. Crop quality, components of yield, and harvesting losses can be related to varieties, cultural practices, weather, and other factors. Also, if deemed worthwhile, information on some types of insect damage, such as the number of ears of maize damaged by maize earworms, can be readily obtained.

Late season forecasts

Forecasting the yield of a crop at periodic intervals during a growing season is obviously much more difficult than estimating yield at time of harvest. It is necessary to discover plant characteristics which may be used to predict components of yield. Forecast formulas must be based upon observable plant characteristics and a comprehensive knowledge of the fruiting behavior of the crop. The formulas must translate plant characteristics observed on any date into accurate forecasts. In contrast to the development of a program for preharvest sampling, any time schedule for developing and perfecting forecasting procedures is much more tenuous. A major reason for this is the necessity of having "between years experience" for the formulation and testing of models. In fact, one may continue to use more than one model for a particular crop after a forecasting program becomes operational in order to give the most promising alternatives a longer time test.

Prediction of number of fruit

It is known that the probability of survival is related to maturity of the fruit, which suggests the following simple model, assuming no weighting because of variation in sampling rates is involved:

$$N = \Sigma p_i N_i$$

where N_i = number of fruit per plot in the ith maturity category,

P_i = probability that a fruit in the ith maturity category will survive and contribute to the fruitage,

N = estimated number of fruit that will be on the plants per plot at the time of harvest.

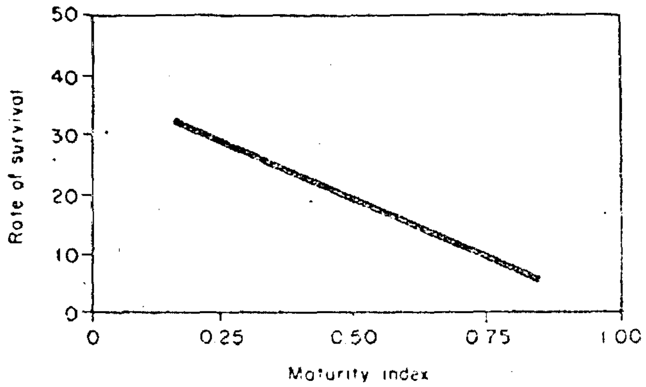
The probability, P_i, is a function of time, that is, the probability of survival for a small cotton boll on 15 August, for example, is not the same as the probability for a small boll on 15 September. Incidentally, our general experience suggests, at least for some crops, that an index of the crop's stage of development may provide a better time reference than a calendar date. More will be said on that point a little later.

The problem of defining maturity classes differs widely among the various crops. Cotton, for example, has clearly demarcated stages. A trained observer can accurately classify the fruit. On the other hand, the demarcation of 'maturity' categories for ears of maize is more tenuous. Consequently, a major, skilled effort is required to establish standards, training, and supervisory procedures for achieving uniformity of classification among field observers and between years.

To obtain adequate information on the probabilities of survival, observations need to be taken at frequent intervals during the fruiting period for several years. This can be done by noting the disappearance of [illegible] maturity categories, [illegible] does not affect the probability of survival.

After several years of experience with cotton, good information by maturity categories became available on rates of survival, that is, the fraction of the fruit that would contribute to the fruitage.

In Figure 1, the average rate of survival in relation to the stage of development of the crop is shown for squares (buds), which is one of the fruit maturity categories used in the forecasting model. The more advanced a crop is at the time of observation the lower the probability that a square will contribute to the yield. The stage of crop development is measured by an index which is the ratio of large bolls to all bolls in the sample plots. From similar relationships for other maturity categories, values for P_i in the forecasting model are obtained.



For some crops the counting of fruit by maturity categories may not be necessary. The orange crop is a good example. The forecast of the number of fruit at harvest is simply the product of the present fruit count and the probability of survival, which is a function of time. Taking maize as another example, after maize ears have silked, there is practically no disappearance of ears. Hence after silking is completed ~~the~~ forecasted number of ears at harvest is the same as the present count. However, the ears may be classified into maturity categories for purposes of forecasting ear size at harvest.

Instead of classifying individual fruit, an alternative is to classify the sample plots by maturity. Thus, with reference to the formula presented above, N_i would represent the total number of fruit in plots classed in the ith category divided by the total number of plots in the sample, and P_i would be the corresponding rate of survival derived from historical data. This would avoid the necessity of tagging fruit, which for some crops may not be practical, as a means of getting information on rate of survival. However, it appears that models based on individual fruit maturity are generally better than models based on average maturity of plots. A second alternative is to use plants as units for maturity classification rather than individual fruit or plots.

Parameters in the models must be continually updated because of changing varieties and cultural practices and the accumulation of additional information. Also, different sets of parameters may be needed by areas because of length of growing season, irrigation, varietal differences, or other factors.

Average weight or size of fruit

As in forecasting the number of fruit at time of harvest, intensive study of growth patterns of a crop is needed to develop reliable means of predicting the average size (or weight) of fruit at time of harvest. Forecasting the number of fruit is generally feasible somewhat earlier in the season than forecasting average fruit size. Thus, for the early part of the late season as defined herein, it may be better to use an historical average fruit size (possibly adjusted for trend) than to attempt a forecast from plant observations. The methods used to forecast fruit size vary with the crop but fall in one of two general categories: (1) projections made from growth curves or (2) regression models obtained by correlating observations on a given date with final size. One example of each will be cited.

Study of the growth of citrus has revealed that the relative increase in size of fruit between 1 September and harvest is nearly constant from year to year. The growth pattern follows a logarithmic curve which provides a good basis for prediction provided stage of maturity is used as a time reference rather than calendar date. Projected estimates of fruit size and number of fruit at time of harvest are converted to number of boxes, using information obtained from packing houses to establish the relationship between fruit size and number of fruit per box. Thus the yield forecasts are expressed as number of boxes.

With regard to maize, two models are used to forecast kernel weight per ear at harvest. One entails predictions by ear maturity categories from measurements of ear size. The other method involves forecasting the harvest weight from current dry weight of kernels as follows:

$$W = \frac{D}{P}$$

where W = forecasted weight of kernels per ear at 15 percent moisture,

D = current dry weight of kernels,

P = estimated proportion of current dry weight to harvest weight at 15 percent moisture. It is a function of the ratio of current dry weight to current total weight of kernels, the function having been established from historical data.

Errors of forecast

For the forecasting of crop yields from plant measurements, the Statistical Reporting Service uses essentially the same sample plots that are used for preharvest sampling (Table 1). The measurements

TABLE 2. – FORECAST AND SAMPLING ERRORS FOR COTTON [1]

Item	Year	August	September	Preharvest	
		FE [2]	FE [2]	Mean	SE [3]
Large bolls (number per plot)	1963	5.6	3.0	415	6.2
	1964	6.1	3.5	428	6.6
Boll weight (grams per boll)	1963	0.025	0.024	5.05	0.037
	1964	0.032	0.029	4.88	0.042
Gross yield (pounds of lint per acre)	1963	7.8	4.8	570	9.8
	1964	9.2	5.9	588	10.3

[1] Data are from a sample of 1,200 fields representing a region comprised of 5 states. – [2] Forecast error, see text. – [3] Sampling standard error of the mean.

taken may differ considerably from one date to another during the season. However, Tables 2 and 3 give a partial summary of the degree of forecasting success. Regarding the terms of reference used in this paper, the September forecast of cotton is a late season forecast, whereas the August cotton forecast and the May and June forecasts of wheat are early season forecasts.

The errors of forecast shown in these tables are root mean square errors computed as follows:

$$FE = \sqrt{\Sigma\,(y_i - \hat{y}_i)^2 / n}$$

where $\hat{y}_i$ = the actual yield, or component of yield, for the two plots in the ith sample field at harvest,

y_i = the corresponding forecast of yield or a component,

n = the number of sample fields, and

FE = error of forecast.

The errors of forecast do not include sampling error associated with selection of fields and of plots within fields. They reflect only between fields within years variability of the forecast component of error. Data for additional years are needed before between years' error of forecast can be adequately measured.

TABLE 3. – FORECAST AND SAMPLING ERRORS FOR WINTER WHEAT [1]

Item	Year	May	June	Preharvest	
		FE [2]	FE [2]	Mean	SE [3]
Number of heads per plot	1962	4.9	5.2	334	4.9
	1963	4.0	2.2	314	2.9
Weight per head (grams) [4]	1962	0.008	0.008	0.466	0.004
	1963	0.008	0.007	0.522	0.004
Gross yield (bushels per acre)	1962	0.655	0.661	27.9	0.42
	1963	0.582	0.442	25.4	0.30

[1] Data from a sample of [illegible] fields representing [illegible] states. – [2] Forecast error, see text. – [3] Sampling standard error of the mean. – [4] The weight may seem low [illegible] wheat grown under dry [illegible] conditions. Also the [illegible] includes those which contribute any grain whatever to the yield. Other kinds of wheat grown elsewhere in the United States have much larger head weights.

Early season forecasts

Research work on early season forecasting from plant measurements has been less extensive than for late season. For tree crops the duration of "late season" is quite long, and "early season" forecasts have not been attempted. Cotton, wheat, maize, and soybeans have received the most attention in the development of early season forecast models.

Growth patterns among different plant species are so varied that not much can be said about a general approach for finding a forecasting model. The nature of the problem obviously changes rapidly with the stage of development. An important aid in developing good hypotheses might be existing detailed data on fruiting and plant characteristics starting in advance of the first forecast date up to harvest. Such data, however, usually come from isolated studies and therefore should be regarded as unreliable for purposes of establishing models, especially values of parameters.

Some crops start fruit over a relatively long period and may have many fruit on a plant with a wide range of maturity. Cotton is a good example. For a forecast of number of fruit, when part of the fruit has been set, one approach is to add a term to the probability of survival model discussed earlier, namely, a term for additional fruit expected at harvest from fruit not set. For the 1 August forecast of cotton, the relationship between "the number of cotton bolls at harvest from fruit not set" and a maturity index is being used. To establish this relationship, fruit set at time of observation must be tagged so that bolls at harvest from fruit not set can be counted. Incidentally, another type of model for early cotton forecasts, called "the rate of fruiting" model, has been developed.[3] This model is more complex and will not be discussed here.

For wheat, the May forecast of number of heads is predicted from stalk counts using a relationship established from historical data. Weight of grain per head is related to plant density. Hence head weight is adjusted for plant density rather than using the average for several years.

It appears that an historical average weight per fruit may be a satisfactory basis for a forecast when there is control of cultural practices such as irrigation and the thinning of tree fruits so the density varies little from year to year. An historical average weight may also be satisfactory if the forecast is for a large

[3] Huddleston, H.F., and Kibler, W.E. *Forecasting cotton yields from fruit and plant characteristics.* Unpublished paper. September 1963.

area, say several states, so that the average environment for the whole area is about the same from year to year even though the environment for any given small locality may vary considerably from year to year.

Summary

The prediction of crop yields from plant counts and measurements, in lieu of farmers' reports on crop condition, has at least two major advantages: (1) by-product information that is available, or obtainable by making minor modifications, and (2) greater objectivity. Possible useful by-product information includes changes in components or attributes of yield over time and comparisons of yield characteristics among varieties or cultural practices. With regard to objectivity, forecasts based on farmers' reports are to a greater degree subject to vicissitude in human judgment. For example, farmers' appraisals tend to be conservative in a year following a poor crop. Also farmers' appraisals may not include an accurate current reflection of the impact of changes in varieties or cultural practices. Although changing farm practices may alter the parameters in the models, the impact of such changes on fruit counts and size is measured currently. We feel confident that a forecasting system based on plant counts and measurements is more responsive to changes in farm practices than farmers' appraisals.

The prediction models are still in the early stages of development. However, as results have been very encouraging, continued rapid development in the use and refinement of models is anticipated.