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INTRODUCTION

The Caribbean Industrial Research Institute (CARIRI) is engaged in a study, the purpose of which is the commercial introduction of a canned yellow-mature blackeye pea product, for wet-season production. Blackeye is traditionally a dry-season crop in Trinidad, that is harvested and sold at the dry-mature stage of maturity. Carr and Caines (1) report, however, the successful cultivation of blackeye in the wet season, at least on an experimental basis. This fact, and the fact that the alternative legumes are relatively limited in the wet season have led to the idea of cultivating blackeye at that time of year. As a wet season crop, however, blackeye has the significant disadvantage that beyond the yellow-mature stage, beans tend to germinate in the pods rendering the product unmarketable. It is at least partly for this reason that in pursuing the idea of a wet season blackeye pea product, that CARIRI opted for picking at the yellow-mature stage of maturity. More than that, however, other considerations such as taste and appearance of the processed product also point towards the selection of the yellow-mature stage of maturity. (See 3).

The need to harvest at the yellow-mature stage raises a problem of harvest programming. Unfortunately, experiments so far conducted with the California No. 5 variety reveal a distinct lack of determinacy in the time of yellow-maturing, at least under Trinidad conditions. This lack of determinacy has the important implication that multiple harvesting is a practical necessity, with the average harvest spanning a three or four week period. This contrasts with harvesting at the dry-mature stage in the dry-season, when a single harvest when the whole crop has reached the dry-mature stage, is all that is usually necessary.

At the very least, the need for multiple harvesting forces the problem of deciding firstly, what days to harvest, and secondly, the number of pickers that would be required on any given day. This paper reports on an investigation into this problem.

The paper is divided into three major parts. In Part 1, an attempt is made to describe with some degree of precision, the basic parameters and processes underlying the system under study. This then forms the foundation for Part 2, which is concerned with modelling the system. Part 3 then deals with the significance of the models developed. The paper is then concluded.

PART 1 - SYSTEM DESCRIPTION

In this part of the paper, an attempt is made to describe the system under study. It is divided into two sections. In the first, some definitions and preliminary notation are introduced. In the second, observed empirical data relating to the parameters and processes defined in the first section are reported.

DEFINITIONS AND NOTATION

In this section, I introduce some definitions and notation to describe the physical parameters and processes underlying the problem under study.

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DEFINITION 1: *Flowering pattern*: By this term is meant the number of flowers per acre appearing by day over the flowering period.

**NOTATION**: Denote by 
\[ F_t \]  
number of flowers per acre appearing on day \( t \) over the flowering period, \( t = 1, 2, \ldots \)

DEFINITION 2: *Maturation pattern*: By this term is meant the frequency distribution over the number of days it takes for a pod to yellow-mature, using date of flowering as the datum.

**NOTATION**: Denote by 
\[ m_i \]  
fraction of pods which reach yellow-mature stage on the \( i \)-th day measured from date of flowering; \( i = 1, 2, 3, \ldots \)

DEFINITION 3: *Staying pattern*: By this term is meant the fraction of pods which having yellow-matured, remains at the yellow-mature stage into a second day, third day, and so on.

**NOTATION**: Denote by 
\[ f_j \]  
the fraction of yellow-mature pods which remains yellow-mature into a \( j \)-th day from initial yellow-maturing; \( j = 2, 3, \ldots \)

DEFINITION 4: *Abortion rate*: By this term is meant the fraction of flowers which abort (for whatever reason) before reaching yellow-mature stage of maturity.

**NOTATION**: Denote by 
\[ a \]  
abortion rate

DEFINITION 5: *Yellow-mature pod weight*: By this term is meant the average weight of a yellow-mature pod.

**NOTATION**: Denote by 
\[ w \]  
yellow-mature pod weight should be given as .01118 lb. not 0.3356 lb.

DEFINITION 6: *Yellow-mature equivalent*: Observed flowering could be converted to a yellow-mature equivalent by weight, by using yellow-mature pod weight as a conversion factor. This makes use of the fact that a one-to-one relationship exists between flower and eventual pod.

DEFINITION 7: *Picking density*: By this term is meant pounds peas (yellow-mature) per acre available for harvesting.

DEFINITION 8: *Harvesting productivity*: By this term is meant average quantity (pounds) of peas picked per man-hour. This is a function (among other things) of picking density.

**EMPIRICAL DATA**

Some empirical data has been collected with a view towards establishing the values of the various parameters defined above. The results so far obtained are indicated below:
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Empirical observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Flowering pattern</td>
<td>See Figure 1 for example</td>
</tr>
<tr>
<td>2. Maturation pattern</td>
<td>See Figures 2a and 2b</td>
</tr>
<tr>
<td>3. Staying pattern</td>
<td>See Figure 3a and 3b</td>
</tr>
<tr>
<td>4. Abortion rate</td>
<td>42.0% - August, 1976 planting</td>
</tr>
<tr>
<td></td>
<td>3.4% - November, 1976 planting</td>
</tr>
<tr>
<td>5. Yellow-mature pod</td>
<td>0.3356 lbs.</td>
</tr>
<tr>
<td>weight</td>
<td></td>
</tr>
<tr>
<td>6. Yellow-mature equi-</td>
<td></td>
</tr>
<tr>
<td>valent</td>
<td></td>
</tr>
<tr>
<td>7. Picking density</td>
<td>Variable</td>
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<tr>
<td>8. Harvesting product-</td>
<td>See Figure 4</td>
</tr>
<tr>
<td>ivity</td>
<td></td>
</tr>
</tbody>
</table>

The results reported above were based upon experiments conducted at the Texaco Food Crops Farm, St. Joseph, Trinidad, during the 1975 and 1976 wet seasons. Data regarding Flowering pattern were obtained by a cross-sectional study (August, 1976 planting) in which a sample of trees was randomly selected and each tree observed daily for pods. Data regarding maturation pattern were obtained by a longitudinal study (August, 1976 and November, 1976 plantings) in which a sample of pods was randomly selected, and each pod in the sample observed daily from flowering right through to the dry-mature stage of maturity. This study provided information regarding Staying pattern and abortion rate also. Yellow-mature pod weight was obtained by simple weighing of product from a September, 1975 planting. Finally, data regarding the relationship between harvesting productivity and picking density were obtained from a semi-commercial 5-acre planting (September, 1975) by observing total man-hours worked pounds picked and acreage covered.

PART 2 - SYSTEM MODELLING

In this part of the paper, I develop the models and solution methods used to deal with the harvest programming problem of deciding (a) what days to harvest and (b) determining the number of pickers required on any given harvesting day. Firstly, a prediction model is described, by which picking density of freshly yellow-maturing peas could be predicted. Secondly a general decision model is developed, which when solved would provide a solution to our harvest programming problem. In the third section an exact method for solving our general model is provided, making use of the dynamic programming technique (see e.g. 4). In the fourth and fifth sections, approximate solution techniques are presented.

PREDICTION MODEL

The empirical data previously reported permit the implementation of a prediction model, by which picking density by day over the crop, of peas freshly yellow-maturing could be predicted. The idea is a simple one: A sample of trees is observed daily for flowers, yielding daily an estimate for flowers per tree. Using an estimate for the number of trees per acre, this is then converted to an estimate of the number of flowers per acre, which in turn is converted to yellow-mature equivalent, using an average figure for yellow-mature pod weight. This is then cast forward
into the future appropriately distributed by maturation pattern, and corrected for a-
abortions, to obtain the contribution in pounds of that day’s flowering to future fresh
picking density, by days corresponding to maturation lags. This scheme is made more
precise in the following:

**NOTATION**: Denote by

- \( Q_t \) - picking density of peas freshly yellow-maturing on day \( t \) of crop;
- \( F_t \) - flowers per acre appearing on day \( t \) of crop (flowering pattern);
- \( w \) - yellow-mature pod weight;
- \( m_i \) - (maturation pattern) fraction of pods yellow-maturing on the \( i \)-th day after flowering;
- \( a \) - abortion rate.

Using the above notation, our prediction model is the following:

\[
Q_t = \sum_{i=1}^{t} (1-a) \cdot m_i \cdot w \cdot F_{t-i+1}; \quad t = 1, 2, ...
\]

The working of the prediction formula is illustrated by figure 6.

**GENERAL DECISION MODEL**

On the one hand, reference to Figure 4 would indicate that the higher the actual picking density, the higher the harvesting productivity and therefore the lower the unit harvesting cost. On the other hand, however, reference to Figure 3a or 3b would indicate the loss of peas to a higher maturity stage, that would result if peas were not harvested the day they achieve the yellow-mature stage. We therefore have the following trade-off to make: if we were to harvest daily, we would be sure to maximize revenues, but unit harvesting cost would be maximum also; while if we were to harvest less frequently, we would reduce unit harvesting cost, but in so doing reduce revenues as well. We therefore have the problem of finding that optimum harvesting schedule where revenue net of harvesting cost is maximized. A model describing this problem is developed in this section.

**NOTATION**: Denote by

- \( y_t \) - the decision whether or not to harvest on day \( t \) of crop. It is sufficient to write
  \[
y_t = \begin{cases} 0, & \text{if it is decided to harvest on day } t \\ 1, & \text{if it is decided not to harvest on day } t \\
\end{cases} \quad t = 1, 2, ..., N.
\]
  (day \( t = 1 \) corresponds to first day of fresh yellow-maturing; day \( t = N \) corresponds to last day of fresh yellow-maturing).
- \( Q_t \) - predicted picking density of peas freshly yellow-maturing on day \( t \); \( t = 1, 2, ..., N \).
- \( X_t \) - actual total picking density of peas at yellow-mature stage available for harvesting on day \( t \); \( t = 1, 2, ..., N \).
f_j - (staying pattern) fraction of peas staying into the J-th day after first yellow-maturing, if not harvested before; j = 2, 3, 4.

Adopting the above notation, we may write the following expression for X_t in terms of the Q_t and the Y_t, as follows:

\[ X_t = Q_t \]
\[ + (f_2 \cdot Q_{t-1}) \cdot Y_{t-1} \]
\[ + (f_3 \cdot Q_{t-2}) \cdot Y_{t-2} \cdot Y_{t-1} \]
\[ + (f_4 \cdot Q_{t-3}) \cdot Y_{t-3} \cdot Y_{t-2} \cdot Y_{t-1} \]

\[ t = 1, 2, \ldots, N. \]

(Note that peas staying over one day, \( f_2 \cdot Q_{t-1} \), contribute to \( X_t \) only if \( Y_{t-1} = 1 \) indicating no harvest on day \( t-1 \); peas staying over two days, \( f_3 \cdot Q_{t-2} \), contribute only if both \( Y_{t-1} = 1 \) and \( Y_{t-2} = 1 \) indicating no harvest on both days \( t-1 \) and \( t-2 \), etc.)

The optimum harvesting sequence, as determined by our choice of \( Y_1, \ Y_2, \ldots, Y_N \), will be determined jointly by revenues from sale of product, and cost of harvesting. (Recall that our objective is the maximisation of revenues net of harvesting cost.) We therefore construct an objective function relating the objective we seek to maximize, to our decision variables, as in the following:

**NOTATION**: Denote by

- \( r \) - price per pound of yellow-mature peas harvested, in dollars;
- \( h \) - maximum number of man-hours of work constituting picker's task;
- \( T \) - Harvesting task wage in dollars;
- \( P(X) \) - harvesting productivity in pounds peas per manhour, as a function of picking density \( X \) in pounds peas per acre;

\[ P(X) = b + c.X, \] with \( b \) and \( c \) empirically estimated parameters:

- \( A \) - acreage planted
- \( U_t \) - total pounds peas available on day \( t \), from acreage planted;
- \( R(U) \) - revenues associated with sale of \( U \) pounds of yellow-mature peas;
- \( H(U,X) \) - harvesting cost associated with the harvest of \( U \) pound of yellow-mature peas, at picking density \( X \);

Using the above notation, we have the following relations:

\[ U_t = A \cdot X_t \]
\[ R(U) = r \cdot U \]
\[ H(U,X) = \{U/(h \cdot P(X)) \} \cdot T, \]
where it is to be understood that the expression in square brackets, which represents number of tasks required to harvest \( U \) pounds, at picking density \( X \) pounds per acre, is to be taken to the nearest higher integer, since harvesting cost is assumed charged at \( T \) dollars per task, or fraction thereof.

If harvesting decision \( Y_t \) (recall \( 0 = \text{harvest}, \ 1 = \text{no harvest} \)) is taken on day \( t \) of the crop, then net revenues (revenues net of harvesting cost) associated with that decision is given by

\[
(6) \quad (1-Y_t) \{R(U_t) - H(U_t, X_t)\}
\]

Total net revenues from the entire crop is merely the summation over all \( N \) possible days of harvest, as given by the following expression:

\[
(7) \quad \sum_{t=1}^{N} (1-Y_t) \{R(U_t) - H(U_t, X_t)\}
\]

This is the objective we wish to maximise.

We are now in a position to state succinctly our mathematical model.

Find the sequence of harvesting decisions \( Y_t, \ t = 1, 2, \ldots, N \), which maximizes total revenues net of harvesting cost

\[
(8) \quad \sum_{t=1}^{N} (1-Y_t) \{R(U_t) - H(U_t, X_t)\}
\]

subject to the conditions

\[
(3) \quad X_t = Q_t
\]

\[
(4) \quad R(U_t) = r_t U_t, \ t = 1, 2, \ldots, N.
\]

\[
(5) \quad H(U_t, X_t) = \{U_t/ (h_t P(X_t))\} . T, \ t = 1, 2, \ldots, N.
\]

and given

\[
(7) \quad Q_{-2} = Q_{-1} = Q_0 = 0
\]

(8) estimates for \( Q_1, Q_2, \ldots, Q_N \) as given by picking density prediction model

\[
(9) \quad P(X_t) = b + c X_t, \ t = 1, 2, \ldots, N.
\]

where \( b \) and \( c \) are empirically estimated parameters (see Figure 4).
DYNAMIC PROGRAMMING FORMULATION

The method of dynamic programming could be used to compute an exact solution to the above formulation of the problem. In what follows, the technical terminology [4] associated with this technique is employed. (See [2] for a computer routine)

Stages: the dynamic programming stages correspond to the days of the crop, \( t = 1, 2, \ldots, N \), on each of which a decision must be made whether or not to harvest.

Decision variable: the decision variable in the analysis is the same as has been previously defined:

\[
Y_t = \begin{cases} 
0, & \text{if decision is to harvest on day } t \\
1, & \text{if decision is not to harvest on day } t 
\end{cases}
\]

\( t = 1, 2, \ldots, N \).

State variable: the state variable in the analysis is the number of days gone by without harvest. Denote this by \( s \).

Transformation function: Denote by \( T(s, Y) \) the transformation function by which decision \( Y \) taken at any given stage, at the current stage to an appropriate value at the next stage.

This transformation function can be defined as follows:

\[
T(s, Y) = \begin{cases} 
0, & \text{if } Y = 0 \\
1, & \text{if } Y = 1 
\end{cases}
\]

Return function: the return function is merely the contribution to total revenues net of harvesting cost consequent upon the decision taken at each stage. Denoting the return function by \( p(s, Y_t) \), we have the following:

\[
p(s, Y_t) = (1 - Y_t) \{ R(U_t(s)) - H(U_t(s), X_t(s)) \}
\]

where the dependence upon \( s \) of \( X_t \) and \( U_t \) is made explicit, and we have:

\[
X_t(s) = Q_t \cdot \sum_{i=1}^{s} f_{i,1} Q_{t-1} \cdot \quad t=1, 2, \ldots, N.
\]

and

\[
U_t(s) = A.X_t(s)
\]

it could easily be verified that our specification for \( X_t(s) \) above is equivalent to our previous specifications in (2), when due regard is taken of the correspondence between \( s \) and the values of \( Y_{t-1}, Y_{t-2}, \ldots \).

Dynamic programming recursion: Denote by \( g_t(s) \) the value of the optimal policy for the remainder of the planning horizon, when at stage \( t \), the state variable has value \( s \);

\( t = 1, 2, \ldots, N \).

We wish to find \( g_1(0) \) and the policy which achieves it.
This may be accomplished by invoking the Dynamic Programming Principle of Optimality (see (4)) to obtain the following recursive relationship, which can then be solved by backwards iteration:

\[
g_t(s) = \text{Maximum } \left[ p(s, Y_t) + g_{t+1}(T(s, Y_t)) \right] \\
y_t \in \{0, 1\} \\
t = N, N-1, N-2, \ldots, 3, 2, 1,
\]

where

\[g_{n+1}(.) = 0.\]

**THE TWO-STAGE, BOOT-STRAPPING APPROXIMATION**

The dynamic programming formulation previously discussed provides an exact solution to the general model, in which the entire sequence of harvesting decisions could be considered all in the same analysis. The two-stage boot-strapping model assumes that this is not necessary, instead looking only one day ahead at a time. The procedure is as follows: we start from day one of crop. We would have an estimate of the picking density in the field and can therefore compute the estimated revenue net of harvesting cost if the decision were taken to harvest on that day. If we look ahead one day however, we have an estimate for the picking density likely to be yellow-maturing for the first time on that day, which coupled with what would stay over from the first day - if no harvesting were undertaken - would mean possibly higher picking density and consequently lower unit harvesting cost if harvesting is delayed. Against this however, would need to be weighed the loss of material (and therefore revenue) through over-ripening. With appropriate calculations, it is possible to decide whether net revenues from the first day’s peas would be higher on the first day or the second, with appropriate implications for the harvesting decision on the first day. A similar analysis could be conducted on the second day, third day and so on each time looking ahead only one day at a time, down to the end of the cropping period. This is the two-stage, "boot-strapping" feature which suggested the term I have used for the procedure.

This procedure is of course not necessarily optimal, being only slightly less myopic than taking each day's decision independently of any other day. The theoretical short-coming of the two-stage boot-strapping technique lies in the fact that only two alternative harvesting days at a time are considered for each day's peas. It in effect assumes that if it is better to harvest today's peas today rather than tomorrow, it is also better to harvest them today rather that the day after tomorrow. As a practical matter, this is almost always the case, but one cannot be sure unless the possibility is explicitly considered. (The staying pattern exhibited by yellow-mature blackeyes indicates that only 11% of peas remain yellow-mature into a third day, which means that in postponing a harvest until the day after tomorrow we would have to suffer a 89% revenue loss, which would hardly likely be recovered through reduced harvesting cost - hence the reason why the two-stage boot-strapping technique has yielded results identical to the dynamic programming technique).

It may also be remarked that since no peas have been observed to stay yellow-mature for as long as five days, that the general N-stage model could without loss of accuracy be converted into a series of 4-stage models. In other words, taking the optimum harvesting decision on any given day never requires one to look ahead more than four days, and as a practical matter, looking ahead only one day seems to be sufficient.

**THE SWITCHING CURVE APPROXIMATION**

If we accept the lesson of the last section that it is generally sufficient to look ahead only one day, and make the further assumptions:
(i) that the rate of yellow-maturing follows a uniform pattern; 
(ii) that fractional tasks can be paid a corresponding fractional task wage,

then we can construct a fairly simple programming device which I have called a switching curve. Basically the switching curve gives for any combination of selling price \( r \) and task wage \( T \), as expressed in the ratio \( r/T \), the level of picking density in pounds peas per acre above which daily picking is optimum and below which every-other-day picking is optimum.

Denote by

\[ Q \] - constant yellow-maturing rate in pounds peas per acre per day.

Net revenue per acre per day from daily harvesting would be given by

\[ r.Q - \frac{Q}{P(Q).h} . T \]

and net revenue per day from every-other-day harvesting would be given by

\[ \frac{1}{2} \left[ r.(Q + f_2.Q) - \{(Q + f_2.Q)/(P(Q + f_2.Q).h)) . T \right] \]

From these it follows that daily harvesting would be preferable to every-other-day harvesting if

\[ r.Q - \frac{Q}{P(Q).h} . T \]

\[ > \frac{1}{2} \left[ r.(Q + f_2.Q) - \{(Q + f_2.Q)/(P(Q + f_2.Q).h)) . T \right] \]

That is, if

\[ \frac{r}{T} > \left( \frac{1}{P(Q).h} - \frac{(1 + f_2)/(2.P(Q + f_2.Q).h))}{1 - f_2} \right) \]

Taking different values of \( Q \), the critical value of \( r/T \) can be worked out and a switching curve plotted. Figure 6 gives the switching curve in the case of \( f_2 = .67 \) (corresponding to the August, 1976 study), \( h = 6 \) and the harvesting productivity function \( P(.) \) is given by a straight line with intercept 6.40 and slope .057, corresponding to Figure 4.

The applicability of this model is limited firstly by its assumption of a uniform yellow-maturing rate. In the case where picking density is below the critical point, suggesting every-other-day picking is optimal, but yellow-maturing rate is decreasing rather than constant as assumed, the switching curve model could lead to erroneous conclusions. It could at such time be optimum not to postpone harvest. This should be borne in mind especially towards the end of crop. It is also conceivable, though unlikely, that the switching curve model could yield an erroneous conclusion in the case where predicted picking density is above the critical point, but yellow-maturing rate is increasing rather than constant as assumed. In that event, it is conceivable that the optimum decision could be to postpone the harvest to take advantage of the high picking density predicted for the following day. In both this eventuality and the one previously mentioned, a quick two-stage analysis should indicate the optimum course of action.

A second consideration limiting the applicability of this model is the assumption of continuity in harvesting cost, rather than say \$10 increments corresponding to a task wage. The implication of this is that the model would be more nearly correct for larger acreage than smaller acreages. The reason for this quite simply is
that the larger the acreage, the greater the number of pickers (tasks) required to harvest it, and therefore the smaller the relative error involved in assuming continuity in harvesting cost rather than say, $10 increments. To illustrate, suppose that for a given level of picking density, a one-acre plot would require .4 of a task to harvest. At $40 per task, the continuity assumption would put harvesting cost at $4, when in actual fact cost would be $10, a task wage, with a relative error of 150%. For an eleven-acre farm, 4.4 tasks would be required. The continuity assumption would put harvesting cost at $44 when in fact actual cost would be $50, for a relative error of 12% as compared with 50% for a one-acre farm. It can therefore be seen that the continuity assumption is more appropriate for larger farms.

PART 3 - MODEL SIGNIFICANCE

In the previous part of the paper, models and solution techniques were developed to deal with the harvest programming problem. This part of the paper will deal with the significance of this modelling, dealing in turn with (i) recommended operational procedures, (ii) remarks on the usefulness of the approach, and (iii) limitations and possible extensions.

RECOMMENDED OPERATIONAL PROCEDURES

In the previous part of the paper, three alternative solution methods were presented for the general model, viz.

(i) via dynamic programming;
(ii) via the two-stage boot-strapping technique;
(iii) via the switching curve technique.

The three solutions are not all equally 'good. The dynamic programming solution solves the general model exactly, but requires use of a computer programme. The two-stage boot-strapping technique would solve the general model exactly if it were sufficient to consider only two days at a time; however, there is no guarantee that this assumption could legitimately be made, although as a practical matter it seems to yield the same results as the exact solution. The computations are somewhat tedious, but could still be done by hand. Finally, the switching curve technique would solve the general model exactly only under the assumptions (i) that only two days need be considered at a time, (ii) that yellow-maturing rate is constant, and (iii) that harvesting cost is continuous. These three assumptions are not strictly valid, but they yield a method that is much simpler to use than either of the previous two. If used intelligently however, the switching curve technique should yield results that are good enough, and this is the technique recommended for general use.

The procedures therefore recommended for farmers to use in programming the harvest can be summarized as follows:

(i) Observe flowering pattern: Select a random sample of trees for observation, and observe the number of flowers per tree appearing each day of the crop. Convert to yellow-mature equivalent using average pod weight and an estimate of trees per acre.

(ii) Predict picking density: Using the observed flowering pattern, predict picking density of freshly-maturing blackeye using the prediction formula. A form useful for this purpose is exhibited in Figure 7.

(iii) Decide what days to harvest: Use switching curve to decide what days to harvest. If on any day predicted freshly yellow-maturing picking density is below the critical point for the appropriate combination of selling price and task cost, postpone the harvest to the next day, unless harvest had already been postponed from the previous day; if above the critical point, harvest on that day.
This procedure must be used however with some discretion; see previous discussion (p.19) for the validity of the switching curve technique.) A form useful for this purpose is exhibited in Figure 8.

(iv) Determine the number of pickers required: First use stay pattern to calculate actual total picking density, depending on the harvesting sequence adopted. Then use Figure 4 to determine number of man-hours required per acre, and hence total number of pickers required.

REMARKS ON THE USEFULNESS OF THE APPROACH

It would have been nice to be able to report cost savings effected by the adoption of the approach reported in this paper. However, this is not possible since the approach was developed to deal with what is in effect a new product for which no prior history of harvesting operations exists. Nevertheless a few remarks could be made regarding the usefulness of the approach adopted.

Deciding what days to harvest

With respect to the problem of deciding what days to harvest the alternative approach that was initially adopted was entirely experimental. The idea was to try various harvesting frequencies on various experimental plots, and choose the one for which results were best. This approach has simplicity to recommend it, but we found in the end its short-comings to be too great.

Firstly, this approach is limited in that as a practical matter, it could evaluate only fixed-frequency harvesting schedules. This does not take into account the practical possibility that the optimum harvesting frequency could change over the life of the crop.

Secondly, this approach forces us to pre-select a number of harvesting frequencies we think worthy of evaluating. If the true optimum frequency is not included in our pre-selected set of alternatives, then it would never be evaluated and hence never used. For example, in our initial experiments, we considered harvesting frequencies of 1x7 (one harvest every 7 days), 1x5, 3x8 and 3x7. It is noteworthy that subsequently observed staying pattern indicates quite clearly that 1x7 and 1x5 frequencies are entirely out of the question, and that 1x1 and 1x2 harvesting are in fact the major contenders. So that experimental effort was wasted on two alternatives (1x7 and 1x5) and the two major contenders (1x1 and 1x2) were never considered! It is also noteworthy to make the calculation that if there are 20 possible harvesting days there are 2^20 possible harvesting schedules altogether, which figure is in the order of 1 million, as compared with four pre-selected, fixed-frequency alternatives.

Thirdly, the simple-minded approach initially considered is extremely resource-consuming by comparison with the approach subsequently adopted. It is far less resource-consuming to obtain data on flowering pattern, maturation pattern, staying and abortion rate, than to carry out a replicated experiment involving a harvesting operation carried out several different ways. In this connection, it is noteworthy that this was a factor militating against the pre-selection of the 1x1 and 1x2 harvesting frequency alternatives - they would have taken too much in the way of experimental resources.

Determination of number of pickers

Remarks on methodology so far have dealt entirely with the determination of optimum harvesting schedules. A second aspect of the work reported in this paper concerns the determination of the number of pickers required on any given day of harvesting. In the absence of a reliable estimate of picking density it is difficult to estimate the number of pickers required to harvest a given acreage, or the
size of task that should be set. I would imagine that very experienced farm operators could "eyeball" a field and make relatively good guesses for the size of task to set and the number of pickers to assign to a field. The "eyeball" method has not however worked so well with blackeye, even with an experienced farm operator. What was observed during the harvest of a semi-commercial 5-acre plot planted September 1975 was that at the beginning of the harvest when picking density was low, an unrealistically high task was set, and too many pickers were employed, and then later on correcting for the initial mis-calculation, tasks and pickers were revised downwards, just at the time when an increasing picking density would have indicated the opposite. Until therefore I come across an operator who can prove the contrary, I would not recommend the "eyeball" method as the way to determine picker requirements. Apart from its inaccuracies, it has the further disadvantage that "eyeballing" must be done on the day of harvest itself, which could be too late to make arrangements for the workers required. For these reasons, I think the prediction model, coupled with the empirical curve relating harvesting productivity to picking density, should prove quite useful, regardless of the precise methods employed to come up with the harvesting schedule itself.

LIMITATIONS AND POSSIBLE EXTENSIONS

On the debit side of things, the usefulness of the approach is limited most importantly, by uncertainty. Error in the prediction model could arise from any of three sources, viz:

(i) error in estimation of abortion rate;
(ii) error in estimation of maturation pattern;
(iii) error in estimation of flowering pattern (yellow-mature equivalent).

Error in the decision model could arise from

(i) error in estimation of staying pattern;
(ii) error in estimation of the relationship between harvesting productivity and picking density.

I have not carried out a formal error analysis, but indications are that of all sources of error, abortion rate will remain the single most significant source of error, in view of the fact figures as disparate as 3.4 per cent and 42 per cent have been observed in two separate studies. Flowering pattern is to be observed separately each application, and a large enough tree sample in each case should minimize error. The other three sources of error - maturation pattern, staying pattern, and harvesting productivity - do not seem as inherently variable as say abortion rate. In two studies, maturation pattern showed little variation from one to the next. Staying pattern showed more variation but nothing alarming. Our best estimate for the relationship between harvesting productivity and picking density is so far just a straight line based on four points of data observed during a semi-commercial 5-acre harvest from a September 1975 planting. Further studies during the 1977 wet season are now underway, and include for the first time a variety of different farms. These studies should shed more light on the inherent variability to expect in the parameters discussed.

Some extensions of the general model are possible. Among these are:

(i) Uncertainty: the impact of uncertainty in the estimation of the parameters could be explicitly considered. To a large extent however, this would only be fruitful after more studies have been undertaken to establish the likely variability in the parameters;

(ii) Revenue function: the revenue function is a simple linear one that assumes that all product is sold at the same price. In the more general case, it is possible that a crop could be harvested at various stages of maturity, each stage
fetching a different price. A dynamic programming method of solution could handle this extension with little extra difficulty.

(iii) Harvesting productivity function: So far a straight-line function has been fitted. More empirical data might permit a more complex specification, but this too could readily be handled by a dynamic programming solution.

(iv) Objective function: The objective that has been assumed in the general model, is "maximize revenues net of harvesting cost". This is appropriate if the grower is separate from the processor. If they are one and the same, however, the objective should be changed to: "maximize revenues net of harvesting and subsequent costs through to processing", and revenues then refer to sale of processed product rather than fresh product.

CONCLUSION

I have in this paper reported on a model developed at CARIRI to assist in programming the harvest of wet-season, yellow-mature blackeye peas. Emphasis has been on the approach adopted, and the modelling devices which have been used. However I have reported empirical data obtained from studies so far undertaken, which are being used to implement the models in our 1977 Wet Season Blackeye Programme. These empirical data are by no means definitive. Indeed, it would only be with the undertaking of more experiments, performed under different agroclimatic and other conditions that a more complete picture of the inherent variability in the parameters would begin to emerge. In spite of these limitations, I have been encouraged to report on the work so far done. I hope that in responding to this encouragement that my judgement was not ill-founded, and that I have succeeded in bringing together into a coherent framework the major considerations affecting the harvesting of wet-season yellow-mature blackeye.

ACKNOWLEDGEMENTS

I have benefitted throughout the execution of the work on which this report is based, from comments, criticisms and discussion with the other members of the project team. These were Mrs. SHIRLEY SEARL and Mr. Edwin Skinner of CARIRI, and Dr. Richard Braithwaite and Mr. John Cropper of the University of the West Indies. I am grateful also to Mrs. Joan Sanchez of CARDI, who assisted in some statistical design work, to Messrs. Harriram and Mayers who diligently performed the field work giving rise to the empirical data reported, and to Mr. Gonzales and staff of the Texaco Food Crops Farm who grew the peas. Also, I am thankful to Mrs. Joycelyn Campbell who did a good job of typing, and good-naturedly endured the time-pressure under which she was put, and to Miss Paula Gilkes and Miss Jackie Hazlewood who helped with the figures. Finally, a debt of acknowledgement is due the Trinidad and Tobago Ministry of Planning and Development which financed the project on which this is based, and to CARIRI which provided the working facilities.

Addendum

A frequency of 3x7 which was considered is close to a 1x2, excepting that a 3x7 schedule would exclude weekend harvesting - this could be a practical necessity, but without a comparison against 1x2 harvesting, one could not evaluate the cost or profit implications of foregoing weekend harvesting.
FIG. 1 FLOWERING PATTERN - NUMBER OF PODS OBSERVED
Of 72 PRE-SELECTED TREES - TOTAL BY DAY
(AUGUST 1976 PLANTING)

FIG. 2a - MATURATION PATTERN
(AUGUST 1976 PLANTING)

FIG. 2b MATURATION PATTERN
(November 1976 Planting)

FIG. I FLOWERING PATTERN - NUMBER OF PODS OBSERVED
ON 72 PRE-SELECTED TREES - TOTAL BY DAY
(AUGUST 1976 PLANTING)
FIG. 3b - STAYING PATTERN
(November 1976 Planting)

NUMBER OF PODS REMAINING

100%

64 48.4%

31 10.9%

16%

FIG. 3a - STAYING PATTERN
(August 1976 Planting)

NUMBER OF PODS REMAINING

100%

61 67%

41 11%

16%

DAYS AT YM STAGE

FIGURE 4
HARVESTING PRODUCTIVITY VS HARVESTING DENSITY

HARVESTING PRODUCTIVITY
lbs/man-hour

PICKING DENSITY lbs/acre
RATIO OF SELLING PRICE TO TASK COST

FIG. 5 - SWITCHING CURVE DIVIDING REGIONS

For which daily and every-other-day harvesting are respectively optimum.

Pig. 5 - Switching curve dividing regions.
FIG. 6—TO ILLUSTRATE PREDICTION FORMULA

Crop

Yellow-maturity on any given day of any variety of peas becoming 
for quantity of peas becoming 

Pie 6 - To illustrate prediction formula
### Worksheet for Prediction of Planting Density of Yellow-Mature Buckeye

#### Maturation Pattern

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#### Predicted Density

- Yellow-Mature Buckeye

#### Observed Flowering

- Density

#### Predicted Planting Date

- Density

#### Planting Date

- Density

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**Figure 7**
REFERENCES

CARR (T.W.A.) and M.T.C. CAINES. - "Wet season trials with Southern Peas (Vigna sinensis) and Lima Beans (Phaseolus Lunatus)", Proceedings, 7th Caribbean Food Crops Society Meeting, Trinidad, 1969.


ABSTRACT

The Caribbean Industrial Research Institute (CARIRI) has been engaged in a study, the purpose of which is the commercial introduction of a canned yellow-mature blackeye pea product, for wet-season production. The necessity to harvest at yellow-mature stage gives rise to the following harvest programming problem : (a) what days to harvest : and (b) determining the number of pickers that would be required on any given day of harvesting. A model is proposed to resolve this problem. It consists of two parts. The first part is a prediction model which attempts to predict the quantity (pounds per acre) of yellow-mature blackeyes that would be available for picking on any given day. The second part is a decision model which takes as one of its inputs the results of the prediction model and recommends to the farmer what days to harvest and the number of pickers that would be required. A general model is constructed, an exact solution to which is offered by the method of dynamic programming. Two simpler but approximate solution methods are also described which should be more practical devices in application. Relevant concepts are defined - flowering pattern, maturation pattern, staying pattern, abortion rate, etc. and observed empirical results are reported.
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