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Bio-economic modelling for better quantification of agriculture environmental impacts

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Abstract: Bio-economic models, through the combination of biophysical crop growth models and economic simulation models, allow a better representation of farmers' behaviour and thus improve the quality of the analysis of policy scenarios. In this paper the principles of this approach and the practical methodological aspects for the construction of bio-economic models are presented.

Keywords: Agriculture, environment, bio-economic modelling, mathematical programming.

Introduction

Agriculture activity is necessary to satisfy human food demand, but it also implies disturbances of natural resources equilibrium. These disturbances can imply resource depletion due to ill-management and thus have negative impacts on the environment. However, in most cases the effects can only be observed in the long-term and farmers do not always consider them when making their decisions. Besides, most policy measures do not take into consideration these impacts and induce farmers reactions that might jeopardise future generations well-being. It is necessary to simulate alternative policy scenarios and evaluate their impact in the short and in the long-term in order to help policy makers.

Economic models can be used for policy analysis. Either considering the economy as a whole (general equilibrium models) or concentrating in a sector (partial equilibrium models), they are based on the hypothesis of a "convex world", implying a convex function of optimal input allocation for a given level of output, any other combination being sub-optimal. They result in associating a unique optimal resource allocation to each policy. Environmental and natural resource economics largely relies on the same methods and hypothesis. However this convexity hypothesis is not always well adapted to represent the complexities of agricultural production systems due to discontinuities in response to physical changes, or for capturing unexpected responses to policies. In agriculture factor substitution is sometimes better represented with a concave function, implying that there might be two optimal levels of input use for the same production, which invalidates the results of the models relying on the convexity hypothesis. Examples of this exception can be found when analysing the relationship between yield levels and temperature (in some cases, higher temperature might decrease the growth cycle and diminish the water stress during critical periods of growth), or the direct impact of fertiliser use and pollution (rotations using higher doses might imply less pollution due to year long soil occupancy), or the physical complementarity between inputs (sometimes the optimal input use is not economically feasible at the household level) or the effects of risk in farmers decision making (implying unexpected substitution between activities with differentiated variability in commodity prices). Divergence from standard economic approach is also necessary when analysing the environmental externalities, for instance looking at the implementation of pollution permits. Additionally, it should not be neglected that the impact of policies on agriculture and on the environment takes place both in the short- and in the long-term. There is a clear need to build up more realistic models that take into consideration this characteristic of the agricultural sector and its impact on the environment, to identify policies able to enhance sustainable use of natural resources without jeopardising agricultural incomes.

To improve the degree of representation of economic models for the agriculture sector they can include engineering production functions, based on pure bio-physical relationships, so as to allow for the consideration of the complex relationships between multiple levels of inputs and consequent outputs in terms of production as well as externalities throughout time. This means a degree of internalisation of some of the externalities of agriculture. The economic models, representing farmers' behaviour, will therefore optimise, as farmers do, the use of inputs and other production factor to enhance the outcome according to their own objective function.

Biophysical models, which provide detailed information on the effects of agricultural activities on the environment in the short and long-run, allow for the required precision in the economic representation of both the input/output relationships and the long-term impacts within behavioural farm models. They can also help to introduce the recursive or dynamic aspects of the decision making process, thus capturing farmers' possible reactions to policies throughout time. Bio-physical models could therefore be combined with mathematical programming models, in which an utility function could be maximised.

The bio-economic models

Bio-economic modelling seeks to improve the representation of reality to enhance policy scenarios analysis in order to facilitate decision making. This approach implies to enhance the consideration of biological and/or physical aspects of agricultural systems in economic models. The first examples of this approach can be found in fisheries economics, where it was used to determine the optimal capture rate and in forestry to estimate the optimal extraction rate. In these cases, the methodology applies an economic function to a population growth function in order to define the maximum sustainable yield and the optimum level of effort of extraction of the renewable natural resource without jeopardising its existence (Clark, 1990). Mathematically, the optimal use of any resource could be found analytically through dynamic programming or optimal control methods. Additional approaches to consider the complexity of agricultural production systems and the importance of externalities can be implemented to find the optimal level of resources use at the farm level, the essential decision making unit.

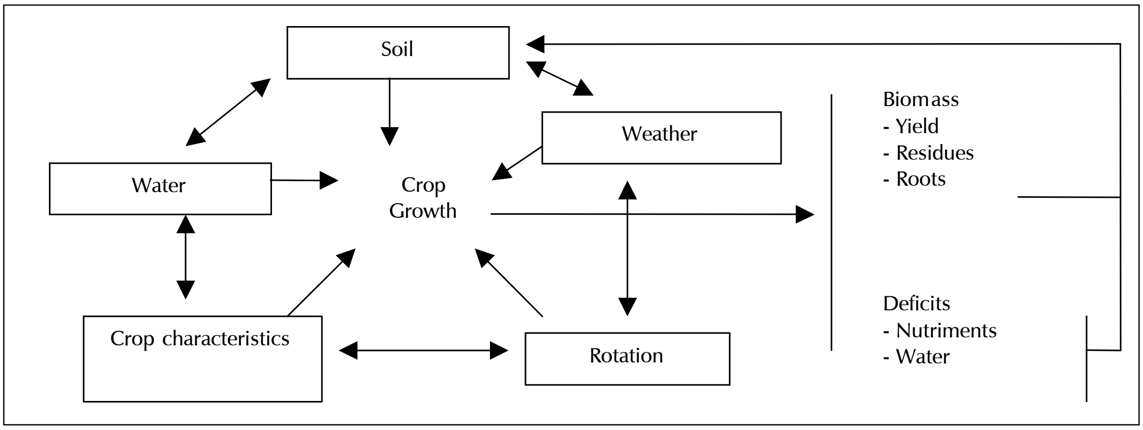

Figure 1. The structure of Crop Growth Models

Farm models can better consider resources by using crop-growth models (GGM). This field of research, which began at the end of the sixties with the pioneering work of De Witt (1992) opened a new perspective because they allow to simulate quite complex agricultural systems. These models, through the integration of several (main) production functions (responses to water, nutriments, soil capacity, etc.), allow the estimation of total plant growth based on the effect of the most limiting factors on potential growth. The first type of models were very detailed and specialised to one individual crop[1]. Later on, the need to take into consideration some cumulative effects on soil characteristics (such as erosion, fertility, water content, etc.) drove the developments of multi-crop multi-year models. They include several simplified production functional forms in order to be able to cope with different crops and allow to simulate rotations and thus short- and long-term impacts on soils. It is possible to study impacts on soil (C content, organic matter, fertility, structure), erosion, nutrients' leaking into ground water, water stress due to lost retention capacity, total bio-mass production, etc. Examples of these models are EPIC (Jones et al, 1991) and CropSyst (Stockle et Nelson, 1996). They carefully distinguish between potential yields, nutrient-limited and water-limited yields, and in some cases yield losses due to pests and diseases (Figure 1).

With information on soil and weather conditions prevailing in specific regions of the world, actual and potential yields can be estimated, and the most limiting factors can be identified, not only for crops and techniques presently done in each area but also for potential crops and techniques. This feature turns the CGM into an extremely powerful tool to objectively compare productivity as well as future variability of yields between activities, because both the soil "behaviour" as well as the weather impacts are homogeneous for each activity in each specific situation: the differences in results are due mainly to farmers' management, i.e. seed choice, technology implementation and alternative factors' use.

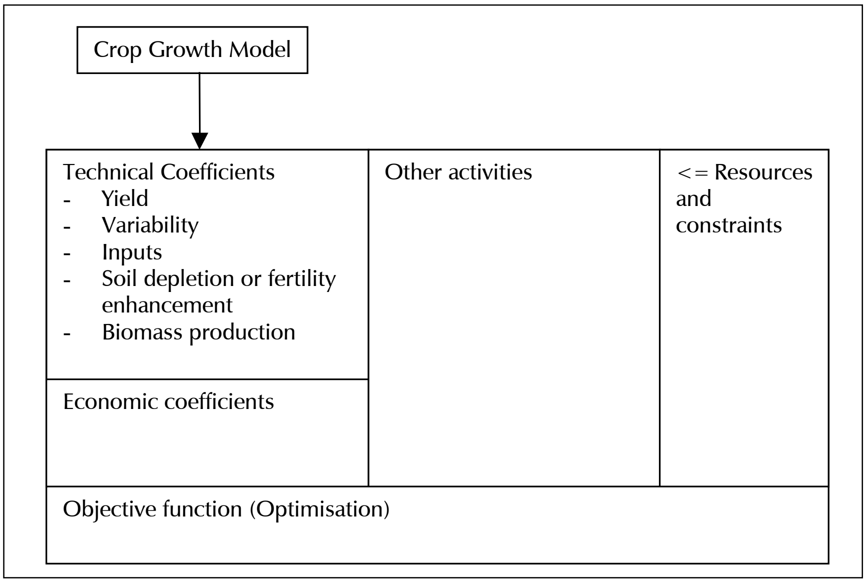

Figure 2. CGM data integration in bio-economic models

For economic evaluation, this feature is extremely important. Policies seek to modify actors' behaviour and induce some specific actions, i.e. increase productivity through the use of subsidised fertilisers, promote a specific crop production through the use of price incentives, enhance bio-diversity by taxing mono-cropping activities, etc. As management is the consequence of human (farmers') behaviour, in order to help policy maker's decision process, economic models try to represent as close as possible actors' behaviour. Thus the possibility to identify and isolate agricultural physical response as a consequence of specific farmer's management enhance considerably the possibility of economic models to better represent farmers' behaviour.

Crop growth model results[2] can then be used to generate the technical coefficients used in economic models (factors requirement such as labour, machinery, fertilisers, irrigation water), the

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[1] CERES (Godwin et al. 1989) family of models is one example: PNUTGROW (Boot et al. 1989), SOYGRO (Jones et al. 1988) See Thornton et al 1991 for an early description of these models.

[2] It is possible to include CGM within the economic models as Barbier,and Hazell did at IFPRI, However resolution time increases exponentially and does not provide more detailed information than when the process is undertaken iteratively.

production indicators (yield, yield variability, bio-mass, etc) as well as some environmental indicators such as erosion, nitrogen leaking, CO_2 fixed (in soil and bio-mass), etc. This inclusion allows: 1. a common basis for comparison between alternatives (they use the same soil and weather characteristics, which implies that the difference in yields can only be due to crop characteristics, management or rotation patterns), 2. to take into account explicitly the long-term impacts and 3. quantify some of the impacts on the environment (erosion, C fixation or CO_2 emissions).

The detailed data from CGM allow for a better representation of substitution and complementarity mechanisms between activities and technologies (Figure 2). But farmers' behaviour is mainly dependant on their objectives, constraints and resource endowment, which have to be first identified and then formalised in mathematical models. Constraints and endowments can be dealt with as inequalities: the use of a given factor can only be equal or less than farmers' availability, except in the case of purchase, location or loan. These three latter mechanisms have to be considered thoroughly: in farm (micro) models, the possibility is included as an exogenous variable, in the case of village or regional models, once the problem of aggregation is solved[3], markets for some of the factors can be included and thus the exchanges are endogenous, which implies that the optimal transfer is estimated to better satisfy the resource allocation of every actor (Figure 3).

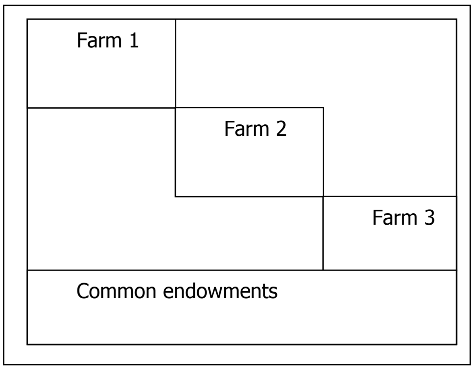

Figure 3. Structure of an economic model with transfers between actors

The inequalities can be represented by :

$$\sum_{i,tech} a_{i,tech}.x_{ex,i,tech} \le b_{ex} \pm \sum_{EX \neq ex} b_{EX}$$

The coefficients $a_{i,tech}$ represent the technical requirements for each activity, and in the case of agriculture, they can be provided by the CGM for each crop $_{i}$ and each technique $_{tech}$, $x_{ex,i,tech}$ represents the activity level in farm $_{ex}$ (i.e. the number of hectares with crop $_{i}$ and technique $_{tech}$), b is the total endowment of a specific factor, which can be increased or decreased through exchanges with other farmers b_{EX}.

The representation of farmers' objectives is more complex, in particular to estimate some of the coefficients that can help in the process. Many behaviours can be identified: income maximisation, cost minimisation, self-consumption optimisation, risk reduction, wealth increase, etc., or in most cases, a combination of all of them. Risk is essentially the consequence of two factors: weather and market prices. CGM are again extremely useful to represent weather and soil use impacts on yields and provide better information to include in the models (coefficients $\sigma_{i,tech}$ and $Y_{i,tech}$). Other important factor that is considered as influencing risk is the financial cost associated with short- and long-term credit, to cover operating costs, investment or exceptional

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[3] This is one of the most difficult issues to deal with. In most models, for simplicity reasons all farmers of a category are supposed to react in the same way, which is proven to be wrong. A partial solution resides in the inclusion of time depending response functions (i.e. adoption of technology, market access) for each category which try to represent the adaptation of farmers to changes in the general or specific context.

requirements of cash. Risk related attitude is one of the main component of farmers' decision making process. Farmers can be risk averse, risk neutral or risk taker, even if this last possibility is rarely found. Thus, the risk attitude has to be considered in the objective function affecting the production plan, i.e. expected income is maximised at the same time that expected variance is minimised (Markovitz, 1959, E-V criterium).

$$Max \quad \sum_{ex,i,tech}[((Y_{i,tech}.P_i - c_{i,tech}).x_{ex,i,tech}) - 1/2\alpha_{ex}\sigma^2{}_{i,tech}.x_{ex,i,tech}$$

Where Y are the yields, P the prices and c the costs of each activity and technique, α_{ex} represents each farmers' attitude concerning risk and σ^2 the variance of the activities revenus.

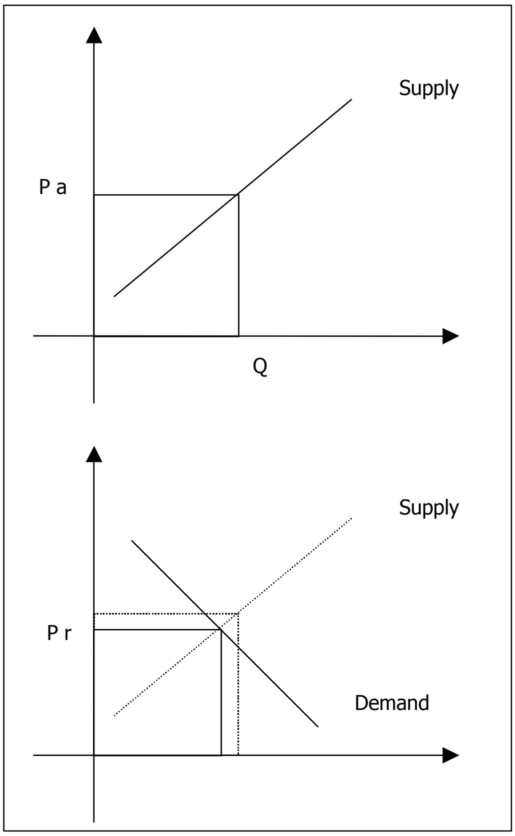

Figure 4. Iimpacts of expected prices on supply and the subsequent impact on "real" prices as a function of the demand

Two more specific features should be taken into account when modelling farmers' behaviour. First, there can be a difference between expected prices and "actual" prices received by the farmers. In most models both prices have the same value, but this is hardly observed in reality. Farmers anticipate prices according to several factors : last year prices, the season, etc. and thus decide their factor allocation. Their income will be the consequence of their total outcome (dependant on weather and management), of other farmers outcome and of consumers' decisions (demand) which influence the level of "actual" prices (Figure 4 and 5). This can be dealt with in a separate model which undertakes a thorough representation of consumers' demand with the corresponding elasticities for the different products according to their different budgetary constraints. In this case, total production arriving at the market is provided by the bio-economic model and the prices for each commodity is the result of this non-linear optimisation of the consumers' utility function (Deybe and Robilliard 1997, Deybe 2001). Second, resource depletion will have an impact on future productivity. These two aspects call for dynamic or recursive models (Gérard et al. 1995). The dynamic models imply to define alternative resource uses for a certain period of time, recursive models call for reinitialising resource status after each model step. In both cases CGM are also useful because they provide precise data on crop responses to rotations or resource depletion (Deybe,2001).

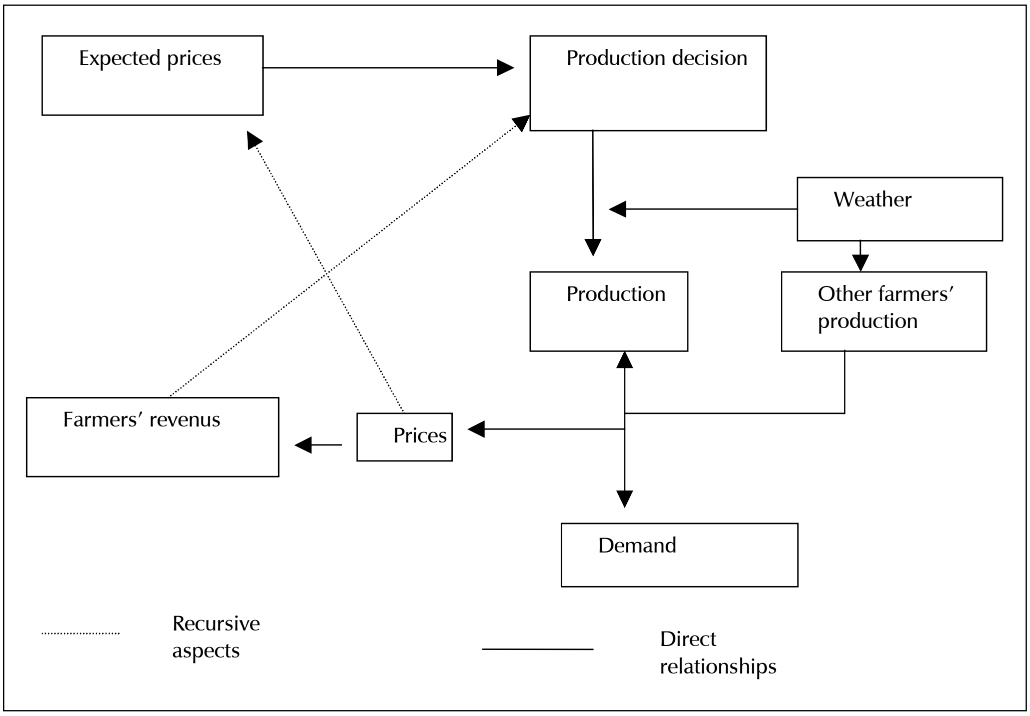

Figure 5. The recursive linkages in the bio-economic model

Experience on bio-economic modelling and the environment

Bio-economic modelling, based on the coupling of biophysical and economic models, started in the USA in the eighties, specially at Iowa State University and Texas A&M University, both for studying problems of nitrate pollution and soil erosion. In Europe, research in this field has been developed in several countries, particularly in The Netherlands, Germany and France. Important progress has been reached by Wageningen Agricultural University in the development of integrated bio-economic modes based on a modular analytical framework. Intensive collaboration between soil scientists, crop and livestock modellers and micro- and macroeconomists enabled the specification of interactive models for land use, farm household choice and regional development. These models were tested and applied in specific semi-arid and humid settings in order to identify specific policy instruments for bridging the gaps between sustainable land use and farmers welfare (van Keulen et al, 1998).

Even if bio-economic models have still many drawbacks to overcome, in particular enhancing the consideration of site specific characteristics as well as the aggregation of farmers' responses, they provide a step forward in the representation of the agricultural component affecting farmers' behaviour. This representation allows to better concentrate in the analysis of specific farmers characteristics, specially on the identification of their objective function and their risk attitude. They also allow to improve the inclusion in the analysis of alternative agriculture activities, for which data is not always available, and which can eventually be adopted by farmers, if the context allow it. Finally, they admit the quantification of some of the environmental impacts (i.e. nitrate lixiviation, erosion, etc.) which can be useful for the policy maker to compare between alternatives.

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References

[1] Barbier B. 2001. Agricultural production and erosion in a small watershed in Honduras: a non-linear programming approach. In Heerink N., van Keulen H. and Kuiper M. Economic policy and sustainable land use. Recent advances in quantitative analysis for developing countries. Heidelgerg: Physica-Verlag.

[2] Barbier B., 1995. Modélisation agronomique et économique de la durabilité d'un système agraire villageois. Le cas du village de Bala au Burkina Faso. Thèse de Doctorat,Ecole Nationale Supérieure d'Agronomie de Montpellier.

[3] Boote K.J., Jones J.W., Hoogenboom G., Jagtap S.S., Wilkerson G.G, 1989 PNUTGRO V1-02 Peanut Crop Growth Simulation Model Users' Guide. Department of Agronomy, University of Florida, Gainsville, Florida.

[4] Clark C.W. 1990.Mathematical bioeconomics. The optimal management of renewable resources. Second Edition. New York: Wiley

[5] de Witt C.T. 1992. Resource use efficiency in agriculture. Agricultural Systems (40): 125-151

[6] Deybe D. 1994. Vers une agriculture durable. Un modèle bio-économic. Paris: Cirad, 194 p.

[7] Deybe D. 2001. Effects of economic policies on farmers, consumers and soil degradation: a recursive dynamic sector model with an application for Burkina Faso. . In Heerink N., van Keulen H. and Kuiper M. Economic policy and sustainable land use. Recent advances in quantitative analysis for developing countries. Heidelgerg: Physica-Verlag.

[8] Deybe D. et Flichman G., 1991. A regional Agricultural Model using a Plant Growth Simulation Program as Activities Generator- An application to a region in Argentina. *in* Agricultural Systems 37, pp. 369-385.

[9] Deybe D., 1989. Politiques agricoles et érosion du sol en Argentine : une méthodologie pour leur analyse. Collection Thèses and Masters. Montpellier, Centre International de Hautes Etudes Agronomiques Méditerranéennes. Institut Agronomique Méditerranéen de Montpellier.

[10] Deybe D., Bendaoud M., 1994. Consideration of long-run effects in choosing farming systems in Morocco. Agricultural Economics Staff paper 94-9. Pullman, Washington State University, 1994, présenté à la 37ème réunion de l'African Studies Association.

[11] Deybe D., Butcher W.R. et Ouedraogo S., 1992. Analysis of sustainability and credit policy using a model for a small village in the west of Burkina Faso. Agricultural Economics Staff paper 92-6 Pullman, Washington State University. Présenté au 35ème "Annual Meeting of the African Studies Association

[12] Deybe D., Robilliard A.S, 1997. Dévaluation et consommation alimentaire en zone franc. Le Cas du Burkina Faso. In : Economie Rural, n° 244, pp. 49-53.

[13] Flichman G., Varela-Ortega C. and Garrido A., 1995. "Agricultural policy and technical choice: a regional analysis of income variation, soil use and environmental effects under uncertainty and market imperfections", 15 p., in Environmental and Land Use Issues: an Economic Perspective. Ed. Luis Miguel Albisu and Carlos Romero, Wissenschaftverlag Vauk Kiel KG, 1995.

[14] Gérard F., Boussard J-M. et Deybe D., 1995. MATA : un outil d'analyse multi-niveaux pour le secteur agricole. *in* "Comportement micro-économique et réformes macro-économiques dans les pays en voie de développement ". Collection Actualité Scientifique. Paris : Aupelf-Uref, pp.347-364.

[15] Godwin D.C., Ritchie J.T., Singh U, Hunt L. 1989 A User's guide to CERES Wheat – V 2.10 Muscle shoals. International Fertiliser Development Center. Alabama.

[16] Hazell P.B.R. 1971. A linear alternative for quadratic and semivariance programming for farm planning under uncertainty. In American Journal of Agricultural Economics 53:53-62.

[17] Jones C.A., Dyke P.T, Williams J.R., Kiniry J.R., Benson V.W., Griggs R.H. 1991. EPIC: an operational Model for evaluation of agricultural sustainability. In Agricutural Systems 37:341-350.

[18] Jones J.W., Boote K.J., Jagtap S.S., Hoogenboom G., Wilkenrson G.G. 1988. SOYGRO v5.41 Soybean Crop Growth Simulation Model Users' Guide. Department of Agricultural Engineering, University of Florida, Gainsville, Florida.

[19] Markowitz H.M. 1959. Portfolio selection: efficent diversification of investments, New York: Wiley.

[20] McCarl B., Schneider U., Murray B., Williams J. and Sands R. 2001 Economic potential of Greenhouse Gas emission reductions: Comparative Role for Soil Sequestration in Agriculture and Forestry. Temple (Tx) : Mimeo.

[21] Stockle C.O., Nelson R.L. 1996 Cropsyst User's manual V2. Biological systems engineering dept. Wahsington State University.

[22] Thornton P.K., Dent J.B., Bacsi Z. 1991. A Framework for Crop Growth Simulation Model Applications. In Agricutural Systems 37:327-340.

[23] Van Keulen H. Kuyvenhoven A. and Ruben R. 1998. Sustainable land use studies and their role in strategic policy making. In Agricultural Systems, 58-3:285-308.

[24] Williams J.R., Jones C.A., Dyke P.T. : "The EPIC (Erosion Productivity Impact Calculator) model and its applications", in Proceedings of International Symposium for Agrotechnology Transfer, ICRISAT, Patancheru, 1984, 111 -121.