Soil Degradation, Technical Change and Government Policies in Southern Mali

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Abstract

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Introduction

This study uses new modeling tools to address the sustainability of technical change in a key agroecological region of West Africa. We link a detailed biophysical model of crop growth to a dynamic model of household behavior in order to simulate farmers' production decisions and their soil resource consequences over time.

The results of the simulation indicate that new farming methods in the Sudano-Guinean region of Southern Mali, where rapid intensification has disrupted traditional agro-pastoral systems, are far more sustainable than many observers have argued--and that additional productivity growth can be sustained with supportive government policies. Key interventions include continued varietal research, maintaining low marketing costs, and imposing pasture taxes to account for the cost of grazing in common areas.

Agricultural sustainability and technical change

A widespread call for more sustainable resource use has shaken the global agricultural research agenda, and is often seen to be in conflict with the adoption of yield-increasing innovations (Lee 1996). However, limited empirical evidence about the sustainability of new techniques is available because their long-run effects have not yet been observed (Lal 1994, GREAN 1995).

Many criticisms of agricultural intensification arise from predictions of a decline in the stock of a specific resource (van der Pol 1992; Hoag and Skold 1996), or in a specific measure of productivity (Lynam and Herdt 1992). The sustainability of income or wealth may be a more relevant criterion (Solow 1986; Norgaard 1991; Horwath and Norgaard 1992), but is much harder to observe, particularly where production techniques can change over time in response to changing circumstances.

Numerous researchers have documented an evolutionary sequence of agricultural techniques, notably the pioneering studies of Boserup (1965), Ruthenberg (1980), Pingali, Bigot and Binswanger (1987) and McIntire, Bourzat and Pingali (1992). Clearly, a sequence of techniques may be sustainable even if each component is not and research can play a key role in providing a sequence of technical interventions from which farmers can draw when economic conditions permit. Other government interventions may also be important in ensuring system sustainability, including policies that influence relative product prices or the use of common-property resources.

Viewing agricultural systems as an evolving sequence of choices is widely seen to make natural resource preservation particularly important, because future technical changes may be dependent upon stock levels (Clarke 1992; Walker and Young 1986; Taylor and Young 1985; Collins and Hotley 1983, Clark and Furtan 1983). But the opposite conclusion is also possible, if innovations can provide substitutes for the depletable resource such as assimilable soil nitrogen and inorganic fertilizer compounds. Clearly, the sustainability of any given system is an empirical question--requiring an empirical model to permit the simulation of production and consumption over time.

An example from Southern Mali

Arguments over sustainability and productivity have particular importance in Africa, where most people still depend on agriculture for their income, and where rapid population growth is putting extreme stress on the natural resource base. Influential studies have argued that resource depletion could lead to sharp declines in productivity, particularly in the areas of greatest agricultural intensification--so that a turn away from the pursuit of higher yields is needed soon. Southern Mali has been a particular focus of this argument, with its exceptionally rapid growth in production and input use. (See van der Pol 1992; also Berckmoes, Jager and Koné 1990; Coulibaly, Niang and van der Pol 1993; Dureau, Traoré and Ballo 1994; and Pieri 1989).

To investigate the sustainability of the agro-pastoral system in Southern Mali under various possible future scenarios, we construct an empirical model of farmer decision making to estimate how production is likely to evolve over time. A scenario with no new technologies is contrasted with one that includes the possibility of adopting various new techniques, including improved cereal varieties, greater use of inorganic fertilizer, and more intensive management of livestock and crop residues--notably the use of covered corrals (*parcs ameliorés*) to confine animals and mix their wastes with grain stalks, producing larger quantities of higher quality organic fertilizer than is possible with traditional methods of grazing field stubble and open-access bush areas. (For details of the *parc amelioré* system, see Bosma, Kamara and Sanogo 1994).

The adoption and long-run impact of these techniques is examined under continuation of current economic conditions, and then in a variety of alternative market environments. In this paper we focus on the results when recent policy reforms continue to reduce farm-to-market transactions costs, and also consider the role of pasture taxes in offsetting the externalities associated with grazing on common property. Other results, as well as more detail on the data and procedures used in developing the model, are provided in Dalton.

The empirical model

Our analysis extends the farm household modeling tradition of Singh, Squire and Strauss (1986) to include farmers' intertemporal investment or resource-depletion decisions, and to use a biophysical simulation model for the purpose of linking soil productivity to cultivation history. The objective function is,

$$\underset{c_t}{Maximize}\ U(\cdot) = \sum_{t=0}^{T} \beta_t u(c_t) + \beta_T W_T, \quad \beta \in \{0,1\} \tag{1}$$

as the producer aims to choose consumption bundles in each time period (c_t) that maximize welfare [$U(\cdot)$], which is each year's utility of consumption [$u(c_t)$] summed and discounted (by β_t) over time, plus discounted terminal wealth (W_T) at the end of the time horizon. In the specific simulations presented below, the annual utility function is linear and the time horizon is 15 years.

Consumption levels are constrained by an expenditure constraint, which is each year's net profits from crop sales, minus savings and investments (notably in livestock operations, including the construction and capital cost of corrals as well as animals and equipment), product marketing costs (including particularly the marketing margin between buying and selling prices for foodgrains), and taxes paid. Livestock operations include several integer variables (equipment sets and the corrals themselves), but the herd size is modeled as a continuous number of tropical livestock units (TLU, of 250 kg liveweight) of adult oxen, donkeys, and goats. All market prices are exogenously determined, although the household's shadow value of food grains can switch from their buying prices to selling prices, or remain in between when the household is self-sufficient.

Crop production activities include a total of 207 possible techniques, each embedded in a multi-year rotation, and subject to constraints on the availability of resources (three types of land, three types of labor, and two types of animal traction sets, across ten time periods), as well as the physical attributes of the soil. To capture soil degradation effects in the context of stochastic rainfall, we estimate a biophysical function for land productivity (*yield*) under each crop (*y*) and technique (*z*),

$$yield_z^y = e^{\gamma \cdot time + \lambda \cdot rainfall} \quad \textbf{(2)}$$

in which annual yield is based on the number of years that technique has been used (*time*), and that season's weather (*rainfall*), using a logarithmic form to capture the nonlinear nature of this relationship. The function's parameters (γ, λ) are estimated from the results of a crop-growth simulation model, through an OLS regression of the logarithm of crop yield under each technique, against total rainfall in that year and the number of previous years that technique had been in continuous use. The crop-growth model used is a version of the Environmental Policy Integrated Climate model (see EPIC 1996), calibrated to local conditions using the results of long term trials, soil surveys, climate data, and interviews with researchers and farmers. Details of the data, procedures and results are documented in Dalton.

The use of a detailed crop-growth model such as EPIC is key to capturing the complex relationship between climate, soil, and plant performance. For example, EPIC uses daily time steps to simulate the flow of moisture and nutrients through the soil and the plant, and the data used in our simulations include 45 years of day-by-day rainfall and temperature observations. Each year's climate is a random draw from that universe of possible weather sequences.

In estimating our reduced-form yield function (equation 2 above) we use the year's total annual rainfall as a proxy for the entire sequence of daily stresses experienced--so that the actual incidence of mid-season dry spells and periods of high temperature or evaporation has a major influence on yields and nutrient uptake. EPIC also captures the influence of crop characteristics and cultivation techniques on nutrient leaching and surface runoff, and the feedback of these factors on crop performance over time.

The use of a biophysical model to estimate yield functions for each technique not only provides a better empirical foundation for estimating soil degradation effects, it also provides a better foundation for *ex-ante* estimates of the payoff from complex innovations such as livestock corrals. Corrals provide a larger quantity of higher-quality organic fertilizer, helping bring nutrients back to the field but also improving soil structure and moisture retention. Linking these effects to the full household model identifies their economic value--in the context of intertemporal welfare--with the optimal timing and extent of corral use linked to soil degradation and farmers' other savings and investment decisions.

Model Results

The model described above is relatively large: written using the General Algebraic Modeling System (GAMS), it was solved on a Pentium personal computer using the XA solver in slightly over two hours--and additional computing time was required to obtain yield parameters for each technique in each year with the EPIC model. Numerous experiments were simulated, as detailed in Dalton.

For this paper we present only the baseline results which are comparable to survey observations for the purpose of model validation (Table 1 and Table 2), followed by a graphical presentation of the intensification process over time under the most likely future scenario (Figure 1).

TABLE 1: Observed and predicted land use and output for 1993-94 and 1994-95

	1993-94				1994-95			
	Land Allocation (ha)		Output (mt)		Land Allocation (ha)		Output (mt)	
	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.	Pred.
Cotton	4.45	5.95	5.55	8.27	5.86	6.33	6.29	8.81
Sorghum	6.29	6.03	7.05	6.56	5.98	6.33	6.03	6.87
Millet	4.00	2.71	4.48	2.74	3.62	3.41	3.06	3.41
Maize	1.45	1.50	2.36	2.53	1.28	1.50	1.69	2.53
Groundnuts	0.83	1.68	0.54	0.82	1.88	1.42	1.19	0.70

Note: Table shows results for highly capitalized farms only. Rice production is not modeled and accounts for 2.5% or 0.47 of a hectare in the observed data in 1994-95 and slightly less in the preceding year.

Source: Observed values are the survey-average data from Giraudy *et al.*; predicted values are the authors' mathematical programming model results.

Despite the slight differences in crop allocation shown in Table 1, total quantities of input use are very close to observed quantities as shown in Table 2.

TABLE 2: Observed and predicted input use for 1993-94 and 1994-95 (kg)

	1993-94		1994-95	
	Observed	Predicted	Observed	Predicted
Cotton Compound	609	633	568	595
Cereal Compound	88	75	74	77
Urea	372	392	343	375
Organic Fertilizer	not available	9,390	not available	9,385

Source: Survey observations are from Giraudy *et al.*; predicted values are from the authors' mathematical programming model results.

Continuing the baseline case over the model's full 15-year time horizon, there is a small degree of nutrient mining to which the household's optimal response is to shift crop allocation towards less nutrient demanding small grains and away from nutrient intensive maize. Under continued baseline conditions the household remains self-sufficient in food grains, as the marketing margin is too wide for either purchases or specialization to be attractive. The household minimizes its market participation on the inputs side because it is not profitable to increase use of inorganic fertilizer or invest in new livestock corrals, although the household does continue to use over 9 mt/yr of organic fertilizer collected from animals' traditional nighttime stalls.

Considering possible changes from the baseline scenario, the most plausible conditions under which there is adoption of confinement corrals within our 15-year time horizon is when a pasture tax is imposed (for details of this policy option, see Dalton, 1996; and Dalton and Masters, 1997). The pasture tax accounts for the value to farmers of grazing in common-property bush areas. A tax of only FCFA 1,000 per TLU per year (about US$2 per donkey, and US$3 per cow) is sufficient to induce farmers to construct and maintain corrals, taking animals off the commons and intensifying the agro-pastoral system.

For the purpose of this study, we are concerned not just with corrals and organic fertilizer, but also with other intensification techniques, notably adoption of improved sorghum varieties and increased use of inorganic fertilizers, as well as a switch to more input-intensive crops. Intensification using all three methods is observed under a scenario that projects forward three key trends: population growth (at 3.3 percent per year), higher food grain prices (due to growth in demand), and declining product marketing margins (due to continued policy reform and increased market activity).

Under this trend-projection scenario, the improved sorghum variety is adopted immediately, raising sorghum output by 32 percent over the baseline, and raising total household consumption by 18 percent. At the same time, the household becomes more market oriented, specializing in sorghum and also maize and cutting back on home production of millet and groundnuts, which are purchased instead. Other key forms of intensification occur progressively in a stepwise manner.

As shown in Figure 1, population growth gradually drives down the household's marketed surplus of food grains, until it becomes attractive to change area allocations or input use levels. The first episode of intensification occurs in the third year (i.e. around 1997-98), when maize area is expanded and fertilizer use rises by 50 kg per year. After five additional years of population growth (and some nutrient mining), some area is switched back to sorghum and fertilizer use is increased of 100 kg per year. By the end of the 15-year time horizon, the household's foodgrain surplus is only slightly lower than at the outset despite increased on-farm consumption, with successful intensification having taken place on a sustainable basis.

Conclusions and implications

Our central finding is that soil degradation and unsustainability are not as severe as some observers have claimed (e.g. van der Pol 1992), and that further intensification can occur without irreversible resource depletion. Current techniques cause little nutrient mining chiefly because environmental stresses on plant growth limit nutrient uptake, and future intensification is likely to be sustainable in the sense that one change will entrain another.

Our results identify three key factors driving the intensification process: population growth, which affects mainly relative labor costs; foodgrain demand, which affects the price of grains relative to fertilizer and nonfood products; and marketing margins, which permits specialization for market and greater use of purchased inputs.

Government intervention is most important in providing research and extension (so that new techniques are available for adoption when the time is right), in supporting market integration (so that specialization can occur), and possibly also imposing pasture taxes (so that the social cost grazing common lands is accounted for, leading to adoption of confinement corrals). In the context of these productivity-enhancing policies, model projections indicate that sustainable intensification is possible in an African environment.

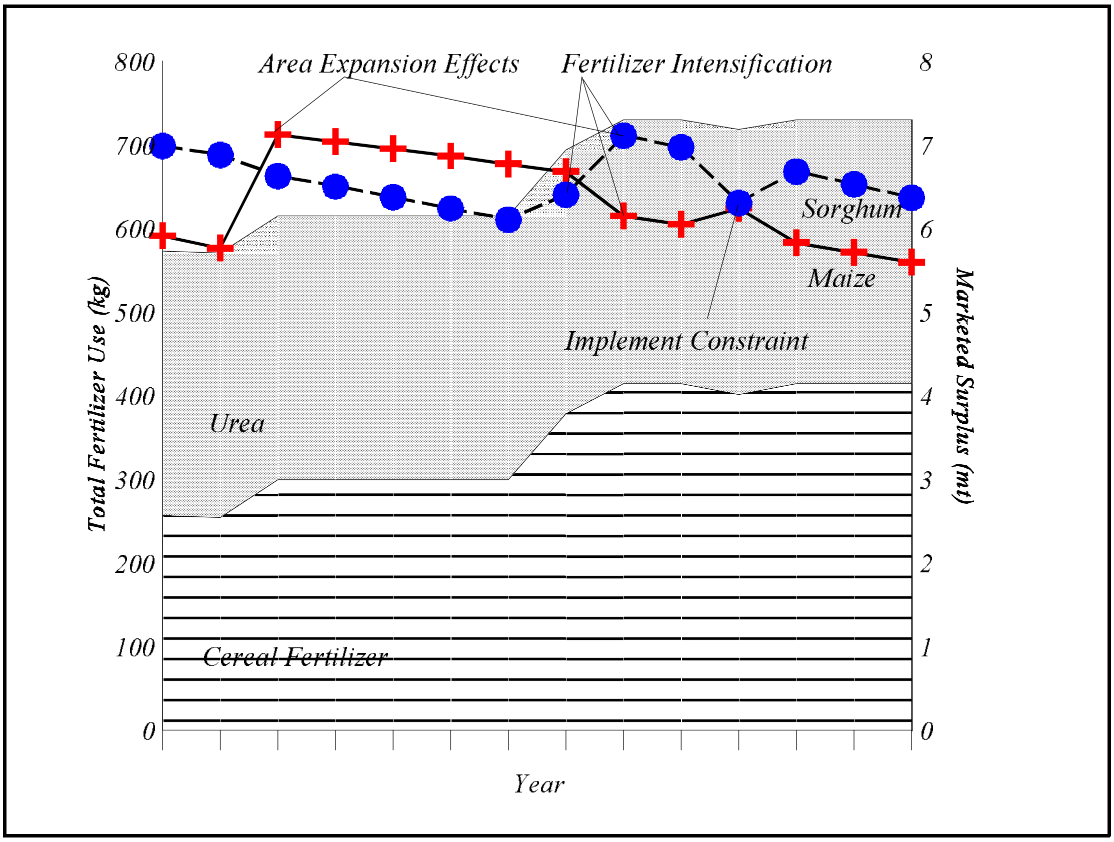

FIGURE 1. Fertilizer Use and Food Surpluses With Projection of Current Trends

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