A Framework for Studying the Supply Response of Perennial Crops

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Division Working Paper No. 1986-1
January 1986

Commodity Studies and Projections Division
Economic Analysis and Projections Department
Economics and Research Staff
The World Bank

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Summary

This paper develops a model of supply of perennial crops which is an alternative to the traditional Nerlovian model. It is argued that a cost-of-adjustment investment model in which capital is heterogeneous provides a suitable basis for a satisfactory approach to the analysis of supply. An essential element in this approach involves the specification of technology of production. In Section II a vintage production function approach is adopted which distinguishes between capital (trees) of different ages which we assume to have different productivities. Using this approach it is possible to define empirically-useful concepts of potential output and feasible output. Section III develops the cost-of-adjustment investment. It is argued that the cost component must be specified with some generality since otherwise it is likely that the model would always yield a corner solution (zero value) for removals. This will occur since removals involve incurring a cost with the potential benefit resulting only if replanting is undertaken subsequently. A cost function which allows for an interaction effect between removals and replanting is specified. The producer's optimization problem involves choice of the subset of the techniques of production and profitable vintages, the optimal amount of labor and the optimal rate of new plantings and the removal of unprofitable capital. This analysis suggests that the importance of "mothballing" or scrapping of unprofitable capital has been neglected or underemphasized in the literature. Given the nature of the first-order conditions are easy to interpret economically. Section IV discusses the econometric implications of the analysis. It is shown that a unique time-invariant long-run response of supply to an exogenous price change need not exist. The absence of a closed form solution for the decision variables will force the econometrician to rely on empirical approximations based on concepts of potential and feasible output which will inevitably lead to loss of structural information.
I. INTRODUCTION*

Econometric models of agricultural commodities make extensive use of supply response functions. Traditionally these supply response functions have been based on Nerlove's seminal contributions (Nerlove 1958). A stylized version of a Nerlovian supply model consists of:

(i) a partial adjustment equation relating the change in the area planted, $A(t)$, to the desired or equilibrium area, $A^*(t)$;

(ii) an equation relating the desired or equilibrium area planted, $A^*(t)$, to the future expected real price or profitability variable, $P^*_t(t)$; and

(iii) an equation specifying the generation of $P^*_t$, often taken to be either the adaptive expectations formulation or some more or less complex extrapolative scheme.

Applied econometric work based on such a framework is extensive (Askari and Cummings, 1977).

The model can be and has been adapted for perennial crops. However, notwithstanding the important role of the basic Nerlovian supply model in applied work, there remain a number of fundamental sources of dissatisfaction with its use for perennial crops. The first and foremost of these is the absence of an integrated theory of factor demands and production, analogous to the standard competitive supply theory, which could provide a coherent framework for analyzing the full range of decision problems confronting the

* This paper was written while on leave from The Australian National University. In writing this paper I have benefitted from comments on earlier versions by Ron Duncan, Christopher Gilbert, Marc Nerlove and participants at the EPDCS internal seminar. However, I retain responsibility for all remaining errors.
suppliers of perennial crops. That is, we need a link between the Nerlovian supply model and the "standard" supply theory which itself must be modified in several ways if it is to serve as a satisfactory vehicle for explaining the peculiar characteristics of perennial crops. Fundamentally, the supply theory for perennial crops must be dynamic because:

(a) Typically there exists a biologically determined gestation lag, whose length depends on the specific crop considered but is sometimes quite long, between planting and obtaining yield. This feature introduces forward-looking behavior on the part of suppliers, forcing them to act on the basis of expected price and profitability considerations.

(b) The production process itself has dynamic features, such as the dependence between current inputs and future outputs, which are inadequately captured by the standard static production function.

(c) There exist significant adjustment costs involved in the investment and divestment process which penalize rapid adjustment.

(d) Current discussions are constrained by past decisions which are reflected in stocks of capital; in turn current decisions imply future constraints.

Intertwined with these intrinsically dynamic factors is a further complication arising from the heterogeneous nature of capital goods employed in the production process. The productivity of yield-bearing trees for any given level of inputs has, in many cases, a biologically determined life cycle. Hence it is fundamentally important to distinguish between trees of different maturities.
Furthermore, the emergence of new varieties, hybrids and clones, with different gestation periods and permitting different combinations of inputs in production, has led to coexistence in production, often within a single productive unit, of more than a single technology. That is, one must allow for differences in production functions as well as heterogeneity of fixed inputs in studying supply behavior.

Some recent empirical work (for example, Hartley, Nerlove and Peters (1985), Akiyama and Bowers (1984)) recognizes the specification-aggregation error implicit in the use of total planted area as a measure of the relevant capital stock. An alternative approach which has been applied with some success in these studies is to carry out the modelling exercise in two stages. At the first stage, an estimate of "potential output" is constructed. This measures output that could be produced from the existing bearing area under the assumption that "normal" yield is obtained for any given age and type of tree. By combining the data on age-yield profiles (usually obtained from surveys) with data on bearing area differentiated by age and type of tree, a scalar valued estimate of "potential output" is calculated. At the second stage a regression of actual output on "potential output" and some price variable(s) is carried out. If there was no price responsiveness on the supply side, actual output would bear a stable relationship to "potential output". In the case of many, if not most, perennials actual output and "potential output" would differ by an amount that reflects the sensitivity of the harvesting decision to the realized price of output or, more accurately, the deviation between the actual and the expected price. The short-run sensitivity of actual output to price changes can be measured by the regression coefficient of the price variable in the output equation. The long-run effect would depend also
upon changes in the age and type of capital stock induced by initial price changes. If the latter is indeterminate, or at least not time invariant, then so is the long-run response of output to changes in prices.

This second non-Nerlovian approach has the advantage of incorporating a number of features of perennial crop production. But it does so in a somewhat pragmatic, even if intuitively appealing, fashion. The approach is ad hoc in the sense that it does not specify and exploit the full range of interrelated producer decisions. Instead it chooses to focus on those decisions, usually only the production decision, for which aggregate data are available. While this is a defensible strategy in aggregative empirical work based on time series data limited in both scope and length, it must be recognized that the essential complexity of the "tree-crop" problem arises from the jointness of a number of producer's decisions.

A satisfactory supply theory for perennial crops would explain interrelated decisions involving both fixed and variable inputs including changes in planted area (new plantings and/or removals), decisions not to harvest all existing planted area, decisions concerning the intensity of use of fixed and variable inputs and last, but not least, the adoption of new varieties and (by implication) new technologies. There have been a number of attempts to specify and estimate models which allow for at least some of the above-mentioned complexities. French and Mathews (1971) and Wickens and Greenfield (1973) are two leading examples of attempts to develop supply theory within the context of a model of production incorporating the vintage (heterogeneous) nature of fixed inputs. More recently Hartley, Nerlove and Peters (1983) have extended the Wickens-Greenfield approach in their empirical study of the supply response for rubber in Sri Lanka where they use aggregate data on new
plantings, replantings and production combined with yield-age profile from estate-level data. For the purposes of this paper, however, a more directly relevant analysis is that of Bellman and Hartley (1983) which provides (in my view) the most complete analysis available to date of the "tree-crop" problem using competitive neo-classical theory and analytical tools of dynamic programming. The Bellman-Hartley paper serves to emphasize the inherent difficulty in any attempt to estimate "structural" parameters underlying the supply decision using aggregative time series data. They argue that a microeconometric approach is likely to be more fruitful in yielding information about structurally interesting parameters. They also show the dynamic structure of optimal decisions having first provided a very complete specification of the technological aspects of the problem.

The objective of the present paper is in some respects similar to that of Bellman and Hartley, but it is also more limited. The paper begins by providing a reasonably general description of the technology of production of perennial crops. Illustrations of specific technologies are applicable to individual perennial crops such as tea, coffee, cocoa and rubber. Using this specification the paper goes on to consider the optimal factor input decisions of a competitive profit-maximizing firm given the time paths of future prices of inputs and outputs. In some respects this approach is simply an extension of "standard" supply theory to perennial crops. As a major objective of the paper is to exposit the interrelationships between decisions confronting the producer, only simple analytical tools are used, involving classical and nonlinear programming concepts. In all cases the economic logic of optimal decisions studied here reduces to the equation of gains and losses at the margin. The analysis of the paper is used to throw light on econometric
attempts to estimate the price responsiveness of the supply of perennial crops.

The rest of the paper is organized as follows. Section II provides a specification of the technology of production and also defines a number of concepts which have a key role in empirical work. Section III deals with the formal specification of the optimization problem facing the producer and necessary conditions for achieving the producer optimum. Section IV discusses the econometric implication of the analysis by reference to empirical illustrations. Section V concludes.
II. TECHNOLOGY OF PRODUCTION

It is assumed that production possibilities can be characterized by the set of vintage production functions \( \{ F^i[K(t,v), L(t,v)] \}; i \in I \) where \( i \) is an index of technology type, \( K(t,v) \) denotes "capital" of vintage \( v \) used at time \( t \) and \( L(t,v) \) denotes "labor" combined with \( K(t,v) \). It is assumed that there exists a finite number of production technologies. In the present use of terms, the choice of a hybrid over a traditional variety of a crop is the choice of a technology. If type \( i \) is chosen, the function \( F^i \) describes the substitution possibilities available under this technology. Different technologies permit different degrees of substitutability. For example, a particular hybrid variety of cocoa tree may permit different capital-labor combinations from those possible under another traditional variety.

It is assumed that it is meaningful to refer to "given technological possibilities", though some writers have emphasized that the concept of "state of technological knowledge" is essentially subjective (Johansen (1972)) in the sense that any individual producer may be aware of only a subset of available technology types and of the substitution possibilities available for a given type, even though in an objective sense other technologies may exist. The optimal choice of the appropriate subset of technologies, if simultaneous adoption of more than one type is feasible, is an essential part of the producer's optimization problem. Optimization in that case will be relative to the individual producer's information set.

1/ Well-known characterizations include "putty-putty", "putty-semi putty", "putty-clay" and "clay-clay" technologies which allow for spectrum of both ex ante and ex post substitution possibilities. "Putty-putty" and "clay-clay" are at the two ends of the spectrum, the former permitting full ex ante and ex post substitution and the latter permitting none. See Fuss (1977) for a diagrammatic exposition.
In the case of perennial crops it is convenient to define capital to mean homogeneous land planted with trees with some specified density and requiring fixed levels of other inputs such as fertilizer and pesticides. Capital is differentiated by the age of trees. If the productivity of trees varies with age then, by implication, so does the productivity of capital. In practice the density of trees per unit area of land is often a choice variable. Within the framework adopted here differences in density will be treated as differences in technology. \footnote{The problem of choosing optimal density is therefore handled as a problem of choosing the technology type. (Compare Bellman and Hartley (1983).)}

As a simplification we allow for only one other input, "labor", in the production function through the introduction of other inputs should not lead to any new difficulties. It is convenient to think of $L(t,v)$ as a composite input, inclusive of all other non-labor inputs which are used in fixed proportion to labor.

Capital goods are assumed to require a gestation period before becoming productive though they do, of course, require labor inputs even before becoming mature/productive. For the technology type $i$ this gestation period is denoted $G_i$, and is assumed to be biologically determined.

The vintage production function may be defined as follows:

$$q^i(t,v) = \begin{cases} F^i[K(t,v), L(t,v)] & \text{if } t-v > G_i \\ 0 & \text{if } t-v < G_i. \end{cases} \quad (2.1)$$

\footnote{This approach accords well with the conventional way of thinking about density. It is also one possible way by which to abstract from the analytic complications of joint production which arises when, for example, interplanting is adopted. Infilling means filling of gaps in the existing stand.}
Equation (2.1) says that only mature vintages produce positive product; \((t-v)\) measures the age of the trees. Output from capital of different vintages is assumed to be homogeneous, as is the labor that is combined with capital. The set of mature vintages is denoted by \(\bar{V}_M\) and the set of immature vintages by \(\bar{V}_M^\prime\). The standard assumptions about \(F^i\) would be

\[
F^i_L(t,v) > 0, \quad \forall \ v \in \bar{V}_M,
\]

\[
F^i_{LL}(t,v) < 0, \quad \forall \ v \in \bar{V}_M
\] (2.2)

It is known that for many perennial crops the application of additional inputs to given amounts of capital may yield additional output in current and/or subsequent periods, as in the case of fertilizers. That is, the technology is of "putty-semi putty" type. In other cases the form of dynamic dependence between inputs and outputs may be more complex. For example, in the case of the coffee shrub "stumping" will reduce to zero the yield in the two subsequent periods but raise it in the later periods; in the case of tea, on the other hand, "coarse plucking" can raise the yield in the current period but reduce it somewhat later (Eden (1965)). The conventional static production function does not capture such dynamic dependence. However, a straightforward modification and reinterpretation goes some way towards that end. To see this write the first line of (2.1) as follows:

\[
q^i(t,v) = F^i[K(t,v), L(t,v) | L(t-j,v')] \quad j > 1, \ v \in \bar{V}_M, \ v' \in \bar{V}
\]
which says that output from the mature vintage \( v \) depends on current inputs, but is also conditional on the past application of (labor) inputs, that is, the historical sequence of input usage matters. However, for reasons of convenience the conditioning operation will be omitted henceforth, although clearly it has a role in determining the optimal use of inputs in the current period.

Total output from trees of age \( t-v > G_i \) is given by

\[
q(t,v) = \sum_{i} q^i(t,v), \quad v \in V, \quad i \in I,
\]

(2.3)

and total output from all mature vintages is given by

\[
Q(t) = \sum_{v} q(t,v), \quad v \in V,\]

(2.4)

Capital stock of current vintage, \( K(t,t) \) equals current investment, denoted \( I(t,t) \), or new plantings. Subsequently new plantings may be removed as an economic decision or may "disappear" due to exogenous events like storms, plant disease or ravages of insects. The surviving capital stock of vintage \( v \) at time \( t \), \( K(t,v) \), is determined by the capital depletion equation

\[
K(t,v) = I(v,v) - \sum_{i} R(t-i,v) - \sum_{i} D(t-i,v), \quad t > v,
\]

(2.5)

where \( I(v,v) \) denotes new plantings in period \( v \), \( \sum_{i} R(t-i,v) \), the removals in all periods since planting, and, \( \sum_{i} D(t-i,v-i) \), the reduction due to exogenous events. An alternative way of writing (2.5) is the following:
\[ K(t,v) = K(t-1,v) - R(t,v) - D(t,v) \]  \hspace{1cm} (2.5a)

Since \( D(t,v) \) is exogenously determined, we shall henceforth set it to zero for convenience. \(^1\)

Dividing (2.1) by \( K(t,v) \) and assuming constant returns to scale we obtain

\[ \frac{q^i(t,v)}{K(t,v)} = f^i\left(1, \frac{L(t,v)}{K(t,v)}\right) \]  \hspace{1cm} (2.6)

which defines the yield-age relationship. Equation (2.6) makes clear that the yield-age relationship is not independent of the labor-capital ratio for capital of age \((t-v)\). In the special case where it is reasonable to suppose that, for a given type of technology, the labor-capital ratio depends on \((t-v)\) alone, so that \( L(t,v)/K(t,v) = \alpha(t-v) \) say, the coefficients \( \alpha(t-v), v<t \) define the yield-age profile. If the labor-capital ratio can be varied at all ages, the concept of the yield-age profile is no longer technological but economic. Since the yield-age profile will also vary with the technology type, it may be useful to consider the concept of an average age-yield profile using the share of output accounted for by technology of type \(i\) as the weight to be attached to the \(i\)th yield-age profile.

\(^1\) Another possibility is to make it proportional to \( K(t-1, v) \) with the proportionality factor depending only on age \(t-v\). \( R(t,v) \) would still play a role in relation to decisions affecting the remaining capital stock.
Total feasible output for all existing vintages is defined as

\[ Q^f(t) = \sum_i \sum_v q^i(t,v), \quad i \in I, \ v \in V_M \]  

(2.7)

\[ = \sum_i a^i(t-v)K(t,v) \]  

(2.8)

where the second line follows only if the fixed-coefficient assumption with respect to other inputs is valid. Later in the paper a distinction will be drawn between feasible output on the one hand and planned or actual output on the other.
III. THE PRODUCER'S OPTIMIZATION PROBLEM

3.1 The assumptions: The framework chosen for analyzing the producer's optimization problem is the neoclassical theory of production and demand for inputs (Nickell (1978)). The objective function of the producer is the maximization of the present value of the net revenue stream under the following assumptions.

(i) The producer is a price-taker in all markets. The price of output, \( p(t) \), the wage rate, \( w(t) \), and the price of a unit of investment, \( q(t) \), are all parametrically given and measured net of any taxes or subsidies.

(ii) The time paths of all future prices, denoted by the sequences \( \{p(t)\}, \{w(t)\}, \{q(t)\} \) and \( \{r(t)\} \) are taken as given for the purposes of the optimization exercise.

(iii) There exists a perfect capital market. Specifically there are no borrowing constraints. The discount rate, \( r(t) \), is the prevailing market rate of interest.

(iv) There exist convex costs of adjustment relating to both new investment (plantings), \( I(t,t) \), and removal of existing trees, \( R(t,v) \). More details about the nature of these adjustment costs are given below.

(v) Labor is assumed to be freely and costlessly variable across vintages and technologies.

Some remarks on these assumptions are desirable. Firstly, in respect of assumption (i) it is clearly desirable to relax it so that it allows for the existence of such things as export taxes, subsidies for land clearance, uprooting and replacement of aged stock and so forth. However, this can be
straightforwardly done using the approach of the investment literature by defining all relevant prices in net or effective terms. Secondly, it should be obvious that assumption (ii) is unrealistic in the sense that it ignores the fundamental difficulties resulting from uncertainty about future prices. In essence this assumption involves replacement of uncertain future values by their certainty equivalents. Nerlove (1979, pp. 878–882) has emphasized the fundamental difficulties in formulating the dynamic optimization problem when certainty equivalents of future price variables do not exist, as may be the case in conditions of discontinuous and uncertain changes to the production technology. Our only justification for ignoring this issue is its intrinsic difficulty and the desire to explore other issues. Thirdly, the assumption about adjustment costs is mathematically convenient but, as Nerlove (1979) has argued, could not be said to be empirically well-founded. Indeed as he has pointed out, little is known about the structure of adjustment costs in the case of perennials. Nickell (1978, Chapter 3.4) has given reasons for considering linear or price-wise linear adjustment costs which lead to significantly different and not implausible patterns of dynamic adjustment. Once again, we defend our maintained assumption on grounds of relative simplicity in the face of extremely complex issues.

3.2. Adjustment costs: The adjustment cost function appropriate to perennial crops should reflect the marginal costs associated with positive rates of new plantings and/or uprooting and removals of areas already planted. If one were to apply the ideas in the adjustment cost literature (Nickell (1978, Chapter 3)), it would seem natural and mathematically convenient to adopt a convex adjustment cost function which is separable in the two types of costs. That is, let
\[ \psi^i[I(t,t), \sum_{v \leq t} R(t,v)] = \psi^i_1[I(t,t)] + \psi^i_2[\sum_{v \leq t} R(t,v)] \quad (3.1) \]

where \( \psi^i_1(.) \) denotes the costs associated with new plantings and these are specified to be dependent upon the technology type \( i \) (the dot denotes the arguments of the function), and \( \psi^i_2(.) \) denotes the cost of removals of old plantings, assumed to depend only on the total removals and not its composition. If the adjustment costs are convex, then

\[ \psi^i_1(0) = 0, \quad \psi^i_1 > 0, \quad \psi^i_1'' > 0; \]
\[ \psi^i_2(0) = 0, \quad \psi^i_2 > 0, \quad \psi^i_2'' > 0. \quad (3.2) \]

where primes denote derivates.

The assumption that \( \psi^i(.) \) is separable in the two types of costs shown in equation (3.1) is likely to prove theoretically unsatisfactory. This will become clear when (3.1) is incorporated into the expression for the net revenue of the producer. Note that while new plantings involve both a direct cost and an additional cost of adjustment, they will yield revenue on maturity. In the case of removals there will be cost only and no return unless the cleared area is replanted. (The area could be replanted with another crop altogether.) Hence the solution to the producer's optimization problem is unlikely to yield a positive rate of removals. In practice, removals followed by replanting is frequently observed, as well as an extension of the existing area planted. This observation could be rationalized if there was a
constraint on suitable available land such that the change in the composition
of maturity of existing trees would be the only possible adjustment. One way
to model this type of availability constraint is to suppose that there are
very sharply rising marginal adjustment costs of new investment. Removals
followed by replanting is a way of attaining lower marginal adjustment costs
and hence an alternative to new planting. To allow for such an "interaction
effect" one might include a third term on the right-hand side of (3.1), namely

$$\frac{\partial^2 v}{\partial I^2} (I(t,t), \sum R(t,v))$$

(3.3)

with the properties that \( \frac{\partial v}{\partial I} (.) = 0 \) if \( I(t,t) = 0 \) or \( R(t,v) = 0 \) and

$$\frac{\partial^2 v}{\partial R \partial I} (.) < 0 \text{ if } I(t,t) > 0 \text{ and } R(t,v) > 0.$$ 

The net effect of

including (3.3) in (3.1) is to lower the marginal cost of any positive \( I(t,t) \),
if \( R(t,v) \) is simultaneously positive. However, we shall continue assume that

$$\frac{\partial^2 v}{\partial I^2} > 0 \text{ and } \frac{\partial^2 v}{\partial R^2} > 0.$$ 

Such a specification allows one to introduce into

the model the benefits of a removals followed by replanting policy and, as
will be clear later, makes it more likely that a positive level of removals
will occur. To reiterate, if removals confer no net advantage on the pro-
ducers, it is unclear why we should ever observe removals followed by
replanting. If removal is followed by replanting under a different crop, then one needs to think in terms of two decisions, whether or not to uproot and then whether or not to replant. These decisions are analogous to the scrapping and replacement decisions which are conceptually distinct.

3.3. The objective function and the constraints: The discounted value of the net revenue function of the producer is given by

$$
\Pi(t) = \sum_{t=1}^{\infty} \frac{1}{(1+r(t))} \left\{ p(t)Q(t) - w(t)L(t) - q(t)I(t,t) - \psi(I(t,t), \sum_{v} R(t,v)) \right\}
$$

(3.4)

where

$$
Q(t) = \sum_{i} \sum_{v} q^i(t,v) \quad (3.5)
$$

$$
L(t) = \sum_{i} \sum_{v} L(t,v) \quad (3.6)
$$

$$
\psi(.) = \sum_{i} \psi^i(.) \quad (3.7)
$$

The function \( \Pi(t) \) is assumed to have a unique maximum. The decision problem of the producer is to choose the following so as to maximize \( \Pi(t) \):

\footnote{A more general assumption would be to allow for possible departures from strict convexity of adjustment costs, at least over certain ranges of the variables \( I(t,t) \) and \( R(t,v) \). Such a modification will permit a richer range of behavior including corner solutions \( (R(t,v) = 0, I(t,t) = 0) \), lumpy adjustment and so forth (Nickell (1978,}
(i) the optimal sub-set of technologies, $I^0, I^0Z I$;

(ii) the optimal subject of vintages, $v^0, v^0Z V^0$, for each type of technology;

(iii) the optimum amount of labor, $L^*(t,v)$, to employ on all employed (but not necessarily currently productive) capital;

(iv) the optimum rate of investment or new plantings, $I^*(t,t)$, in new capital;

(v) the optimum rate of removal, $R^*(t,v)$, of vintage $v$ capital, $v \notin V^0$.

The maximand is subject to the following constraints:

(i) the vintage production function defined by (2.1);

(ii) the capital depletion equation given by (2.5a);

(iii) the cost of adjustment function defined by (3.3) - (3.3);

(iv) the non-negativity constraint, $I(t,t) \geq 0$;

(v) the non-negativity constraint, $R(t,v) \geq 0$, $v \notin V^0$;

(vi) the non-negativity constraint, $L(t,v) \geq 0$, $v \in V$.

To obtain a more convenient expression of the optimization problem $Q(t)$, $L(t)$ and $\Psi(.)$ can be eliminated from (3.4) using (3.5) - (3.7). The resulting objective function must be maximized subject to the constraints

\[ K(t,v) = K(t-1,v) - R(t,v), \quad v \in V, \quad (3.8a) \]
\[ I(t,t) > 0, \quad (3.8b) \]
\[ R(t,v) > 0, \quad v \notin V^0, \quad (3.8c) \]
\[ L(t,v) > 0, \quad v \in V. \quad (3.8d) \]
As stated this is a nonlinear optimization problem. Let $\lambda_K(t,v)$, $\lambda_I(t)$, $\lambda_R(t,v)$ and $\lambda_L(t,v)$ denote the non-negative Kuhn-Tucker multipliers associated with the constraints (3.8a) - (3.8d) respectively. If the optimum constitutes an "interior solution", so that $I(t,t)$, $R(t,v)$ and $L(t,v)$ are all strictly positive then we can neglect (3.8b) - (3.8d) and proceed as in a classical optimization problem. (However, note that there is an element of discreetness introduced by the assumption of discrete technologies and vintages.) The discussion of the necessary conditions for optimum can be usefully divided into two parts, the first dealing with the interior case and the second with the more general case which would permit corner solutions.

3.4. **The interior solution case:** Assuming an interior solution exists, there are five first order conditions corresponding to the optimal choice of technology, vintages, new plantings, removals and labor. Each of these is considered in turn, with emphasis on economic interpretation. Firstly, consider the choice of techniques that can be profitably employed. Since the objective of the firm is net value maximization, any technique which, when used adds to the net present value of the firm will be adopted. By corollary a technique will not be used if it fails to cover the factor costs and investment costs (including costs of adjustment) associated with that technique. If there are large fixed costs in the adoption of new techniques and significant discontinuities in the cost function, costs and benefits may have to change a lot before a technique of production is adopted or dropped. A technique of production $j$ may be said to be marginal when at best it will yield zero discounted profits; that is, when
\[ \sum_j (1+r(t))^{-1} p(t) q^j(t,v) = \sum_j (1+r(t))^{-1} (w(t)L^j(t,v) - q(t)I^j(t,t)) - \psi^j(.) \]  \hspace{1cm} (3.9) \]

where the superscript \( j \) refers to the values associated with technique \( j \). Secondly, consider the choice of profitable vintages employed in production. For any and every profitable or marginal technique of production, all vintages which yield positive discounted profit will be used and the marginal vintage denoted \( T^* \), will earn zero discounted profits; that is, it will just cover discounted variable factor costs. \( T^* \) must satisfy the equation

\[ \sum_t (1+r(t))^{-1} w(t) L^t(t,T^*) = \sum_t (1+r(t))^{-1} p(t) q(t,T^*) \]  \hspace{1cm} (3.10) \]

for all profitable techniques of production. There is no guarantee that there will be a unique value of \( T^* \) which satisfies (3.10). Given our assumption of an interior solution value for \( R(t,v) \), it follows that all vintages that fail to earn at least zero discounted profit will be removed. Compare King (1972).

Thirdly, consider the optimal rate of investment. Here the result is familiar from the cost of adjustment literature. For every optimal technique of production the optimal rate of investment must be such that the discounted value of the increment to the revenue is just equal to the marginal adjustment cost plus the cost of the additional unit of investment. That is,

\[ \frac{\partial \psi^i(.)}{\partial I(t)} + q(t) = \sum_t (1+r(t))^{-1} p(t) \frac{\partial \psi^i}{\partial I(t,t)} \]  \hspace{1cm} (3.11) \]
where the right-hand side is simply the discounted value of the marginal revenue product of capital of the current vintage $t$ and the left-hand side is the sum of marginal adjustment cost and the current cost of an additional unit of investment. Compare Wickens and Greenfield (1973). The logic of this condition is straightforward. If the left-hand side exceeds the right-hand side, then revenue can be increased by reducing the rate of investment. The only difference between (3.11) and similar conditions given in the literature, for example Nickell (1978, equation 3.7), is that here both the adjustment cost function and the production function are specific to the type of technology chosen. Consequently, choice of technology and the rate of investment are jointly determined.

Fourthly, consider the optimal rate of removal, $R^*(t,v)$, of uneconomic vintages. Since the removal of uneconomic capital has a cost, the direct effect of removal is to always lower the revenue stream. However, if removal is followed by replanting (investment), the marginal adjustment cost associated with investment is lower since we have specified $3\gamma^i 3R(t,v)$. If, therefore, the marginal reduction in the incremental investment adjustment cost exceeds the direct cost of removals, then the rate of removals should be increased. The optimal rate of removal of any uneconomic vintage $v$, given any technique of production $j$, is determined such that the marginal benefits (reduction in investment adjustment cost) is exactly offset by the marginal cost (increase in the direct cost of removals). That is, optimal $R(t,v)$ must satisfy the equation
\[ \frac{\partial \psi_2}{\partial R(t,v)} = \frac{\partial \psi_3}{\partial R(t,v)} \quad (3.12) \]

Finally consider the choice of the optimal amount of labor \( L(t,v) \). Since capital labor substitution is assumed possible on all economic vintages, given any technique of production \( j \), labor will be employed up to a point such that its marginal revenue product equals the nominal wage rate; that is, \( V_i \), and \( v \in V^t \),

\[ w(t) = p(t) \frac{\partial F}{\partial L(t,v)} \quad (3.13) \]

exactly as in the static production theory. Note also that we can substitute the right-hand side of (3.13) into the left-hand side of (3.10) to obtain the following:

\[ \sum_t (1 + r(t))^{-1} w(t)L_i(t, T^*) = \sum_t (1 + r(t))^{-1} p(t) \frac{\partial F}{\partial L(t,v)} \quad (3.14) \]

which says that the discounted value of the wage-bill on the least profitable vintage \( T^* \) must equal the discounted value of the marginal revenue product on any other profitable vintage. Condition (3.14) highlights the possibility of labor-labor substitution which is a feature of vintage production models. Labor can be combined with capital of different vintages and moved between different vintages to equalize marginal revenue product across all profitable techniques and vintages, that is,

\[ p(t) \frac{\partial F}{\partial L(t,v)} = p(t) \frac{\partial F}{\partial L(t,v)} \quad , \quad (3.15) \]
and to equalize the discounted wage bill on the least profitable vintage across all techniques of production, that is,

\[ \sum_{t} (1+r(t))^{-1}w(t)L_{t}(t,T^*) = \sum_{t} (1+r(t))^{-1}p(t)L_{i}(t,T^*). \]  \hspace{1cm} (3.16)

3.5. **Some possible corner solutions**: Two interesting corner solutions that can arise in the present model are (i) \( R(t,v) = 0 \) and \( I(t,t) > 0 \), and (ii) \( R(t,v) = 0 \), and \( I(t,t) = 0 \). Both can be rationalized easily by considering the associated adjustment costs. Suppose, for example, that \( \frac{3\bar{y}^i}{3\bar{R}(t,v)} = 0 \), which means that there is no reduction in marginal cost of investment due to removals. In that case, there would be no pay off to the policy of remove-and-replant. Instead a policy of new plantings alone will be chosen. The second corner solution will arise whenever both conditions (3.10) and 3.11 fail to hold. This would imply that there is no positive rate of investment for which the marginal benefits are at least equal to the marginal cost of investment. Once a zero rate of investment is found to be optimal the associated adjustment costs are also zero and hence cannot be reduced any further. It follows that \( R(t,v) \) would also be zero.

It is tempting to conjecture that it is only when suitable land is in limited supply that one is likely to observe a positive rate of removals and replanting. Indeed, under these conditions removals-and-replanting may be favored over new planting. This is because such a policy is more likely to be cost-saving compared with a situation where suitable and available land is relatively more plentiful.
3.6. **Possibility of closed-form solution:** In general, the optimality conditions (3.9) - (3.13) cannot be solved explicitly to obtain a closed form solution for $I(t,t)$, $R(t,v)$, $L(t,v)$ and the optimal subset of vintages and techniques of production. There are several reasons for this and, broadly speaking, they are consequences of the technological specification of the model and the assumptions about the time path of prices.

When dealing with the optimality condition such as (3.11) it is sometimes assumed that the equation can be inverted to provide a closed form solution for $I(t,t)$. See, for example, Wickens and Greenfield (1973) and Hartley, Nerlove and Peters (1983). This will not be true under general assumptions about the time path of all prices and the nature of the production function. In a similar problem, Gould (1968) assumed a constant discount rate, static price expectations and constant returns to scale to derive a closed form solution for investment. Under the assumption of constant returns to scale the marginal product of capital along the optimum path will depend only on relative prices, through the optimal labor-capital ratio, such that the whole of the right-hand side of (3.11) will be a function of current discount rate and relative prices. If, in addition, the adjustment cost function is quadratic, the left-hand side will be linear in $I(t,t)$ and a closed form expression for $I(t,t)$ will follow.

Even if one were to make the necessary restrictive assumptions about expectations and returns to scale, it is not clear that in a vintage model a closed form solution will be possible. The relationship between the set of optimal vintages to be employed in production and relative prices is fundamentally nonlinear, as shown by equation, such as (3.10), and one will need to rely on iterative procedures for solving the value(s) of $T^*$ for each type of
technology. See also Bliss (1968). Analogously, the optimal subset of profitable technologies will be determined iteratively and will depend once again on current and expected prices.

3.7. **Some questions about the optimum solution:** Given the fundamental nonlinearities in the first-order conditions for optimum, a number of interesting questions about the nature of the optimum solution arise. One concerns the possibility that when $T^\ast$ is the (marginal) least profitable vintage, then all vintages older than it will be unprofitable also. This is not ruled out by the first order condition, but when will it occur? Equation (3.1) provides the insight that this is likely to occur when the average labor productivity is a smooth monotonic declining function of age. In such a case, the average productivity on the marginal vintage will be just equal to the market real wage. On all older vintages it will be less than that and hence they will be uneconomic.

Of course, age-yield profiles are not known to be always monotonically declining. Approximate single humped age-yield profiles have been reported in the empirical literature. (Hartley, Nerlove and Peters (1985).) In such cases the market wage may be at a level that would make some young and some older vintages uneconomic. Figure 1 and accompanying notes show some possibilities. Clearly it is more helpful to think of uneconomic vintages in terms of the associated average labor productivity rather than age.

A second and perhaps more difficult question concerns the condition under which a steady state is obtained. In a stationary steady state we would obtain constant capital stock of each vintage and hence a time invariant distribution of vintages. Some of the necessary conditions for this can be deduced from (3.10) - (3.15) in the case where an interior optimum exists.
These include, not surprisingly, constant values of the variables $p(t)$, $q(t)$, $w(t)$ and $r(t)$, constant rate of investment, and constant (but not necessarily equal) rates of removals for each vintage and a constant technology. However, even with these strong assumptions it is not clear that convergence to steady state will occur from any initial age distribution of capital stock.
Real wage, average labor productivity

$t - \tau^*$  $t - \tau^*$  $t - \tau^*$  $t - \tau^*$  $t - v > \tau_i$ (Age)

**Figure 1(a):** The case of monotonically declining average productivity.

Real wage, average labor productivity

$\tau_1^*$  $\tau_2^*$  $\tau_3^*$  $t - v > \tau_i$ (Age)

**Figure 1(b):** The case where average productivity-age profile has a humped shape.

Real wage, average labor productivity

$\tau_1^*$  $\tau_2^*$  $\tau_3^*$  $t - v > \tau_i$ (Age)

**Figure 1(c):** The case where average productivity-age profile has an oscillating pattern.
Notes to Figure 1: Figures 1(a) to (c) show age on the horizontal axis and real wage and average labor productivity on the vertical axis. For simplicity we assume constant values of \( r(t) \), \( p(t) \) and \( w(t) \). The diagrams represent a solution to equation (3.10) to determine uneconomic vintages, assuming three possible patterns of average productivity-age profile for bearing vintages. In Figure 1(a) average productivity declines monotonically. At the prevailing real wage all vintage older than \( T^* \) (shown as hatched area) are uneconomic. This corresponds to equation (3.10) having a unique root. Figure 1(b) depicts an hump-shaped average productivity-age profile. In this case, vintages younger than \( T_1^* \) and older than \( T_2^* \) are found to be uneconomic. Figure 1(c), which depicts an oscillating pattern of average productivity, also corresponds to a situation where equation (3.10) has multiple roots. The diagram shows vintages \( T_1^*-1, T_2^*-1 \) and \( T_3^*-1 \) to be uneconomic. In all cases, a sufficient reduction (increase) in the real wage (profitability) will make some older vintages economic.
3.8. **Planned output, actual output and the harvesting decision:** Given the solution values for the optimal subset of profitable vintages and technologies it is possible to derive the expression for planned or potential output, denoted $Q^P(t)$ and defined as

$$Q^P(t) = \sum_{i \in I^0} \sum_{v \in V^0} q^i(t,v)$$

where the summation is over profitable vintages only. Planned or potential output is, therefore, the profit-maximizing level of output conditional on a given set of future input and output prices, and on given initial conditions which consist of the full age distribution of the capital stock. The determinants of $Q^P(t)$ are expected future price vectors $(p(t), w(t), q(t))$ and the vector of capital stock variables $K(t,v), v \in V^0$. The determinants of $I(t,t)$ and $R(t,v)$ are, of course, the same also.

In general, planned and feasible levels of output would be different. It is tempting to characterize the situation where $Q^P < Q^F$ as one of excess capacity. Such a measure of excess capacity is of interest when one considers the impact of possible errors of expectations. Suppose that actual product price in period $t$ turns out to be higher than anticipated. Now, of course, planned output would have been higher had the price been correctly anticipated. To the extent that the higher price makes the previously marginal vintages of capital now profitable and some previously unprofitable vintages just marginal, and, furthermore, to the extent that additional labor can be hired at the prevailing wage, there would be additional production at the extensive margin. The higher product price will raise the marginal product of all labor and thereby make more profitable the expansion of production from
the intra-marginal capital. Thus production will expand at the intensive margin also. (This conclusion depends upon the marginal products on all vintages having been equalized initially.) An implication of this analysis is that errors of expectation (which do not lead to expectations revision) will cause in general postponement or bringing forward of removals. An exception to this arises in the case where a corner solution for removals was initially optimal and remains optimal under the new price.

Differences in "spare capacity" may provide a partial explanation of why long-term responses to price changes may vary between countries and sectors. Contrast two countries one of which is a "mature" producer and another which is a relative "newcomer". Assume that in the first there exists spare capacity as a result of decisions taken in the past whereas in the second that is not the case. Furthermore, in the first there may be either higher marginal adjustment costs or tighter constraint on the availability of suitable land than in the second. As a consequence the stimulative effects of an exogenous price increase may take different forms. In one possible scenario, no new investment may be undertaken at all by the mature producer; the supply response would take the form of more intensive utilization of existing productive capacity. The new producer facing different initial conditions could have a limited scope for responding at the intensive margin and may respond by undertaking new planting. The long-run supply response in the two cases could be different. In the specific case of tea, Akiyama and Trivedi (1985) have examined new planting behavior in three countries, India, Kenya and Sri Lanka, and have found empirical evidence consistent with the above observations.

In summary, the distinction between actual and planned output arises essentially from the errors of expectation (neglecting the effect of exogenous
natural events like storm and pest damage). The harvesting decision is essentially a problem concerning the optimal response of factor use to errors of expectation. If the production function permits factor substitution with respect to all existing capital, we should expect changes in production at both the intensive and the extensive margin of production. If, on the other hand, factor substitution is of limited importance only, the response to errors of expectations would be observed at the extensive margin only. In this case, replantings may be brought forward or postponed depending upon the direction of the forecast error.
IV. ECONOMETRIC IMPLICATIONS

This section has been devoted to an informal discussion of the implications of the analysis of Section III. The main issues of interest concern the choice of variables to be studied, the functional forms of the associated behavioral equations, the choice of exogenous and predetermined variables in the behavioral equations and various extensions and modifications to accommodate factors which are absent in the model of the proceeding section.

4.1. Implications for measuring supply response: The basic insight provided by the analysis of Section III is based on the recognition of the possibility of substitution at a number of margins, both extensive and intensive. Within the adopted framework the producer can substitute one technique of production for another, one vintage of capital for another, capital for labor on any given vintage and labor for labor on different vintages. In the long run the producer could operate simultaneously at all these margins which would imply sizeable long run supply response to price incentives. Even in the short run, with the techniques of production and the vintage structure of the productive capital stock substantially determined by past decisions, there may exist a substantial scope for supply to respond to price incentives through capital-capital, labor-labor and capital-labor substitution. On a priori grounds, therefore, the assumption of zero short-run price elasticity is needlessly strong. Of course, there would be differences in responsiveness between different perennial crops because of differences in the technology of production. More importantly, supply responsiveness can vary substantially between time periods or regions even for a given crop. These are issues for an empirical inquiry. Theory suggests the reason why the short run or long run
supply response is not time invariant lies essentially in the highly probable empirical fact that the relevant "initial conditions" will be changing all the time. For accurate prediction of quantity responses to anticipated price changes it is important to have and to use information on both the average age-yield profiles and on the vintage structure of the capital stock.

In empirical work on supply response it is fairly conventional to distinguish between long run and short run responses. Sometimes the former refers to the case in which production changes as a consequence of a change in the planted area and the latter refers to a situation in which only the factor inputs on "existing area" changes. Such a distinction is unsatisfactory because even in the short run it may be feasible to change production at the extensive margin. A more satisfactory distinction may be based on the distinction between output that could be obtained from a given capital stock vector, for any vector of exogenous variables, and that which can be obtained when that vector has attained its steady state value. However, it was pointed out in Section 3.7 that such a steady state may not be obtained from just any set of initial condition. If so, it is not clear what "long run" response coefficients mean. A more meaningful calculation would be one in which induced changes in feasible output over a specified time horizon are calculated. Such a calculation would take into account the direct effects on output due to changes in the harvesting decision and the indirect longer run effects due to changes in new plantings and removals.

4.2. Implications for econometric modelling: For purposes of econometric modelling one is interested in the guidance that the theoretical analysis provides in (a) the choice of variables to be studied, (b) the choice of the functional form and stochastic specification to be used, and (c) the choice of
exogenous and predetermined variables to be included. Each of these will be discussed in turn.

(a) The analysis of Section 3 indicates five decision variables: the choice of profitable techniques of production and vintages, the planned level of new plantings and removals and the planned demand for labor. The first two of these involve discrete choices and the last three involve variables whose values must be non-negative. Although these decisions are jointly determined by essentially the same set of variables, see (c) below, in practice the choice of technique is usually treated as a long term decision which can be ignored in a study of short run supply response. To the best of my knowledge, there is no published study dealing with the producer's choice of employed vintages in the context of perennial crops. Structural type equations dealing with new plantings and removals have been recently estimated by Hartley, Nerlove and Peters (1985) for Sri Lankan rubber and by French, King and Minami (1985) for California cling peaches. As is well known, the commonest equation in empirical work on perennials is a reduced form type equation for output, analogous to the one derived from equations (2.4) and (2.1) by substituting into the latter the optimal (planned) levels of factor inputs. (Such an equation must be distinguished from a production function type relationship which is "structural" and of considerable independent interest.) Unfortunately, however, planned supply depends upon the sub-set of optimal vintages, for which an explicit closed form expression is not available. The use of planned area, bearing area and bearing area weighted by age-yield coeffi-
cient are three possible proxy variables for the theoretically more appropriate vector of areas of economically viable vintages. Though the use of any of the three measures involves a specification error, the third measure seems the most preferable.

(b) With or without specific parametric form for the production function and the cost of adjustment function, closed form structural equations for any of the five decision variables cannot be derived. It follows that the conventional linear equation must be regarded as an approximation only.

If the producer's supply response were to be studied using microeconomic data, the stochastic specification of various equations must take account of the discrete nature of some of the choices and the possibility of corner solutions in respect of new plantings and removals. Multinomial logit or probit models seem obvious discrete choice models that might be used and the Tobit model an obvious choice for analyzing new plantings and removals. At present, however, studies based on micro data are somewhat rare. In aggregate time series data such as that used by Hartley, Nerlove and Peters and by French, King and Minami the problem of corner solutions is not serious. Indeed it would be unusual to expect simultaneous occurrence of corner solutions for all producers. Therefore, despite the absence of explicit aggregation theory to justify it, linear equations for new plantings and removals may serve as reasonable initial approximations.

(c) Finally, we turn to the issue of appropriate explanatory variables. Here the distinction must be drawn between equations
which explain planned values of the decision variables conditional on expected values of future variables and actual values of the same decision variables. The determinants of planned new plantings and removals and the profitable sub-set of vintages and technologies, are, firstly, the expected real prices of inputs and output, net of taxes and subsidies and, secondly, the vector of capital stock of different vintages. In practical applications a number of simplifications are usually made. For example, a single expected average rate of return might be used as a proxy for the full vector of expected input and output prices (French, King and Minami, Tables 2 and 3). Alternatively only a sub-set of prices augmented by dummy variables to take account of financial incentives for removals or new plantings may be included. The vector of capital stock may be proxied by a "potential output" variable, as in Hartley, Nerlove and Peters, equation (41), or by the planted area broken down into several age-classes, equation (39). In the absence of detailed annual data on the age distribution of capital stock such approximations seem justifiable. In the specific case of tea, a number of these issues have been pursued empirically by Akiyama and Trivedi (1985).

We now turn to the determinants of actual new plantings, actual removals and actual output. The simplest hypothesis would seem to be the divergence between planned and actual values arises from an error of expectation. If, ceteris paribus, actual price exceeds the previously expected price the producers will wish to supply larger quantities. They will do so by operating at the extensive margin, the intensive margin or some combination of the two. The simplest
way to measure the short-run price responsiveness of the decision variables is to include the error of expectation variable in all behavioral equations. Its coefficient is expected to be positive in the "supply" equation, negative in the removals equation and possibly negative also in the new planting equation.
V. CONCLUSION

This paper began with a brief discussion of the traditional Nerlovian supply model and a non-Nerlovian supply model based on the concept of "potential output". We shall now comment on these two approaches in the light of the analysis of Sections II and III.

The basic Nerlovian area adjustment equation has two important limitations when viewed as a theory of supply of a perennial tree crop. It takes inadequate cognizance of the heterogeneous nature of the capital stock and it fails to accommodate explicitly and completely for the various margins of adjustment available to the producer. The model focusses almost exclusively on one particular extensive margin of adjustment to the exclusion of several others which were identified and discussed in earlier sections. When the technology of production permits substantial adjustment at the intensive margin, and when the adjustment costs of the capital stock are very substantial, a mechanical application of the area adjustment equation can be very misleading. A theory of area adjustment is not, in itself and by itself, an adequate theory of supply behavior.

The alternative approach, which makes the deviation between actual output and a synthetic measure of "potential output" a function of errors of expectation, has the merit that firstly it makes some allowance for heterogeneity of capital and secondly it can incorporate technological information embodied in the yield-age profiles. It was argued in earlier sections that historical yield-age profiles in general do not embody technological information alone. If, however, the data are collected and processed in such a way that the yield-age profile corresponds to normal utilization of all other variable inputs, then it will approximate technological coefficients more
closely. In any case, the synthetic measure "potential output" is an endogenous variable, itself dependent on past new plantings and current removals which are themselves decision variables. Therefore, in recognition of this endogeneity, this second approach should be based on equations for new plantings and removals in addition to the output equation.

The approach outlined in Section III also has its limitations. Perhaps one of the most serious is the strong assumption regarding the existence of certainty equivalents for all future prices. In the absence of a formal analysis, any consideration of the consequences of relaxing this assumption can be considered at an intuitive and conjectural level only. For example, consider the consequence of replacing the dotted line in Figure 1 which represents the (present value of) real wage bill by a band which covers the range in which the true value might lie. Such uncertainty in turn will lead to uncertainty about the subset of marginal vintages and we shall have to characterize them as "probably marginal". The subset of "probably marginal" vintages will be, of course, somewhat larger. The decisions of the producers in respect of this larger subset in response to uncertain price signals deserves some consideration. Given risk aversion on the part of the producers, it is likely that they will respond to price signals more slowly and to a smaller extent (Batra and Ullah (1974)). 1/ That is, removals and new plantings might be based not only on the level of future expected prices but also

1/ The partial adjustment model can be rationalized in terms of a slow response of producers to an uncertain economic environment, especially where factors determining future profitability are only dimly perceived. Some have argued, for example Nickell (1978, Chapter 6) that uncertainty provides a more convincing explanation of sluggish investment behavior than do convex costs of adjustment.
on the extent of variability around that level. Possibly also, the higher the
degree of variability around a given price level, the smaller would be the
response of new investment and removals. The extent to which such a response
is muted will itself depend upon the degree of risk aversion amongst producers
and on the nature of the production function. Uncertainty and risk averse
behavior may have a substantial role to play in explaining the existence of
spare production capacity. Consideration and conjectures such as these suggest
that both theoretical and empirical analyses of supply response would benefit
from greater attention to the role of price variability as an additional
factor.
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