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. 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. 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

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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).

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

<table>
<thead>
<tr>
<th>Climate</th>
<th>Semi-arid</th>
<th>Semi-arid</th>
<th>Sub-humid</th>
<th>Humid</th>
<th>Mountainous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Countries</td>
<td>Niger</td>
<td>Burkina Faso</td>
<td>Burkina Faso</td>
<td>Brazil</td>
<td>Honduras</td>
</tr>
<tr>
<td>Region</td>
<td>Niamey</td>
<td>Central plateau</td>
<td>Mouhoun</td>
<td>Acre et Rondônia</td>
<td>Central Region</td>
</tr>
<tr>
<td>Villages</td>
<td>Banizoumb ou</td>
<td>Kolbila</td>
<td>Bala</td>
<td>-</td>
<td>LaLima</td>
</tr>
</tbody>
</table>

5 Equilibrium models have been applied to villages and consider that some prices are endogenous to the villages (Taylor et Aldeman 1997).
<table>
<thead>
<tr>
<th>Altitude</th>
<th>300</th>
<th>300</th>
<th>300</th>
<th>110</th>
<th>800 à 1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>500 mm</td>
<td>600 mm</td>
<td>900 mm</td>
<td>2000 mm</td>
<td>1200 mm</td>
</tr>
<tr>
<td>Mode</td>
<td>Unimodal</td>
<td>Unimodal</td>
<td>Unimodal</td>
<td>Bimodal</td>
<td>Bimodal</td>
</tr>
<tr>
<td>Natural vegetation</td>
<td>Steppic</td>
<td>Savanna</td>
<td>Savanna</td>
<td>Equatorial forest</td>
<td>Pine tree forest</td>
</tr>
<tr>
<td>Landscape</td>
<td>Flat</td>
<td>Flat</td>
<td>Flat</td>
<td>Flat</td>
<td>Hilly</td>
</tr>
<tr>
<td>Soil texture</td>
<td>Very sandy</td>
<td>Clay and sandy</td>
<td>Clay and sandy</td>
<td>Sandy</td>
<td>Clayish</td>
</tr>
<tr>
<td>USDA soil classif.</td>
<td>Arenosols</td>
<td>Alfisol</td>
<td>Alfisol</td>
<td>Oxisol</td>
<td>Ash from basalt</td>
</tr>
</tbody>
</table>

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

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

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

<table>
<thead>
<tr>
<th>Climate</th>
<th>Semi-arid</th>
<th>Semi-arid</th>
<th>Sub-humid</th>
<th>Humid</th>
<th>Hillside</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale</td>
<td>Village</td>
<td>Village</td>
<td>Village</td>
<td>Farm</td>
<td>Small watershed</td>
</tr>
<tr>
<td>Planning horizon</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Season number</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>12</td>
<td>4</td>
</tr>
</tbody>
</table>

6
### 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

<table>
<thead>
<tr>
<th>Climate</th>
<th>Semi-arid</th>
<th>Sub-humid</th>
<th>Sub-humid</th>
<th>Humid</th>
<th>Hillsides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>Discrete, sequential, stochastic</td>
<td>Target Motad</td>
<td>Target Motad</td>
<td>Mean variance</td>
<td>-</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Climate</th>
<th>Semi-arid</th>
<th>Semi-arid</th>
<th>Sub-humid</th>
<th>Humid</th>
<th>Hillsides</th>
</tr>
</thead>
</table>
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

<table>
<thead>
<tr>
<th>Climate</th>
<th>Semi-arid</th>
<th>Semi arid</th>
<th>Sub humid</th>
<th>Humid</th>
<th>Hillsides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil major problem</td>
<td>Phosphorus, Nitrogen</td>
<td>Erosion, Organic matter</td>
<td>Erosion, organic matter</td>
<td>Nitrogen</td>
<td>Erosion</td>
</tr>
<tr>
<td>Erosion type</td>
<td>Soil depth and nutrient loss</td>
<td>Soil depth and nutrient loss</td>
<td>Soil depth and nutrient loss</td>
<td>-</td>
<td>Soil depth and nutrient loss</td>
</tr>
<tr>
<td>Number of type of soils in the model</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>18</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Climate</th>
<th>Semi-arid</th>
<th>Semi-arid</th>
<th>Sub-humid</th>
<th>Humid</th>
<th>Mountainous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees</td>
<td>-</td>
<td>Acacia,</td>
<td>Acacia, eucalyptus</td>
<td>Coffee, fallow,</td>
<td>Pine tree,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>eucalyptus,</td>
<td>eucalyptus, Bush</td>
<td>guineas</td>
<td>coffee</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bush trees</td>
<td>trees</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>-</td>
<td>Fuelwood</td>
<td>Fuelwood</td>
<td>Hedges, timber</td>
<td>Fuelwood</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>sales</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>-</td>
<td>Irrigated</td>
<td>Irrigated land</td>
<td>-</td>
<td>Springs</td>
</tr>
<tr>
<td>Irrigation</td>
<td>-</td>
<td>Gravity</td>
<td>Gravity</td>
<td></td>
<td>Sprinkler</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Climate</th>
<th>Semi-arid</th>
<th>Semi-arid</th>
<th>Sub-humid</th>
<th>Humid</th>
<th>Mountainous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usual factors</td>
<td>Land, labor, labor</td>
<td>Land, labor, capital</td>
<td>Land, labor, capital</td>
<td>Land, labor, capital</td>
<td>Land and labor</td>
</tr>
<tr>
<td>Mechanization</td>
<td>-</td>
<td>Donkeys / Weeder</td>
<td>Oxen /plough +weeder</td>
<td>Chainsaw</td>
<td>Oxen/plough</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Climate</th>
<th>Semi-arid</th>
<th>Semi-arid</th>
<th>Sub-humid</th>
<th>Humid</th>
<th>Mountainous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilization</td>
<td>Manure, estiercol, NPK</td>
<td>Compost, manure, estiercol, NPK</td>
<td>Compost, manure, estiercol, NPK</td>
<td>NPK, fallow and improved fallow</td>
<td>Compost, manure, estiercol, NPK</td>
</tr>
<tr>
<td>Improved technologies</td>
<td>Pastures</td>
<td>Planted pastures</td>
<td>Planted pastures</td>
<td>Pasture, animals, crops</td>
<td>-</td>
</tr>
<tr>
<td>Others</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Wood extraction</td>
<td>Wood extraction</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>Climate</th>
<th>Semi-arid</th>
<th>Semi-arid</th>
<th>Sub-humid</th>
<th>Humid</th>
<th>Mountainous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biophysical model</td>
<td>-</td>
<td>EPIC</td>
<td>EPIC</td>
<td>-</td>
<td>EPIC</td>
</tr>
<tr>
<td>Simulated cropping patterns</td>
<td>-</td>
<td>Sorghum-sorghum</td>
<td>cotton-maize-sorghum stylosanthes</td>
<td>-</td>
<td>maize-maize potatoes, maize-onion</td>
</tr>
</tbody>
</table>

**Conclusions by agro-ecosystem**

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

Table 10: Scenarios
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
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.

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