INCORPORATING BIOPHYSICAL AND MULTIPLE OBJECTIVES IN PLANNING MODELS OF LOW RESOURCE FARMERS IN GHANA: A MULTILEVEL SYSTEMS APPROACH

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ABSTRACT.—Integrating sustainable land use in a fashion which is sensitive to the wishes of immediate stakeholders and broader society yet avoids biophysical and environmental risks, involves many inherent conflicts. These conflicts can be captured and explored in mathematical programming models (MPM). The appropriate levels of detail can be obtained by imbedding the output from simulation models of biophysical processes into a farm-level socio-economic framework represented in the MPM. Simulated results for different spatial units can be visually represented with the use of Geographic Information Systems. This approach allows the user to define and simulate alternative farm plans, and to test hypotheses about which are most sustainable and stable.

INTRODUCTION.

The development and use of biophysical models to generate key data for farm and regional-level models is now widely acknowledged (Dent and Thornton, 1988; Dent and Mcgregor, 1993; Fawcett and Nkowani 1996; Fresco, 1995; Jansen, 1995). These process based models are useful for pre-screening potential land-use options prior to expensive experimental research, development and extension programs being committed. Specific attributes would include the identification of suitable germplasm, and the identification of appropriate management packages for a particular locality in response to alternative input strategies. Climate, soil data and genetic parameters can be varied and results assessed in terms of their suitability. Estimates of yield variability under different crop/tree layouts and mixtures can be assessed in relation to alternative treatments. In addition, modeling speeds the long-term process of testing crops, particularly where it involves the inclusion of trees in the field for suitability and compatibility. The human intervention in the form of husbandry practices specifies the 'treatment' setting the parameters for the simulation run which can span many years. The results of the treatment are 'returned' as matrix coefficients rewarding the husbandry practice.

The imbedding of the output from simulation models of biophysical processes into the farm-level socio-economic framework provides useful mechanisms to explore ways in which farm households would react to new circumstances (such as a new policy instrument) or would permit a comparison of policy scenarios in terms of economic and social benefits and costs (Dent, 1991). This gives an opportunity for decision makers to judge the relative merits of a range of alternative management regimes under various policy scenarios.

GIS is a computer-based information system designed to facilitate integration and analysis of geographically referenced data (Mallawaarachchi et al., 1996). Generally, it possesses the capacity to store, evaluate, combine and conditionally extract information from maps and associated attribute data. Simulated results of biophysical process for different climate and soil domains can be used to predict balanced land-use strategies over spatial units, both in the study area and beyond.

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However, it remains an elusive goal to integrate socio-economic and productive uses of land whilst avoiding biophysical and environmental risks as well as being sensitive to the wishes of immediate stakeholders and broader society (Nkowani et al., 1995a). Nevertheless, the ability of these models to provide an insight and understanding of the interactions between competing objectives and linkages between all levels, particularly trade offs between economic, social and environmental imperatives (Cocklin et al., 1988), make them appropriate tools to explore constrained resource use options.

The purpose of this paper is to explore the possibilities of setting-up a multitiered modeling framework. Three model levels are suggested: biophysical simulation models (examples of which are provided by Hypar, DSSAT, etc.) which provide crop/tree yields under alternative management to whole farm socio-economic models which define the results of decisions taken by farmers in their daily lives. A similar approach was used by Veloso et al., 1994 in a Brazilian context. Aggregate results of individual farmers may be represented in a regional-level model which provides the mechanism for examining the trade-offs between policies for economic development and for environmental enhancement. This paper continues with a brief contextual definition of the problem in Ghana, a short argument about the need for a multilevel systems framework, and a description of how output from biophysical models in conjunction with GIS may be used within a mathematical programming framework, potentially improving the operational efficiency of the farming systems research. It appears that the integration of biophysical modeling output into the socio-economic framework of the whole farming systems is both desirable and feasible, although problems remain to be overcome before it can be considered as a routine methodology for the design of appropriate policy and/or technology packages for smallholder farmers.

DEFINITION OF THE PROBLEM.

Human endeavors to enhance the quality of life of people rest closely with the consumption of natural resources required to generate material wealth and amenities (Mallawaarachchi et al., 1996). Land degradation, or more specifically, stock depletion and declines in productivity, have led to wide concerns about the potential endurance of current agricultural production systems (Asamoa, 1991). The result has been a call for policies that promote ecologically sustainable development. The challenge to decision makers has been how to raise smallholder productivity at farm-level without long-term resource depletion while at the same time recognizing the endemic poverty, seasonal food shortages and disease, poor soil fertility and seasonal labor shortages already present (Fawcett and Nkowani, 1996). Biological methods of maintaining soil fertility, and agroforestry technologies in particular, were suggested as possible means to sustain soil fertility and loss. The aims and rationales of agroforestry systems were to emphasize the positive interaction in order to obtain a higher total, a more diversified and/or more sustainable production from available resources than is possible with other forms of land-use under prevailing ecological, technological and socio-economic conditions (Nair, 1990).

But the non adoption on a wide scale of alley farming (the most prominent agroforestry system) by Ghanaian and generally West African farmers has been a set back to policy makers, research and extension workers. The reasons for non adoption have been documented by Bayliss-Smith et al., (1993) and Reynolds (1994). Both studies seem to suggest that the incorporation of farm family objectives into farming systems research should provide a mechanism for rejecting options at the systems design stage where conflicts with family seasonal labor supply, lifestyle, gender issues, tastes and preferences are significant. A thorough understanding of traditional farming systems is, therefore, a prerequisite both to examining the appropriateness of each option, and in understanding farmers' responses to technology. This paper suggests a multi-tiered modeling framework where broad constraints for the region (e.g. land suitability, climate, soil, credit availability etc.) are set by the biophysical and socio-economic factors.

THE NEED FOR A MULTILEVEL SYSTEMS APPROACH.

It might be assumed that the most appropriate approach to integrating objectives between the land-users (farmers) and those concerned with regional or national development is to create a unified programming model. Such a model is specified by McCarl (1992) to maximize the satisfaction of a regional developer but subject to a *notional* response of the farmer to regional policies. McCarl (1992) argues that such a model is an appropriate conceptualization of the policy process but that it is difficult to solve due to the existence of many local optima. In addition, this author calls for care in the application of such a unified model approach because results can be misleading. Moxey et al., (1995) argued that although such an approach may overstate flexibility and coordination of agricultural production, it is a widely accepted means of modeling large areas: a statement backed by Norton and Schiefer (1980).

The development of a region is, however, determined by decisions at micro (family), (village), and regional-levels (Werner, 1994). Decisions are made according to the needs and objectives of the decision makers, availability of resources, and constraints. Micro, and regional-levels should be integrated in a multisystems concept to understand and model decisions and linkages at and between levels. The unified (partial) approach can be corrected by using a multistage model which separates the modeling applications between farmers and regional (national) planners as demonstrated in the work by Dent and McGregor (1993) The conceptual development of the multilevel systems approach is illustrated in Figure 1.

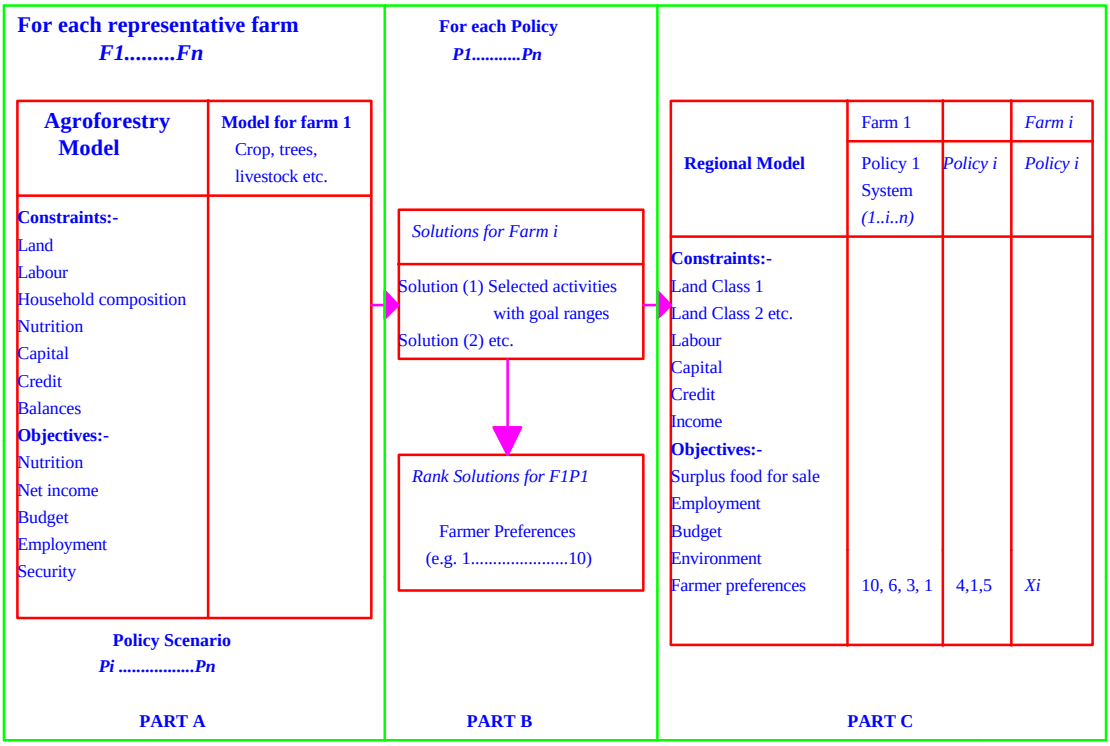


Figure 1.—The Conceptual Development Framework of a Multilevel Model.

The three linked parts (see Fig. 1) cab be interpreted as follows:

(a) Part A is a generalized goal format for a single farm. The model would run for each defined representative farm for each spatial unit within the region (F_1 to F_n) with provision for the objectives, goal levels, priorities and weights to be included.

(b) For each representative farm, the above procedure would be repeated for each potential regional policy (P_1 to P_n). Part B of Figure 1 first shows that a set of solutions for F_i and P_i will be generated.

The goal programming model solutions for $F_iP_i$will provide a set of solutions with different characteristics but all meet the goal ranges and are feasible within the constraints specified. These may be ranked by farmers to reflect their preferences using for instance a simple scale (say 1 to 10).

Solution sets for all (F_n) farm household types each operating under all potential (foreseeable) policies (P_n) may now be transferred to Part C of Figure 1 along with the relevant farmer preferences. Some culling of solutions may take place at this stage but it would be desirable to retain all options until it is obvious which solutions are dominant.

Part C provides the format of the regional-level model. Constraints may refer, for example, to total regional area available of different land classes and budget. The regional objectives may relate to surplus food for sale and overall or district employment levels. The activities represent each of the solutions for F_i P_i (generated in Part B). Hence, for farm household type 1 and policy 1 there will be a range of possible systems (S_1 to S_n) as shown in Part C. This would be repeated for each policy over all farm household types. The Land Class 1 coefficient for activity S_i will be for the total area in the region required for this type of farm operated under Policy P_i.

An additional objective is defined in the example - farmer preferences. This will indicate the subjective level of preferences which farmers of this type have for this policy and system. The target level can be varied to reflect the speed of uptake or level of acceptance (high target values indicating greater and faster acceptance).

An important feature of the representation is that policy options must be made mutually exclusive but this constraint could be partially relaxed if it was appropriate for different spatial areas to have individual policy specifications.

The successful adoption of this approach, which is conceptually tidy and appealing, is dependent on elicitation of appropriate preference functions from farmers for each policy/system combination once the individual farm models have been developed and run. This framework sets out the farm family objectives and the resource constraints under which smallholders operate thereby, allowing the user to define alternative farm plans, simulate them, and test the hypotheses about which are most sustainable and stable. Sensitivity analyses can also be carried out to examine the effects of different internal and external factors on farm behavior.

INTEGRATION OF BIOPHYSICAL AND SOCIO-ECONOMIC MODELS

Biophysical crop and agroforestry models have developed to a stage where they can provide insight into land-use planning choices for localized smallholder traditional and agroforestry systems (Fig. 2 Section A). For example, the model (Hypar/DSSAT) used in this study permits the yield of certain tropical and sub-tropical crops such as: maize, cassava and yam to be predicted in different mixtures and lay-outs with key tree species (e.g., *Leucaena leucocephala*, *Gliricidia sepium*, and *Cassia siamea*) across a wide range of climate and soil types (Lawson et al., 1995). Daily weather patterns are simulated for 1/2 degree latitude/longitude cells using a well-established weather-generator (Richardson and Wright, 1984). Predictions of crop yields and yield variation can thus be made on a regional scale over a long-term periods (Mobbs et al., 1995). Parameterization for a wider range of crops and agroforestry trees is underway, and efforts are being made to extend the database of climate and soil data provided to the model. However, these models remain weak by themselves in their ability to fully appreciate spatial and temporal heterogeneity in agricultural and natural resource systems due to non-incorporation of socio-economic aspects of a farmer.

The storage of the simulated output from biophysical models within a GIS has advantages for this multi-tiered modeling approach. Firstly, the use of a common geo-referencing system enables disparate datasets, previously in the domain of individual disciplines, to be integrated. The implications of the results of biophysical simulations for land-use can then be assessed, based on a more interdisciplinary perspective. Secondly, the ability to visualize spatial data provides a means for a user to investigate different scenarios, as well as an interpretative tool for the modeler. In this way, the user can define alternative farm plans, simulate them, and test the hypotheses about which are most sustainable and stable. Sensitivity analysis can be also carried out to examine the effects of different internal and external factors on farm behavior.

In Section B of Figure 2, data sets from socio-economic questionnaires covering all spatial units (agro-ecological zones) are shown as being formatted on a series of spread sheets to be processed into appropriate statistical entities. This information, when merged with secondary data, is used to establish the socio-economic characteristics of farm and families. Farm typologies are then formulated from the structural and functional description of farms to construct representative farm models for each defined agro-ecological zone. The models developed are used to estimate the optimum value for the objective function for a linear programming farm-level model and serve two main purposes as demonstrated by Nkowani (1996);

(a) to examine options for development or change on typical representative farms.

(b) the output runs, in multiple runs, set-up input data for formulation of a region model.

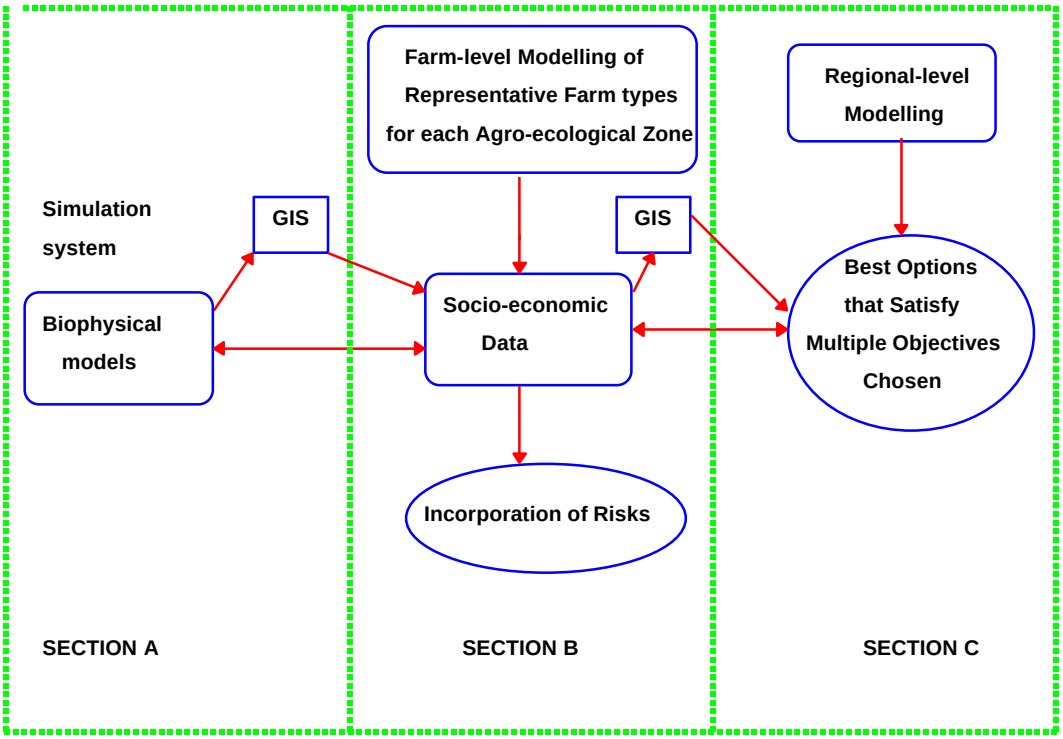
The linear programming model provides data to focus discussion at the interface between farmers (land-users) and wider community (see Fig. 2 Sections B and C). This is a useful device to create dialogue about:

(i) the relationship of the farm systems with the outside community in order to attempt a balance between technology, infrastructure inputs and socio-economic elements;

(ii) policy agenda, research and extension priorities which are set within the wider systems boundary.

The farmers' land-use decision-making process is driven by a number of objectives which include minimizing risks, improving food security, involvement in community and fulfilling cultural obligations and concerns about income (Nkowani et al., 1995b) (Fig. 2 Section B). Fundamentally, smallholders should be seen in the light of having multiple objectives, and profitability is not the only criterion to decide about a particular mix of crop enterprises.

The information on farmers' objectives on the other hand provide the basis for converting the linear programming models at farm-level into Goal Programming regional model dealing with multiple objectives and the system is operated in pursuit of the goals and aspirations of the decision makers.



Adapted from Fawcett & Nkowani (1996).

Figure 2.—Integration of biophysical and socioeconomic models.

A multiple objective linear goal programming model is developed to represent opportunities for change at regional-level. The model, is used to analyze a range of solution sets for all (F*n*) farm household types each operating under all potential (foreseeable) policies (P*n*) along with relevant farmer preferences with the aim of selecting management options which satisfy the set of regional objectives (see Fig. 2 Part C).

The matrix has minimal additional data requirements in that it summarizes the transactions of the real system and contrasts with the information produced in the biophysical simulation of growth processes which function on a daily basis.

In this approach, a range of land-use management scenarios can be analyzed and management options which meet social objectives, enhances food production and/or food security, and at the same time maintains ecological stability through improved land-use - especially but not only by the incorporation of trees into the farming systems can be selected and promoted (see Fig. 2 Section C).

METHODOLOGICAL CHALLENGES FOR THE APPLICATION OF MULTILEVEL SYSTEMS ANALYSIS TOOLS

The adaptation of systems analysis tools poses unique methodological issues due to extreme variability of the natural environment. Variation in terrain, soils, pest, disease and weed levels, in biophysical models, intercropping competition and general land-use produce micro-environments that may be difficult to reproduce in crop, tree and livestock simulation models. Hence, potential inaccuracies in model assumptions and the uncertainty of environmental variables need to drive the models, and problems related to integrating information at different levels need to be studied. These concerns point to at least four methodological issues.

Aggregation

Understanding of biophysical and socio-economic issues typically occurs at the level of some relatively small unit of analysis, usually the plant or farm household-level. There are still gaps in our understanding of how biophysical, socio-economic, and policy factors interact to affect farming systems. Studies at the components and farming systems level cannot be generalized since the relationships between soils, climate and vegetation are scale and spatial specific (Fresco, 1995; Jansen, 1995). This is particularly important when dealing with more than one agro-ecosystem and where heterogeneity of the physical and socio-economic environment is extreme. It is essential that scale appropriate models that can be parameterized for different crop and tree species and for livestock be developed so that, when used in conjunction with GIS and local data, allows the determination of options for land-use for each spatial unit.

Paucity of Data

Detailed data related to current land-use and aspects of management may be limiting. But as Dent (1996) confessed, "models are definable systems developed from understanding basic processes and operationalized by coupling with limited amounts of information". Accordingly, Dent (1991) argues that the development of models that mimic the decision-making processes of farm-level decision-making unit can help planning for change at regional-level in two ways. The first is that such models provide useful mechanisms to pre-screen the ways in which farm households would react to new circumstances (such as a new policy instrument) or would permit a comparison of a possible policy scenario with another in terms of its economic and social benefits and costs. Second, these models are also useful for pre-screening potential land-use options prior to expensive research, development and extension programs being committed. This gives an opportunity to decision makers to judge the relative merits of one research development and extension programs against another (Edward's-Jones and McGregor, 1994; Nkowani, 1996). Additionally, for many aspects of production systems and the socio-economic conditions being modeled, there are gaps in understanding or uncertainties regarding the values of particular parameters, so that very detailed representation of the aspects is not warranted (Rae, 1994).

The Definition of Socio-Economic Framework

The definition of the socio-economic framework within which the farmers' operate presents problems for modeling studies. As Anderson (1985) notes, it will usually be expedient to side-step the issue of what the society as a whole, and not just the farming sector, regards as being desirable and concentrate on goals and objectives of farm families, whilst recognizing that there will be times when the goals of other sections of the society simply cannot be ignored. Even if the framework is restricted to the farm family, Dent and Thornton (1988) noted that there are problems in trying to elicit what will inevitably be multi-attribute preference functions. The building of a whole farm model requires that decision-making in constraint-riddled production systems can be represented in some algorithmic way (see Nkowani, 1996 for instance). Such assumptions are justified in part by consideration that there is little else that can be done if the problem is to be tackled at all, and that it is better to use internally-consistent framework than an inadequate one. The practical problems of measurement remains.

Level of Accuracy

Modeling any given system is an elaborate task and requires careful quantification and calibration of many relationships (Nkowani, 1996). Choosing an appropriate level of approximation involves making a difficult trade-off between the expense of a larger, more complex model against the benefit of greater precision. The cost of increased size and complexity include not only man hours and computer time but mainly difficulties of

understanding the models. Benefits of increased detail are in the dependability of results, although it has been observed that improvements in the accuracy from increased detail are subject to the law of diminishing returns (Morrison et al., 1986).

CONCLUSION

It is concluded that the integration of simulation output from biophysical processed models into the socio-economic framework of the whole farming systems, is both desirable and feasible, although problems remain to be overcome before it can be considered as routine methodology for the design of appropriate policy and/or technology packages for smallholder farmers.

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