United States
Department of
Agriculture

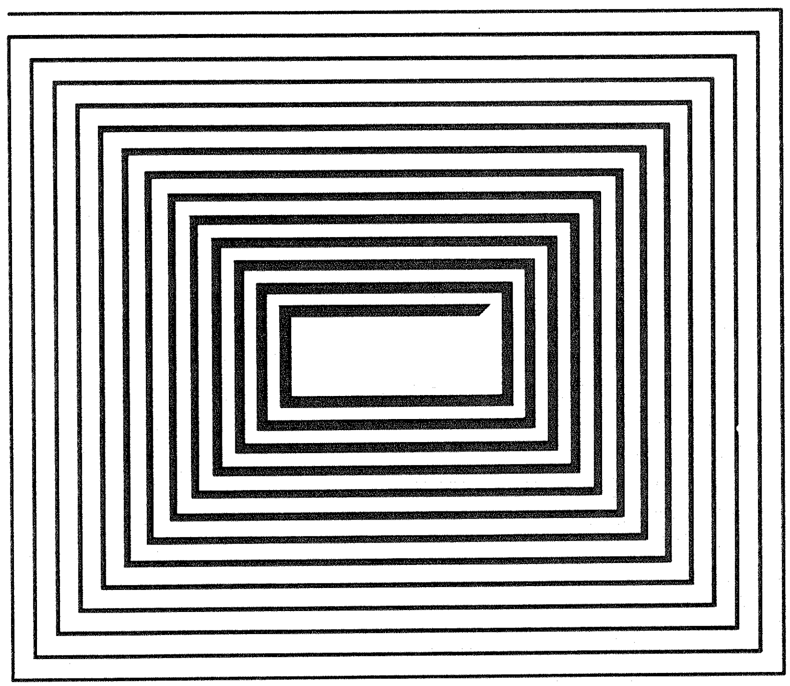
Forest
Service

North Central
Forest Experiment
Station

General Technical
Report NC-109

A Framework for Identifying Public Research Priorities: An Application in Forestry Research

Glenn Fox



CONTENTS

North Central Forest Experiment Station
Forest Service—U.S. Department of Agriculture
1992 Folwell Avenue
St. Paul, Minnesota 55108
Manuscript approved for publication June 23, 1986
1986

A FRAMEWORK FOR IDENTIFYING PUBLIC RESEARCH PRIORITIES: AN APPLICATION IN FORESTRY RESEARCH[1]

Glenn Fox, *Assistant Professor,*
Department of Agricultural Economics and Business,
University of Guelph,
Formerly Research Assistant,
Department of Agricultural and Applied Economics,
University of Minnesota

ECONOMIC MODELS FOR ASSESSING RESEARCH PRIORITIES

Introduction and Overview

In recent decades, major research effort has been devoted to modeling and measuring the relation between research and development activity and the rate and nature of technical change. The notions that such change responds, at least in part, to the amount of resources allocated to research, and that invention responds to economic incentives, have become well established. This report reviews efforts to model optimal research resource allocation, and presents a model for southern pine forestry research.

The discussion will focus on two aspects of the available models: (1) the general structure of the optimization procedure, including the objective function to be optimized, the nature of constraints imposed on the model and the characteristics of solutions which emerge, and (2) the information required to employ the model for applied research budgeting questions.

The problem of determining an optimal level of research and development activities within an organization can be viewed as a component of the overall capital budgeting decision. Research competes for resources with the purchase of durable assets and current inputs and like durable assets and current inputs, contributes to achievement organizational goals. While varied techniques have been developed to guide the research resource allocation decision, a common theme has been an attempt to measure both the degree to which alternative research activities contribute to organizational goals and the opportunity cost of resources devoted to research. The procedures vary in the formality and detail with which these measurements are accomplished.

Although research funding needs to be seen as part of the broader capital budgeting process, the nature of research confounds the resource allocation problem. Perhaps the most outstanding feature of scientific research as an investment activity is the uncertainty inherent in most projects. *Ex ante,* it is never clear how much investment will be required to achieve a particular result, and even if success is achieved there is no guarantee that the net contribution to organizational goals will warrant the investment. Furthermore, because most research organizations have multiple goals, estimating contributions of a research project to specific goals and subsequently weighing the goals is difficult.

[1]*While preparing this paper, the author benefitted from discussions with Hans Gregerson, Christopher Risbrudt, Vernon W. Ruttan, and Pamela Jakes. Research support was provided by Minnesota Agricultural Experiment Station Project 14-064, Technical and Institutional Sources of Change in Agriculture, by a Resources for the Future Dissertation Fellowship Grant in Food and Agricultural Resource Use Policy, and by the U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station (Cooperative Agreement 23-84-13).*

Scoring Models and Multiple Goal Linear Programming

One of the earliest approaches to research budget allocation has been called the Scoring model. Panels of researchers and administrators identify organizational goals for research, attach weights to goals and to estimate relative contributions to goals of specific research projects. This information can be incorporated into a linear programming framework by adding resource requirements of projects and measures of organizational resources.

A scoring model approach was used in a national assessment of U.S. agricultural research priorities in 1965 and 1966 (USDA 1966). A similar exercise was conducted at the state level in North Carolina, beginning in 1972 (Shumway and McCracken 1975). Russell (1973, 1975) extended a scoring model to a linear programming approach in the U.K., applying a framework outlined by Kaldor (1966), Hildreth (1966), and Paulson and Kaldor (1968).

This approach usually involves two panels. The first typically consists of senior administrators whose task is to identify a set of organizational goals for research and to establish weights for each goal. Tables 1 and 2 report the criteria and weights employed in the USDA and North Carolina studies. Table 3 reports Russell's criteria. The second panel establishes scores for each proposed project for each criterion.

The weights are then used to construct an ordinal ranking of projects. Scores are computed either additively,

$$S_i = \sum_{j=1}^{J} W_j C_{ij}$$

or multiplicatively

$$S_i = \prod_{j=1}^{J} W_j C_{ij}$$

where S_i is the score of project i, j is the index for criteria, W_j denotes the weight attached to the jth criterion and C_{ij} is the score of the ith project on the jth criterion.

Russell's approach maximized the linear function

$$\sum_{j=1}^{J} W_j C_j$$

Table 1.--Criteria and weights used to set research organizational goals in "A National Program of Research for Agriculture"

Criteria	Weight
Extent to which the research meets State experiment station, USDA, and national goals.	9
Scope and size, considering area, people, and units affected.	8
Benefits of research in relation to costs.	7
Urgency of research.	10
Contribution to knowledge.	9
Feasibility of implementation and likelihood of successful completion in a reasonable period.	5
Likelihood that research results will not be available elsewhere.	6
Likelihood of extensive and immediate adoption of results.	6

Source: U.S. Department of Agriculture (1966, p. 29).

Table 2.--Research areas, criteria, and weights used to set organizational research goals in North Carolina

Research area	Criteria	Weights
Biological sciences and technology	1. Urgency--basic information needed to aid in solution to threat or problem	20
	2. Cost relevance--expected long-term benefits in relation to costs	15
	3. Degree to which similar research is not now being conducted or not likely to be conducted elsewhere (higher scores assigned if inadequate research results expected elsewhere)	15
	4. General importance and potential for contribution to knowledge; higher scores assigned for greater scientific merit and potential for contribution to faculty development and improved academic performance	50
	Total =	100
Animals and plants	1. Extent to which proposed research is consistent with station, regional, and national goals in agriculture and forestry; economic value of the crop or animal enterprise and its products to people of North Carolina.	35
	2. Cost relevance--expected benefits in relation to costs	20
	3. Degree to which similar research is not now being conducted or not likely to be conducted elsewhere (higher score for research and sub-research problem area for which adequate results are not likely to be available elsewhere) and for which there is an urgent need for research results	20
	4. Potential for contribution to knowledge	25
	Total =	100
Environment and natural resources	1. Extent to which proposed research is consistent with station, regional and national goals in natural resource development and conservation	35
	2. Cost relevance--expected benefits in relation to cost	15
	3. Degree to which similar research quality on this resource is not now being conducted or likely to be conducted elsewhere (higher scores for inadequate research elsewhere) and concerning which there is public pressure, a threat to the natural resource, or a critical need for environmental protection	15
	4. Potential for contribution to knowledge	20
	5. Extent to which the research will aid in meeting broader public service commitments of the school and university beyond traditional statutory charge of the experiment station	15
	Total =	100
Food-fiber-people economics	1. Extent to which recommended research is consistent with station, regional and national goals of promoting and protecting public health and improving family living; potential for improving quality of life and developing rural communities in North Carolina	35
	2. Cost relevance--expected benefits in relation to increased costs of research in these areas	20
	3. Degree to which similar research is not now being conducted or likely to be conducted elsewhere (higher scores for inadequate research elsewhere) and for which there is public support for research to evaluate the impact of improved agricultural technology, a threat to public health, or a need for information to support new processing industries	20
	4. Potential for contribution to knowledge	25
	Total =	100

Source: Shumway and McCracken (1975).

Table 3.--Organizational research goals and rating system employed by Russell

Goal dimension and aspect		Proposed rating system
CONSUMPTION CATEGORY		
1. Quantity	-Productivity	-Percentage increase in social profitability per unit of output.
	-Total production	-Cumulative discounted net social profitability for relevant time period.
2. Quality	-Appeal, nutritive value, reliability, versatility	-Scoring model from present or low levels to arbitrarily defined ideal levels.
3. Availability	-Growth cycle limitations	-Percentage increase in effective season.
	-Supply/demand equilibrium instability	-Ratio of cost with instability to cost with stability.
	-Number of substitutes	-Percentage increase in number of substitutes.
SECURITY CATEGORY		
4. Human Safety	-Risk of accident	-Percentage reduction in a particular type, weighted according to the severity of the type of accident.
	-Risk of disease	-Percentage reduction in contradictions, weighted according to the severity of the disease.
5. Economic Defense	-Balance of payments	-The ratio of the value of potential reduction in imports to present value of imports.
	-International dependence	-The ratio of the expected reduction in trade to total trade.
6. Food Sources Security		-Reduction in probability of loss attributable to the research.
7. Conservation	-Utilization efficiency	-The ratio of the per unit nonrenewable resource saving to per unit requirement before the research.
	-Depletion rate	-The ratio of the reduction in rate of nonrenewable resource depletion to the depletion rate prior to the research.
EQUITY CATEGORY		
8. Distribution	-Consumption, wealth	-Scoring model based on value of increased income to various groups.
9. Individual Rights	-Opportunity, discrimination	-Scoring model from present levels to ideal levels.

Source: Russell (1975).

where C_j represents the contribution of all $i = 1$ to I projects to criterion j. C_j is computed as

$$C_j = \sum_{i=1}^{I} (C_{ij}/\bar{r}_i)\, r_i$$

where r_i is the level of funding of the ith project and $\bar{r}_i$ is an upper limit to the size of the project. The maximization problem is constrained by the total research budget $\bar{R}$,

$$\sum_{i=1}^{I} r_i \leq \bar{R}$$

and the feasibility constraints

$$0 \leq r_i \leq \bar{r}_i,\ i=1 \ldots I.$$

Work by Fishel (1970, 1971) and Grieg (1979) are extensions and adaptations of scoring models. Fishel developed a stochastic cost-benefit model. Rather than seeking expert opinion in the form of scores, Fishel sought estimates of the parameters of a cost-benefit model. His approach synthesizes subjective probability distributions of key variables from panel and survey data. Researchers and administrators were asked to estimate annual costs and benefits and expected times to completion of several projects. These responses were used to generate point and interval estimates of the variables used in the cost-benefit analysis.

The Fishel approach to measuring benefits computes the sum of the gains in human capital among the researchers engaged in the project, the present salvage value of equipment purchased and the expected net benefits from the knowledge derived.

Grieg developed a stochastic simulation model to study two poultry research projects. Discussions with researchers were used to establish parameters for a single firm and an aggregate simulation. The framework developed was quite complex and costly to implement. It was also difficult to independently verify the information obtained from the research expert. Extending scoring models to create stochastic cost benefit analysis is fraught with the same limitations as scoring models in general. It is expensive to accumulate the required data, and validation is difficult.

Scoring and multiple-goal LP models require a list of potential projects, a set of criteria with associated weights, and in the programming version resource requirements of projects including any relevant feasibility constraints. The output of the analysis is an ordinal ranking of projects which can be used to exhaust the research budget. Because the method has been popular in agricultural research as well as in military and industrial research considerable effort has been made to evaluate the technique. Moore and Baker (1969) in assessing scoring models in military and industrial research, found the advantages of this approach to include: (1) broad participation of research personnel at several administrative levels, (2) limited requirements for technical skills of formal cost-benefit analysis, and (3) explicit identification of and relationship to organizational goals.

Some of these advantages, however, can also be seen as liabilities. Broad participation can be expensive, particularly in its use of senior administrators' time. The absence of formal benefit-cost calculations gives an impression of subjectivity and arbitrariness in the selection of criteria and weights. Also, there is no mechanism to weed out redundancy and overlap among criteria. While the relationship to organizational goals is emphasized in this approach, it really gives no guidance in the solution of $\bar{R}$, the overall research budget. While in principle an ordinal ranking could be constructed to include all investment opportunities available to an institution, this has not been done in practice.

In addition, several technical problems remain unsolved. Should S_i be computed as an additive or multiplicative formula? Should project alternatives be identified on the basis of problem areas, commodity groupings or scientific disciplines? Should the variation of S_i scores among panelists play a role in the ordinal ranking? Finally, Moore and Baker report that scoring models are not always able to give similar ordinal rankings to cost-benefit procedures.

An LP Model for Evaluating Research Projects

Klein and Kehrberg (1981) have developed a model to help researchers choose among crossbred lines at early stages of a livestock breeding program. In principle, the approach could be applied to plant breeding, but cost savings would be lower because of lower maintenance costs for plants.

Linear programming is used to trace a unit isoquant of a crossbred line under alternative factor price regimes. The objective function minimizes unit costs. Results of performance trials of first-generation offspring are used to compute an input requirements matrix, A. Several modes of production were considered, with each column of A representing the vector of input requirements necessary to achieve a unit of the production activity. The set of production activities, each representing a unique combination of housing, feed, and breeding methods, is represented by the vector L. Total output is represented by Y^o, and D is a vector of estimates of output levels per unit of each activity in L. Therefore $DL = Y^o$. Total input use is AL, which must equal IX, where I is the identity matrix. In summary, the LP model seeks to

$$\begin{aligned} &\text{Minimize } (C + \theta)X \\ &\text{Subject to } DL = Y^\circ \\ &\qquad\qquad AL - IX = 0 \end{aligned}$$

θ is a vector of parameters used to describe alternative factor price regimes.

Ten crossbreeds were compared using the model. Some were found to be of lower unit cost for all factor price combinations. Some lines never achieved lowest unit cost for any input price set. The authors argued that this information, tempered with the judgments of the research team, could be used to identify the most promising crossbred lines for further investigation. Embryo storage could preserve the genetic material of the least promising crossbreeds.

Precedence and Congruence

Precedence and congruence models are arguably the least costly means of establishing funding guidelines for public research. The precedence approach reinforces the status quo. According to this model, the share of research funds allocated to a particular commodity remains constant through time. Each component of the budget expands or contracts at the same rate as the overall budget.

The congruence model, as developed and used by Boyce and Evenson (1975), Evenson *et al.* (1979), Ruttan (1982, 1983), Pinstrup-Anderson (1982) and Salmon (1983) allocates research resources to commodities according to the economic significance of those commodities. Under Salmon's approach, a congruence ratio is computed for each commodity i, as

$$CR_i = \frac{\dfrac{r_i}{\overline{R}}}{\dfrac{P_iY_i}{\sum_{k=1}^{n} P_kY_k}}$$

where r_i is the research expenditure on commodity i, $\overline{R}$ is the total research budget, P_iY_i is the gross revenue from market sales of commodity i and

$$\sum_{k=1}^{n} P_kY_k$$

is the gross revenue earned from all commodities being considered in the research budget. There is an ambiguity in this definition in that it is not clear if gross revenue or value added should be employed in computing CR_i.

Advocates of congruence ratios tend to downplay the prescriptive power of the approach. Their use is seen as a way of relating the size of research expenditure to the size of an industry. An important suggestion in these studies is that outliers in the vector of congruence ratios are to be viewed with suspicion as being potentially sub optimal. In other words, congruence ratios should be equal to one unless there are "good reasons" for them not to be.

Both the precedence and congruence models have limited data requirements for implementation. Indeed, the precedence approach requires only a copy of last year's budget and the size of this year's funding increase or decrease. The congruence model additionally requires information on gross revenues of commodity groups.

Many of the disadvantages of these approaches derive from their simplicity—for instance, they aren't capable of dealing with imminent breakthroughs in a particular area. If a crop has been of little economic importance in the past and its research budget is small, an extremely productive sequence of research discoveries would go unacknowledged in either of these funding models. Also, neither technique gives any help in determining $\overline{R}$, the overall level of funding.

Bredahl and Peterson (1976) have interpreted congruence ratios as the inverse of average products of research. By assuming a particular model of production, average products can be related to marginal products and subsequently to marginal interest rates of return. Substantial gains in the usefulness of the approach for resource allocation questions can thereby be achieved.

Dynamic Cost-Benefit Models

Public investment in agricultural research is made over a protracted period, and benefits occur after a lag of several years. Several analysts have acknowledged this fact by pursuing formal techniques of dynamic cost-benefit analysis to improve the efficiency of research resource allocation.

Net Farm Income

Barker and Herdt (1982) developed a model to allocate research resources for rice. A similar framework was advanced by Araji *et al.* (1978). Barker and Herdt proposed that research resources should be allocated across types of rice to maximize the discounted streams of expected changes in net farm income (NFI) for the commodities in question. This amounts to choosing a vector of research funding levels, $R_0 = \{r_{10}, r_{20}, r_{30}, \ldots r_{n0}\}$, to maximize

$$\psi\,(R_0; \Gamma) = \sum_{i=1}^{n} \left\{ \sum_{t=0}^{\infty} (1+\rho)^{-t}\, \Delta\, NFI_{it}\,(r_{i0}, \Gamma) \right\}$$

where ρ is the discount rate, $\Delta\ NFI_{it}\ (\cdot)$ denotes the change in aggregate net farm income for commodity i in period t as a function of r_{i0}, and Γ is a vector of parameters.

While this criterion has a certain intuitive appeal, it fails to take into account the benefits accruing to consumers in the form of lower commodity prices. When an industry faces inelastic demand, net farm income can be depressed by technological change, and yet the net benefit to society as a whole is positive. From this perspective, the net farm income criterion will, in general, be a poor guide to the allocation of research resources.

Social Surplus Criterion

A surprising feature of much of the literature addressing the problem of *ex ante* optimal research allocation is that it bears little relation to the analytical framework used in studies of *ex post* estimates of gains to research. The latter studies measure the gains from research in terms of changes in consumers' and producers' surpluses and in input use savings. For *ex ante* allocation decisions, it would be useful to have a model of the future pattern of these changes in social surpluses and input savings where these benefits depend on current research expenditure. The approach taken here is an adaptation of Peterson (1967) and Ayer and Schuh (1972).

The payoff from research is not immediate. Research funded today induces a sequence of supply shifts in the future. These supply shifts bring about gains in consumers' and producers' surpluses as commodity prices change and also yield resource savings when demand is inelastic. Figures 1 and 2 identify these gains for a sequence of supply shifts.

The demand curve in the figures is written in inverse form as

$$P^D{}_{it} = \gamma_i\, Y_{it}^{\frac{1}{\eta_i^D}}$$

where i denotes the commodity, t represents time, P is the price of commodity i paid by consumers and Y is the quantity that would be purchased at price P. This is a constant elasticity demand curve, where η_i^D is the elasticity of demand for commodity i. The figures are drawn for the case $-1 < \eta_i^D < 0$. The situation for $\eta_i^D < -1$ can be derived in a straightforward

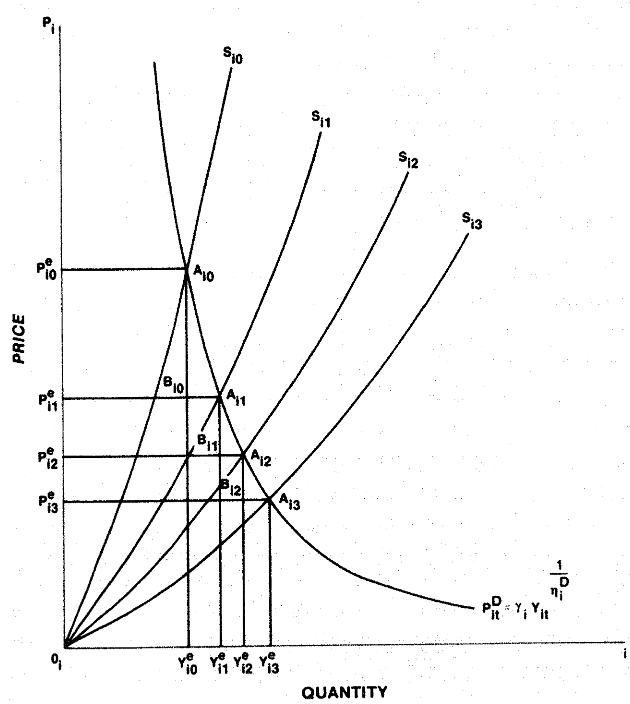


Figure 1.—*Changes in consumers' and producers' surpluses for a sequence of supply shifts.*

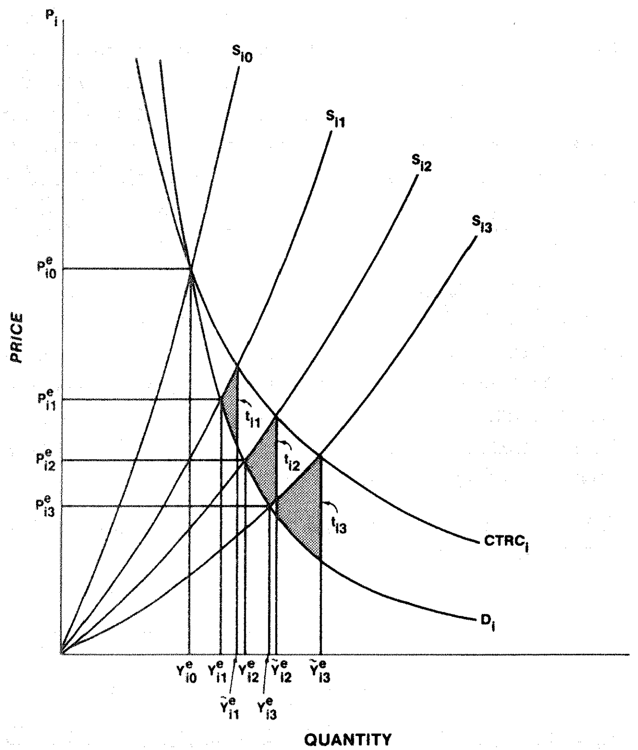


Figure 2.—*Gains from resource transfer under technological change.*

manner. Referring to figure 1, as the supply curve shifts in response to research in t = 0, the market clearing price falls successively from P^e_{i0} to P^e_{i3}. The equilibrium quantity of consumption and production rises from Y^e_{i0} to Y^e_{i3}. This sequence of price changes induces a sequence of changes in consumers' surplus. Between t = 0 and t = 1, consumers gain the area $P^e_{i0}A_{i0}A_{i1}P^e_{i1}$. Between t = 1 and t = 2, they gain $P^e_{i1}A_{i1}A_{i2}P^e_{i2}$. In general, between periods t and t + 1, consumers gain $P^e_{it}A_{it}A_{it+1}P^e_{it+1}$.

Producers' surplus also undergoes a sequence of changes. Between t = 0 and t = 1, producers lose the area $P^e_{i1}B_{i0}A_{i0}P^e_{i0}$ and gain $0_iB_{it}A_{it+1}$. If we consider the net gain to consumers (ΔCS) and producers (ΔPS) to be of equal weight, then the net change in these surplus areas between period t and t + 1 is $0_iA_{it}A_{it+1}$. That is, the incremental change in social surplus is the area between the two adjacent supply curves and under the demand curve. If this incremental change in social surplus is denoted as ΔSS_{it}, then

$$\Delta SS_{it} = \Delta CS_{it} + \Delta PS_{it} \ .$$

In measuring the total benefit to consumers and producers of commodity i in time period t, the standard of comparison is the pre-research equilibrium. The social surplus gains are cumulative. Let the benefit accruing to producers and consumers of commodity i in period t be denoted as B_{it}. We can compute the benefit for each time period as

$$B_{it} = \sum_{j=1}^{t} \Delta SS_{ij}$$

The present value of the sequence of benefits beginning at t = 0 is

$$B_i = \sum_{t=0}^{T_i} (1+\rho)^{-t} B_{it} + \sum_{t=T_i+1}^{\infty} (1+\rho)^{-t} B_{iT_i}$$

where T_i is the last time period in which a shift in supply is experienced from research in t = 0 and ρ is the social discount rate. It is conceivable that research investment may depreciate, so the sequence of supply shifts generated by research in a period may move the supply schedule initially to the right, but eventually the curve will shift back so that $B_{iT_i} = 0$.

This measure of the social benefits from research is incomplete, however. Under conditions of inelastic demand, as the supply curve shifts down and to the right, total expenditure on the commodity at successive equilibria falls. If constant returns to scale and constant factor shares prevail at the industry level, and if variable inputs are supplied perfectly elastically to the industry, then the quantity of variable inputs falls in the industry undergoing the supply shift. To calculate the total social benefit from research in the market for commodity i in period t, we need to measure the net value to society of these released inputs and add this value to the net change in social surpluses (fig. 2). In figure 2, a rectangular hyperbola is drawn through the pre-research equilibrium. A property of this curve is that the product of price and quantity is a constant along the curve, and hence it is labeled as the Constant Total Revenue Curve ($CTRC_i$). Given the assumptions pertaining to scale economies, factor shares and input prices, the quantity of variable inputs is constant along this curve, and is equal to the level of variable input use in the pre-research equilibrium. I have labeled the abscissa of the intersections of the CTRC with the sequence of supply curves as $\tilde{Y}^e_{it}$. They represent the level of output forthcoming in period t under the technology of period t if the input use level is held constant at the pre-research level.

The net social gain of declining input use levels can be seen through a simple thought experiment. Suppose an artificial barrier forced a constant level of input use in an industry as the supply curve shifts. In our example, with inelastic demand for the commodity, the level of output with constant input use, $\tilde{Y}^e_{it}$, exceeds the market equilibrium level of output, Y^e_{it}. The total cost of variable inputs required to attain $(\tilde{Y}^e_{it} - Y^e_{it})$ is the area under the supply curve between $\tilde{Y}^e_{it}$ and Y^e_{it}. The valuation placed on this output, however, is the area under the demand curve between $\tilde{Y}^e_{it}$ and Y^e_{it}. The shaded area, in figure 2, identified as τ_{it}, is the net loss from our artificial barrier, or the net gain from allowing the release of resources to the rest of the economy. Therefore, the total benefit obtained from research in time t is the cumulative change in social surplus areas, B_{it}, plus τ_{it}. If we define $\overline{B}_{it}$ as

$$\overline{B}_{it} = B_{it} + \tau_{it}$$

so that the present value of benefits of research on commodity i, denoted as $\overline{B}_i$, is

$$\overline{B}_i = \sum_{t=0}^{T_i} (1+\rho)^{-t}\, \overline{B}_{it} + \sum_{t=T_i+1}^{\infty} (1+\rho)^{-t}\, \overline{B}_{iT_i}$$

A version of $\psi(R;\tau)$ can be constructed by simply summing the $\overline{B}_i$'s. In mathematical notation, the objective function is

$$\psi(R;\tau) = \sum_{i=1}^{n} \overline{B}_i$$

which is to be maximized subject to $\sum_{i=1}^{n} r_{i0} \leq \overline{R}$.

Since this version of the objective function comprises a comprehensive accounting of all the gains from technological change, it is a more reliable target than the versions based on changes in net farm income discussed earlier. Furthermore, at least in principle, the relationship between research expenditure and the vector of benefits

$$\overline{B} = (\overline{B}_1, \overline{B}_2, \ldots \overline{B}_n)$$

can be computed from measurable commodity market parameters. This introduces an element of economy into the implementation of the model that is not available in the multiple goal linear programming framework. Also, an optimal $\overline{R}$ can be identified as the level of funding which gives a value of $\psi(R;\tau) = 0$ for a social discount rate of ρ.

Several studies have used versions of this model to study research resource allocation. Ramahlo de Castro (1974) and Ramahlo de Castro and Schuh (1977) developed a model for cotton, sugarcane, corn, rice, and edible beans for Brazil. Supply and demand elasticities were allowed to vary by commodity, but a given level of research expenditures was assumed to shift the supply curve by the same proportion for each commodity. This implies that generating technical change through research is equally easy for each of the named commodities. Annual gross benefits of each supply shift were measured and estimates of the share of gains going to producers and consumers were computed. The general findings indicated that crops with higher gross revenues provided larger research benefits than smaller crops, and that the distribution of gains between producers and consumers depended on the relative absolute magnitudes of the supply and demand elasticities. Producers received a larger share of the gross gains when the absolute magnitude of the demand elasticity was larger than the supply elasticity.

Scobie (1979) developed a model in which the size of the supply shift depends upon the level of research investment. The supply function is written as

$$P^S_t = \beta Y_t^{\frac{1}{\eta^S}}$$

The rate of supply shift is determined by β. If no research is done, $\beta = 1 + \alpha_{min} \cdot \alpha_{min}$ is a minimal annual percentage shift attributed to factors other than research. As research investment increases, approaches $1 + \alpha_{max}$ asymptotically. For intermediate values for research investment, R,

$$\beta = 1 + \alpha_{max} - \left\{ \frac{\alpha_{max} - \alpha_{min}}{1 + \frac{R}{P \cdot Y}} \right\}$$

Scobie does not clarify if R is a stock variable or an annual investment level.

Habib (1980) and Habib *et al.* (1981) evaluated the relative net benefits of research on jute, rice, sugarcane, and tea for Bangladesh. Their supply model has much in common with the Scobie model. The supply function for each commodity was written as

$$Y^S_i = (1+h_i)\, \alpha_i\, P_i^{\eta_i^S}$$

The h_i term represents a percentage shift in the supply function in response to research. The size of the shift is a linear function of the research investment, so that

$$h_i = S_i R_i$$

up to a maximum possible shift of h_i^u. It is not made clear if R is an annual investment level or a stock concept. Values for the S's were obtained by comparing crop yields in Bangladesh with yields elsewhere in Asia. The study concluded that potential gains from research were highest for rice and then for sugarcane.

All of the models discussed in this section make important strides in conceptualizing the research budgeting process as an optimization problem. They also highlight some critical data requirements which were ignored in the models of earlier sections. The magnitudes of supply and demand elasticities, the functional forms of these schedules, the mechanism by which research investment shifts supply all receive a deserved emphasis. All of this, however, tends to show that these models are more costly to estimate and use than the precedence or congruence approaches, but are likely to be less costly than the use of scoring models. Furthermore, reliance on the notions of consumers' and producers' surpluses makes these models vulnerable to all of the theoretical arguments that undermine the credibility of those measures of economic welfare (Chipman and Moore 1976, 1980; McKenzie 1982).

Models of Regional Spillover Effects

Lessons learned from agricultural research in one region can often be adapted and applied in another region with similar agro-climatic characteristics. These spillover effects have important consequences for optimal public financing of regional research centers by a federal government. Simply put, a region which generates large spillover benefits should receive a commensurately higher level of federal funding than a region which doesn't generate this effect. Several economists, including Garren and White (1981), Garren (1981), Ziemer *et al.* (1982), White and Havlicek (1981), and Havlicek and White (1983) have recently turned their attention to this regional allocation question for the case of the U.S. economy.

As with the dynamic cost-benefit models, the analytical framework employed in these regional spillover models represents the contribution of research as a shift variable in the production or supply function. In the Ziemer *et al.* (1982) study, the supply function for aggregate agricultural output in a region i is represented as

$$Y_{it} = \alpha_i P_{it}^{\eta_i^s} Y_{it-1}^{1-\delta_i} \exp\left\{\delta_i \sum_{j=0}^{t-1} g_{ij} + g_{it}\right\}$$

The shift function, exp {·} reflects the effects of research inside and outside of the region through the formula that determines the g_{it}'s. The effect of research on output was estimated using an adaptation of the technique introduced by Cline (1975). A multifactor productivity index (PR) for each region was regressed on lagged research inside (RI) and outside (RO) of the region, the level of farmers' education in the region (E) and a weather index (W). The functional form employed was

$$PR_{it} = \prod_{j=0}^{13} RO_{it-j}^{\alpha_{ij}} \prod_{j=0}^{13} RI_{it-j}^{\beta_{ij}} E_{it}^{\alpha_i} \exp\{\delta_{0i} + \delta_{1i} W_{it}\}$$

The value of the α's and the β's were then used to compute the g functions, according to

$$g_{it} = 0.10\ \alpha_{it} S_i + 1/(1-R_i) \sum_{\substack{j=1 \\ j\neq 1}}^{10} 0.10\ \beta_{it} S_j R_j$$

S_k represents the share, in value terms, of national crop and livestock output originating in region k. R is the regional percentage of research expenditure as a share of the national total. The 0.10 coefficient indicates that the analysis was conducted to consider a hypothetical 10 percent increase in research expenditure. Weighting the contribution of other regions research by $(1 - R_i)^{-1}$ means that a region which has a high value for R_i would benefit more from spill-ins than a region with a lower level of internal research investment.

The findings of this set of studies indicate that federal research funding in the United States has not reflected regional patterns of benefit transmission. A realignment of funds to increase research in regions generating large spillovers was recommended. None of the papers cited above, however, took the final step of computing an optimal regional allocation pattern.

The analytical framework employed in these regional studies is essentially the same as that in the cost-benefit models outlined above, and is subject to the same information requirements and theoretical limitations. Additional care was taken in the regional models to identify the time lag structure of research benefits, and this is an important contribution.

Optimal Growth Models[2]

The study of optimal economic growth has traditionally been the province of development specialists, macroeconomists, and theorists. More recently, resource and agricultural economists have begun to apply this approach to the study of technological change. Optimal growth models have typically been used to study resource allocation at the national or sectorial level, but some less aggregate efforts have been undertaken.

One of the earliest applications of control theory to technical change was made by Uzawa (1965). In his model, the allocation decision focuses on dividing the total labor force at time t, L(t), between employment in production, Lp(t), and employment in the educational or research sector, Le(t). The production function is represented as:

$$Y(t) = F\,[K(t),\ T(t)\ Lp(t)]$$

where T(t) is an index of labor efficiency. This index increases as a larger share of the labor force is employed in the research sector. Research workers produce knowledge that makes production workers more effective. The movement of T(t) through time is governed by

$$\dot{T}(t)/T(t) = \emptyset\,[Le(t)/L(t)] = \emptyset\,[1-u(t)]$$

where $u(t) = Lp(t)/L(t)$. $\dot{T}(t)/T(t)$ denotes the growth rate of T(t). It is assumed that increasing the share of the labor force employed in research increases the rate of growth of T(t), so that $\emptyset' \geq 0$. This effect is subject to decreasing returns, however, so $\emptyset'' \leq 0$.

Other assumptions in the model include full employment of a finite labor force at each moment of time,

$$Lp(t) + Le(t) = L(t)$$

[2] *Readers unfamiliar with the techniques of control theory are referred to Intrilligator (1971), Takayama (1974), and Kamien and Schwartz (1981).*

a constant growth rate of the total labor force

$$\dot{L}(t)/L(t) = n$$

Output is allocated between consumption, C(t), and gross investment, I(t)

$$I(t) + C(t) \leq Y(t)$$

at each moment of time, and the capital stock, K(t), evolves according to

$$\dot{K}(t) = I(t) - \delta K(t)$$

A constant rate of depreciation is represented by δ.

These constraints are imposed on the objective function, which seeks to maximize the discounted stream of consumption per caput. The problem is set up for an infinite horizon and with a constant rate of social time preference, ρ.

Thus

$$\int_0^{\infty} [c(t)/L(t)]e^{-\rho t}\,dt$$

Functional forms for the production function and the technology index are not specified, so a quantitative solution to the model is found. It is useful to develop some additional notation. The effective capital-labor ratio is defined as

$$x(t) = K(t)/[T(t)\cdot L(t)]$$

The savings ratio is defined as

$$s(t) = I(t)/Y(t)$$

The optimal solution obtained is a balanced state described by the time paths of u(t), x(t) and s(t). Let a superscript* denote the value of a variable in its optimal state. If, by coincidence, the initial effective capital-labor ratio is optimal, that is

$$x(0) = x^*$$

then optimal growth is achieved by choosing a savings rate and an allocation of the labor force so that the technology index increases at the same rate as the capital labor ratio. Mathematically,

$$\dot{T}(t)/T(t) = \dot{k}(t)/k(t)\ ,$$

where $k(t) = K(t)/L(t)$.

By manipulation of the definitions above, this allocation rule can be written as

$$\emptyset\,[Le(t)/L(t)] = \frac{I(t)}{K(t)} - (\delta + n)$$

If $x(0) > x^*$, the savings rate falls to zero until $x(t) = x^*$ is achieved. If $x(0) < x^*$, then all output is saved ($S(t) = 1$), until $x(t) = x^*$. Once $x(t)$ achieves the optimal level, the labor and savings rule described above is followed.

By the late 1970's the model of endogeneous technological change introduced by Uzawa began to attract the attention of several economists, after an extended period of neglect. Ironically, it was concern for the problem of depletion of nonrenewable resource stocks that rekindled interest in the Uzawa model and not the study of technical change itself. Resource economists began to analyze conditions under which investments in technical change and in conventional capital could potentially stave off the apocalyptic vision described in the *Limits to Growth* literature for an economy with finite nonrenewable resources.

Robson (1980) studied a specialized version of the Uzawa model. The objective function was written as

$$\int_0^{\infty} e^{-\rho t}\left[\frac{C(t)}{1-\sigma}\right]^{1-\sigma} dt$$

The elasticity of the objective function with respect to an instantaneous increase in C is $1 - \sigma$, which is a constant. If $\sigma = 0$, then aggregate consumption is the preference indicator. For $\sigma = 1$, the objective function is logarithmic.

The production function is Cobb-Douglas, with

$$Y(t) = A(t)\, Lp(t)^{\alpha}\, K(t)^{\beta}\, E(t)^{\gamma}$$

The output elasticities are assumed to be strictly positive and to sum to a constant strictly less than 1. The effect of technical change is captured in the term $A(t)$, the rate of extraction and use of a nonrenewable essential resource is represented by $E(t)$. Because the resource is nonrenewable, the initial stock is fixed

$$S(0) = S_0$$

and the stock at any point in time constrains the total available for future consumption

$$S(t) = \int_t^{\infty} E(t)\, dt\ .$$

The rate of resource depletion is

$$\frac{\dot{S}(t)}{S(t)} = \frac{E(t)}{S(t)}$$

Output can be either invested or consumed, and the capital stock is assumed to not depreciate, for simplicity. Therefore

$$\dot{K}(t) = Y(t) - C(t)$$

$K(0) = K_O$ is given. Technical change shifts the production function. The intercept term $A(t)$ changes in response to the proportion of the labor force devoted to research. A linear relationship is assumed,

$$\frac{\dot{A}(t)}{A(t)} = \delta\,\frac{Le(t)}{L(t)} = \delta\left[\frac{L(t) - Lp(t)}{L(t)}\right]$$

From the necessary conditions for a solution to this optimal control problem, it can be shown that

$$Y_k(t) = \rho + \tau\,\frac{\dot{C}(t)}{C(t)}$$

$$Y_k(t) = \frac{\dot{Y}_E(t)}{Y_E(t)}$$

and

$$Y_k(t) = \frac{\dot{Y}_L}{Y_L} + \frac{\delta L_p(t)}{\alpha L(t)}$$

In each case, $Y_k(t)$ is the marginal product of capital. The right hand side of the first condition is often called the consumption rate of interest. If consumption is increasing (i.e., $\dot{C}/C>0$), then the marginal product of capital needs to be greater than the rate of time preference, ρ.

The second condition requires that the rate of growth of the marginal product of the nonrenewable resource be equal to the marginal product of capital. Since the stock of the nonrenewable resource is falling through time, and the production function is Cobb-Douglas, this condition implies that the marginal product of capital is increasing through time.

Robson also characterizes the asymptotic steady state to which the optimal solution converges. In the steady state, a constant share of output is allocated to research. If labor is paid its marginal product, then the share in value terms of output devoted to research is

$$f = \frac{Y_L(t) \cdot L_E(t)}{Y(t)}$$

Y_L denotes $\alpha Y/\alpha L_p$. It can be shown that

$$f = \frac{\delta[(1-\beta) - \sigma(1-\sigma)] - \rho\alpha(1-\beta)}{\rho(1-\beta) - \delta(1-\sigma)}$$

In the case of a logarithmic objective function, $\sigma = 1$, and

$$f = \frac{\delta}{\rho} - \alpha$$

Chiarella (1980) chose to view the research resource allocation problem by treating research as an investment good. The discounted stream of the logarithm of consumption was used as the objective function

$$\int_0^\infty e^{-\rho t} \ln C(t)\, dt \ .$$

Consumption of a nonrenewable resource, E(t), capital, K(t), and the level of technology, Z(t), are inputs in a Cobb-Douglas production function.

$$Y(t) = Z(t)^\beta K(t)^{\alpha_1} E(t)^{\alpha_2}$$

As resources are used for production, the stock, S(t), is depleted, so

$$\dot{S}(t) = -E(t)$$

The level of technology changes with the rate of research investment, according to

$$\dot{Z}(t) = R(t)^\delta$$

Output is either consumed, invested in capital or invested in research, so

$$\dot{K}(t) = Y(t) - C(t) - R(t)$$

Here again, conventional capital does not depreciate, nor does research.

Since the objective function of the Robson model is reduced to the special case of the Chiarella model when $\sigma = 1$, it is not surprising that necessary conditions for an optimal solution include

$$Y_K(t) = \rho + \frac{\dot{C}(t)}{C(t)}$$

and

$$Y_K(t) = \frac{\dot{Y}_E(t)}{Y_E(t)}$$

These are identical to the Robson results for $\sigma = 1$. The third condition in the present context is

$$Y_K(t) = \frac{\delta R(t)^{\delta-1}}{\frac{\beta Y(t)}{Z(t)}} - \frac{(\delta - 1)\dot{R}(t)}{R(t)}$$

The first term is the ratio of the marginal product of research in the technology function to the gross rate of return to technology. The second term is a constant times the rate of growth of research expenditures. For a given value of the marginal product of capital, this condition requires that the higher the value of the marginal product of research in the technology function, the faster the growth rate in research investment should be.

Chiarrella's result can also be manipulated to show the optimal steady state share of output that should be devoted to research. The solution is

$$\frac{R^*}{Y^*} = \left[\frac{\delta^2 \beta\alpha_2}{\delta(\beta+\alpha_2) + \alpha_1 - 1}\right] \ .$$

In the same volume as the Chiarella paper, Takayama (1980) develops two models of technical change using optimal control techniques.

Little emphasis has been placed on empirical estimation in the control theoretic literature on research resource allocation. Nevertheless, the work suggests potential applications. It has been an important contribution to formally characterize the problem as a special case of dynamic investment. Techniques of control theory based on continuous time suffer from the limitation of not being able to handle very detailed problems. As the number of choice variables increases, the set of differential equations describing the necessary conditions becomes very difficult to solve analytically. Some progress has been made, however, through the use of dynamic optimization models in discrete time. The work of Knutson and Tweeten (1979) and Fox (1986), to which we now turn, is in this tradition.

The applications of Knutson and Tweeten and Fox employed optimal growth models to determine socially efficient levels of public agricultural research for the U.S. farm sector. Knutson and Tweeten considered the farm production sector as a unit. Fox's model had separate livestock and crop sectors. Both studies used a revised version of Cline's model of the production function for agriculture. The Knutson and Tweeten study considered three scenarios for real increases in funding:

1. Expenditures would grow in real terms by 3 percent per year from 1976-2015, which represents an extrapolation of the trend from 1939-1972.
2. Real funding growth of 10 percent per year for 1976-1980, followed by 3 percent real growth to 2015.
3. Ten percent growth from 1976-1980 followed by 7 percent growth annually to 2015.

The effect of these research investments on output prices and production levels was estimated with the National-Interregional Projections system (Yeh 1976) for various assumptions about the rate of growth in demand for farm products. Social rates of return to research investments were computed for each of the funding and demand growth combinations. Research investment was considered socially profitable if the rate of return was not depressed below 10 percent. If demand growth was held to 1.2 percent per annum, then the historical rate of increase in funding was found to be consistent with the optimality criterion. This would lead to a doubling of annual support for research by the end of the century. Higher rates of research funding were optimal for higher levels of demand growth. The effect of export market behavior on demand growth was not reported.

The Fox study used a three sector growth model. Livestock production, crop production, and the rest of the economy were represented. The model sought to maximize the discounted stream of the logarithms of annual consumption of output of the three sectors weighted by shares of annual consumption expenditure. The objective function was constrained by production functions for each sector and by factor endowments. Crops could be exported in exchange for goods which substituted for the output of the nonfarm sector. Four categories of research were identified. "Basic", or non-commodity specific biological research, and "applied", a commodity specific research aimed at the farm production sector, were identified for each of the two farm sectors. These public investment variables competed with consumption and with conventional capital investment inside and outside of agriculture.

The findings of this report contrasted with the results of the Knutson and Tweeten study. Both found evidence of underinvestment in agricultural research, but the solution of the Fox model indicated that optimal funding for each of the categories of research was on the order of four times the actual level in the late 1970's. The aggregate underinvestment problem was found to be equally serious for each of the four research types. Neither crops nor livestock research or basic nor applied research was found to be relatively more inadequately supported.

IDENTIFYING SOUTHERN PINE FORESTRY RESEARCH PRIORITIES

Background

The southern pine forestry research effort has recently become a focus of attention, due in part to the Southern Timber Study. The USDA Forest Service has brought together the diverse forestry interest groups in the South in an effort to develop an analytical database for formulating and guiding public and private forest policies. It is possible to apply techniques discussed earlier to southern pine forestry to determine research priorities.

The research resource allocation question concerns the choice of funding levels for types of forestry research for essentially a single output. Categories include fire, insect, disease[3], renewable resource evaluation, renewable resource economics, timber management, forest products utilization, forestry engineering and other[4]. The last three categories are predominantly concerned with post-harvest research problems. The focus of this study is on the allocation of research resources for pre-harvest forestry problems.

Congruence Calculations

While congruence ratios possess limited prescriptive power, the approach does give some insight into the intensity of research investment across commodity groups and regions. Tables 4 and 5 document the level of Federal research funding in the South. Volume and value of production are reported in table 6.

---

[3]*As of 1974, the insect and disease categories were reported as a combined total.*

[4]*Includes cooperative aid, insect and disease control detection and appraisal, range, recreation, requirements and supply, research construction, watershed, wildlife and fish habitat, and miscellaneous.*

Similar tables could be constructed for the other regions in the United States and sets of congruence ratios could be formulated. Comparisons could be made of functional activity categories of research per $1,000 of product value across regions. Using the USDA Forest Service *Wildfire Statistics*, comparisons could be made of the levels of fire prevention and control research relative to the actual incidence of fires across regions.

It should be noted that tables 4 and 5 report Federal research allocations. If it is suspected that State allocations among functional activities vary among regions, similar tables for State expenditures would be necessary to complete the congruence picture.

A Social Surplus Model of Research Resource Allocation

Data on inputs up to the point of harvest are quite limited, which precludes the use of a production function model. It is possible, however, to develop a social surplus model along the lines of those presented earlier. A model of supply and demand are needed. A log-linear version of the demand function could be estimated as

$$\ln Y_t^D = \sigma^D + \eta^D \ln P_t + \eta^I \ln I_t$$

Table 4.--Federal research funds allocated to the Southern Forest Experiment Station by functional activity, 1955-1983

(In current dollars)

Year	Functional activity					
	Fire	Insect	Disease	Renewable resource evaluation	Renewable resource economics	Timber management
1955	8,500	31,200	32,750	105,000	12,000	341,846
1956	8,500	49,624	32,750	105,000	12,000	544,513
1957	36,786	65,000	52,000	136,000	42,100	686,000
1958	38,276	68,058	54,145	176,565	44,956	767,440
1959	38,276	68,054	54,145	176,529	44,956	986,381
1960	40,496	72,613	57,725	185,813	47,916	1,044,830
1961	50,791	88,175	73,133	187,253	48,224	1,161,315
1962	78,091	147,975	152,633	219,903	80,924	1,348,965
1963	78,091	168,975	166,633	217,903	80,924	1,339,965
1964	82,691	205,095	178,233	231,703	86,124	1,538,745
1965	84,070	425,355	215,510	264,640	87,740	1,583,910
1966	85,550	432,605	220,500	270,390	89,800	1,649,790
1967	87,850	472,305	253,500	296,090	99,030	1,683,759
1968	89,900	601,200	268,000	328,600	140,100	1,786,800
1969	91,900	621,200	276,800	339,700	144,800	1,847,400
1970	111,700	639,600	285,300	381,400	151,200	1,924,100
1971	115,700	683,600	331,300	490,400	207,200	2,081,100
1972	123,100	749,700	510,800	536,400	228,100	2,248,200
1973	123,500	888,000	476,200	538,100	228,900	2,770,600
1974	123,500	1,400,200		538,100	228,900	2,347,600
1975	134,100	1,521,100		588,400	252,300	2,669,900
1976	138,300	2,063,400		710,300	265,200	2,671,500
1977	145,900	2,262,200		1,059,000	284,900	2,871,900
1978	152,700	2,371,200		1,445,000	301,300	3,556,100
1979	159,000	2,532,000		1,485,000	313,000	4,211,000
1980	103,000	2,650,000		1,511,000	321,000	4,361,000
1981	174,000	3,607,000		1,716,000	389,000	5,196,000
1982	155,000	3,516,000		1,572,000	394,000	4,621,000
1983		3,506,000		1,673,000	385,000	4,601,000

Table 5.--Federal research funds allocated to the Southeastern Forest Experiment Station by functional activity, 1955-1983

(In current dollars)

Year	Functional activity					
	Fire	Insect	Disease	Renewable resource evaluation	Renewable resource economics	Timber management
1955	25,477	30,714	62,158	90,000	14,500	320,040
1956	25,477	30,714	62,000	90,000	15,000	430,198
1957	40,112	45,000	68,000	120,000	42,000	454,000
1958	132,033	47,908	82,900	164,500	43,500	510,196
1959	202,083	47,909	82,900	164,500	43,500	643,526
1960	213,859	51,731	87,774	173,145	46,374	691,997
1961	214,732	76,917	112,780	173,640	46,651	739,512
1962	275,032	132,417	214,980	202,459	74,051	848,312
1963	278,032	163,066	269,246	200,459	85,701	770,837
1964	294,432	270,265	345,946	213,159	91,101	818,037
1965	299,360	423,880	425,750	240,740	92,800	925,060
1966	458,950	458,770	434,850	247,560	94,450	949,510
1967	459,350	502,270	453,550	283,340	152,920	1,089,641
1968	469,800	514,700	469,400	313,500	162,600	1,169,700
1969	463,800	533,300	486,500	324,800	168,100	1,255,300
1970	479,900	549,500	528,900	356,900	171,600	1,292,300
1971	508,900	586,500	525,900	426,900	181,600	1,406,300
1972	569,600	645,700	575,100	465,800	197,900	1,707,900
1973	1,097,800	648,500	577,200	467,400	198,600	1,720,300
1974	917,800	1,225,700		467,400	198,600	1,791,900
1975	978,500	1,330,700		516,100	184,200	1,971,400
1976	1,122,300	1,907,900		630,200	193,200	2,367,800
1977	1,201,600	2,000,900		973,900	207,000	2,524,000
1978	1,251,100	2,071,200		1,328,300	215,700	3,013,600
1979	1,297,000	2,067,000		1,380,000	222,000	3,188,000
1980	1,364,000	2,103,000		1,430,000	253,000	3,066,000
1981	1,459,000	2,303,000		1,656,000	384,000	3,699,000
1982	1,276,000	1,990,000		1,407,000	330,000	3,285,000
1983	1,257,000	2,179,000		1,614,000	343,000	3,095,000

where Y_t^D is the level of production from table 6, P_t is the stumpage price of table 6 suitably adjusted for inflation, and I_t is a measure of real national income. η^D and η^I are the elasticities of demand with respect to price and income respectively.

Because trees take time to mature and can be harvested at various stages of growth, supply is more difficult to model. Conceptually, we want to relate the level of harvest activity, Y_t^s, to the stumpage price, P_t, and to lagged expenditures of research, R_{t-i}. To reflect the dynamic nature of the production process for wood, a variable which is intended to approximate the stock of wood, S_t, is also included. A constant elasticity log-linear supply schedule could be estimated as

$$Y_t^s = \alpha \left(\prod_{i=0}^{I} \prod_{j=1}^{J} R_{jt-i}^{\beta_{ij}} \right) P_t^{\eta_S} F_t(S_t)$$

R_{jt-i} is the level of research expenditure on functional activity j in time period t − i. There are five relevant categories of functional activities. It is suggested, based on the agricultural research literature, that a quadratic distributed lag with zero-

Table 6.--Volume of southern pine production and stumpage prices, 1950-1981

Year	Production	Stumpage prices
	Million board feet	Nominal dollars per thousand board feet
1950	9,939	26.70
1951	8,495	34.60
1952	8,572	38.50
1953	7,581	34.20
1954	7,332	29.70
1955	7,360	32.00
1956	7,740	37.40
1957	6,568	31.50
1958	6,410	31.10
1959	6,716	35.20
1960	5,660	34.50
1961	5,622	26.80
1962	5,733	26.00
1963	6,055	25.10
1964	6,414	27.80
1965	6,628	31.70
1966	6,609	38.60
1967	6,511	38.30
1968	6,901	42.40
1969	7,181	51.70
1970	7,063	44.10
1971	7,736	52.20
1972	7,884	65.60
1973	7,895	93.40
1974	6,921	76.20
1975	6,967	57.00
1976	7,598	100.30
1977	8,239	134.50
1978	8,267	155.20
1979	8,034	155.40
1980	6,880	172.00
1981 (preliminary)	6,824	127.20

Source: Historical statistics of the United States: colonial times to 1970, U.S. Department of Commerce, Statistical abstract of the United States, various years.

constrained end points be imposed on the β_{ji}'s to economize on requirements for data.

We only have periodic estimates of the stock variable, S_t—that is, the present inventory of standing timber. However, if we assume that the age profile of the annual harvests remains relatively stable, a series for S can be constructed from planting and seeding rates from table 7, from harvested acres and regeneration rates reported by Tansey (1983a, 1983b), and from average yields from table 8. Let $PL_t - i$ represent the average planted, seeded, or naturally regenerated i periods ago. Let Y_t represent the harvest level in period t, and θ_i be the average yield in board feet per area of a stand of timber i years old. The stock variable can be constructed as

Table 7.--Total annual planting and seeding in the Southern Region, 1925-1979

(In acres)

Year	Area	Year	Area
1925	32,038	1951	255,099
1926	6,530	1952	256,624
1927	3,203	1953	431,047
1928	9,857	1954	520,026
1929	13,470	1955	501,746
1930	13,221	1956	601,288
1931	8,460	1957	820,078
1932	8,650	1958	1,110,103
1933	2,770	1959	1,679,944
1934	19,901	1960	1,581,408
1935	45,595	1961	1,211,131
1936	114,342	1962	834,579
1937	118,117	1963	813,306
1938	194,018	1964	777,484
1939	173,391	1965	728,050
1940	178,750	1966	718,039
1941	194,821	1967	782,101
1942	66,213	1968	812,605
1943	19,838	1969	806,477
1944	10,879	1970	876,794
1945	56,782	1971	1,024,545
1946	57,004	1972	1,016,122
1947	57,110	1973	1,052,708
1948	187,708	1974	1,051,246
1949	226,037	1975	1,272,018
1950	294,377	1976	1,195,865
		1977	1,323,618
		1978	1,338,353
		1979	1,370,168

$$S_t = \sum_{i=0}^{t} \theta_i \, PL_{t-i} - \sum_{i=0}^{t} Y_{t-i}$$

In choosing a harvest strategy, owners of forested land consider the current stumpage price, the expected gain in wood volume at some future date, the expected stumpage price at that date, and the opportunity cost of postponing harvest. These factors are embedded in the function $F_t\,(S_t)$.

Values of θ are only available for 5-year intervals, so an interpolation technique would need to be employed to obtain the full set of θ_i's. Also, the average yields for the four species would need to be collapsed into a weighted average since the model is formulated at an aggregate level of all southern pine output.

Given projected values of national income, I_t, a dynamic cost-benefit model can be used to compute changes in social surplus as a function of research expenditures. The optimal size and composition of the research budget can be computed by choosing levels of the $R_j t$'s that give a discounted present value of the social surplus gains equal to the marginal opportunity cost of public funds[5] for each of the categories of research.

[5]*It should be noted that the marginal opportunity cost of $1 of public funds exceeds $1 (Browning 1976, Stuart 1984).*

Table 8.--Average volume per acre of southern pine species

(In board feet per acre)

Age of stand	Species: Loblolly pine (Site Index 90)	Longleaf pine (Site Index 70)	Shortleaf pine (Site Index 70)	Slash pine (Site Index 80)
15	850	200	--	1,500
20	5,000	1,000	250	4,000
25	9,500	3,000	2,800	7,500
30	14,500	5,500	6,900	12,000
35	19,000	8,000	11,750	16,000
40	24,000	10,500	16,400	19,000
45	28,000	13,000	20,250	22,000
50	31,500	16,000	23,800	24,000
55	34,500	18,000	27,000	26,000
60	37,000	20,500	29,700	27,500
65	39,500	22,500	32,000	
70	41,500	24,500	34,100	
75	43,000	26,500	35,900	
80	44,500	28,000	37,700	

Source: Volume, yield and stand tables for seasonal growth of southern pine, U.S. Department of Agriculture, Forest Service, Misc. Publ. 50, August, 1976.

REFERENCES

Araji, A. A.; Sim, R. J.; Gardner, R. L. Returns to agricultural research and extension programs: an *ex-ante* approach. American Journal of Agricultural Economics. 60(5): 764-768; 1978.

Ayer, H. W.; Schuh, G. E. Social rates of return and other aspects of agricultural research: the case of cotton research in Sao Paulo, Brazil. American Journal of Agricultural Economics. 54(400): 557-569; 1972.

Barker, R.; Herdt, R. W. Setting priorities for rice research in Asia. In: Anderson, R. S.; et al., eds. Science, politics and the agricultural revolution in Asia. Boulder, CO: Westview Press; 1982: 427-462.

Boyce, J. K.; Evenson, R. E. National and international agricultural research and extension programs. New York: Agricultural Development Council; 1975.

Bredahl, M.; Peterson, W. The productivity and allocation of research: U.S. Agricultural Research Stations. American Journal of Agricultural Economics. 58(4): 684-692; 1976.

Browning, E. K. The marginal cost of public funds. Journal of Political Economics. 84(2): 283-298; 1976.

Chiarella, C. Optimal depletion of a non-renewable resource when technological progress is endogenous. In: Kemp, M. C.; Long, N. V., eds. Exhaustible resources, optimality and trade. North-Holland; 1980: 81-94.

Chipman, J. S.; Moore, J. C. The Scope of consumer's surplus arguments. In: Tang, A. M.; *et al.*, eds. Evolution, welfare and time in economics: essays in honor of Nicholas Georgesen-Roegen. Lexington; 1976: 69-124.

Chipman, J. S.; Moore, J. C. Compensating variation, consumer's surplus and welfare. American Economic Review. 70(5): 933-949; 1980.

Cline, P. L. Sources of productivity change in United States agriculture. Oklahoma State University; 1975. Ph.D. thesis.

Evenson, R. E.; Waggoner, P. E.; Ruttan, V. W. Economic benefits from research: an example from agriculture. Science. 205: 1101-1107; 1979.

Fishel, W. L. Uncertainty in public research administration and scientists' subjective probability estimates about changing the state of knowledge. North Carolina State University; 1970. Ph.D. thesis.

Fishel, W. L. Resource allocation in agricultural research. Minneapolis: University of Minnesota Press; 1971.

Fox, G. Underinvestment, myopia and commodity bias: a test of three propositions of inefficiency in the U.S. agricultural research system. Canada: University of Guelph, Department of Agricultural Economics and Business; February 1986. (mimeo)

Garren, N. M. The efficient allocation of agricultural research investment with externality considerations. University of Georgia; 1981. Ph.D. thesis.

Garren, N. M.; White, F. C. An analytical framework for the efficient allocation of agricultural research expenditures by states. Agriculture Administration. 8(4): 279-287; 1981.

Grieg, I. D. Research management: a probabilistic *ex ante* evaluation of two broiler research proposals. Agric. Econ. Bull. 23. Armidale, NSW, Australia: University of New England, Department of Agricultural Economics and Business Management; 1979.

Habib, M. A. Optimal research, induced innovation and agricultural development: an application to Bangladesh. McMaster University; 1980. Ph.D. thesis.

Habib, M. A.; Butterfield, D.; Mestelman, S. An *ex ante* model for the allocation of research expenditure among competing crops. Working Pap. 81-09. McMaster University, Economics Department; 1981.

Havlicek, J., Jr.; White, F. C. Inter-regional transfer of agricultural research results: the case of the Northeast. Journal of the Northeastern Agricultural Economics Council. 12(2): 19-30; 1983.

Hildreth, R. J. Issues and implications in current procedures for establishing research priorities. Journal of Farm Economics. 48(5): 1641-1650; 1966.

Intrilligator, M. D. Mathematical optimization and economic theory. Prentice-Hall; 1971.

Kaldor, D. R. A framework for establishing research priorities. Journal of Farm Economics. 48(5): 1629-1637; 1966.

Kamien, M. I.; Schwartz, N. L. Dynamic optimization: the calculus of variations and optimal control in economics and management. North-Holland; 1981.

Klein, K. K.; Kehrberg, E. W. The use of an innovation possibilities frontier to evaluate an applied animal breeding research project. Canadian Journal of Agricultural Economics. 29(2): 141-158; 1981.

Knutson, M.; Tweeten, L. G. Toward an optimal rate of growth in agricultural production research and extension. American Journal of Agricultural Economics. 61(1): 70-76; 1979.

McKenzie, G. W. Measuring economic welfare: new methods. Cambridge University Press; 1982.

Moore, J. R.; Baker, N. R. Computational analysis of scoring models for R and D project selection. Management Science. 16(4): B-212-B-232; 1969.

Paulson, A.; Kaldor, D. R. Evaluation and planning of research in the experiment station. American Journal of Agricultural Economics. 50(5): 1149-1160; 1968.

Peterson, W. L. Return to poultry research in the United States. Journal of Farm Economics. 49(3): 656-669; 1967.

Pinstrup-Anderson, P. Agricultural research and technology in economic development. New York: Longman; 1982.

Ramahlo de Castro, J. P. An economic model for establishing priorities for agricultural research and a test for the Brazilian Economy. Purdue University; 1974. Ph.D. thesis.

Ramahlo de Castro, J. P.; Schuh, G. E. An empirical test of an economic model for establishing research priorities: a Brazil case study. In: Arndt, T. M.; *et al.*, eds. Resource allocation and productivity in national and international agricultural research. Minneapolis: University of Minnesota Press; 1977: 498-525.

Robson, A. J. Costly innovation and natural resources. International Economic Review. 21(1): 17-30; 1980.

Russell, D. G. An investigation into the use of mathematical models for resource allocation in agricultural research. Scotland: University of Stirling; 1973. Ph.D. thesis.

Russell, D. G. Resource allocation in agricultural research using socio-economic evaluation and mathematical models. Canadian Journal of Agricultural Economics. 23(2): 29-52; 1975.

Ruttan, V. W. Agricultural research policy. Minneapolis: University of Minnesota Press; 1982.

Ruttan, V. W. Agricultural research policy issues. Horticulture Science. 108(6): 809-818; 1983.

Salmon, D. C. Congruence of agricultural research in Indonesia 1974-1978. Bull. 83-1. Minneapolis: University of Minnesota, Economic Development Center; 1983.

Scobie, G. M. Investment in international agricultural research: some economic dimensions. World Bank Staff Working Paper. 361; 1979.

Shumway, C. R.; McCracken, R. J. Use of scoring models in evaluating research programs. American Journal of Agricultural Economics. 57(4): 714-718; 1975.

Stuart, C. Welfare costs per dollar of additional tax revenue in the United States. American Economic Review. 74(3): 352-362; 1984.

Takayama, A. Mathematical economics. Dryden Press; 1974.

Takayama, A. Optimal technical progress with exhaustable resources. In: Kemp, M. C.; Long, N. V., eds. Exhaustable resources, optimality and trade. North-Holland; 1980: 95-110.

Tansey, J. B. The pine resource in South Carolina: an interim assessment, 1983. Res. Pap. SE-244. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station; 1983a.

Tansey, J. B. Forest statistics for the southern coastal plain of North Carolina, 1983. Resour. Bull. SE-72. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station; 1983b.

U.S. Department of Agriculture. A national program of research for agriculture. Report of a study by the Association of State Universities and Land Grant Colleges and the U.S. Department of Agriculture, October; 1966.

Uzawa, H. Optimal technical change in an aggregative model of economic growth. International Economic Review. 6(1): 18-31; 1965.

White, F. C.; Havlicek, J., Jr. Interregional spillover of agricultural research results and intergovernmental finance: some preliminary results. In: Norton, G. W. *et al.*, eds. Evaluation of agricultural research. Misc. Publ. 8-1981. St. Paul: University of Minnesota, Minnesota Agricultural Experiment Station; 1981: 60-70.

Yeh, C. J. Prices, farm outputs and income projections under alternative demand and supply conditions. American Journal of Agricultural Economics. 58(4): 703-711; 1976.

Ziemer, R. F.; White, F. C.; Cline, P. L. Regional welfare and agricultural research and extension in the U.S. Agricultural Administration. 9(3): 167-178; 1982.

Fox Glenn.
A framework for identifying public research priorities: an application in forestry research. Gen. Tech. Rep. NC-109. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1986. 21 p.

Discusses attempts to model and measure the relationship between research and development activity and the rate and nature of technological change in recent decades. Reviews efforts to model optimal research resource allocation, and presents a model for southern pine forestry research.

KEY WORDS: Optimal budget allocations, resource allocation, optimal research budgets, optimization procedures, research evaluation.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1986—755-151/40078

1966-86

NORTH CENTRAL

FOREST

EXPERIMENT STATION

20th Anniversary