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Induced innovation and land degradation: Results from a bioeconomic model of a village in West Africa

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Abstract

This paper introduces a modeling method which simulates a village's response to population and market pressure. The method combines a recursive and dynamic linear programming model with a biophysical model of soil condition and plant growth that predicts yields and land degradation for different type of land, land use and cropping patterns. The linear programming model simulates farmers' plans aggregated at the village level under constraints of risk aversion, food consumption, land area, soil fertility, soil depth, labor and cash availability. Detailed agroecological factors determine the main processes of land degradation. A large number of technological alternatives, representing different degrees of labor and/or land-saving techniques available in the study areas, are introduced, taking into account their respective constraints, costs and advantages. The method has been calibrated for a village located in the sub-humid region of Burkina Faso. Several simulations are carried out to the Year 2030. The results show that population pressure leads to intensification and investment in land conservation practices but not necessarily to better farm incomes. Increasing market opportunities can play a more positive role in boosting productivity, but for the next decades the best way to increase production per farmer is to let farmers migrate from the high-population-density areas to the low-population-density areas because, under the current economic conditions of most Sahelian countries, intensification per hectare is stil more expensive than the fallow system.

Keywords: Linear programming; Biophysical model; Simulations; Farming systems; Agricultural policy; Induced innovation; Environment; Burkina Faso; West Africa

1. Introduction

There is still debate and disagreement over the conditions that can lead to simultaneous improvement in agricultural productivity, reductions in poverty and protection of the environment. The 'induced innovation' theory which states that, as populations grow and markets expand, the values of land and labor change, inducing the discovery and the adoption of needed new technologies (Ruttan and Hayami, 1990) but the outcome of population-driven intensification on per-capita incomes and on the environment is less clear. The continuing debate contrasts Boserup's optimistic theory (Boserup, 1965) with the pessimistic neo-Malthusian approach (Malthus, 1798; Higgins, 1982; Cleaver and Schreiber, 1995). For Boserup, the inten-

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sification[1] process leads not only to higher yields but also to increasing production per capita. Many empirical studies have confirmed an optimistic point of view, but there are many exceptions where population pressure has also led to greater poverty in Europe (Eiras-Roel, 1987), and elsewhere (Geertz, 1968; Von Braun et al., 1991). Based on the observation that there are sparsely populated regions with high agricultural productivity and, conversely, highly populated regions with low productivity, other authors have suggested that high rural population density is not a prerequisite to intensification. Better access to markets, infrastructure and sound agricultural policies may also lead to intensification and better incomes (Pingali et al., 1987; Lele and Stones, 1989).

Recently, environmental considerations were added to the debate. Population and market pressures are usually associated with deforestation, land degradation and pollution, but this view is challenged by new evidence showing that population and market pressure can be associated with adoption of land conservation techniques and even with reforestation (Templeton and Scherr, 1996; Tiffen et al., 1994).

Difficulties in identifying clearly the causal factors of sustainable intensification stem from lack of suitable historical data, but also from the complexity and variety of situations in which agroecological conditions and market pressures confound the effects of population pressure (Smith et al., 1994; Reardon et al., 1991). One way to overcome these difficulties is to develop models that reproduce both biophysical processes and socio-economic behavior (Hengsdijk and Kruseman, 1993) and then to disentangle the factors and processes involved. For that purpose, we constructed a bio-economic model of a typical village located in the sub-humid region of Burkina Faso. Annual precipitation are ca. 800 mm, the distance to the closest city is 60 km and the current population density is 30 inhabitants per square kilometer. The main productions are cotton, maize, sorghum and livestock (Faure, 1991).

[1]We define intensification as an increase in labor or capital per unit of land. In most cases, it leads to higher yields per unit of land. Boserup defined intensification as a decrease in the fallow time, but her definition is consistent with the former because a decrease in fallow time usually leads to more labor or more inputs per hectare to control weeds and restore fertility.

2. Modeling method

The modeling approach here combines a linear programming model (LP) of economic behavior with a biophysical model of plant growth and the condition of the soil. The LP model is specified at the village level, and has as its objective the aggregate welfare of the community, measured as the discounted value of future monetary income and the opportunity cost of leisure, subject to constraints on the level, quality and distribution of key production factors (livestock numbers, land, capital, soil condition, etc.) and on market demand for foods. It is assumed that all resource allocation and production decisions are made on the basis of a three-year planning horizon.

The problem of land degradation is usually addressed at the farm level, but there are major limitations to this level of analysis. First, several farm level constraints such as labor, capital and risk are not strictly binding at the farm level and, because family relations are still strong in an African community, various exchange arrangements exist between individual farmers. Furthermore, many natural resources are managed at the community level in West Africa, and individual farmers have access to different landscape units for cropping, grazing or fuelwood collection. Natural degradation processes, such as erosion or deforestation, occur at a more aggregate level than the farm. Problems and solutions, therefore, include transhumant livestock and nutrient transfers across plot and farm boundaries. For these reasons, the village appears to be an appropriate level of analysis (Benoît-Cattin et al., 1991).

2.1. Population growth and migration

Birth and death rates are considered to be exogenous in the model because most demographers think that the lag time between the perception that more children are costly, and the decision to reduce the number of births may take as long as a generation (Stephen et al., 1991; Ruas and Benoît-Cattin, 1991). However, population density remains endogenous in the model because immigrants and emigrants can change the size of the population according to what is more profitable for the village. As hospitality is still a strong tradition in rural regions of Africa, immigrants are rarely denied access to remaining fallows. The model stops immigration, and even produces emigration when the population size reaches the point where another person consumes more than he/she produces. Temporary migration is permitted during each period of the year to capture off-farm opportunities for young males to work temporarily in urban regions or in coastal plantations at a given wage minus transport cost.

2.2. Production function

Simplified crop production functions are used in the LP model to represent farmers' yield expectations for cotton, corn, sorghum and irrigated rice. In the LP model, yields depend on the type and fertility of soil, the amount of input application (fertilizer, seeds and pesticides), and the quantity and quality of organic matter applied (manure, compost, corralling or crop residues). It is also assumed that insufficient soil depth and insufficient soil organic matter (SOM) depletes yields. If decreasing soil depth begins to affect root growths, it decreases yields. Also, when the SOM content reaches a threshold level, yields begin to decrease. Animal-drawn activities increase labor productivity and increase yields but they also increase SOM mineralization rates. Stone lines reduce erosion but require labor for their construction and maintenance. Stone lines also occupy some space within the field.

Parameters for these production functions were obtained from the results of the model EPIC (Erosion Productivity Impact Calculator) developed by Williams et al. (1987) which has been calibrated with real data from different sources (see Barbier, 1996). EPIC describes how land-use practices affect current crop yields and the condition of the soil, including land degradation, and how this, in turn, affects future crop yields. Plant yields may be affected by lack of water, inadequate temperature, soil compaction, loss of soil depth, lack of nutrients, aluminum toxicity and acidity. EPIC can also simulate the affects of alternative cropping patterns not yet tested in the region, such as new forage crops or different input amounts. EPIC was calibrated for cotton, maize and sorghum rotation in the study regions with data.

2.3. Production allocation

In the LP model, production of maize, sorghum/millet and rice may be stored, consumed by the population and livestock, or sold. The population is assumed to consume a fixed amount of grain throughout the year. Grain may be produced in the village or bought. The annual sale of grain is limited by market demand, which is exogenous to the model. There are three seasons per year in the model: the rainy season, the dry-and-cold season and the dry-and-hot season, with different activities each season. Grain production is consumed, sold or stored for the next season. The model seeks the best moment to sell or store grain depending on seasonal prices and family food needs. It also chooses which cereals are profitable to sell or to consume.

2.4. Cash constraint

In the same way that grains are managed, any cash not reinvested at the end of one period is saved for the next period. Monetary net income left at the end of the year also contributes to monetary consumption in the next year. The model chooses the optimal way to manage cash flow during each period in order to maximize the monetary net income over the planning horizon. In the model, there is a possibility of borrowing money from the bank for input purchases but have to be paid back with interest before the end of the year.

2.5. Risk aversion

The Target MOTAD (minimizing of total absolute deviation) method (Tauer, 1983) is used to simulate farmers' aversion toward risk, and this restricts the optimal solution to a relatively secure combination of activities. The variability of past yields and prices are captured in annual income equations, which require that income each year at least exceeds specified target income levels. The model is set up to maximize the utility function subject to achieving a satisfactory level of compliance with the target income. Variables measure any deviations in income below the target, and these deviations are collected and multiplied by the probabilities of the states of nature in which they occur to give the expected sum of the deviations below the target income. This value is then minimized for such level of expected income.

2.6. Natural resource management

There are five landscape units of different sizes and with different soil properties in the model: (1) the lowland humid area; (2) the area with flat, deep soils; (3) the area with medium soils; (4) the area with marginal soils on sloping land; and (5) the non-cultivable area. The natural resources whose condition/stock changes in the model are wood, forage, SOM, and soil depth. Natural resources such as wood, SOM or soil depth have a yearly balance in the model. For example, erosion reduces soil depth but there is also a small yearly amount of soil formation which deepens the soils. Cropping and grazing activities increase this basic level of erosion. If soil depth becomes insufficient, root problems occur and yields are affected. Then the model may adopt techniques such as rock lining to reduce erosion, but only if these techniques are profitable. Rock lining consumes little cash, but requires labor for installation and annual maintenance. Slopes may also be abandoned if yields are too adversely affected by erosion and if restoration activities are not cost-effective.

Similarly, SOM mineralization depletes the initial natural resource stock (Pieri, 1989). Urea application, plowing and erosion increase the rate of mineralization. When SOM quantities reach a minimum threshold, different agronomic problems occur and yields decrease. There are different thresholds for each crop, reflecting the relative resistance of some crops to soil structural disintegration. The model can choose between types and levels of manure to reduce the SOM deficit. These activities consume livestock manure or crop residues. Trees in the field (agroforestry) also contribute to SOM restoration.

At the beginning of the model period, each land unit has different volumes of wood stocks and different wood productivity levels. Wood volume is diminished when a plot is cleared or when wood is cut for human consumption. Wood consumption is a function of the population and livestock herd sizes.

2.7. Livestock and forage

There are four kinds of livestock in the village: transhumant cattle, intensive cattle, oxen and donkeys. Herd growth is determined by weight gain, calf numbers and the mortality rate. If it is economically attractive, new cattle can be bought. Herd size can also decrease through sales. Each adult equivalent livestock unit requires labor time, veterinary expenses and forage energy throughout the year. Forage grows in non-cultivable areas and in the fallow areas, but the model can also produce new forage crops (*Stylosanthes* and *Panicum*) on cultivated land. There is also some additional forage from trees and crop residues. Grains produced either by the village or purchased may be used as a feed supplement. The type and quantity of forage output differs by season. A part of the unused stock of forage is carried over from one season to the next. Crop residues are available during the two dry seasons but with decreasing quality over time.

2.8. Recursivity

The model is multiperiodic, but is limited by the duration of the assumed planning horizon (initially three years). Since we are interested in what will happen in 20 or 30 years, when the population is likely to have doubled or when prices could be very different, a recursive framework is used. Thus, the results of the first year of the planning horizon, in terms of population, money, livestock, wood, soil depth and SOM become the initial resources of a new model which is solved for the following year and beyond. In this way, the model was solved 40 times representing 40 future years. Thus, it is possible to provide results about the long-term consequences of alternative assumptions about policy, demographics, and market factors that are exogenous to the model.

Since yields and soil erosion outcomes are affected by stochastic weather events, the recursive framework also allows adjustments to be made between expected and actual outcomes each year. The multiperiod model is solved each year, and assumes that farmers hold expectations about the most likely outcomes for relevant random variables. Given the model's solution for the year t and its optimal cropping pattern and yields, and associated level of soil erosion, EPIC is then run to simulate random weather outcomes, and to generate 'actual' outcomes for yields and soil erosion that year. Their actual values are then used to adjust total production and income, and to recalibrate the closing stocks of cash and grain and the level of erosion that

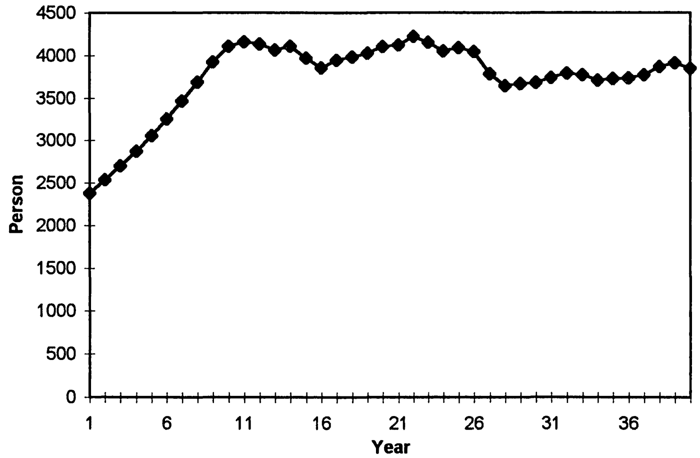

Fig. 1. Village population.

enter the constraint set for the multiperiod model in year $t+1$.

3. Results of the simulations

The model simulations run from 1990 to 2030. The exogenous variables are: population birth and death rates, market demand for surplus food, and prices of inputs and outputs. Unless otherwise stipulated, the market demand constraint on food is increased by 2% per year, and the prices of fertilizers, cotton, rice and cereals are increased by 40, 40, 40, and 10%, respectively, in 1994 to reflect the CFAF devaluation. We first report the baseline projection, then show how the projected development pathways change under alternative assumptions about key model parameters.

3.1. The base scenario

Population size doubles in the first decade, through birth and immigration, and stabilizes at a population density of 60 inhabitants per square kilometer (Fig. 1). This density appears to be the carrying capacity of the village under the current economic conditions. Higher or lower densities would lead to lower village income. Beyond this number, immigrants no longer settle in the village and even some native farmers migrate out. Fig. 2 shows the simulated use of land over time. With increasing population pressure, the fallow area (which is a combination of forest, bush, savanna and grassland) is initially reduced. The CFAF devaluation of 1994 (Year 4 in Fig. 2) reinforces this crop area expansion, particularly as the sharp increase in fertilizer prices relative to crop prices made intensification less profitable. Sorghum, which needs less fertilizer than maize, also substitutes for maize after the devaluation. However, this agricultural area expansion halts after a decade, because soil fertility loss eventually affects yields. The model responds to this problem by concentrating production on a smaller area, returning a fraction of the arable land to fallow, and composting more crop residues. Concerning crop allocation in the model[2], cotton disappears in the long run because maize is no longer constrained by market demand and because cotton contributes less to SOM restoration than cereals.[3] Sorghum is progressively replaced by maize after Year 10 because maize responds better than sorghum to animal-drawn plowing which increases over time in the model, and because the market demand for cereal increases. The area of maize, however, is limited to the best soils. Sorghum, which is more resistant to low-soil-fertility conditions, remains a profitable crop on marginal soils. The model also invests in small irrigation

[2]The maximum area for cotton is constrained not to exceed the 1990 level, because production is controlled by quotas by the parastatal.

[3]In reality, if farmers were to reduce the cotton area in this way, the cotton parastatal would, most likely, react by increasing the price of cotton. This case already occurred in Burkina Faso in the eighties.

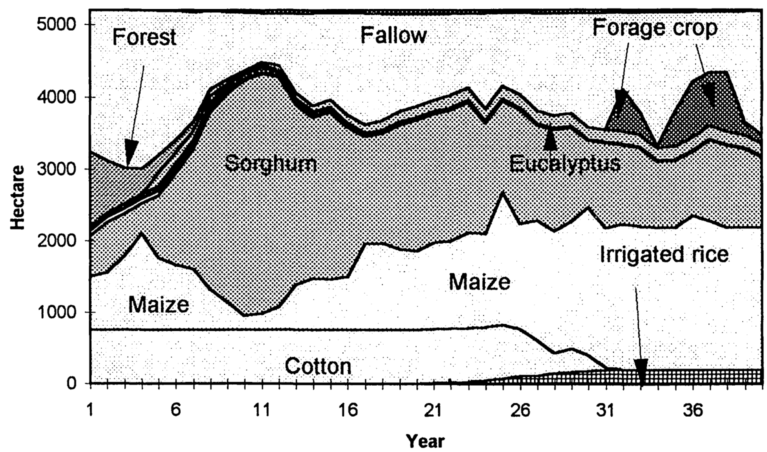

Fig. 2. Land use in the village.

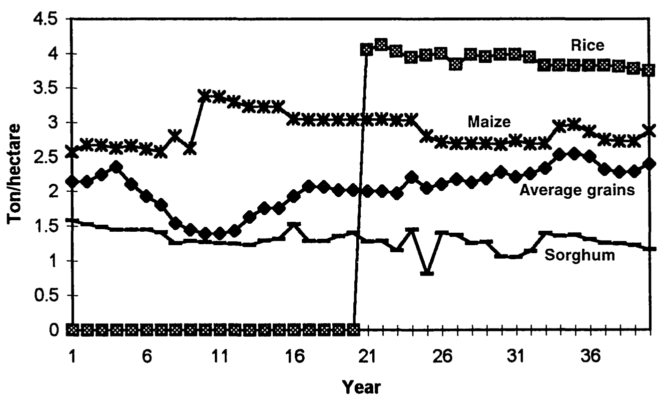

Fig. 3. Cereal yields.

schemes in the lowland areas in order to produce irrigated rice. After three decades, the model replaces grassland fallow with forage crops on several hundred hectares. This forage crop is expensive because the plots have to be fenced to avoid grazing by itinerant animals. With this crop/forage rotation, the farming system reaches a stable phase comparable to the 'regulated ley system' described by Ruthenberg (1980) in the semi-arid regions of Africa.[4]

[4]The adoption of a regulated ley system requires fences which, in turn, requires an important social change. The current land tenure system which is communal, would have to move toward a private system unless the community could successfully organize to collectively develop a fencing system. In reality, this shift could take more time than in the model, making the achievement of a sustainable system even more difficult.

Fig. 3 shows that crop yield first decrease after the devaluation (Year 4) because fertilizer prices have been increased. An interesting paradox is also shown after Year 10. While the yields of each grain crop (maize, sorghum and rice) show a long-term decline due to land degradation, the average yield of grains increases over time. The reason is the progressive substitution of less productive by the more productive grain crops.

Values of shadow prices from the model help clarify the discussion about the linkages between population size, market opportunities and productivity.[5] Fig. 4

[5]The shadow price of a factor is the amount by which global net income will increase if one unit of this factor is added. If the factor is not limiting, the shadow price is equal to zero. However, as a factor becomes more scarce, its shadow price increases.

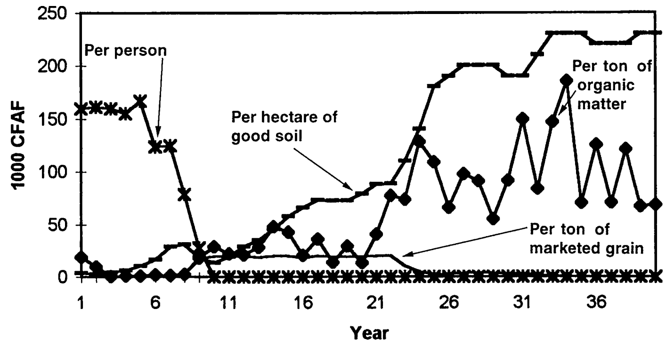

Fig. 4. Shadow prices of different factors of production.

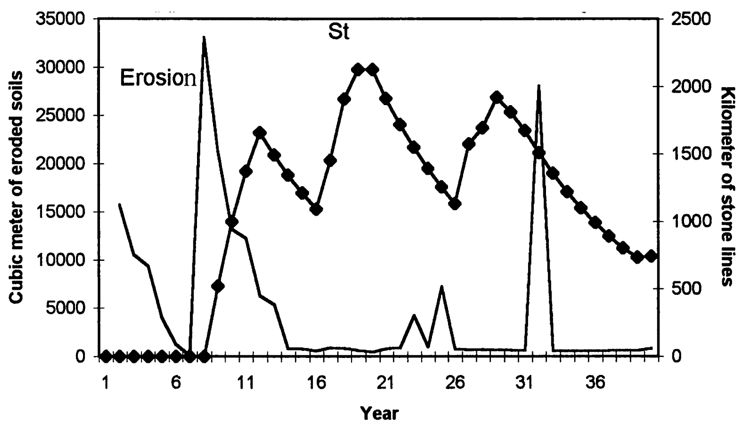

Fig. 5. Erosion and erosion control practices.

illustrates the 'induced innovation' theory by showing how the price of labor, which declines over time as labor becomes more abundant, is matched by an increase in the shadow price of land over time as this becomes the scarce resource.[6] The shadow price on the grain market constraint is also shown in Fig. 4. This is binding in years 10 to 23, and hence contributes to the slow rise in the value of land during this period. This means that agriculture in this region could be more productive and profitable, if it were better connected to food markets. Fig. 4 also shows that as land becomes more valuable so does SOM. The growing scarcity of organic matter should encourage greater development and adoption of new conservation techniques.

[6]When the dual value of a person reaches zero, immigration stops and when the value becomes negative, out migration begins.

Transhumant livestock herders have access to fewer pastures in the village over time during the dry season, leading to a sharp decline in their herd size. This herd is replaced by farm livestock and oxen, which are mainly fed with crop residues and, later, with cultivated forage. Animal-drawn mechanization is adopted extensively and the whole cultivated area is plowed by animal drawn plows over a period of 30 years. As transport of commodities, compost and wood increases over time, the model also invests in carts.

The cultivation of marginal land causes greater soil erosion than cultivation of the good and the medium soils. The model reacts three times during the 40 simulated years, firstly by building stone lines and, then, secondly by restoring these lines (Fig. 5). The model reacts only when erosion starts to have an economic impact. When marginal land is abandoned, farmers no longer maintain the stone lines, which are

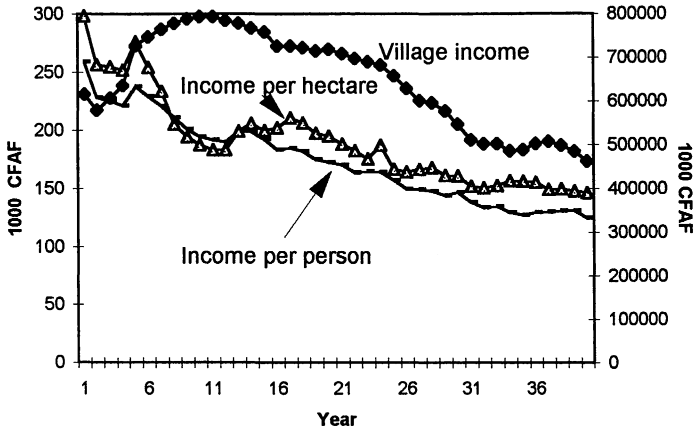

Fig. 6. Village income.

then progressively dismantled. The model abandons marginal land because of SOM shortages, not because of soil loss problem.

Population pressure first leads to deforestation, but around the Year 2000, because of fuelwood scarcity and higher erosion, *Eucalyptus* are planted. Other tree species included in the model are better for soil fertility, but they grow too slowly to be profitable for adoption by the model.

One of the most important results of these simulations is that population-driven intensification does not lead to higher incomes (Fig. 6). Despite higher yields, monetary income per hectare decreases over time because the costs of intensification and land conservation techniques surpass the gain in yields. Per capita net income declines at a similar rate than income per hectare, because longer harvest periods and the adoption of labor intensive conservation practices require more workers per hectare of crop. These results are not encouraging for the Boserupian-induced innovation theory. It appears that under the sub-humid ecological conditions, which are characterized by a high level of SOM oxidation, the fallow system was more profitable than permanent agriculture. As the fallow system disappears because of growing population pressure, the options for the future will be to find more profitable techniques of soil conservation or to let farmers migrate to less populated areas.

3.2. *Scenarios with different population assumptions*

Additional simulations were run to examine the induced innovation theory, which predicts how farmers adapt to population and market pressure. We first simulated changes in population by varying possibilities of out migration. In Fig. 7, the base scenario (where the population can immigrate or emigrate freely) is compared to two other scenarios. In the first, the population is not allowed to emigrate, leading to continuous population growth. This could be the case in regions where alternatives for migration are limited or are very costly. The second scenario shows what is likely to occur if population does not increase at all; as for example, in regions with good access to employment in nearby towns. The results show that population growth leads to declining per-capita net incomes. In the scenario without emigration possibilities, the model is no longer feasible (this situation occurs after the 40th year) because the labor-intensive techniques available to the model are not sufficient to generate minimum income needs. In the absence of population growth, per-capita income remains constant over time because farmers can keep their fallow system. When population increases, farmers have to find other solutions to the soil fertility problem, and these solutions are more expensive than the fallow system.

3.3. *Results for alternative soil fertility assumptions*

On removing the soil fertility constraint imposed in the baseline scenario, the results become very different (Fig. 8). Village incomes are initially similar in the two scenarios as long as the population can convert forest and fallow into cropland. But village income in

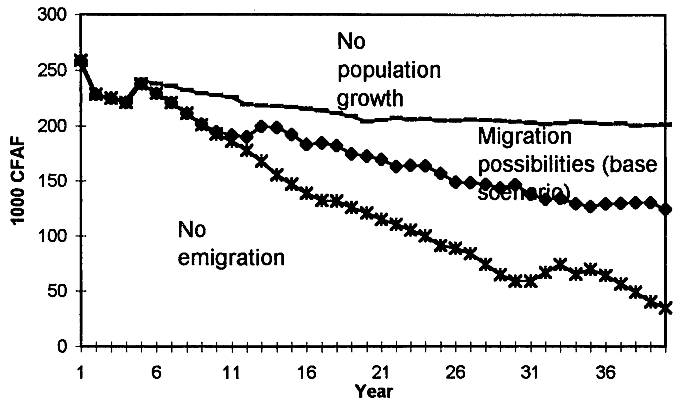

Fig. 7. Per capita net income (alternative population scenarios).

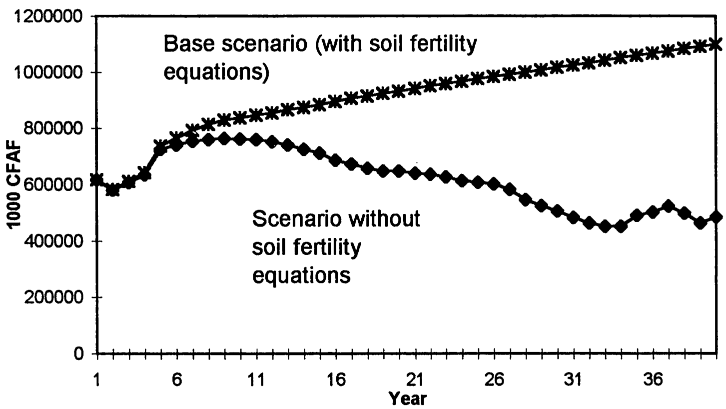

Fig. 8. Village income (scenarios with soil fertility constraints).

the simulation without a soil fertility constraint increases progressively over time, whereas in the scenario with soil fertility constraints, problems begin to appear in Year 5 as the area in fallow on good soils becomes scarce. The shortage of SOM affects yields and farmers have to invest their time and money in various regeneration practices. Over time, the cost of land degradation increases. An equilibrium is reached after three decades when the population size stabilizes. The difference in village income between these two trajectories constitutes the cost of land degradation (and restoration) over time. This cost consists of the loss in yield, the loss in cropped area and increasing soil conservation practices (compost, lime, legume crops) which have a cash cost and require additional labor. Divided by the number of hectares this cost reaches US$140 per year by the Year 2020, which represents more than 50% of the net income per hectare at this time.

4. Conclusion

The model results address several of the controversial issues highlighted earlier in the debate about agricultural growth and intensification. The results of the model show that, if land is still available, farmers actually prefer extensification to intensification, even if this land is marginal and produces lower yields. This point has been widely observed in West Africa where farmers still have a choice between extensive techniques on a large area or intensive techniques on a small area; they adopt more extensive techniques not because they are not able to use intensive techniques but because extensive techniques have a higher return to labor. An additional explanation suggested by the model's results is that, under population pressure, SOM and soil nutrients become scarce. Thus, the most effective way to maintain the productivity per worker is to abandon the overused area and to clear and cultivate new land. This is currently the case in most West African countries where populations move from highly populated areas to less populated areas. But if the population is constrained to stay in the area, thus increasing the population density, the economic results deteriorate and lead to a situation similar to that in Burundi, Rwanda or Ethiopia where farming systems are intensified but welfare deteriorates because the existing technologies and limited markets for agricultural products are not sufficient to maintain per-capita incomes. Another interesting outcome of the modeling exercise is that intensification can occur even when the rural population is no longer growing. Yields increase without population growth because of expansion in the market demand for food. In this case, the factor of intensification is the market growth for food.

The proposed strategy for West Africa over the next few decades is to promote the extensive use of the remaining unused land areas. Instead of trying to intensify agriculture in already highly populated and degraded areas, policy makers should promote migration toward the less populated areas by improving infrastructure in those areas. Under these conditions, farmers will be able to crop larger farms on a sustainable basis and contribute more positively to the agricultural growth of their countries.

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