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Dynamic modelling of agroforestry and soil fertility interactions: implications for multi-disciplinary research policy

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Abstract

This paper attempts to contribute to one of the major aspects of international research agenda in agroforestry. A general framework is developed in this paper to capture the dynamic interactions of various components of agroforestry system. Using a multi-seasonal model of agroforestry, the competition among the system components in resource and input use and the trade-offs between different outputs of agroforestry system are analyzed. Policy implications for multi-disciplinary research are derived. It is argued that quantifying the potential benefits of agroforestry system requires reformulation of existing economic methods of analyzing agroforestry technology to contribute to the fuller understanding of the dynamic interactions among its various components.

1. Introduction

The potential benefits of agroforestry systems to the basic human needs and welfare as well as to the local and national economies have been well documented (Nair, 1990). However, given the long-term nature of realizing these benefits, quantified evidence on the impact of agroforestry in improving the economic welfare of the rural households has been scanty (ICRAF, 1990). This is partly due to the limited number of studies conducted on the analysis of economic benefits of agroforestry systems. Further, inherent difficulties in quantifying non-measurable benefits that are associated with agroforestry, confines scientists to a less than thorough analysis of the contributions from it. While it is widely recognized that such non-measurable benefits should be accounted for in analyzing the agroforestry systems, the existing methods of economic analysis of agroforestry do not lend themselves to incorporating the environmental and sustainability gains associated with adopting agroforestry. The favourable but long-term beneficial attributes of agroforestry which are not readily quantified in terms of lower unit costs or increased productiv-

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ity will remain "invisible" to economists unless methods to incorporate them in economic analysis are developed (Nair, 1990). Thus there exists an urgent need to analyze all possible benefits of agroforestry which could be quantified or otherwise. This requires developing a general framework that includes various components of agroforestry system and studying their biological and economic interactions with a view to increasing the management options available to resource-poor farmers. This is also one of the major objectives of International Center for Research on Agroforestry for its strategic programmes towards the year 2000 (ICRAF, 1990).

To minimize competition and enhance productivity among various components of agroforestry systems, it is important to study their bioeconomic interactions in various land use systems. Also, a careful analysis of the agroforestry system as a whole is essential for decision making on the choice of its components. This requires a basic understanding of the biophysical and bioeconomic processes involved in agroforestry systems. While concrete but limited efforts have been made to understand the biophysical interrelationships in agroforestry (ICRAF, 1992), the methods and tools for conducting bioeconomic research are grossly inadequate and are yet to be developed (Kidd and Pimentel, 1992).

Despite its potential benefits and increasing evidence on the actual benefits, the adoption of agroforestry has been rather slow and below the expectations of the researchers. This is possibly due to the fact that the farmers in general are interested in short run gain from the crop lands ignoring the long run benefits that a system such as agroforestry would bring about (El-Swaify et al., 1985). Under some land tenancy arrangements, agroforestry systems installed by the tenant could be considered as a method of land improvement and a long-term investment in improving the soil fertility if agroforestry is used for green manures (Babu, 1992). To the extent the current land tenure systems in developing countries exhibit ownership uncertainties, the investment in the form of planting trees and conversion of traditional farming systems into agroforestry systems will be limited.

Establishment of agroforestry systems does not come free of resource cost. In regions of land scarcity, a part of already existing crop land has to be allocated to tree component which competes with field crops (Walker, 1987). It may be more rewarding to the farmer, at least in the short-run, to grow field crops and forego the stream of benefits that agroforestry would provide from the same piece of land. Besides the land area, tree component in agroforestry system may also compete for soil nutrients and water with the field crops (Nair, 1990). Given that most of the agroforestry systems also include a livestock component, the benefits from agroforestry should be shared between the competing uses such as green manure and animal feed. In addition, the twigs and branches of trees are also used as sources of fuel wood, which may restrict the growth of tree component if the timing and quantity of pruning for firewood are not optimal. Associated with this is the dynamic nature of soil nutrients depletion through crop removal and their addition through chemical fertilizers and through organic manures from other agroforestry components.

Interactions among the above components of an agroforestry system, in resource use patterns and the trade-offs between different outputs from it, pose considerable challenge to researchers attempting to quantify the benefits from agroforestry. The complexity of interactions of various components in an agroforestry system, increases the number of variables to be studied and this has been one of the contributing factors to the weak scientific evidence to support several beneficial aspects of agroforestry (Kidd and Pimentel, 1992). Furthermore, agroforestry systems involving perennial tree crops need an evaluation of their economic benefits over a long period of time. Thus, models using single period and static formulations may not capture the dynamic benefits of agroforestry systems. The dynamic nature inherent in the benefits received through various agroforestry components and their interactions call for reformulation of existing models of economic analysis of agroforestry systems (Babu and Rajasekaran, 1991). The interactions of agroforestry components with already existing crop and animal production systems have to be understood thoroughly so that the joint contribution of components of agroforestry could be quantified. To address these issues a research agenda with a multi-disciplinary focus is imminent.

The purpose of this paper is to provide a general framework for analyzing these issues by identifying important linkages that are to be considered in establishing interactions among different components and in quantifying the benefits, when tree component of agroforestry is incorporated into the already existing crop–livestock production system. While evaluating a specific system of agroforestry is a matter of empirical investigation, the present paper models a general multi-seasonal agroforestry system along with animal production. Using the contributions of various components in agroforestry systems to soil fertility of crop lands as a linking factor, conditions are derived for successful adoption of agroforestry. Policy implications for multi-disciplinary research are also derived.

The rest of the paper is organized as follows. A dynamic economic model of agroforestry system is presented in the next section in three parts; crop production and soil fertility, agroforestry and dynamic soil fertility and agroforestry and animal production. Issues relating to testing and verifying the model results are discussed in section three. Policy implications for multi-disciplinary research are derived based on model results in section four and concluding remarks form the last section.

2. A dynamic model of an agroforestry system

Bioeconomic modelling of the agroforestry system as a whole is a complex process. Given the biological inter-relationships involved among the components in such a system, the method adopted here for modelling purposes is one which enables grafting of animal production and tree production components on the already existing crop production system. This provides an opportunity to understand the economic relations which make the agroforestry system environmentally sustainable and economically viable.

3. Crop production and soil fertility

To start with a simple model of private decisions in selecting optimal soil fertility inputs for a field crop at the farm level is presented. The farmer is assumed to grow a single crop throughout her planning horizon of T seasons. The crop yield is assumed to be a function of soil fertility reflected by the humus content of soil and other available soil nutrients given by $\mathbf{Q}_{1t} = \mathbf{Q}_1(\mathbf{X}_t, \mathbf{U}_t, t)$, where $\mathbf{Q}_{1t}$ is the yield of crop in season t, $\mathbf{X}_t$ is a vector of soil fertility indicators namely, humus (x_1) and other major soil nutrients (x_2; soil nitrogen, soil phosphorus and soil potassium) $\mathbf{U}_t$ is a vector of inputs, namely organic manure, farm yard manure, compost and green manure (u_1), and chemical fertilizers (u_2). See appendix for a description of variables used in this paper. Given the price vector of inputs, K_t and the price of output, P_t in any season, the profit from farming can be written as

$$\pi_t = P_1 Q_1 - \boldsymbol{K}_t \boldsymbol{U}_t - \boldsymbol{C}_t \boldsymbol{Z}_t \tag{1}$$

where $\mathbf{C}_t$ is per unit cost vector of other inputs $\mathbf{Z}_t$ than $\mathbf{U}_t$. The growth of humus content and other available soil nutrients (N,P,K) in the soil in any season is represented by a growth function for each of the soil fertility indicators that appear in the yield function Q_{1t};

$$\dot{x}_{it} = f_{it}(\boldsymbol{X}_t, \boldsymbol{U}_t, t), i = 1,2 \tag{2}$$

Recently much importance has been given to the carry over effects of soil nutrients to the subsequent seasons (Ackello-Ogutu et al., 1985; Lanzer et al., 1987; Hallam and Babu, 1988; Jauregui and Sain, 1992). The use of equation of motion for the soil nutrients (eq. 2) enables one to capture the effects of soil nutrients on the future yields of crops and consider them in current decisions on optimal fertilizer use. This is particularly important when we consider the long-term effects of agroforestry system in building up soil fertility which is discussed later in a greater detail. Assuming that the farmer maximizes the present value of the future stream of profits and the value of the crop land at the end of planning horizon, the problem of optimal input choice in a dynamic context can be written as

$$J(X_o) = \underset{Q,U}{\text{Max}} \int_{t=0}^{T} e^{-\delta t} [P_1 Q_{1t}(X_t, U_t, t) - K_t U_t - C_t Z_t] dt \quad (3)$$

$$= \underset{Q,U}{\text{Max}} \int_{t=0}^{T} e^{-\delta t} \pi_t dt \quad (4)$$

Where δ is the discount rate of the farmer (Hoekstra, 1985).

Let $J(X_T)$ be the value of the crop land at the end of planning horizon (T), which is assumed to be a function of quality of land reflected by the fertility of soil given by X_T. This implies that the farmer will place importance on maintaining the long-term soil fertility to increase the value of farming land. This condition is also useful in analyzing contractual arrangements between the owner and the tenant in different farming systems, which will determine the level of soil fertility investment of the farmer (Feder and Onchan, 1987; Babu, 1992).

The farmer will then maximize

$$J(X_o) + J(X_T) e^{-\delta t} \quad (5)$$

subject to (eq. 2) and initial stock of soil fertility indicators;

$$X(0) = X_o, \textit{ and } [X_t, U_t] \geq 0. \quad (6)$$

The maximization of (eq. 5) subject to (eq. 2) and (eq. 6) can be formulated as an optimal control problem (Chiang, 1992). The Hamiltonian function associated with the above problem is given by

$$H_t = e^{-\delta t} \pi_t + \Sigma_{i=1}^{2} \phi_i f^i(X_t, U_t) \quad (7)$$

Where ϕ_i is the co-state variable associated with the equation of motion of state variable x_i.

An explanation of notation used in the paper and the definition of various variables are given in appendix for quick reference. According to the maximum principle (Chiang, 1992), the optimal paths of **X, U, Z** and ϕ satisfy the following conditions:

$$H_{u1} = e^{-\delta t}[P_1 Q_{1u1} - K_1] + \Sigma_{i=1}^{2} \phi_i f_{u1}^i = 0 \quad (8)$$

$$H_{u2} = e^{-\delta t}[P_1 Q_{1u2} - K_2] + \Sigma_{i=1}^{2} \phi_i f_{u2}^i = 0 \quad (9)$$

$$H_{zt} = e^{-\delta t}[P_1 Q_{1zt} - C_t] = 0 \quad (10)$$

$$H_{xi} = -\dot{\phi}_i = e^{-\delta t}[P_1 Q_{xi}] + \Sigma_{i=1}^{2} \phi_i f_{ixi};\ i = 1,2 \quad (11\text{–}12)$$

$$H_{\phi i} = f_i(X, U, t);\ i = 1,2 \quad (13)$$

$$\phi_i(T) = \partial J[x(T)] / \partial x_i(T);\ i = 1,2 \quad (14\text{–}15)$$

Assuming that the second order conditions are satisfied, conditions (eq. 8) – (eq. 15) are necessary and sufficient to obtain optimal solutions of soil fertility inputs namely the organic manures and chemical nutrients of the above problem. The conditions (eq. 8) – (eq. 9) imply that the optimal level of any soil fertility input should be so chosen that the net marginal benefit from its use $e^{-\delta t}[P_1 Q_{1ui} - k_t]$ be equal to the marginal effects of these inputs on the growth of soil nutrients $\Sigma \phi_i f_{ui}$, where ϕ_i represents the marginal value of soil nutrient i at any time t.

According to the conditions (eq. 11) – (eq. 12), the rate at which the marginal value of any soil nutrient i changes ($-\dot{\phi}_i$) is equal to the sum of increases in the profit due to its use and its contribution to the improvement of soil fertility $\Sigma \phi_i f_{ixi}$ at any season t. Condition (eq. 13) states that the change in the value of Hamiltonian function due to change in the marginal value of the soil nutrient i by the equation of motion of stock of that nutrient x_i. Conditions (eqs. 14–15) indicate that the marginal value of the nutrient i at the end of planning horizon should be equal to the change in the value of land at T due to change in one unit of the nutrient. In other words it is the marginal value of land due to addition of soil nutrients. These conditions are also known as transversality conditions.

It could be observed that the dynamic production efficiency of the optimal input use decisions derived here are different from the usual results of static economic analysis. For any two soil fertility inputs, organic manure (i) and chemical fertilizer (j) from (eq. 8) and (eq. 9) we have

$$\frac{P_1 \partial Q_1 / \partial u_i - K_i}{P_1 \partial Q_1 / \partial u_j - K_j} = \frac{\Sigma_i \phi_i \partial f / \partial u_i}{\Sigma_i \phi_j \partial f / \partial u_j} \quad (16)$$

The condition (eq. 16) equates the marginal rate of technical substitution between organic matter (i) and chemical fertilizer (j) with respect to the growth function $f(\mathbf{X},\mathbf{U},t)$ (RHS) to the ratio of the net marginal value product of these two inputs (LHS). This condition is different from the usual static result in agricultural production analysis in which marginal rate of technical substitution of any two inputs equals the input price ratio. This is because in the dynamic analysis presented above we have two technical relations that are used to optimize the input use namely; $Q_1 = Q_1(\mathbf{X},\mathbf{U},t)$ and $\dot{X}_i = f(\mathbf{X},\mathbf{U},t)$. Thus, these optimality conditions for farm level decision making in the current season take into account the carry over effects of the soil nutrients to the subsequent seasons. Due to the dynamic nature of the contribution of agroforestry to organic manure and soil physical properties over several seasons and the associated dynamic substitution of chemical fertilizers, these conditions play an important role in studying the component interactions of agroforestry systems. These dynamic relations in crop production and input use are utilized in the next sections where tree component of agroforestry and animal production components are introduced to study the interaction between various components of agroforestry systems.

4. Agroforestry and dynamic soil fertility:

It is well known that trees restore soil fertility through their potential to increase supply of organic materials and nutrients, to reduce nutrient losses and to control the quality and timing of inputs (Young, 1989). Agroforestry also improves the fertility status of agricultural lands through additional amounts of nitrogen that could be added to the system by the nitrogen-fixing tree legume component (Nair, 1984).

The objective function of the farmer given in (eq. 3) could be rewritten when the tree component is introduced in her farming system. This is given as:

$$J(x_o) = \underset{Q,U}{\text{Max}} \int_{t=0}^{T} e^{-\delta t}[P_1Q_1(X, U, t) - K_tU_t - C_tZ_t + P_2Q_{21}(X, U, t)]\,dt \qquad (17)$$

subject to (eq. 2) and an additional constraint on the growth of biomass of tree component,

$$\dot{x}_3 = f_3(X,U,t) \qquad (18)$$

Where P_2 is the per unit price of the agroforestry product Q_2 such as green manure which also depends on the soil fertility component similar to crop production. As it is assumed that tree component of agroforestry does not require application of fertilizer, no additional cost is included in the model. However, they may compete for the nutrients applied to the field crop component. Condition (eq. 18) presents the equation of motion for the biomass of the agroforestry component. Once again, $J[X(T)]$ represents the value of the agroforestry system at the end of planning horizon which should also be maximized.

Using the procedure developed in the earlier section and forming Hamiltonian as in (eq. 7), the first order conditions for optimal choice of inputs with tree component of agroforestry are given by

$$H_{u1} = e^{-\delta t}[P_1Q1_{u1} - K_1 + P_2Q_{21u1}] + \Sigma_{i=1}^{3}\phi_i f_{u1}^{i} = 0 \qquad (19)$$

$$H_{u2} = e^{-\delta t}[P_1Q_{1u2} - K_2 + P_2Q_{21u2}] + \Sigma_{i=1}^{3}\phi_i f_{u2}^{i} = 0 \qquad (20)$$

$$H_{xi} = -\dot{\phi}_i = e^{-\delta t}[P_1Q_{1xi} + P_2Q_{21xi} + \Sigma_{i=1}^{3}\phi_i f_{xi}^{i} \quad i = 1,2 \qquad (21\text{–}22)$$

$$H_{x3} = -\dot{\phi}_3 = e^{-\delta t}[P_1Q_{1x3} - P_2Q_{21x3}] + \Sigma_{i=1}^{3}\phi_3 f_{ix3} \qquad (23)$$

$$H_{\phi i} = f_i(X,U,t);\ i = 1,2,3 \qquad (24)$$

$$\phi_i(T) = \frac{\partial J[X(T)]}{\partial x_i(T)};\ i = 1,2,3 \qquad (25)$$

$P_1Q_1u_1 + P_2Q_{21}u_1$ is the value of the marginal products of crop output and agroforestry output due to an additional increase in the use of organic manure. The price of agroforestry product is determined by its market value. If the agroforestry component is a fruit tree then the P_2 is determined by the market value of the fruit. However, if the Q_{21} is the green manure then P_2 is the implicit value of the green manure that is recycled by the farmer into the crop land to increase the soil fertility. Also Q_{21} in season t will then become u_3 in season $t+1$ and P_2 will become K_3 the implicit cost of green manure u_3. Then there will be an additional one more first order condition for the green manure which is explicitly used for crop production and is given by

$$H_{u3} = e^{-\delta t}[P_1 Q_1 u_3 - k_3] + \Sigma_{i=1}^{3} \phi_i f_i u_3 = 0 \quad (26)$$

Condition (eq. 26) captures the dynamic soil fertility benefits of green manure from the tree component to the crop production component in the agroforestry system. It states that in any season t, the level of green manure use from agroforestry tree component should be chosen such that the discounted marginal benefits of green manure use $(e^{-\delta t} P_1 Q_1 u_3)$ and the cumulative value of soil fertility to the farmer represented by $\Sigma \phi_i f_i u_3$, (the value of soil nutrients added by green manure from agroforestry tree component) should be equal to the discounted marginal cost of using it $e^{-\delta t} K_3$.

Rewriting the optimality condition (eq. 26) as described above gives

$$e^{-\delta t} P_1 Q_1 u_3 + \Sigma \phi_i f_i u_3 = e^{-\delta t} K_3 \quad (27)$$

Similarly for chemical fertilizer, using (eq. 20), the optimality condition could be compared with that of single field crop only (eq. 9). This is analogous to the problem of deviations in private and societal decisions in agricultural production. If private farmer wants to maximize his net return from land without worrying about the future fertility of his soil, he may not consider planting of trees as an improved land management option at least in the short-run. However, for the society as a whole, planting of trees may be beneficial both in the short and in the long-run.

There are two possible linkages. First the green leaf biomass produced in one season could be directly used in the next season as green manure (u_3). Also, the green manure could form an input in the production of other organic manures such as compost and farmyard manure. For simplicity and to avoid introduction of another production system u_1 will be treated as green manure from tree component in the following discussion.

Several studies have attempted to analyze combinations of chemical fertilizer and green manures from alley cropping (Kang et al., 1989; Mittal et al., 1992). Typically these studies compare the rate of substitution of nutrients between the contributions of tree component and the chemical fertilizers (Ehui et al., 1990). With tree component of agroforestry, the condition for optimal combination of organic manure and chemical fertilizer in agroforestry systems in a dynamic context will be given by

$$\frac{P_1 Q_{1u1} + P_2 Q_{21u2} - K_1}{P_1 Q_{1u2} + P_2 Q_{21u2} - K_2} = \frac{\Sigma \phi_i f^{i_{u1}}}{\Sigma \phi_i f^{i_{u2}}} \quad (28)$$

Comparing condition (eq. 28) with condition (eq. 16), it could be noted that the ratio of net value of marginal product of these two inputs now includes, ratio of the value of marginal products of tree component due to these inputs (LHS). The right hand side of condition (eq. 28) could be interpreted as the marginal rate of technical substitution between the green manures and chemical fertilizers in the production of both field crop and tree component in an agroforestry system. To the extent the inputs are used by the tree component, they are deprived from the use by the field crops (ICRAF, 1992). However, if the value added by the tree component (due to use of these nutrients) to the output of the system as a whole is more than the costs of inputs diverted to them due to competition, such benefits will be captured in the model by two ways. First, the opportunity cost of soil fertility inputs is higher in the next season (ϕ_{t+1}) due to addition of green manures from tree components. Second, the productivity of green manure in $t+1$ by incorporating Q_{21t} in season t will reduce the level of use of chemical fertilizers (u_2) in $t+1$ and thereby reducing the cost of soil fertility management in agroforestry systems.

In case of severe land availability constraints, the additional benefits from agroforestry could be off-set to some extent by the reduction in the output from field crop component due to reduced land availability resulting from introduction of the tree component (Walker, 1987; Nair, 1990). Such consideration could be easily introduced in the model presented above without loss of generality. For example, if the percentage of land allocated to tree component in the agroforestry system is known to be α, then the joint revenue from the field crop and tree component could be represented as $(\alpha P_1 Q_1 + (1-\alpha) P_2 Q_{21})$. While adding mathematical complications to the model, this formulation does not add much to the discussions of the present paper. However, in choosing appropriate tree component as an output in the farmer's portfolio, this constraint could easily be introduced in a programming framework (Babu and Rajasekaran, 1991).

The above model could be easily extended to include animal production to the already existing crop–tree production system. Addition of livestock production however, has several implications for input use and resource allocation decisions. The model with livestock component will include a growth constraint of livestock. Animal manure, a by-product of livestock component, would enter the crop production function as an input in the next season thus forming a substitute to greenmanure and chemical fertilizer already applied to crop production. Also the green leaf biomass from tree component would enter the production of livestock as an input. Thus, the model involves three (crop, tree, livestock) production functions. The process of choosing inputs use and their combinations in livestock produciton becomes a two stage process. In the first stage, the production possibility levels of livestock and field crop should be considered given the total availability of green leaf biomass (u_1). In the second stage, optimal combination of inputs such as purchased animal feed and green leaf from the tree component should be chosen to maximize livestock production (Babu, 1993).

5. Testing and verifying the model

The major interactions that are addressed in this paper include the dynamic relationship between the growth of field crop and the soil fertility; the interaction of soil fertility variables and the green manure added from the tree component, and the growth of tree component and its contribution to green manure use. If the tree component is a multi-purpose species, then there is a need also for quantifying the tradeoff between its use as green manure and as livestock feed. Additionally the tree component's contribution to the livestock production should be evaluated.

The economic data required to apply the model include the estimation of cost of produciton of tree and field crops, the commodity prices for the outputs from crop and tree production, the unit cost of offsite value of the greenmanure produced from tree component and applied to field crops and the private and social discount rates. The physical data required for testing and verifying the model are the coefficients of the equations of motion for the growth of soil nutrients, growth of field crop and the growth of green leaf biomass.

Quantifying the relationships established by the model presented in the previous section requires data collection on a time series basis. For example the carry-over effects of organic nitrogen added through the tree component of agroforestry system would require collection of periodic information on the humus and other indicators of soil fertility and the data on the inorganic and organic fertilizers added to the same area of the crop field. The empirical estimation of the parameters presented in the model is currently thwarted by the lack of time series data on these variables.

Alternatively, agroforestry experiments could be designed in such a way that the different levels of green manures are applied to plots that are replicated to keep other variables constant. Estimation of the lagged effects of organic nitrogen added through tree component could then be made combining this cross-sectional information with a shorter time series of data. Quantifying tradeoff of land between crop and tree components also requires data on the competition of these two for space, water and nutrients. This data can be generated by studying the profile of the rhizosphere of trees and its interaction with that of the field crops.

Only a handful of agroforestry systems have been studied on a continuous basis for more than 5 years. Even among the systems that have been evaluated, the data collected from most of them are less reliable due to faulty design of the experiments which ignored the interaction effects of various components of agroforestry. The framework developed in this paper is an attempt to delineate the variables which require data collection from various components of agroforestry system to help better design the agroforestry field experiments. However, it should be mentioned that new experiments which have been initiated by ICRAF (1992) are promising for quantifying and evaluating various contributions of agroforestry systems in the future.

6. Policy implications for multidisciplinary agroforestry research

It is generally agreed that the analysis of integrated resource management systems such as agroforestry, their components and their interactions has been limited. This is partly due to lack of multi-disciplinary approach in developing the agroforestry research strategy (Kidd and Pimentel, 1992). The models of agroforestry systems presented in the previous sections have a number of implications for multidisciplinary agroforestry research. The overall emphasis of the framework presented above is that the knowledge of biological growth of various components of agroforestry needs to be incorporated into the study of economic efficiency of mixing these components. The production processes of these components are inherently dynamic in nature. Because of this, the growth and production of crop, livestock and tree components should be modeled as continuous processes (Fewcett, 1973). However, unavailability of data to determine the economic efficiency of interactions of various components in the agroforestry system largely limits empirical investigation of such dynamic models. The conceptual framework developed in this paper is an attempt to identify the areas where multidisciplinary research would enhance the understanding of the interaction of components in a system and thereby identification of improved agroforestry technologies. The models developed above provide a starting point to delineate the areas of joint research by multidisciplinary group of scientists.

In the past, the economic evaluation of agroforestry technology have relied on static framework with evaluation of only a selected aspects of contributions of agroforestry to human welfare. This approach has failed to incorporate the dynamic production relations among various components of agroforestry systems. This points out to the need for multi-disciplinary approach which could provide information for estimating the dynamic relationships among various components of agroforestry systems. The model and the framework presented in the previous sections could be used with such data to estimate the quantitative benefits of agroforestry systems under variety of combinations of system components. Empirical information on the dynamic relations among the components of agroforestry system would also be helpful in answering the problems of decision making in adopting agroforestry systems.

The dynamic nature of soil fertility contributions of tree component in agroforestry and the long-term benefits associated with it can not be captured by static formulations. The dynamic model developed in this paper provides a framework for analyzing such issues. The carry-over effects of nutrients applied through tree component of agroforestry to subsequent crops need to be monitored. This helps in recommending optimal levels of nutrient applications thereby reducing the chemical fertilizer use without compromising the yields of field crops (Mittal et al., 1992). This requires a long-term collaborative data collection efforts of agronomists and social scientists in various systems of agroforestry.

The terminal value of land $J(X_{\mathrm{T}})$, under agroforestry systems which is usually ignored in the analysis of the impact of agroforestry technology, has been accounted for in the model presented in earlier sections. The productivity improvements due to agroforestry reflected by soil fertility status and yield levels of crops should be incorporated by land husbandry scientists in their procedures of land valuation. This would require their increased interaction with and feed-back from agronomists and social scientists involved in the analysis of agroforestry systems. Such an approach to land valuation would also provide incentive for adoption of long-term land management practices which improve soil fertility.

Changes in the marginal value of soil nutrients or their opportunity cost depend on both short-term and long-term influences of soil fertility inputs. This would further influence changes in present profit and its contribution to long-term soil fertility through increased availability and enhanced use of soil nutrients from various components of agroforestry systems. It is important to recognize the role of such cyclical processes in improving the productivity of smallholder farmers. This would involve a long-term approach to gather information through tracer studies by a multi-disciplinary group of scientists both on the experiment station and on the farmers' fields.

Use of output from one component of agroforestry in season t as an input in the production of another component in season $t+1$, introduces an element of continuity. Such interactive benefits need to be captured in the analysis of agroforestry systems. Multiple and joint outputs from tree component and multiple output of livestock component are also interactively used in agroforestry systems. They should be valued at market cost to understand the benefit foregone if they are not used effectively. This is possible by documenting such uses on a long-term basis.

Transversality conditions given by the model results determine the optimal level of stock of state variables such as x_1, x_2, x_3 at the end of planning horizon. Data collected on the levels of these variables and their rates of change under various agroforestry systems could be used in a simulation model to predict their values at different terminal periods. Such information could prove valuable in deciding optimal levels of agroforestry investments under various types of land tenure systems.

The choice of levels of input use in the production of one component can not be made in isolation of other production systems. For example, in choosing the optimal use of green manure, its value of marginal products of both crop and livestock production should be considered. This would enable more efficient use of limited resources to increase the overall productivity of agroforestry system. Given the interactions of inputs and outputs within various components of agroforestry system, the choice of inputs should be made in two stages; first, the determination of combination of output levels of the components and second, the allocation of competing input to these components according to their values of marginal product in their production.

The complementarity of inputs such as green manures from the tree component and the chemical fertilizers applied to field crops and its long-term benefits in improving the production efficiency could be analyzed using the model presented above. Such attempts are already being made through collaborative research efforts between agronomists and economists (Mittal et al., 1992). These efforts should be encouraged through adequate funding both at the national and international levels.

Agroforestry is a technology that is beneficial to the society as a whole beyond the farm level (Ehui and Hertel, 1989). This nature of agroforestry introduces an element of free riding in determining optimal provision of private trees in a village economy. The role of such externalities in the choice of species and its implications for component interactions need to be analyzed at a society level.

Agroforestry is a science of multi-disciplinary nature. While information and experimental data generated by individual fields such as agronomy, soil science, forestry, and ecology are important and useful in their own right, they will be of limited value in implementing agroforestry technology in farmers' field unless it is combined in a multi-disciplinary manner to address the issues discussed above. Such an approach is particularly important in on-farm research trials where farmer participation through incorporation of already existing indigenous knowledge could enhance the benefits from agroforestry systems (Rajasekaran et al., 1992). Thus, in setting agroforestry research priorities and in allocation of research funds both at the national and at the international levels a multi-disciplinary approach is imperative to increase the overall returns from such investments.

7. Concluding remarks

An attempt has been made in this paper to provide a general framework for analyzing the interactions of various components in an agroforestry system. Using a multi-seasonal model of agroforestry, the competition among the system components in resource and input use and the trade-offs between different outputs of agroforestry system are analyzed.

In the past, the economic evaluations of agroforestry technology have relied on a static framework with evaluation of only selected aspects of contributions of agroforestry to human welfare. This approach has failed to incorporate the dynamic production relations among various components of agroforestry systems. The model presented shows that the tradeoffs between various production components is inherently more complicated when considering dynamic production systems such as forestry and carry-over of soil nutrients. Previous models that have ignored these interactions may lead to incorrect resource allocation decisions. This points out the need for a multi-disciplinary approach which could provide information (data) for estimating the dynamic relationships among various components of agroforestry systems. The model and the framework presented in the previous sections could be used with such data to estimate the quantitative benefits of agroforestry systems under variety of combinations of system components. Empirical information on the dynamic relations among the components of agroforestry system would also be helpful in answering the problems of decision making in adopting agroforestry systems.

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Appendix

For any function $f^1(x)$; $f_x^1 = \partial f^1/\partial x$, $f_{xx}^1 = \partial f_x^1/\partial x$ and where meaning is clear the time subscripts have been dropped ($f_{xt}^1 = f_x^1$).

$\mathbf{Q}_{1t}$	production function of field crop component
x	vector of soil fertility indicators
x_1	soil humus
x_2	soil nitrogen
x_3	biomass of green manure
u_1	green manure
u_2	chemical fertilizer
π_t	profit from Agroforestry system
$\mathbf{K}_t$	price vector of inputs
$\mathbf{C}_t$	cost vector of inputs other than fertilizer
$\mathbf{Z}_t$	vector of inputs other than fertilizer
$\dot{x}_{it}$	dx_i/dt growth rate of variables in vector $\mathbf{X}$
f_{it}	function for equation of motion
$J(X_o)$	present value of future stream of profits
δ	discount rate of the farmer
$J(X_T)$	value of profit at time T
$\mathbf{X}_T$	vector of $\mathbf{X}$ at time T
ϕ_i	co-state variable associated with state variable x_i
P_{21}	price of output from agroforestry
Q_{21}	output from agroforestry (green manure)
f_3	growth function for x_3
u_3	green manure in $(t+1)$
K_3	implicit cost of green manure u_3
α	percentage of land allocated to trees

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