The conditions for sustainability of tropical agriculture. Bioeconomic models applied to five contrasting farming systems.

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Abstract

Bioeconomic models (BEMs) are models that simulate biophysical processes and economic activities based on optimization algorithms. This paper describes five applications of BEMs in five contrasted tropical farming systems from Africa and Latin America. The objective of this study is to understand the land use dynamic, assess the strengths and limitations of each agro-ecosystem, and predict the response farmers are likely to give to various external changes such as prices and population growth. Since these models are reasonable approximation of what is likely to happen in the future, we made recommendations about the possibilities of boosting production, alleviating poverty and maintaining the environment. The simulations show contrasting results for each site. The main factor of differentiation between each site is rainfall with the more challenging area being the Sahel. However the more humid area is not the better area. The seemingly better area is the hillside area of Honduras because springs and good access to a large city made intensification a reality. The problems are of different nature in each site. The African villages have the greatest challenges since population growth requires intensification and that intensification under warm climate is more expensive than under colder climate. Indeed the central problem of most African soils is its low natural fertility and then the high oxidation rates which makes permanent cultivation difficult. In the Amazonian settlement project, the farmers' situation is less dramatic since 50 hectares is large enough to sustain a family with extensive cattle ranching. In such a system there is little incentive for intensification. The question is whether such an extensive system is a good alternative to deforestation.

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Introduction

Scientists developed the first BEMs in the eighties to operationalize the concept of sustainability by adding environmental components to classic economic models. There were at the time serious difficulties to define sustainability and even more difficulties to operationalize it. Most economists describe a sustainable system as a system the produces more while permitting the natural resource base to keep its productive potential (Parikh 1991). For economists the concept is dynamic. For instance sustainable agriculture does not need to be sustainable now but can have a period of unsustainability and then of recuperation of the natural resources or even a period of substitution by a man made resource. A farmer does not need to fertilize a field if he can return the field into fallow when the field will be exhausted. A farmer can also start putting fertilizers only when the field natural fertility starts to decrease. This dynamic definition of sustainable agriculture contrasts with more static definitions but a dynamic definition is also more complex to operationalize.

Scientists developing BEMs no longer try to determine if a system is sustainable or not but prefer to determine under which conditions a system is likely to be more or less sustainable. Scientists no longer present BEMs results in a normative way but in a descriptive way where different scenarios are compared.

In this paper, we present five applications of BEMs in tropical agro-ecosystems. Section one is a review of the use of BEMs in agriculture. Section two presents the five tropical agro-ecosystems where we applied the models. Section three includes the description of the models. Section four includes the results and section five the conclusions derived from the results.

Bioeconomic models (BEMs)

Scientists use the expression BEM for models that link biophysical components with economic components of different sorts. The economic component of these models can be an optimization framework, optimal control models, cellular automater or simple budgets. We can distinguish the BEMs in two categories based on the use or not of an optimization framework.

Optimization BEMs

Optimization models are sometimes called mathematical programming models. This family of models includes linear programming models and non-linear programming models. They consist in maximizing or minimizing an objective function under different constraints.[3] Optimization models are widely used in industry for minimizing costs (Shrage, 1997). In agriculture optimization models are frequent but applications to agricultural problems encounter the difficulty to model the climatic variability of the production.

In agriculture most models maximize a utility function under constraint of land, capital

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3 In the academic world optimization models such as mathematical programming models are no longer considered to be at the frontier of economic science. Many economists turned toward optimal control theory models with infinite time horizons or toward game theory. Academics use these models to simulate stylized facts while mathematical programming models are more used by multidisciplinary teams in operational research.

and labor. In temperate countries, scientists have extensively used optimization models to simulate farming systems to determine the factor explaining agricultural supply and farm incomes under different policy options (Boussard 1977; Hazell et Norton 1985; Mc Carle and Spreen 1998). Scientists encountered more difficulties to model tropical agro-ecosystems because of their complexity.

The BEMs appeared more recently. The BEMs presented in this paper are optimization models including explicit environmental components.[4] We can distinguish two ways to include environmental problems into BEMs. The most common way is to simulate what will be the effect of economic decisions on erosion, water production, contamination and deforestation. In this case there is no feedback of the effect on the production function of the model. In developed countries, studies based on this type of BEMs are numerous (Shortle 1984, Ellis, Hugues, and Butcher 1991; Dosi and Moretto 1993; Carpentier, Bosch, and Batie 1998). Policy makers increasingly use these models as decision support systems. In the US for instance, the congress is regularly asking the US department of agriculture to simulate the effect of different policies on production and the environment. In tropical countries, the use of BEMs as decision support systems is still rare though the fathers of farming system research in the tropics promoted the use of optimization models to study the limits and the potential of local farming systems (Benoit Cattin 1982, Ruthenberg 1980; Beets 1990). The first BEMs applied in developing countries compared the trade off between production and soil components such as erosion in Indonesia (E. Barbier 1988), organic matter in India (Parikh 1991), soil nutrients in Mali (Kruseman et al. 1995) and Indonesia (Van Rheenen 1995).

It is more difficult to model the feedback of natural resource degradation on agricultural production. The processes such as erosion, soil fertility depletion and regeneration are not well modeled yet. There are three ways to overcome this problem. The first consists in generating the data in the sites in collaboration with nature scientists such as ecologists and agronomists. A second way is to use biophysical models that can estimate the necessary numbers for a wide range of conditions. The third way is to run a sensitivity analysis with the optimization model and compare the results to identify at which level of degradation natural resource degradation really matters.

It is also difficult to include biophysical processes in optimization models. Most models used to simulate farming systems have been linear programming models. These models have been criticized for being linear given that natural resources processes are non-linear and involve threshold effects. However it is relatively easy to approximate non-linear production and damage functions with linear segments (Barbier and Bergeron 1999). It is also easy to use directly non-linear programming models (Barbier 2000).

Most BEMs have been applied at the farm level but farm level models have their limitations. In many developing countries natural resources such as land, wood and water are used in common. Several attempts have been made to model communities (Kebe et al. 1992; Deybe, Ouedraogo and Butcher 1993; B. Barbier and Benoit-Cattin 1997) or small

4 One can argue that any farm optimization model already are BEMs since these models implicitly include production functions based on biophysical processes. Furthermore, cost, labor time and risk are greatly explained by the biophysical characteristics of the local ecosystem.

regions (Veeneklas 1990).[5]

Non optimization types of BEMs

BEMs non based on optimization framework are of different sorts. Cellular automaters is one of them. These are models where the different cells of a landscape have different simple rules in regards of neighboring cells. Then a stimulus is sent to some cells and each cell reacts to its neighboring cells change in an iterative way. The final mapping of the grid then gives an idea of the results of the interactions between the different cells. This way one can model a landscape with its different interacting actors.

Cellular automater are sometimes opposed to optimization models because optimization models assume that the actors maximize utility while some social scientists contest the validity of this assumption. Actors would be more in a prey-predator system, or actors are more reactive than planing, actors do not maximize but try to survive, poor actors are not profit maximizers but first consume what they produce. The challenge consist now in linking optimization framework within a cellular automater framework. It permits to simulate the behavior of many individual agents in a space where they can interact through a market based on shadow prices.

This study shows the application of 5 BEMs based on optimization to 5 ecosystems in Burkina Faso, Niger, Brazil and Honduras.

The five studied agro-ecosystems

The five systems are illustrations of five major tropical climates such as the semi-arid, sub-humid, humid and mountainous climates. The three African climates illustrate three representative situations from West Africa. The three villages are located on a transect North South, drier and in the north. The tow Latin American villages are representatives of two major contrasting situations. The humid Brazilian case is a the situation of frontier agriculture. The mountainous case is one of a settled village facing the typical situation of population growth on steep slopes.

Table 1: Ecosystem characteristics

Climate	Semi-arid	Semi-arid	Sub-humid	Humid	Mountainous
Countries	Niger	Burkina Faso	Burkina Faso	Brazil	Honduras
Region	Niamey	Central plateau	Mouhoun	Acre et Rondônia	Central Region
Villages	Banizoumbou	Kolbila	Bala	-	LaLima

[5] Equilibrium models have been applied to villages and consider that some prices are endogenous to the villages (Taylor et Aldeman 1997).

Altitude	300	300	300	110	800 à 1200
Rainfall	500 mm	600 mm	900 mm	2000mm	1200 mm
Mode	Unimodal	Unimodal	Unimodal	Bimodal	Bimodal
Natural vegetation	Steppic	Savanna	Savanna	Equatorial forest	Pine tree forest
Landscape	Flat	Flat	Flat	Flat	Hilly
Soil texture	Very sandy	Clay and sandy	Clay and sandy	Sandy	Clayish
USDA soil classif.	Arenosols	Alfisol	Alfisol	Oxisol	Ash from basalt

The Sahelian village of Banizoumbou in Niger (ILRI dataset) was used to predict the future of transhumance in the Sahel (Barbier 2000). Increasing population growth and expansion of cropland makes the traditional transhumance from north to south more difficult every year. While most experts consider that transhumance has no future, a recent school of thoughts consider that transhumance is the best way of adapting to the Sahelian ecosystem.

The other semi-arid village, the semi-arid village of Kolbila in Burkina Faso (ICRISAT dataset) illustrates the problems of the highly populated semi arid areas of West Africa where resources are now insufficient to sustain the human and animal population (Barbier 1999).

The sub-humid village of Bala is located in the Cotton producing area of Burkina Faso (CIRAD dataset) (Barbier and Benoit Cattin 1997). The village has seen the arrival of migrant from the semi-arid area. The main challenge of the village is to increase production per hectare through land intensification. Since population is increasing rapidly one has to find a way to replace the fallow system. Agronomic researchers suggest that pure chemical fertilization is not sustainable but that organic fertilization is necessary. The question is whether the system can produce enough biomass to maintain soil organic matter content.

The Amazonian model is a farm level model reproducing a typical farm of the southern border of the Amazonian forest (IFPRI dataset). The problem is one of deforestation and resettlement programs. The model helped identify the second best options to deforestation (Vosti, Witcover, et Carpentier,1999; Carpentier, Vosti, et Witcover, 2000; Fernandes and de Souza Matos 1995).

The Honduran model was applied in the village of Bala in the mountains of central Honduras (IFPRI dataset) (Barbier and Bergeron 1999). The objective to is to understand how the land use changed during in the last 20 years in term of sustainable intensification. We used also the model to predict the future land use of the village.

Table 2: Socio-economic characteristics

Climate	Semi-arid	Semi-arid	Sub-humid	Humid	Mountainous
Population density	34	62	32	4.2	65
Population growth % in the nineties	3	3	3	2.4	3
Social groups	Farmers/ Pastoralists	Farmers/ Pastoralists	Farmers/ Pastoralists	Farmers	Farmers / Ranchers
Land tenure	Free access / common access	Free access / common access	Free access/ commons access	Private property	Private property
Cultivated area per person	0.5	0.5	1	1.4	1

The five systems are semi-subsistence systems which means that they are no longer purely subsistence systems and not yet completely integrated to the market. The two semi-arid systems are the least integrated to the market but are also highly populated. Farmers currently cope with this situation by migrating to more humid and less populated areas.

In the five systems cropped area per farmer are small because in the five villages cultivation is manual with little mechanization. The five systems include pastures and livestock. The first limiting factor of production is rainfall but this factor can become less important with adoption of new technologies such as irrigation and fertilization.

The main features of the five bio-economic models

The five models are multi annual to include natural resource processes. They also include dynamic interrelations between livestock, crops and forest. Some of the models incorporate results from biophysical models and use different scales to better respond to the initial questions of the studies. Four of the five models include risk aversion.

Table 3: Model features

Climate	Semi-arid	Semi-arid	Sub-humid	Humid	Hillside
Scale	Village	Village	Village	Farm	Small watershed
Planning horizon	4	3	3	6	5
Season number	3	3	3	12	4

Simulation time frame	50	40	40	25	70
Discount rate	10	15	15	9	15

Descriptive models

Model results are not analyzed in a normative but in a descriptive way. This means that the models do not pretend to simulate the optimal way to run a farming system. We rather present the results in a descriptive way meaning that the models describe what are the likely futures of a farming system under different hypothesis. The descriptive approach makes the hypothesis that farmers are already optimizing and that, once the model is calibrated and validated, the model just behaves similarly to farmers.

Multi-annual models

The five models have a multi-annual planning horizon. The models with short term planning horizon are the one with higher discount rates. These are the poorer villages and also the ones where little is expected from perennials. The Amazonian model has a 15 year planning horizon because the problem is based on the potential of perennials. The discount rates are the interest rates utilized in these areas. We analyzed the sensitivity of the results to changes in the discount rates. All models were not sensitive to small changes of the discount rate. However the higher the discount rate, less sustainable the system.

Recursive models

The main originality of the five models is their recursivity. It means that the results of one simulation become the starting point of a new simulation. The resources that are carried over in a recursive way are animals, food reserves, money, area under different kind of land uses and its content in soil organic matter, soil nutrients and arable soil depth.

With a recursive framework a model can predict a very long futuristic pathway. For instance the Brazilian model takes the result of year 5 as a starting point for a new run. Repeating the run five times helps to predict what will happen in 25 years. The four other models realize the operation every year but predict further in the future because we wanted to assess the effect of long-term population growth.

Adapted scales

The models simulate farming systems at different scales to better respond to the problem at hand. The main factor explaining the scale of the model is the access to land. In developed countries farm level model are well suited to predict future events. In developing countries one has to think about a larger scale because resources are less individualized.

In the Burkina and Niger agro-ecosystems land access is a typical open access for pastures and common access for cropland. In other words there is no rule to access the pastures during the dry season but there are rules to start a field. The 3 African models are designed at the village level but including distant transhumant pastures to include the possibility of farmers and nomads to use common and open access land (Benoit-Cattin 1994).

The Honduran case is a latifundias / microfundias type of individual land tenure where land is individualized but access to tree product is open to all. The Honduran model was designed at the sub-watershed level (900 hectares) to include the possibility for farmers to access the waterstreams for irrigation. The sub-watershed scale is also particularly relevant for mountainous agro-ecosystems because of the importance of water and erosion (Thurow and Juo 1995; International Development Bank 1995).

The Amazonian case is an agricultural frontier where land is individualized. The Brazilian model works at the farm level.

The four aggregated models however distinguish the characteristics of different social groups. In Honduras the ranchers are distinguished from small farmers. In the African models, farmers are distinguished from nomads. In all aggregated models, farmers can exchange labor within the community.

Risk aversion

Risk aversion is included in four of the five models. In Honduras it was not because inter-annual risk was considered relatively low. In Burkina Faso the Target Motad method allowed to include the income variability in the constraints. The Sahelian model includes a sophisticated discrete stochastic programming framework which is a decision tree formulation. This framework was coupled with a mean variance formulation in the objective function. In Brazil, the risk was modeled with mean variance method.

Table 4: Risk in the models

Climate	Semi-arid	Sub-humid	Sub-humid	Humid	Hillsides
Method	Discrete, sequential, stochastic	Target Motad	Target Motad	Mean variance	-

Activities

The models include the main activities characterizing each system. The activities are described by their cost, benefit, labor time, variability of each activity and their effect on the environment.

Table 5: Activities of the models

Climate	Semi-arid	Semi-arid	Sub-humid	Humid	Hillsides

Annual crops	Millet-bean	Sorghum-miller	Cotton-Maize-sorghum	Rice, maize, cassava, local bean	Grain horticultural
Perennial crops	-	-	-	Café, banana	Coffee
Breeding system	Meat / milk	Mechanization	Mechanization and meat	Meat, milk	Mechanization, Meat, milk
Other activities	Migration to Coast			Extraction of Brazil nut and wood	

In addition to the agricultural activities described above, each model includes the possibility to migrate temporarily or definitively except the Brazilian model.

Natural resources

The most sophisticated aspect of these models is the inclusion of natural resource management.

Table 6: Natural resources features in the models

Climate	Semi-arid	Semi arid	Sub humid	Humid	Hillsides
Soil major problem	Phosphorus, Nitrogen	Erosion, Organic matter	Erosion, organic matter	Nitrogen	Erosion
Erosion type	Soil depth and nutrient loss	Soil depth and nutrient loss	Soil depth and nutrient loss	-	Soil depth and nutrient loss
Number of type of soils in the model	1	5	5	3	18

Soils were simulated dividing farming systems in several units. For instance in the Honduran case the watershed is divided in 18 units characterized by altitude, slope and land tenure. Each area has an initial set of variables that change through time. These variables are population, land use, soil organic matter, soil nutrients, tree volume, soil conservation structures. Some characteristics such as access to roads and irrigation were changed exogenously according to past events or to future hypothesis.

The most difficult aspect in modeling land use is that one land unit is a combination of several land use. Each land unit has several stocks of soil nutrients and these change over time in a different way. For simplification we distinguished three types of stocks: the stocks bellow crop, pasture and forest. Without intervention the stock of soil nutrients diminishes under crop, increases under pastures and forests. If there is a rotation between the three land uses. For instance if an area of forest becomes a crop, the stock of soil nutrient of the reclaimed area of forest is transferred to the stock of soil nutrients under crop. This way the average level of soil nutrients under crop increases and permits a better crop yield. This way the model is able to reproduce was is likely to be the soil fertility management of a farm, a community or a watershed.

Table 7: Trees and water in the models

Climate	Semi-arid	Semi-arid	Sub-humid	Humid	Mountainous
Trees	-	Acacia, eucalyptus, Bush trees	Acacia, eucalyptus, Bush trees	Coffee, fallow, guineas	Pine tree, coffee
Wood	-	Fuelwood	Fuelwood	Hedges, timber sales	Fuelwood
Water	-	Irrigated land	Irrigated land	-	Springs
Irrigation	-	Gravity	Gravity	-	Sprinkler

Except the Nigerian model, each model includes a detailed forestry and agroforestry component. Trees are modeled as area or volume of trees. Trees increase, can be cut or planted. Their productivity changes over time.

Production factors

Table 8: Production factors in the models

Climate	Semi-arid	Semi-arid	Sub-humid	Humid	Mountainous
Usual factors	Land, labor	Land, labor, capital	Land, labor, capital	Land, labor, capital	Land and labor
Mechanization	-	Donkeys / Weeder	Oxen /plough +weeder	Chainsaw	Oxen/plough

The models include the most common production factors such as land, capital and labor. They also include the possibility to adopt more input and more mechanization.

Most of these remote markets are considered to be imperfect because the number of traders is limited and have a much better access to information. The local labor market is explicit in the Honduran model but implicit in all the other models meaning that farms have the possibility to hire or sell labor within the community.

Table 9: New technologies

Climate	Semi-arid	Semi-arid	Sub-humid	Humid	Mountainous
Fertilization	Manure, estiercol, NPK	Compost, manure, estiercol, NPK	Compost, manure, estiercol, NPK	NPK, fallow and improved fallow	Compost, manure, estiercol, NPK
Improved technologies	Pastures	Planted pastures	Planted pastures	Pasture, animals, crops	-
Others	-	-	-	Wood extraction	Wood extraction

Biophysical model

A biophysical model has been used to determine the main factor of yields, such as cropping patterns, soil condition, and climate.

EPIC (Erosion Productivity Impact Calculator) developed by Williams, Jones, and Dyke (1987) was used in Burkina Faso and Honduras. Epic computes erosion thanks to RUSLE which the revised version of Universal Soil Loss Equation (Wishmeier and Smith 1978). Results were compared to erosion measurement

Table 9: Biophysical models

Climate	Semi-arid	Semi-arid	Sub-humid	Humid	Mountainous
Biophysical model	-	EPIC	EPIC	-	EPIC
Simulated cropping patterns	-	Sorghum-sorghum	cotton-maize-sorghum stylosan-thes	-	maize-maize maize-potatoes, maize-onion

Conclusions by agro-ecosystem

Conclusions stem form the different scenarios that were run under different assumptions.

Table 10: Scenarios

Climate	Semi-arid	Semi-arid	Sub-humid	Humid	Mountainous
Prices	Grain, NPK	Grain, NPK	Grain, NPK	Coffee, meat, NPK	Grain
Migrations and local population increase	Yes	Yes	Yes	No	Yes
Organic agriculture	-	-	-	-	Yes
Markets	-	-	-	Credit	Agrarian reform
Monetary policies	-	Currency devaluation	Currency devaluation	-	Liberalizatio n
Roads	-	-	-	Better road	What if no road?

The semi-arid agro-ecosystem in Niger

Experts are relatively pessimistic about the future of the transhumance in the Sahel. Rapid population growth induces crop expansion and increasing conflicts between farmer and herders. The results of the different simulations indicate that the conflict could be solved because the conversion of pasture in cropland does not mean a reduction of potential forage quantity and quality. Millet, beans and weeds are good substitutes to pastures. Crop expansion means a more change of access than a change of potential forage. The model explored a few alternatives such as subsidized feed complements to cope with extreme droughts and the fencing of pastures.

Another simulation was the long term change of relative prices. If world grain prices continue to decrease, it is probable that millet production will decrease in Niger. If imported grains become more competitive, farmers may buy food and migrate temporarily. If agriculture decreases, herders could get back more space for transhumance. The key question would then remain the access to wells.

The semi arid agro-ecosystem in Burkina Faso

The results of the simulations for semi arid village of Burkina Faso show that promoting sustainable agriculture is very difficult in the semi-arid area. The main reason is that sustainable farming requires an excessive amount of organic matter; farmers do not have enough crop residues and animals in their agro-ecosystem to produce the necessary organic fertilizers. The model suggests that once the cultivable area is cultivated, income per capita of the population will drop despite the likely adoption of some new techniques. We predict that for more villages of this eco-system, once a “carrying capacity” is reached farmers will start to migrate. A realistic agricultural policy would be to let farmers emigrate toward less populated regions. The cost of maintaining many farmers in degraded land is too high.

The sub-humid agro-ecosystem in Burkina Faso

The sub-humid region of Burkina Faso still has good land available. However it will be cultivated soon by migrants. The sustainability of the system is at risk because organic matter in the soil will become a limiting factor. According to our model the fallow system will remain because it will be difficult to maintain a good level of organic matter in the soil. The situation is less dramatic than in the semi arid area though. Maize and cotton will become the main crop of the area at the expense of sorghum and millet.

The humid agro-ecosystem in Brazil

The current settlement project in the regions of Acre and Rondonia consists in allocating 50 hectares per family in forested regions. It is expected that farmers will not touch half of the holding leaving a relatively forested area. A first result of the simulations is that the 50 ha lots are large enough for one family to practice a sustainable farming system within the 25 hectares a family can deforest. A family can sustain a decent living with ranching. Agriculture only is not a sustainable option because slash and burn agriculture would mean a destruction of the forest in 25 years. The simulation also shows that coffee production would be cost-effective only with a sharp increase of the coffee price. The limiting factor of coffee production is labor. Concerning the option of paying for carbon sequestration, the simulations suggest an unrealistic high price per ton of carbon to keep the 50 hectares under forest. Similarly, the sustainable forestry alternative is not cost effective. It would require a much higher price of timber products.

Hillside regions in Honduras

In the Honduran case we simulated the last 20 years using historical data for prices and population. The results show that the price control effective until 1993 depressed agricultural productivity. Similarly the devaluation of 1993 boosted the production in communities involved in horticulturals.

The results shows that the limiting factor of horticultural production is not land or water. Hillsides of Honduras still have many non used springs and intensive horticultural is common on steep slopes. What is limiting horticultural production in La Lima is not land or capital but manpower.

However horticultural development in mountainous areas is likely to increase erosion than the extensive maize bean system even if the area will decrease due to intensification. Horticultural crops are more erosive than extensive maize/bean production because horticulturals are weeded more thoroughly. The traditional production of associated Maize and bean requires little plowing.

Among the land conservation techniques, grass strips were found to be the more appropriate. These are cheaper than terraces and live barriers. Overall the benefit of these barriers as well as the cost are low.

A simulation comparing the use of chemical fertilizers with a simulation barring the use of chemical fertilizers show that incomes would decrease substantially despite the possibility of using organic fertilizer. It would also increase erosion because farmers would use more extensive techniques.

Conclusion

The scenarios exposed in this paper were realistic. The constraints facing tropical farming systems are sufficiently strict to avoid unrealistic predictions. The results were thoroughly discussed with the local researchers and extensionists and in some cases with the farmers. Local experts considered the scenarios realistic and comparable to more advanced villages in the same agro-ecological regions.

The five studies based on the results of BEM helped to compare the potential of different tropical ecosystems. Contrarily to the common assertion that tropical climate are adverse to agricultural intensification, the results suggest that there is a good potential for intensification. Intensification will require the use of chemical fertilization because an exclusive organic fertilization is impossible.

However tropical agro-climatic conditions have some characteristics that make the production more difficult to sustain than in temperate country where exclusive chemical fertilization is sustainable. According to most soil scientists, tropical soils are not suited for exclusive chemical fertilization. Sustainable agriculture requires additional costs to maintain soil organic matter in the soil.

Most scenarios were pessimistic about the outcome of population growth on farmers' incomes. The results show that incomes per capita decrease as population growth forces farmers to cultivate more marginal land. Population growth induces an intensification process only when the area of good cropland is totally cultivated. Until then there is no benefit in adding extra labor or capital per hectare. When the good land becomes limited, the model intensifies production per hectare but incomes per worker do not increase. Unless there is possibilities of emigration incomes decrease faster.

Incomes per worker can increase if new technologies are on the shelves and farmers can adopt them when population is increasing. If there is no new technology available to farmers in the area it will be difficult to compensate the diminishing amount of land with increasing yields.

Also incomes per capita can increase with new markets. Most rural areas have limited access to urban markets and thus find only a limited number of options to diversify production beyond what is already cultivated in the region. The models showed good response to the development of new markets such as cotton in Africa or horticulturals in Honduras.

The BEMs proved their usefulness in understanding complex realities. The BEMs helped draw a coherent picture from abundant research results accumulated through time by agronomic research in these sites. There exist many more of these data rich sites in tropical countries.

References

Avila, Marcelino, ed. 1994. *Alternatives to slash-and-burn in South America: report of research-site selection in Acre and Rondônia states of Amazon region, Brazil.* Nairobi, Kenya: International Center for Research in Agroforestry.

Barbier B. 2000. Erosion modeling with Non Linear programming models. In Economic reforms and sustainable land use in less developed countries: Recent advances in quantitative analyses. Edited by Wageningen University.

Barbier B. et P. Hazell. 2000. Declining access to transhumant areas and sustainability of agro-pastoral systems in the semi-arid areas of Niger. In: Property Right and Collective action edited by ILRI/IFPRI.

Barbier B. and G.Bergeron. 1999. Impact of policy interventions on land management in Honduras: Results of a bioeconomic model. *Agricultural Systems* no 60 1-16.

Barbier, B. 1998. Induced innovation and land degradation: Results from a bioeconomic model of a village in West Africa. Special issue of *Agricultural Economics*.

Barbier, B. and M. Benoît-Cattin. 1997. Viabilité à moyen et long-terme d'un système agraire villageois d'Afrique Soudano-Sahélienne: Le cas de Bala au Burkina Faso. *Economie Rurale* 239 (May).

Barbier, E. 1988. The economy of farm level adoption of soil conservation measures in upland Java. World Bank Environment Division Working Paper No. 11, Washington, D.C.

Beets, W.C. 1990. *Raising and sustaining productivity of small holders in the tropics*. Agpe: Alkmaar, Netherland.

Brooke, A., D. Kendrick and A. Meeraux. 1988. *GAMS: A user's guide.* Redwood City, Calif.: Scientific Press.

Carpentier, C.L., D.D. Bosch, and S.S. Batie. 1998. "Using Spatial Information to Reduce Costs of Controlling Agricultural Nonpoint Source Pollution". Agricultural and Resource Economics Review 72-84 (April).

Carpentier, C. Line, S. Vosti, et J. Witcover. Sous press.FaleBEM: A Farm Level Bioeconomic Model for the Western Amazonian Forest Margin. Washington, DC: International Food Policy Research Institute. EPTD Discussion Paper.

Deybe D., Ouedraogo, S. And Butcher, W.R. 1993. Alternative policies for common resource management, the case of a small village in the West of Burkina Faso. Economics staff paper 93-9. Washington, USA: Washington State Univerisity, Department of Agriculture.

Dosi, C., and M. Moretto. 1993. Nonpoint-source pollution control, information asymmetry, and the choice of time profile for environmental fees. In *Theory, Modeling and Experience in the Management of Nonpoint-Source Pollution,* eds C. S. Russell, and J. F. Shogren. Boston: Kluwer Academic Publishers.

Ellis, J.K., D.W. Hugues, and W.R. Butcher. 1991. Economic Modeling of Farm Production and Conservation Decision in Response to Alternative Resource and Environmental Policies. Northeastern Journal of Agricultural and Resource Economics 20 (April): 198-208.

Fernandes, E.C.M., and J.C. de Souza Matos. 1995. Agroforestry strategies for alleviating soil chemical constraints to food and fiber production in the Brazilian Amazon. In *Chemistry of the Amazon: Biodiversity, natural products, and environmental issues,* eds. P.R. Seidl, O.R. Gottlieb, and M.A.Coelho Caplan. Developed for the First International Symposium on chemistry and the Amazon, November 21-25, 1993. Washington DC.: American Chemical Society.

Hazell, P. B. R. and R. D. Norton. 1986. *Mathematical programming for economic*

analysis in agricultural. New York: MacMillian Publishing Company.
Inter-American Development Bank (IDB). 1995. Concepts and issues in watershed management. Working Paper WP2/95, Evaluation Office, EVO. Inter-American Development Bank, Washington, D.C.
International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT). 1994. A decision support system for agrotechnology transfer (DSSAT), G. Y. Tsuji, G. Uehara, and S. Balas. eds. Volume 1,2, and 3. Honolulu: University of Hawaii.
Kebe, D. 1992. Modélisation de l'impact technico-économique de l'introduction de stylosanthes hamata dans les systèmes agraires villageois au Mali-Sud. Paper presented at the workshop Stylosanthes as Feed and Fallow, October, Kaduna, Nigeria.
Kruseman, G., R. Ruben, H. Hengsdijk and M. K. van Ittersum. 1995. Farm household modeling for estimating the effectiveness of price instruments in land use policy. *Netherlands Journal of Agricultural Science* 43: 111-123.
McCarl B.A. and T. H. Spreen. 1998. Applied Mathematical Programming Using Algebraic Systems. Texas A&M University. http\\:agrinet.tamu.edu\mccarl
Oriade C.A. and C. A. Dillon. 1997. Developments in Biophysical and Bioeconomic Simulation of Agricultural Systems: A Review. *Agricultural Economics* 17 (October): 45-58.
Palm, C.A., M.J. Swift, and P.L. Woomer. 1996. Soil biological dynamics in slash-and-burn agriculture. *Agriculture, Ecosystems and Environment* (58): 61-74.
Parton, W.J., R.L. Sanford, P.A. Sanchez, and J.W.B. Stewart. 199?. Modeling soil organic matter dynamics in tropical soils. In *Dynamics of soil organic matter in tropical ecosystems,* eds. D.C. Coleman, J.M. Oades, and G. Uehara. Honolulu: University of Hawaii Press.
Parikh, K. S. 1991. *An operational definition of sustainable development.* Bombay, India: Indira Gandhi Institute of Development Research.
Rheenen, T. van. 1995. Farm household optimal resource allocation; an explorative study in the limestone area of East Java. PhD thesis, Department of Theoretical Production Ecology and Department of Development Economics. Wageningen Agricultural University, the Netherlands.
Ruthenberg, H. 1980. *Farming systems in the tropics.* Oxford: Clarendon Press.
Shortle, J.S. 1984. The use of estimated pollution flows in agricultural pollution control policy: Implications for abatement and policy instrument." *Northeastern Journal of Agricultural and Resource Economics* 13 (October 1984): 277-285.
Shrage L. Optimization modeling with Lindo. Brooks/Cole publishing company.
Taylor, E. and I. Adelman. 1997. *Village economies.* New York: Cambridge University Press.
Thurow, T.L. and A. S. R. Juo. 1995. The rationale for using a watershed as the basis for planning and development. In *Agriculture and the environment: Bridging food production and environmental protection in developing countries. American Society of Agronomy* Special Publication 60.
Veeneklaas, F.R. 1990. Competing for limited resources: The case of the fifth region of Mali. Report 3. Formal description of the optimization model MALI5. CABO/ESPR, Wageningen.

Vosti, S., J. Witcover and C. L. Carpentier. 2000. *Agricultural Intensification at the Forest Margin: from Deforestation to Sustainable Land Use by Smallholders in the Western Brazilian Amazon*. Washington, DC: International Food Policy Research Institute. IFPRI Research Report.

Vosti, S. A., and J. Witcover. 1996. *Arresting deforestation and resource degradation in the forest margins of the humid tropics: Policy, technology, and institutional options. Review of methodology*. Multi- Country Research Program No. 8. Mimeo. Washington, D.C.: International Food policy Research Institute.

Williams, J. R., C. A. Jones and P. T. Dyke. 1987. EPIC, the Erosion Productivity Impact Calculator. Temple, TX.: U.S. Department of Agriculture, Agricultural Research Service, Economics Research Service, and Soil Conservation Service.

Wischmeier, W. H. and D. D. Smith. 1978. Predicting Rainfall Erosion Losses. A Guide to Conservation Planning. Agricultural Handbook #537. Washington, D.C. USDA.

Witcover, J., S. A. Vosti. 1996. *Alternatives to slash-and-burn agriculture (ASB): A characterization of Brazilian benchmark sites of Pedro Peixoto and Theobroma*, August/September 1994. MP-8 Working Paper No. US96-003. Washington, D.C.: International Food Policy Research Institute.