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DYNAMIC ANALYSIS OF SOIL FERTILITY IMPROVEMENT: A BIOECONOMIC MODEL FOR SENEGAL

By

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BACKGROUND: Soil fertility decline threatens agricultural productivity growth and food security in Sub-Saharan Africa (SSA), especially in agroecologically fragile regions like the Sahel. At present, low-external-input farming practices are mining SSA's nutrient-poor soils, which are subjected to continuous cropping and wind and water erosion. Despite evidence that inorganic fertilizers can contribute substantially to sustainable land use and crop production (Mudahar 1986; Padwick 1983; Larson and Frisvold 1996; Shapiro and Sanders 1998), farmers in SSA use fertilizers sparsely—9 to 10 kg/ha, vs. 54 kg/ha in Latin America, and 80 kg/ha in South Asia. Moreover, governments and donors are currently reluctant to invest in programs to promote fertilizer use and other soil investments, particularly in difficult production environments.

Most empirical studies on fertilizer uptake in SSA focus on the effects of fertilizer use on current production and returns to land, paying little attention to the effects on future production flows due to maintained or improved land quality. Research results summarized in this brief illustrate that a failure to account for the dynamic effects of soil fertility investments when making decisions about government policies and resource allocations may lead to missed opportunities for stimulating agricultural productivity growth, increasing rural incomes, and encouraging the adoption of sustainable agricultural production practices. Taking these dynamic effects into account, however, requires deciphering how they are mediated through the effect of policy and market signals on the farmer's choice of production activity and technology.

OBJECTIVES: This paper reports on a bioeconomic modeling exercise that analyzes the dynamic effects of fertilizer use and employs the results to answer fertilizer policy questions (Diagana 1999). Using data from the Senegalese Peanut Basin, the model (1) simulates yield and soil nutrient impacts of selected cropping practices, and (2) integrates the simulated yield and soil nutrient outcomes into a multi-period linear programming model (LPM) that takes into account current and future input/output prices, and farm household resources and objectives. The model results are used to address two important questions facing Senegalese policymakers:

1. Are recent price, credit and capital transfer policies in Senegal likely to encourage farmers to increase fertilizer use over time?

2. Will the optimal cropping practices identified by the LPM have a positive impact on the soil macro-nutrient stocks of N and P as well as on farm income?

THE PRODUCTION AND POLICY ENVIRONMENT: This study focuses on the central and southern Peanut Basin where farmers rotate their land on an annual basis from millet (a food crop) to peanuts (both a food and an export crop). The climate in the Peanut Basin is Sahelian with a single 4-6 month rainy season averaging 400-500 mm and 700 mm in the central and southern zones, respectively. The majority of soils are deficient in nutrients, particularly phosphorus. Typical farms in both zones have similar amounts of labor (4 man-equivalents) and agricultural equipment (one horse, seeder, and hoe). These resources are applied to a larger cultivated area in the south (11 ha vs. 8 ha in the center), and are associated with more total income per adult equivalent (72,000 vs. 56,000 CFA franc [about $102 vs. $80] in the center). The share of nonfarm income in total income is also slightly larger in the south (29% vs. 24%).

Six production options available to farmers are examined in the biophysical and LP models (for specific quantities of inputs see notes to Table 1):

1. The *traditional* option is most common, characterized by use of recommended seeding densities and no fertilizer.
2. The *high density* peanut seeding option uses double the seed per hectare but no fertilizer (an attempt to diminish yield losses due to poor soil fertility, seed quality, and lack of fertilizer).
3. The *semi-intensive rotation* uses relatively low doses of fertilizer on both crops.
4. The *intensive peanut* option uses high rates of fertilizer on peanuts and none on millet.
5. The *intensive rotation* uses high fertilizer application rates on both crops.
6. *Plus P*, a one-time basal dose of phosphates followed by the *intensive rotation* option.

Table 1. Simulated Long-term Average Yield and Soil Nutrient Effects of Selected Millet-Peanut Cropping Practices in the Senegalese Peanut Basin: 1977-96 (kg/ha/year)

	Traditional a/		High density peanut seed b/		Semi-intensive rotation c/		Intensive peanut d/		Intensive rotation e/		Plus P f/	
	millet	peanut	millet	peanut	millet	peanut	millet	peanut	millet	peanut	millet	peanut
Center												
Crop yield	306	332	301	352	793	950	545	849	545	849	853	1015
Labile P g/	*-1.5*		*-1.5*		*2.6*		*.9*		*.9*		*2.6*	
Inorganic active P	-2.5		-.2.5		-1.8		-2		-2		-1.7	
Organic active P	-3.3		-3.3		-3		-3.1		-3.1		-3	
Inorganic N	*3.5*		*3.7*		*14.9*		*4.4*		*4.4*		*14.8*	
Organic N	-46		-44.6		-31.5		-35.2		-35.2		-30.5	
South												
Crop yield	294	533	290	554	839	1556	560	1370	560	1370	902	1652
Labile P	*-1.5*		*-1.7*		*1*		*-.15*		*-.15*		*1.7*	
Inorganic active P	-2.5		-2.2		-1.9		-2.1		-2.1		-1.8	
Organic active P	-4		-4		-3.6		-3.7		-3.7		-3.6	
Inorganic N	*3.2*		*3.3*		*7.6*		*2.7*		*2.7*		*7.6*	
Organic N	-90		-88		-77		-80		-80		-76	

Notes: **a/** 60 kg/ha peanut seed, no fertilizer; **b/** 120 kg/ha peanut seed, no fertilizer; **c/** 60 kg/ha peanut seed, 75 kg/ha NPK 6-20-10 on peanut; 150 kg/ha NPK 14-7-7 and 100 kg/ha urea on millet; **d/** 60 kg/ha peanut seed, 150 kg/ha NPK 6-20-10 on peanut; **e/** same as d/ plus 200 kg/ha NPK 14-7-7 and 200 kg/ha urea on millet; **f/** same as e/ plus one time dose of 200 kg/ha of both tri-calcium phosphate and phosphogypsum; **g/** nutrient pools in *italics* represent plant-available nutrients and figures for nutrients are average annual changes in nutrient stocks (kg per ha).

The *Plus P* option was introduced by the GOS (Government of Senegal) in 1997/98 as a four-year program to distribute locally produced phosphate products free. Two other key agricultural policy changes were implemented at that time: (a) a 14% increase in the producer price of peanuts; and (b) easing of agricultural credit constraints through a reduction in the down-payment (to 10% of loan value) and in the annual interest rate (from 12 to 7.5%).

SIMULATED BIOPHYSICAL OUTCOMES: Table 1 summarizes the simulation results on yields and indicators of soil nutrient content following 20 years of millet/peanut rotations for the six production options.

Yields. Moving from *traditional* methods to *high density* seeding adds very little to average peanut yields over time (though farmers believe it has short-run yield benefits). Incremental increases in fertilizer intensity are associated with increases in average annual yields for the remaining four production options. The *semi-intensive rotation* has higher yields than the *traditional* and the *high density* options, but is surpassed by the *intensive peanut* option which not only increases average annual peanut yields but also exhibits spillover effects reflected in millet yields that surpass those of the *semi-intensive rotation*. The *Plus P* option demonstrates the highest overall yields for both peanuts and millet.

Soil Impacts. P nutrients inhabit soils in two "pools": (1) the "plant-available" or labile pool which is immediately available for plant uptake, and (2) the "active" or "capital" pool (containing both organic and inorganic P) which is not directly available to plants but replenishes the labile P taken up by plants. The biophysical model predicts that "plant-available" P will be depleted when no fertilizer is used, and replenished with fertilizer use, with the *intensive rotation* and *Plus P* options showing the highest levels of replenishment. The active pool (organic and inorganic P combined) is depleted under all production scenarios, but the overall rate of depletion is lowest for the *intensive rotation* and the *Plus P* option.

The N pools have "plant-available" N coming from inorganic N, with the organic N serving to replenish the inorganic pool over time. The biophysical model predicts that inorganic N will be replenished under all practices, but the net accumulation is much greater when more N is externally applied. This is an encouraging result, since N is more difficult to build up than P and tends to disappear through leaching and volatilization more rapidly than P. By contrast, the stock of organic N goes down under all practices, with the smallest decline for the *intensive rotation* and *Plus P* options. Stores of organic N are even more difficult to build up than inorganic N, particularly if there is no application of organic fertilizers such as manure or crop residues.

In sum, the biophysical model results show that the *intensive rotation* and the *Plus P* production options have the greatest potential to improve soil nutrient content and yields.

LINEAR PROGRAMMING MODEL: ACTIVITIES, CONSTRAINTS, AND POLICY SCENARIOS: The LPM maximizes net returns to crop and off-farm activities subject to a set of constraints, discounted over five two-year periods, each representing a complete millet/peanut rotation. Borrowing is allowed for purchases of production inputs and for grain to cover food needs. End-of-period cash reserves are transferred to the next period.

Per-period constraints are placed on availability of human and animal labor, cultivated land, and soil nutrients. Labor is supplied entirely from the household for both on- and off-farm activities during different seasons of the year (i.e., there is no hiring of outside labor). Constraints on starting capital, available credit, and the amount of nonfarm income (restricted by limited opportunities in the study zones) reflect empirical observations in the study zones.

For food security, grain consumption requirements must be satisfied by own production and/or purchases. Because the biophysical modeling of crop production already captures most production risk, the model uses a simple "safety-first" approach in which the food security objective must be achieved under three states of nature ("bad," "average" and "good"), defined for each crop and level of fertilization based on the mean and standard deviation of yields simulated in the biophysical model.

Other (nonfood) living expenditures vary positively with earned income. This makes total consumption expenditures endogenous to farm income, consistent with economic theory.

The LPM was run using four policy scenarios where the ease of access to fertilizer ranges from very favorable (scenario A) to very unfavorable (scenario D). Details of each policy scenario are presented below in conjunction with the model results.

LINEAR PROGRAMMING RESULTS:

Policy A: *Free phosphate program, access to credit and nonfarm activities.* Optimal land allocation is a combination of three production options. In the center, 6 of 8 ha are put in *intensive peanuts* during the first period then shifted towards the *Plus P* option (4.8 ha) and the *semi-intensive* options (1.8 ha) during the remaining four periods. Similarly, in the south, farmers start with most land (5.8 ha) in the *intensive peanuts*, and then shift towards the *semi-intensive* option (4.3 ha) and the *Plus P* option (3.6 ha), leaving only .5 ha to *peanut intensification* from the second to the last periods.

Policy B: *Access to credit and nonfarm activities but no phosphate program.* Results are similar across zones. During the first period in both zones, most land goes into *intensive peanuts* (4.0 and 5.8 ha, respectively), but shifts in the second through fifth periods to a more balanced fertilization of both peanut and millet using a combination of the *intensive rotation* (4.8 ha in the center and 3.5 in the south) and the *semi-intensive rotation* (2.8 and 4.4 ha in center and south).

Policy C: *Phosphate program and credit available, but no nonfarm income.* Restoring the phosphate program but removing the nonfarm activity (forcing all financial resources to come from farm income and credit) results in optimal plans that are quite similar to those of scenario A. This stems from the fact that in A, farm activities do not use all available labor. Thus, removing nonfarm activities does not change the optimal land allocation, but only decreases the level of cash income available, thereby increasing the amount of credit needed. Overall, the most binding constraint is that of initial capital, which conditions the path (based on optimal cropping practices) taken in later periods.

Policy D: *No credit, nonfarm income, or phosphate program*. This scenario is relevant for the many low-resource households who do not have access to credit and nonfarm income. With initial cash as the only source of capital, grain consumption needs could not be met. Removing the consumption constraint left most land unused in the last period because not enough income is carried over from previous periods to finance production. Surprisingly, despite the capital constraint, traditional (no fertilizer) cropping practices do not enter the optimal solution, evidently a result of their negative impact on soil nutrient balances and significantly lower profitability compared to fertilizer-using activities. Millet production meets only 2% to 36% of food grain needs in the center and 11% to 67% in the south. The results raise questions about the viability of low-resource households. Perhaps the best option for assisting them would be to develop full-time, off-farm employment opportunities.

Scenario A (credit, nonfarm income, phosphate program) yields the highest discounted net income level after ten years, followed by B (no phosphate program) and C (phosphate program and credit but no nonfarm income) (Table 2). These income levels are always higher in the south than in the center, because of higher yields and more cultivated area.

Table 2. Discounted Net Income and Soil Nutrient Levels after Ten Years of Using Optimal Long-term Cropping Plans under Different Policy Scenarios

Policy ➜ a/	A: credit, NF, PP		B: credit, NF, no PP		C: credit and PP		D: no credit, no NF b/	
Zones ➜	Center	South	Center	South	Center	South	Center	South
Objective function:								
('000 FCFA)	259	685	177	573	179	493	24	183
Nutrients (kg/ha) c/								
Labile P change	18	5	16	3.3	18	5	1.7	-.5
Inorganic P_a change	-19	-15	-19	-15	-19	-15	-3.5	-7
Organic P_a change	-30	-28	-30	-27	-30	-28	-5.5	-12
Inorganic N change	109	45	116	43	109	45	7.8	9
Organic N change	-327	-597	-333	-569	-327	-602	-62	-250

Notes: **a/** NF = nonfarm activities available; PP = phosphate program; **b/** Results for this scenario are obtained when food security requirements are dropped in both zones; **c/** Labile P, Inorganic P_a, Organic P_a (active pool), Inorganic N and Organic N change are total changes in the stocks of nutrients in different pools (labile and active for P, inorganic and organic for N) at the end of the 10-year period in kg/ha.

Thus, the answer to our first policy question appears to be "yes"—the policy options introduced by the GOS in connection with the phosphate program should have a positive impact on farmers' willingness to adopt more intensive practices over time. Easing the capital constraint through access to credit and nonfarm incomes, especially at the initial stage, will increase the incentives for farmers to intensify.

The second question addressed by this study concerns the potential impact on soil fertility of the optimal cropping plans under the various policy scenarios. In all cases but one (scenario D, south zone), the modeling predicts replenishment or a build-up of the two plant-available soil nutrient stocks after ten years. Labile P and inorganic N are being replenished in both zones, the highest build-up being reached under the A and C scenarios. On the contrary, the stocks of non-directly-available nutrients (inorganic and organic P in the active pool, and organic N) are depleted under all scenarios. This stems from the flows between the different nutrient pools and from the mineralization process that releases inorganic forms of these nutrients that the crop plant can use.

The LP model results also provide a number of insights that cut across the different scenarios:

1. Practices which use no fertilizer are never optimal, in any zone, scenario, or period. This result contrasts sharply with those of earlier studies in Senegal (e.g., Diagana and Kelly 1996), which did not take into account long-run negative changes in productivity associated with the use of low-external-input techniques.

2. Sensitivity analyses showed that easing capital constraints (reducing credit down payment requirements from 20% to 12.5%), leads to earlier and greater investment in capital-demanding cropping practices. While not surprising, this shows how credit can stimulate adoption of more profitable technology, generating higher net incomes which can then be used in place of credit to finance future input acquisition.

CONCLUSIONS:

1. When evaluated in a dynamic framework that takes into account yield impacts over a 20-year period, fertilizer use increased farm incomes in the Peanut Basin while simultaneously improving the nutrient content of soils.

2. This implies that financial and economic analyses which do not take into account the long-term impacts of fertilizer use or non-use may severely underestimate the returns to soil fertility investments, particularly in difficult production environments such as the Sahel.

3. Policies that reduce the capital constraint stimulate farmers to adopt fertilizer sooner and in larger quantities, thereby increasing incomes and improving the nutrient content of soils more rapidly.

4. Costly government programs such as free rock phosphate distribution can have a very significant impact on yields, farm incomes and soil nutrient content *if properly implemented*. This implies timely distribution of P products, correct incorporation of the P in the soil by farmers, and concomitant application of recommended NPK fertilizers; these conditions were not met during the first two years of the program (Sonko 1999).

5. Further research is needed to:

   a) evaluate the costs and benefits of a phosphate program versus programs to reduce capital constraints; and

   b) compare the impacts of fertilizer practices examined here with (1) practices that rely entirely on organic inputs, and (2) practices that combine organic and inorganic fertilizers.

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