This is to certify that the

dissertation entitled

ESSAYS ON THE ECONOMICS OF SOIL NUTRIENT REPLENISHMENT IN ECOLOGICALLY FRAGILE REGIONS OF SUBSAHARAN AFRICA: EVIDENCE FROM SENEGAL

presented by

Bocar Nene Diagana

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Agricultural Economics

Major professor

Date 12/16/99

ESSAYS ON THE ECONOMICS OF SOIL NUTRIENT REPLENISHMENT IN ECOLOGICALLY FRAGILE REGIONS OF SUBSAHARAN AFRICA: EVIDENCE FROM SENEGAL

By

Bocar Nene Diagana

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Economics

1999

ABSTRACT

ESSAYS ON THE ECONOMICS OF SOIL NUTRIENT REPLENISHMENT IN ECOLOGICALLY FRAGILE REGIONS OF SUBSAHARAN AFRICA: EVIDENCE FROM SENEGAL

By

Bocar Nene Diagana

Soil fertility decline has been said to constitute a major cause of low agricultural productivity and a threat to food security in SubSaharan Africa, especially in its ecologically fragile regions. Already nutrient-poor soils, subjected to continuous cropping, wind and water erosion, are mined of their nutrients by farming practices that include very low use of mineral and organic fertilizer. Reversing nutrient depletion of soils by replenishing macronutrient pools requires policy measures that provide incentives and improve farmers' capacity to make the necessary short- and long-term investments in land productivity and quality maintenance.

Price policy, credit and capital input distribution are commonly used policy instruments to influence farmers' long-term production choices of activities and technologies. The effects of these policies on soil fertility are not clear and direct; they are mediated through farmers' responses which can take different paths (extensify or intensify crop production in a sustainable or unsustainable way). These paths and their conditioners are not well understood, though they are crucial to determining the fate of these policies.

This research uses the semiarid area of the Senegalese Peanut Basin to empirically explore the long-term production paths followed by farmers in response to selected policies and their subsequent impacts on soil nutrient pools. It is organized in three interrelated essays.

Essay one uses a theoretical dynamic farm household model and shows that intertemporal tradeoffs (current versus future output due to soil nutrient replenishment or mining) and time preferences, i.e., discount rates affect farmers' optimal input (especially fertilizer) decisions.

The second essay uses a biophysical crop simulation model to predict the plot-level production and soil nutrient impacts of a set of cropping activities (millet and peanut rotation) and technological (fertilizer-based versus others) choices. Results confirm that in the Peanut Basin of Senegal fertilizer-based cropping practices lead to more millet and peanut crop output, contribute more to replenishing soil nutrients, and are financially more attractive in the long term than practices that do not use fertilizer.

The third essay uses a bioeconomic model that integrates simulated plot-level biophysical outcomes with current and future input/output prices, and farm household resources and objectives to predict the effects of selected policy measures on the farm household's optimal crop and technology choices, and their implications in terms of soil nutrient replenishment. Optimal cropping practices on millet and peanut suggested by a multi-period (10-year) linear programming model are those that use fertilizer and lead to replenishing the plant-available soil nutrient pools. However, overcoming initial financial constraints is key to launching the process of intensifying crop production through increased fertilizer use.

DEDICATION

This dissertation is dedicated to my father Abdoulaye who did not live long enough to see me become who I am today, but was able to sow very early in me the seeds of hard work, family spirit and faith in God.

ACKNOWLEDGMENTS

First of all, all my thanks go to ALLAH The Almighty for having blessed me with the opportunity and the capacity in all dimensions to engage in and successfully complete this doctoral program!

Secondly, my sincere thanks to:

- USAID for having funded in its entirety my academic program under the Food Security Project II of the Dept of Agricultural Economics of Michigan State University;

- my advisor Dr. T. Reardon for constantly believing in me, challenging me to always do a bit more while backing it up with an unconditional all-around support;

- Drs. E. Crawford, J. Ritchie, J. Strauss and S. Swinton for serving in my committee;

- Drs. S. Daroub and A. Gerakis, along with B. Baer of the Dept of Plant and Soil Sciences at Michigan State University whose tremendous assistance was instrumental in sharpening my (biophysical) modeling skills;

- Dr. S. Harsh for his review and suggestions on my linear programming model;

- Drs. V. Kelly and A. Fall, M. Sene and O. Ndoye for their help in data collection.

Thirdly, my deepest and heartfelt gratitude to:

- my wife Thioro and my daughters Nabou and Rokhaya who, silently and with dignity, endured my being away for almost five years and provided me with a

relentless support that helped me go through the challenges, frustrations and loneliness of this journey;

- to my mom, dad, my brothers and sisters, nephews and nieces back in Thies, Senegal for their prayers and encouragement during every walk of this endeavor.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

CEC:	Cation Exchange Capacity
CIMMYT:	Centro Internacional de Mejoramiento de Mais Y Trigo
DSSAT:	Decision Support System for Agrotechnology Transfer
FAO:	Food and Agriculture Organization of the United Nations
GRS:	Groupe de Reflexion Strategique
IBSNAT:	International Benchmark Sites Network for Agrotechnology Transfer
ICS:	Industries Chimiques du Senegal
ICRAF:	International Center for Research on AgroForestry
IFDC:	International Fertilizer Development Center
IFPRI:	International Food Policy Research Institute
ISRA:	Institut Senegalais de Recherches Agricoles
LP:	Linear Programming
MA:	Ministry of Agriculture
Mg:	Magnesium
MOTAD:	Minimization Of Total Absolute Deviation
MSU:	Michigan State University
N:	Nitrogen
NF:	Nonfarm
P:	Phosphorus

PB:	Peanut Basin
PP:	Phosphate Program
PRISAS:	Projet de Recherche Institutionnelle sur la Securite Alimentaire au Sahel
S :	Sulfur
SD:	Stochastic Dominance
SSA:	Sub-Saharan Africa
SSPT:	Societe Senegalaise des Phosphates de Thies
UNDP:	United Nations Development Program
UNECA:	United Nations Economic Commission for Africa
WB:	World Bank
Zn:	Zinc

INTRODUCTION

1. Soil Fertility Decline, a Major Cause of Low Agricultural Productivity in Sub-Saharan Africa:

Agricultural productivity and food security in Sub-Saharan Africa (SSA) are being seriously threatened by the steady decline in soil fertility, defined as "a net decrease in available nutrients and organic matter in the soil"[1] (Scherr, 1999), and caused by the continued mining of soil nutrients by farmers seeking to increase output. Declining soil fertility jeopardizes the sustainability of farming systems in regions of SSA, especially those in semi-arid West Africa that are ecologically fragile. Cultivated soils in these areas are poorly endowed in macronutrients (N, P, S, Mg, Zn), heavily leached, acid and have low soil organic matter (Wong *et al.*, 1991).They have also been subjected to continuous cropping, wind and water erosion. These characteristics determine their fertility status, hence their agricultural potential.

Brady (1990) estimated only 12% of African soils to be "moderately fertile, well-drained soils", compared to 33% in Asia. Highly variable and declining rainfall patterns observed since the 1970s compound the ecological fragility of the arid and semi-arid regions which account for half of the cultivable land in SSA (Marter and Gordon, 1996). It is also

---

1 This view of soil fertility effects can be contrasted with alternative perspectives from other disciplines:

- an agronomic one which defines soil fertility as "the capacity of soils to create more food of high quality; ...food is fabricated soil fertility" (Sheldon, 1987) or
- a soil scientist one for which it refers to the "capacity of a soil to supply essential elements (nutrients) for plant growth without a toxic concentration of any element" (Foth, 1990).

estimated that 65% of SSA's agricultural land is degraded because of water and soil erosion, chemical and physical degradation (Oldeman *et al.*, 1991; Scherr, 1999). Research has shown that soil nutrient depletion resulting from soil mining or the practice of growing crops with insufficient replacement of macro-nutrients removed from the soil is an important problem in low income countries (Bishop and Allen, 1989; Stocking, 1987; Stoorvogel and Smaling, 1990), and a fundamental biophysical constraint to steady growth of food production (Donovan and Casey, 1998). On a per ha basis, 22 kg N, 2.5 kg P and 15 kg K are being lost annually as a result of long-term cropping with little or no external nutrient inputs and returned crop residues (Stoorvogel and Smaling, 1990; Smaling *et al.*, 1993;Weight and Kelly, 1998).

Particularly serious is the phosphorus (P) deficiency that affects 80% of SSA's soils. Studies by IFDC and others have firmly established that P is the most limiting nutrient in soils in semi arid West Africa (Bationo and Mokwunye, 1991; Bationo and Vlek, 1997). This deficiency not only affects plant growth and crop quality, but it also constrains response by crops to other nutrients (Gerner and Mokwunye, 1995; WB/IFDC/ICRAF, 1994; Jones *et al.*, 1991; Brady and Weil, 1996). Consequently, increasing the supply of available soil P is essential for productivity growth (increasing crop yields) and environmental quality (stopping or slowing land degradation). Since the P content of crop residues and manures does not usually cover crop requirements, P fertilizer inputs are almost always necessary to correct P deficiency (Breman, 1990; McIntire and Powell, 1995).

2. The Productivity Growth Challenge and its Soil Fertility Implications:

Partly as a result of these adverse agroecological conditions in SSA, agricultural production grew annually at less than 2% between 1965 and 1980, and at around 1.4% during the 1990s (UNDP/UNECA Report, 1997), well under the rapid pace of demographic growth at around 3% per year. To meet soaring food and fiber needs from a fast growing population, it's been argued that agricultural production should grow at an estimated rate of 4% per annum. This would then require an annual increase of 1.5% for labor productivity and of 3% for land productivity (Delgado *et al.*, 1987; Cleaver and Schreiber, 1992; Larson and Frisvold, 1996).

Several production paths can be theoretically envisioned to meet this serious agricultural productivity growth challenge. First, extensification by expanding on to new and marginal lands offers limited potential as the population pressure on the available agricultural land has prompted a nearing of the land frontier, making it much more difficult or even impossible to increase production on the existing but degraded farmlands. Worse, extensification is likely to put further pressure on forested areas and resources, leading to more land degradation and deforestation (Marter and Gordon, 1996).

Second is the intensification of agricultural production by using more productivity-enhancing inputs per unit of land area (improved seeds, chemical inputs, labor). But, intensification paths can be of different types: sustainable and unsustainable (Reardon *et al.*, 1997; 1999). One major difference between them depends upon whether they result in negative or positive soil fertility and productivity impacts. Whatever the production path, there is a growing consensus that the appropriate one capable of meeting the productivity challenge must be sustainable, i.e with a real potential to reverse the declining crop yield trends, to ensure a concomitant and appropriate replenishment of soils while still being profitable

3. Soil Replenishment Alternatives:

3.1 Technological solutions:

To reduce net soil nutrient losses, hence soil fertility decline, several options are available to farmers: crop rotation, fallows or fertilization, or a combination of them. Rotating or sequencing crops, for example nitrogen-fixing legumes followed by nitrogen-demanding cereals on a given piece of land, allows a smoothing of macronutrient consumption across crops. Higher crop yields than those from monocropping could follow (Bationo and Lompo, 1999), in addition to reduced soil erosion, less negative environmental externalities, better soil fertility and less need for commercial fertilizer (Gebremedhin and Schwab, 1998). Where land is abundant relatively to labor, regenerative long-term fallows or shorter improved fallow techniques are also used to replenish soil nutrients. But these fallow strategies have been progressively abandoned or reduced under the pressure of high population densities (Dalton, 1996).

In the mean time, the utilization of productivity-enhancing inputs and technologies is very low. A key intensifying input such as fertilizer is only sparsely used. Average fertilizer use has been estimated in SSA at less than 15 kg per hectare as of 1994/95, compared to more than 200 kg in East Asia, 125 kg for Asia as a whole and 65 kg in Latin America (UNDP/UNECA Report, 1997). Annual growth in fertilizer consumption per ha has been declining in the 90s: .3 % between 1990 and 1993, and negative between 1993 and 1995. Use of manure is constrained by availability. McIntire and Powell (1995) underscore the enormity of the required pasture areas to produce enough manure to maintain soil fertility in the absence of mineral fertilizer whereas Williams *et al.* (1995) claim that, with present intensity of land use in semi-arid West African countries, manure alone would not increase crop yields in a sustainable manner. Competing livestock feed, fuel and construction uses of crop residues constrain their availability for incorporation in soils. Consequently, soil organic matter drops, lowering crop yields or soil productivity (Bationo and Vlek, 1997).

Given the feasibility limits of the technological options presented above, increased inorganic fertilizer is the remaining option (Mudahar, 1986), along with soil organic matter improvement. As concluded by Padwick (1983) in his review of 50-year soil fertility studies in tropical Africa, "inorganic fertilizers are an essential part of any system aimed at maintaining good yields over large areas in the absence of sufficient organic manures". To "jump-start" the process of soil replenishment, use of inorganic fertilizer must be increased first from its current 10-15 kg/ha levels to at least 30-50 kg/ha [2](Larson and Frisvold, 1996; Weight and Kelly, 1998), helping thereby to reduce soil organic matter loss, sustain crop production, raise agricultural productivity, improve food security and preserve the natural resource base, all features of a sustainable intensification of agricultural production.

2 While overuse of fertilizers has lead to environmental problems in other parts of the globe, applying this level of inorganic fertilizer should not cause similar problems in SSA.

3.2 Policy alternatives:

For policymakers, the challenge is to put in place policies that provide suitable incentives to farmers and improve their capacity to increase factor productivity while maintaining appropriate levels of the physical resource base (Kruseman *et al.*, 1993). Under market-oriented reforms, product and factor prices, financial and physical capital transfers are commonly used instruments by policymakers to influence the behavior paths described earlier. One objective of these policies which has recently received a lot of attention is the World Bank-led soil recapitalization programs in SSA (WB/FAO, 1996). These programs treat the soil as a natural capital asset[3] in whose maintenance or fructification both farmers and society have an interest. This natural capital resource provides service flows positively (negatively) influenced by soil replenishment (mining). Thus, where soil fertility is declining, reversing it by replenishing the soil should be interpreted as a process of "recapitalizing" the soil asset (de Alwis, 1995; Sanchez *et al.*, 1995).

4. Problem, Gap and Research Objectives:

Achieving this long term objective depends a great deal upon the prevailing physical and socioeconomic environment, i.e the links to agricultural input and output market conditions (Debrah and Koster, 1999) shaped by policy measures that influence farmers' incentives and capacity to engage in soil recapitalization. These policies, however, do not have clear, direct and linear effects on soil fertility outcomes. The reality is that these effects

---

3 Along with water, atmosphere, forests, fish, wildlife and wetlands, soil is one of the environmental assets that make up the stock of natural capital (Sanchez *et al.*, 1997).

are mediated by farm producers' behavior in response to policy shocks. Their response can follow different paths. These paths and their conditioners (activity and technology choice, agroclimatic context) are not well understood, but are crucial to determining the performance of the applied policies. Moreover, the evidence is mixed on the farm profitability of these conditioners.

Thus, the challenge is for policy researchers to fill this empirical knowledge gap. The main objective of this research is therefore to empirically explore these farm production behavior paths and their conditioners using the Senegalese physical and economic context as a study case.

From this overall research objective, there follow two specific empirical analyses around which this work is organized (figure 1). The discussion of these analyses is preceded by the presentation of a theoretical dynamic framework to understand intertemporal considerations involved in optimal farm household cropping decisions to ensure soil nutrient replenishment. Then, the first empirical analysis uses a biophysical model of crop production to measure the production and soil fertility impacts at the plot level of a set of conditioners available to farm producers, i.e an array of cropping activities and technological (fertilizer-based versus others) choices under the agroclimatic conditions of our study area. A second empirical analysis includes these measured plot-level outcomes along with input/output prices in a linear programming model to predict the effects of selected policy measures on the farm household optimal crop and technology choices and their implications in terms of soil fertility outcomes. Particular attention is paid to the issue of the long term profitability of inorganic

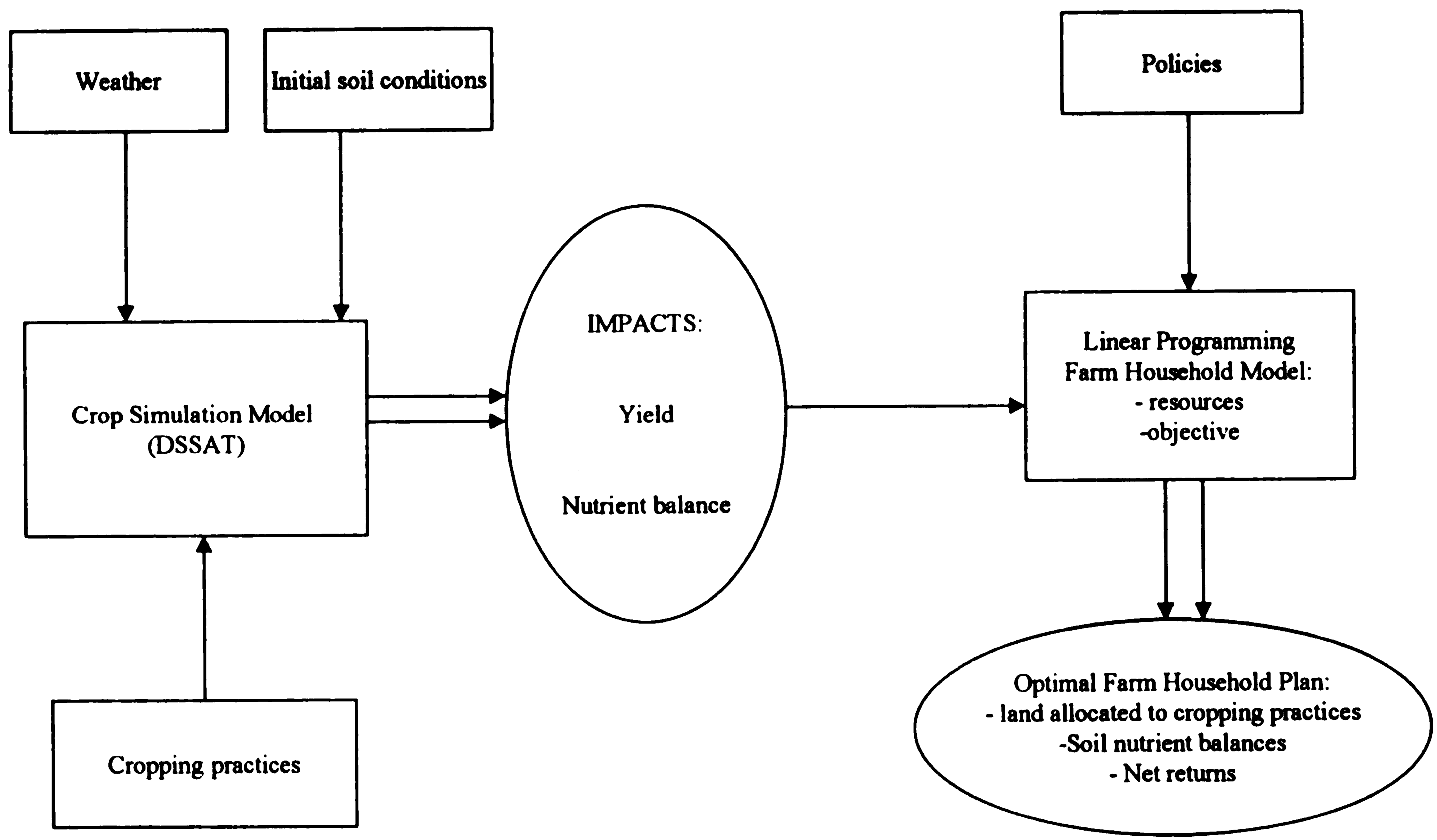


Figure 1: Organization of research analysis

fertilizer use at the farm level in SSA. By focusing on this still-debated fertilizer profitability issue, we are hoping to add much needed evidence to the body of existing but conflicting findings from other works in the region (McIntire, 1986; Adesina *et al.*, 1988; Diagana *et al.*, 1995; Sanchez *et al.*,1997; Coulibaly *et al.*, 1998; etc.).

5. Data/Context/Research Questions:

The Western Sahelian country of Senegal provides the study case for our research. This application will offer interesting policy insights in that it is based on a set of common price and capital transfer policy measures contained in the multi-year 'Agricultural Program' launched in 1997/98 (Republic of Senegal/MA, 1996; see details in appendix A.1) and seeking to recapitalize soils in a country which presents most of the agroecological and socioeconomic features discussed earlier in SSA: a) smallholder rainfed agriculture, b) ecologically fragile areas with variable and low rainfall and poor soils, c) rapid demographic growth, d) unstable price and input distribution policies, e) low rural incomes and limited cash availability, and f) low fertilizer use.

Data have been collected on socioeconomic (factor and product prices, household characteristics) and biophysical variables (weather, soils, cultivars, yield and input use on peanut and millet) in two zones of the Senegalese Peanut Basin. They will help answer the following general research questions:

(i) Have fertilizer-using cropping practices become more profitable at the farm level in the long run than others that do not use fertilizer under the 'Agricultural Program' context in Senegal?

(ii) If not, under what price conditions would fertilizer use be profitable at the farm level?

(iii) What are the corresponding soil fertility impacts, i.e on soil macronutrient balances, especially N and P?

6. Research Methods:

To meet our research objectives, we are taking a relatively recent and pluridisciplinary-based methodological route that directly links biophysical soil-plant-weather mutual interactions (physical realm of crop production) to the economic decision analysis (behavioral side of crop production). Feeding economic analysis with inputs from other disciplines and vice versa has led to the development of bioeconomic models in the agricultural production literature in the last two decades (Oriade and Dillon, 1997; Roberts and Swinton, 1996). Bioeconomic models, though complex because of the breadth of their scope, are handily solved by today's computer programs, lend themselves for multi-faceted policy analysis, and offer great perspectives for bridging gaps between academic disciplines and between scientists and policymakers (Ruben *et al.*, 1998). Our work will use a crop growth simulation model whose results are linked to a linear programming-based farm household model to explore our general research questions.

7. Organization of Thesis:

This dissertation is organized in three related, but separately treated essays. The first essay is a short attempt to construct a theoretical dynamic farm- household model that analyses optimal crop management decision rules (for example how much fertilizer to use) under a soil nutrient replenishment concern. The second essay centers on using a crop simulation model to measure plot-level crop yield and soil fertility impacts of selected crop rotation practices. The third essay uses these plot-level results to analyze the optimal farm household production choices under various policy scenarios with a special focus on fertilizer long term profitability.

References

Adesina, A.A., P.C. Abbott and J.H. Sanders.1988. Ex-ante Risk Programming Appraisal of New Agricultural Technology: Experiment Station Fertilizer Recommendations in Southern Niger. *Agricultural Systems*, 27:23-35.

Bationo, A. and F. Lompo. 1999. Available Technologies for Combating Soil Nutrient Losses in West Africa. *in* Debrah, S.K. and W. G. Koster (eds). Linking Soil Fertility Management to Agricultural Input and Output Market Development: the key to Sustainable Agriculture in West Africa. IFDC-Africa, Lome, Togo.

Bationo, A. and P.L.G. Vlek. 1998. "The Role of Nitrogen Fertilizers Applied to Food Crops in the Sudano-Sahelian Zone of West Africa" *in* G. Renard, A. Neef, K. Becker and M. Von Oppem (eds) "Soil Fertility Management in West African Land Systems" Proceedings of the University of Hohenheim (Germany), ICRISAT Sahelian Center and INRAN regional workshop, 3-8 March 1997 Niamey, Niger. Werkersheim: Margraf Verlag.

Bationo, A. and A.U Mokwunye. 1991. Alleviating Soil Fertility Constraints to Increased Crop Production in West Africa. The Experience in the Sahel. p.195-215. *In* A.U. Mokwunye (ed.) Alleviating Soil Fertility Constraints to Increased Crop Production in West Africa. Kluwer Academic Publications, Dordrecht, the Netherlands.

Bishop, J. and J. Allen. 1989.On-Site Costs of Soil Erosion in Mali. Environment Department Working Paper No. 21, World Bank, Washington DC, November.

Brady, N.C. 1990. The Nature and Properties of Soils. Tenth edition. New York: MacMillan.

Breman, H. 1990. No Sustainability Without External Inputs. p. 124-134. *In* sub-Saharan Africa beyond adjustment. Africa seminar, Maastricht. Project Group Africa. Directorate General for Int. Coop., Ministry of Foreign Affairs, the Hague, the Netherlands.

Cleaver, K. and G. Schreiber. 1992. The Population, Agriculture and Environment Nexus in Sub-Saharan Africa. Agriculture and Rural Development Series No. 1, Technical Department, African Region, World Bank, Washington, DC.

Coulibaly, O., J. Vitale and J. Sanders. 1998. Expected Effects of Devaluation on Cereal Production in the Sudanian Region of Mali. *Agricultural Systems*, vol. 57, no.4.

Dalton, T..1996. Soil Degradation and Technical Change in Southern Mali. Ph.D Dissertation. Department of Agricultural Economics, Purdue University. West Lafayette, IN.

Diagana, B., V. Kelly and A. A. Fall. 1995. "Dévaluation du Franc CFA et Décisions de Production Agricole: Une Analyse Empirique de l'Impact de la Dévaluation du Franc CFA sur les Choix de Culture et de Technologies de Production par les Ménages Ruraux du Bassin Arachidier du Sénégal" paper presented at PRISAS regional workshop "Impact de la Dévaluation du Franc CFA sur les Revenus et la Securité Alimentaire en Afrique de l'Ouest", Bamako, Mali, June.

de Alwis, K. A.. 1995. Recapitalization of Soil Productivity in Sub-Saharan Africa.Rome: FAO Investment Center, Discussion Paper.

Debrah, S.K. and W. G. Koster (eds). 1999. Linking Soil Fertility Management to Agricultural Input and Output Market Development: the key to Sustainable Agriculture in West Africa. IFDC-Africa, Lome, Togo.

Delgado, C., J. Hopkins and V. Kelly. 1994. Agricultural growth linkages in sub-Saharan Africa: A synthesis. p. 22-26. *In* Proc. of a Workshop on Agricultural Growth Linkages in Sub-Saharan Africa, Washington, DC. 26 May 1994. Int. Food Policy Res. Inst., Washington, DC.

Donovan, G. and F. Casey. 1998. Soil Fertility Management in sub-Saharan Africa. World Bank Technical Paper No. 408

Foth, H. D.1990. Fundamentals of Soil Sciences. Eighth edition. John Wiley and Sons.

Gebremedhin, B. and G. Schwab. 1998.The Economic Importance of Crop Rotation Systems: Evidence From the Literature. Michigan State University Department of Agricultural Economics Staff Paper no. 98-13, August.

Gerner H. and A. Uzo Mokwunye (eds). 1995. Use of Phosphate Rock for Sustainable Agriculture in West Africa, International Fertilizer Development Center - Africa, Lomé, Togo.

Jones, C.A., K.J. Boote, S.S. Jagtap, and J.W. Mishoe. 1991. "Soybean Development" Ch. 5 *In* J. Hanks and J. T. Ritchie (eds). Modeling Plant and Soil Systems. Number 31 in the series of Agronomy. American Society of Agronomy, Inc. Madison, Wisconsin, 71-90.

Kruseman, G., H. Hengsdijk and R. Ruben. 1993. Disentangling the Concept of Sustainability: conceptual Definitions, Analytical Framework and Operational

Techniques in Sustainable Land Use. AB-DLO/WAU DLV Report No. 2, Wageningen.

Larson, B.A. and G.B. Frisvold. 1996. Fertilizers to Support Agricultural Development in Sub-Saharan Africa: What is needed and Why? *Food Policy*, vol. 21, no. 6: 509-525.

Marter, A. and A. Gordon. 1996. Emerging Issues Confronting the Renewable Natural Resources Sector in SSA. *Food Policy* 21(2), pp. 229-241, May.

McIntire, J., and J.M. Powell. 1995. African Semi-arid Tropical Agriculture Cannot Grow Without External Inputs. p. 539-554. *In* J.M. Powell *et al.*, (eds.) Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa. Vol. II. Tech. Pap. Int. Livestock Ctr. for Africa, Addis Ababa, Ethiopia.

McIntire, J. 1986. Constraints to Fertilizer Use in sub-Saharan Africa. In *Management of Nitrogen and Phosphorus Fertilizers in sub-Saharan Africa*. eds A. U. Mokwunye and P. L.G. Vlek Proceedings of a symposium. Martinus Nijhoff Publishers.

Mudahar, M. S. 1986. Fertilizer Problems and Policies in sub-Saharan Africa. In *Management of Nitrogen and Phosphorus Fertilizers in sub-Saharan Africa*. eds A. U. Mokwunye and P. L.G. Vlek Proceedings of a symposium. Martinus Nijhoff Publishers.

Oldeman, L.R., R. T. A. Hakkeling and W. G. Sombroek. 1991. *World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note*. Wageningen, The Netherlands and Nairobi, Kenya: International Centre and United Nations Environment Programme.

Oriade, C.A., and C.R. Dillon. 1997. Developments in Biophysical and Bioeconomic Simulation of Agricultural Systems: A Review. *Agricultural Economics*. 17: 45-58.

Padwick, G.W. 1983. The Maintenance of Soil Fertility in Tropical Africa: A Review. *Experimental Agriculture*. vol. 19: 293-310.

Reardon, T., C. Barrett, V. Kelly and K. Savadogo. 1999. Policy Reforms and Sustainable Agricultural Intensification in Africa. *Development Policy Review*, forthcoming.

Reardon, T., V. Kelly, E. Crawford, B. Diagana, J. Dione, K. Savadogo and D. Boughton. 1997. Promoting Sustainable Intensification and Productivity Growth in Sahel Agriculture after Macroeconomic Policy Reform. *Food Policy*, 22(4): 317-327.

Roberts, W. S. and S.M. Swinton. 1996. Economic Methods for Comparing Alternative Crop Production Systems: A Review of Literature. Reprint from *American Journal of Alternative Agriculture*, Vol.11, No. 1.

Ruben, R., A. Kuyvenhoven and G. Kruseman. 1998."Bio-Economic Models for Eco-Regional Development: Policy Instruments for Sustainable Intensification" 1998 AAEA Preconference workshop, Salt Lake City, Utah.

Sanchez, P.A, K. Shepherd, M. Soule, F. Place, R. Buresh, A-M. Izac, U. Mokwunye, F. Kwesiga, C. Ndiritu and P. Woomer. 1997. Soil fertility Replenishment in Africa: An Investment in Natural Resource Capital. In *Replenishing Soil Fertility in Africa* eds R. Buresh, P. Sanchez and F. Calhoun SSSA Special Publication Number 51. Madison, Wisconsin, USA: Soil Science Society of America and American Society of Agronomy.

Sanchez, P.A., A-M. Izac, I. Valencia, and C. Pieri. 1995. Soil Fertility Replenishment in Africa: A Concept Note. (Nairobi: ICRAF, and Washington D.C.: World Bank, draft).

Scherr, S. J. 1999. "Soil Degradation: A Threat to Developing-Country Food Security by 2020?" IFPRI, Food, Agriculture and The Environment Discussion Paper 27, February.

Senegal, Republic of, Ministry of Agriculture.1996. Programme Agricole 1997/98. December.

Smaling, E., J.J. Stoorvogel and P. Windmeijer.1993. Calculating Soil Nutrient Balances in Africa at Different Scales. II. District Scale. *Fertilizer Research*. 35(3): 237-250.

Stocking, M. 1987. Measuring Land Degradation. *In* Land Degradation and Society, eds. P. Blackie and H. Brookfield, Methuen, London.

Stoorvogel, J.J., and E.M.A. Smaling. 1990. Assessment of Soil Nutrient Depletion in Sub-Saharan Africa: 1983 - 2000. Report 28, Winand Staring Centre, Wageningen.

UNDP/UNECA/FSSDD, 1997. "Capacity Building in Support of Food Security and Sustainable Agricultural Development in Sub-Saharan Africa: Towards a Comprehensive Framework for Future Action." Draft Report, Addis Ababa: May.

Weight, D. and V. Kelly. 1998. Restoring Soil Fertility in Sub-Saharan Africa: Technical and Economic Issues. A Policy Synthesis Note for USAID - Africa Bureau, Office of Sustainable Development. Food Security II Project, Dept. of Agricultural Economics, Michigan State University, October.

Williams, T.O., J.M. Powell and S. Fernandez-Rivera. 1995. Manure Availability in Relation to Sustainable Food Crop Production in Semi-Arid West Africa: Evidence from Niger. *Quarterly-Journal-of-International-Agriculture*. 34:3, 248-258.

Wong, M.F.T., A. Wild and A.U. Mokwunye. 1991. Overcoming soil nutrient constraints to crop production in west Africa: importance of fertilizers and priorities in SF research. *Fertilizer Research*. Dordrecht: Kluwer Academic Publishers. Vol. 29 (1) p. 45-54, July.

World Bank, IFDC and ICRAF. 1994. Feasibility of Rock Phosphate Use as a Capital Investment in Sub-Saharan Africa: Issues and Opportunities. (draft)

World Bank and FAO. 1996. Recapitalization of Soil Productivity in Sub-Saharan Africa: Identification and Measurement of Benefits and Costs. Discussion paper.

Appendix A1. PRESENTATION OF THE AGRICULTURAL AND PHOSPHATE PROGRAM IN SENEGAL:

A multi-year "Agricultural Program" has been launched in 1997/98 in Senegal. It basically consists of the following measures:

+ increase peanut producer price from 132 to 150 CFA/kg;

+ change input price or ease input credit conditions (seeds, fertilizer, etc.):

. reduce down payment to 10% of requested loans

. reduce annual interest rate to single digit: 7.5% from 12% the year before;

. eliminate tax on agricultural equipment and

+ distribute P products to farmers under a 4-year publicly-funded national program.

In Senegal, as part of the Agricultural Program, a phosphate distribution program (PP) has been launched this last cropping season. Publicly-funded, it distributes to farmers via CNCR (council body of federated farmer organizations) local phosphate products (blend of tri calcium phosphate and phosphogypsum, aluminum phosphate) for basal application to address P-deficiency in soils. According to Government figures, estimated costs of this program are around CFA 3.2 billion (almost $5 million)[4]. Details of the program implementation are the following:

+ the Government of Senegal (GOS) orders from local fertilizer manufacturers (ICS/Senchim, SSPT) phosphate products (by-products and waste);

+ A parastatal (Sonagraines) is asked by GOS to deliver P products from plants to selected rural community (CR) centers in all regions of Senegal;

---

5 *In* 'Le Soleil', a daily Senegalese newspaper, 19 November 1999.

+ CR-level committees (made up by local authorities) reporting to CNCR select beneficiary villages;

+ Village-level subcommittees select recipient farmers based on following criteria:

. have adequate equipment to incorporate products in soils before rains,

. get seed and NPK fertilizer to use in complement to soil-incorporated P-product,

. pay 2 CFA/kg , i.e 800CFA for the recommended dose of 400 kg/ha (product is now given away, free of charge); each recipient farmer is expected to apply product to 3(?) ha,

. transport product from CR center to village.

+ This 4-year program covers all agroclimatic regions:

. year 1: around 50,000 tons for an estimated 117,000 ha;

. year 2-4: 500,000 ha treated annually.

+ Although CNCR is responsible for managing this distribution program (monitoring tasks are planned), it is not clear whether and how selection criteria will be enforced, and evaluation tasks will be are performed.

So far, no economic study has been carried out at any level in Senegal to support or justify this program. Little, if anything, is known about the financial and economic profitability of this PP which is affected by

+ the time span over which its impacts can be traced out

+ the complementary actions that are proposed to ensure the effectiveness of the PP.

ESSAY I:

MICROECONOMICS OF SOIL NUTRIENT REPLENISHMENT: A THEORETICAL DYNAMIC MODEL OF FARM PRODUCTION BEHAVIOR

1. Problem Statement

Low levels of fertilizer use by farmers on already nutrient-poor and degraded soils in SSA have been documented in numerous farm production studies. In the face of growing population pressure on lands, low crop yields, low output production and fast soil nutrient depletion, the lack of significant fertilizer use seriously puts in jeopardy the option of intensifying crop production in a sustainable manner to keep up with the region's increasing food and fiber needs. Such an intensification is considered inevitable to meet the 4% annual growth rate in agricultural production necessary to improve conditions of living of millions of rural populations living in this area (Delgado *et al.*, 1987; Larson and Frisvold, 1996).

Increasing farmers' use of fertilizer from its current levels is one of the key components of any overall strategy to achieve a sustainable intensification of agricultural production in SSA. But, the main problem is how to do it. Answers to this challenging policy question depend not only on the policy environment, but also on a thorough understanding of the microeconomic behavior of farm households. Applying more fertilizer generates service flows that include increased current and future crop output (to be realized later because of nutrient replenishment, hence of improved soil fertility), both valued by individual farmers according to their time preferences, i.e their discount rates. We contend in this essay that, when making optimal short term fertilizer use decisions, farmers face intertemporal production tradeoffs coming from the long term soil fertility issue, and how its time-dependent benefits and costs are valued by farmers determine, among other things, these decisions. Consequently, current as well as future benefits and costs of this decision must be accounted for when determining optimal fertilizer use decisions and assessing its farm profitability.

2. Profitability of Fertilizer Use in SSA:

2.1 Mixed evidence:

Conflicting empirical evidence exists on the fertilizer profitability question in SSA, making it a still hotly debated issue in policy and research circles as well. McIntire (1986) postulates that low nutrient responses to millet and sorghum, two widely cultivated rainfed crops, reduce the profitability of fertilizer and thus explain to a large extent its low application rates in SSA. On the same tone, Sanchez *et al.* (1997) underscore that fertilizer use on food crops by smallholder farmers has often not been profitable in SSA because of high fertilizer prices, low producer prices of food crops and risk. Even when profitable, purchase of this input has been hindered by competing urgent and basic needs for the limited liquidities available to farmers at the beginning of the cropping season.

In contrast to this assessment, Shapiro *et al.*(1998) argue that inorganic fertilizer is the only technically efficient and economically profitable way to overcome soil fertility constraints in semi-arid West Africa. In Senegal, research work by Diagana *et al.* (1995) based on a static risk-free farm household model for two zones of the Senegalese Peanut Basin, including various cropping modules and non farm activities showed that the use of fertilizer-based technologies was not financially profitable at the farm level under prevailing inp

its

usi

tha

inte

2.2.

use

to e

com

mos

offe

ques

impli

from

adop

over

also

beha

today

cropp

input and product prices, and thus provided a short run financial justification that corroborates its observed limited use by farmers in the studied areas. Conversely, Coulibaly *et al.*,(1998), using a farm risk-programming model for the Sudanian agroecological zone in Mali, found that, contrary to conventional wisdom about African farmers diversifying rather intensifying, intensification of cereal production using fertilizer is financially profitable.

2.2. Dynamic dimensions:

The evidence presented above paints a mixed picture of the profitability of fertilizer use to SSA farmers, especially those in semi arid areas. Several hypotheses have been offered to explain this ambiguity, among which the removal of fertilizer subsidies, which has been common in many SSA countries under the Structural Adjustment Programs of the 1980s. But, most of these profitability studies have been done in a simplified static context, and hence offered only a partial view of the question that did not address two important dynamic questions for farmers: soil quality and uncertainty, each with important behavioral implications.

In so far as the concern for the quality of land is reflected in how future crop output from that piece of land evolves and is subsequently valued by the farmer, it then influences adoption of fertilizer. This concern is not only formed based on farmer's observations made over time of soil quality indicators, mainly the trend of output obtained per unit area, but it also depends on how much they trade present for future output. As a result, it triggers a behavioral response by the farmer. The more he/she values tomorrow's output relative to today's, the former depending, among other things, on maintaining the fertility status of the cropped soils, the more likely he/she is to use fertilizer to restore the soil's productive capacity, other things being equal. Another view of soil quality separates it from crop production flows. Van Kooten *et al.*, (1990) included soil quality in the farmer's utility function to investigate the tradeoffs between net returns and stewardship practices that require the soil resource to be used so that long term productivity is not impaired, and they found that a substantial amount of concern for soil quality must be felt before changes in agronomic practices are observed.

The farming environment in SSA is marked by uncertainty due to erratic rainfall, unstable prices and unpredictable input distribution policies, etc. Such uncertainty makes farming activities risky. Farmers deal with this situation by adopting different risk management strategies that are reflected in their crop, input and technological choices (Anderson *et al.*, 1977; Sadoulet and DeJanvry, 1995). Young (1979) and Saha (1994) note a substantial body of evidence from India, Brazil, Mexico, etc that suggests that the typical farmer in developing countries is risk averse (Moscardi and DeJanvry, 1977; Dillon and Scandizzo, 1978; Binswanger, 1980). Risk, especially risk aversion, deters adoption of fertilizer as uncertainty affects the ability of farmers to make good guesses on critical variables that affect their cropping decisions. Adesina *et al.* (1988), using a MOTAD risk programming model, found that the more risk averse farmers in Southern Niger applied fertilizer only on a limited crop area, and the less risk averse would use more fertilizer, even though cash and seasonal labor constraints would limit it.

In sum, an evaluation of fertilizer profitability and its use should include these long term soil quality and uncertainty issues. A good deal of attention has been paid in the adoption literature to the uncertainty/risk problem which has been dealt with in different empirical ways ("safety-first", mean-variance, target MOTAD, chance-constrained models, etc.) whereas the soil quality issue still remains underinvestigated. Moreover, hardly have the two of them been explicitly addressed simultaneously. In this essay, we will ignore uncertainty and focus on the intertemporal tradeoffs involved in the soil quality issue. This analysis is done in a dynamic framework that reflects the farmer decisionmaking process. Such a process takes place in an integrated system framework that includes the farm household set of economic activities, its labor, capital and other resource constraints, its food security needs, etc.

3. Objective of Essay:

The main objective of this theoretical essay is to construct a dynamic multi-sectoral bioeconomic model of farm households that helps explain how the consideration and the valuation of time-dependent service flows (crop production) from soil quality maintenance or improvement affects optimal crop and technological choices, hence fertilizer demand and use in an uncertain farming environment. The model is dynamic because it looks at decisions that have observable effects over multiple periods. It is multi-sectoral as it considers different activities from different sectors (in and off-farm) that are available to the farm household. It is bio-economic because it links biophysical crop production processes to economic management decisions. However, it departs from the standard economic model by explicitly considering the dynamic production effects of replenishing soil nutrients via fertilizer use as a way to enhance agronomic sustainability and economic profitability of farming. It does so by incorporating a soil quality variable as an argument in the crop production function and by keeping track of the motion of the soil asset.

Defined as "the inherent capability of the soil to perform a range of productive, environmental and habitat functions" (Scherr, 1999), the soil quality variable has been represented in different ways in the farm production literature. Most soil or land quality studies refer to the productive function and are based on an aggregate index of selected soil physical or chemical characteristics with unknown or subjective weights. For example, to name a few, Van Kooten *et al.*, (1990) measured soil quality by soil depth and available soil moisture. Burt (1981) characterized soil quality by topsoil depth and organic matter. Following those lines, our model uses soil macronutrients (N, P) and organic matter as an indicator of the quality of the soil resource.

4. Dynamic Bioeconomic Model of Farm Household Behavior

Our theoretical model incorporates a soil quality variable in a farm household model that uses the standard expected income maximization approach along the lines presented in Singh *et al.* (1986) and Sadoulet and DeJanvry (1995). Biophysical processes of plant, soil and weather interactions are included in the production part of the model. Nonfarm is included in the rural farm household's total set of choice activities.

For farm households assumed to be expected income-maximizers, the multi-period objective function is to maximize the discounted expected stream of income or net farm returns to cropping and noncropping activities. Mathematically specified, it is as follows:

$$\text{Max} \quad \Sigma_t (1+\delta)^{-t} E(Y_t) = \Sigma_t (1+\delta)^{-t} (Y_{at} + Y_{nt})$$

$$= \Sigma_t (1+\delta)^{-t} [\, p * E(Q_t) - r * X_t + w_n * n_{nt} \,] \tag{1}$$

subject to

$$Q_t = Q\,(X_t,\ n_{at},\ NB_t), \text{ production function} \tag{2}$$

$$L = n_{at} + n_{nt}\ , \text{ labor constraint} \tag{3}$$

$$NB_{t+1} = NB_t + nb_t\,(X_t,\ q_t |\ NB_t)\ , \text{ with } NB_0 \text{ specified} \tag{4}$$

where

E: expectations operator;

Y_t: net farm income;

δ: discount rate;

t: time period;

Y_a: net cropping income;

Y_n: net non farm income[5];

Q: vector of agricultural output per cropping practice;

X: vector of variable input (labor excluded) used per cropping practice;

p: agricultural output price vector;

r: agricultural input price vector;

L: total family labor;

n_a: labor days devoted to cropping activities and

n_n: labor days devoted to noncropping activities;

w_n: net returns to a day of noncropping activity;

NB_t: stock of soil nutrient reserves at beginning of time t;

nb_t: flow of soil nutrient at time t;

q_t: yield of output per cropping practice at time t.

---

1 Nonfarm and noncropping income are used interchangeably throughout the text.

Equation (2) describes the crop production process in which yield for a crop is the result of the interaction of biophysical processes with management decisions: amount and type of inputs used, and soil nutrient balance (NB) and other factors (rainfall, etc.). Equation (3) assumes away leisure time and states that the fixed family labor stock is allocated between farming and non farm activities. It follows that

$$n_{nt} = L - n_{at} \qquad (5)$$

Equation (5) illustrates one of the ways nonfarm activity affects farming. Via the labor constraint, it can affect farming negatively by competing with it for the household labor. Another way not modeled here is that nonfarm activity, a main source of cash income for rural households in different parts of semi arid West Africa, helps relax the cash constraint, and finance capital input acquisition (Reardon *et al.*, 1994; Kelly *et al.*, 1993; Savadogo *et al.*, 1994; Honfoga, 1999).

Also, with predetermined levels of X_t and n_{at}, equation (2) represents a crop response function which depicts a direct relationship between output and soil nutrient conditions, ceteris paribus. It then allows soil quality to influence the effectiveness of inputs and technologies (Dalton, 1996).

In equation (4), the levels of the stock of each of the soil macro nutrients at the beginning of next period t+1 are in turn affected by their previous levels (NB_t), but also by nutrient inflows from current input use (X_t) and outflows due to crop yield thru nutrient uptake (q_t). These stocks are also affected by losses from erosion, leaching, volatization, etc. This difference equation defined for each soil macronutrient illustrates the recursive nature of soil condition dynamics as changes in soil conditions between two consecutive periods are determined, controlling for other factors, by input use and crop yield levels in the previous period.

Rewriting the household problem on a per hectare basis ($Q_t = q_t$) after substituting equations (5) and (2) into (1), the present value of a stream of normalized expected net farm returns to be maximized is

$$\max \Sigma_t (1+\delta)^{-t} E(Y_t) = \Sigma_t (1+\delta)^{-t} [(p^* E\, q_t(X_t, n_{at}, NB_t) - r^* X_t + w_n (L - n_{at})] \quad (6)$$

subject to

$$NB_{t+1} = NB_t + nb_t (X_t, q_t | NB_t).$$

This is a dynamic problem with NB as a state variable and X_t and n_{at} as control or instrument variables. It is one of determining the optimal values for X_t and n_{at} which will, via equations (2)-(5), imply values for q_t and NB_t.

5. Solving the Model

Using the Bellman equation specification to solve this dynamic resource allocation problem, we have

$$\max\ \Sigma_t Y_t + (1+\delta)^{-1} E_t V_{t+1} (NB_{t+1})$$

with V_{t+1}, the value function at the beginning of t+1 being equal to $\Sigma^T_{i=t+1} (1+\delta)^{-t} Y_i(X^*_i, n^*_{ai})$.

This can be written out as

$$\begin{aligned} \max \quad & p^* q_t(X_t, n_{at}, NB_t) - r^* X_t + w_n (L - n_{at}) \\ & +(1+\delta)^{-1} E_t [V_{t+1} (NB_t + nb_t (X_t, q_t | NB_t))] \end{aligned} \quad (7)$$

Assuming the nonnegativity of the decision variables (X_t, n_{at}), one can solve (7) via the first order conditions:

$$X_t: \quad p\,(\partial q_t / \partial X_t) - r + (1+\delta)^{-1} E_t\,[(\partial V_{t+1} / \partial NB_{t+1}) * (\partial nb_t / \partial X_t)] = 0 \quad (8)$$

$$n_{st}: \quad p\,(\partial q_t/\partial n_{st}) - w_n + (1+\delta)^{-1} E_t\,[(\partial V_{t+1} / \partial NB_{t+1}) *(\partial nb_t/\partial q_t) * (\partial q_t/\partial n_{st})] = 0 \quad (9)$$

6. Discussion of Theoretical Results

6.1 Interpreting the first-order conditions:

Equation (8) typically defines a marginal condition that X_t must satisfy. Let's assume that X_t is reduced to a fertilizer capital input, i.e with nonzero residual factor that is applied annually (Chiao and Gillingham, 1989). Then, the optimal choice condition stated in equation (8) reflects intertemporal considerations to be accounted for in making the decision to use fertilizer. The optimality rule requires that the sum of current (marginal value product or the first term of the left hand side) and discounted future benefits of applying fertilizer (last term) be equal to its price, r. The future benefits are realized because of the replenishment of soil nutrients. As we know, applying fertilizer under normal conditions increases crop yield output and helps replenish soil by compensating for extracted nutrients; thus its overall benefits, ceteris paribus, are not only current yield increase, but also future yields, income, etc. Simply said, economically rational farmers will engage in replenishing soil nutrient up to the point where the marginal costs of replenishing nutrients by applying fertilizer are covered by the current and future marginal benefits. This result implies no value to the farmer to replenish the soil, except the benefits of increased future output.

Equation (8) also illustrates the impacts of having negative soil nutrient balance (or soil mining): in this case, the third term would be negative. X would then not include fertilizer, but practices that negatively affect nutrient flows. Then, for that equation to hold, current benefit i.e the marginal value product must be higher. In other words, mining the soil of its nutrients today to increase output is done at the expense of tomorrow's output. It follows from this optimal condition, farmers adopting nutrient-mining cropping practices incur a cost in terms of future output reduction, unless they replenish the soil.

Thus, farmers' behavior with respect to soil mining or replenishment will depend, among other things, on how much they trade off the present for the future, i.e, on their time preferences given by the discount rate. The less myopic preferences they have, the less they discount the future, the higher the cost, hence, the more nutrient replacement they will invest in.

Moreover, high subjective discount rates in excess of social rates of time preferences can cause farmers to undervalue the costs of soil mining, or equivalently the returns to soil-replenishing investments (McConnell, 1983). Another reason for this underinvestment by farmers, beyond the scope of this model, is related to the social emphasis argument of the imperfect market for environmental goods because of externalities (social benefits) and/or imperfect knowledge that leads individual producers to undervalue them and, hence, underinvest in them.

Equation (9) governs labor allocation within the farm household between on and off-farm activities. It states that labor is optimally allocated at the point where the marginal value product of farm labor equates the returns to nonfarm labor, w_n. The last term of this equation shows the effect of labor allocation on future income via soil conditions: as more labor is withdrawn for farming to be engaged in nonfarm, the second term is reduced (less crop output, less future benefits), the current productivity of farm labor has to increase for that equation to hold.

6.2 Predicting the impacts of selected policy measures:

This theoretical model not only captures the biophysical interactions between crop yields and soil nutrient stocks (equations 2 and 4), but also can be used to describe the behavior of a rational farmer seeking to maximize returns to farming and having to choose among different cropping practices and mindful of the soil fertility impacts[6] of each of them. His decision rules defined by equations (8) and (9) can be used to trace out the expected farm-level impacts of selected policy measures. Using the above model, the following effects can be anticipated.

Changes in input and output prices (increase in p and decrease in r) affect the choice of input sets (X_t) through equation (2). Physical capital transfers such as the phosphate product give-away program launched in Senegal affect the initial stock of soil nutrients, NB_0. Under this program, phosphate products are distributed to farmers to apply to their cropped soils in order to remedy their deficiency in the phosphorus nutrient. These combined changes have an impact on land productivity. Anticipated direct effects on crop production are positive according to equation (2). Impacts on soil nutrients are traced through equation (4): (i) positive since changes in X_t and NB_0 affect directly NB_{t+1} and (ii) negative as increased crop yields (q_t) mean higher nutrient uptake by crop plants from the soil. Therefore, the net effects i.e the soil nutrient balance will be determined by the magnitude of these opposing effects.

2 This may be a strong assumption, but one can argue that while most farmers cannot measure these impacts, they recognize that certain practices contribute in the long run to the decline or increase of crop production due to land quality changes.

7. Conclusions

This theoretical model conceptualizes farm household decisions in a dynamic multi-sectoral framework and provides an opportunity to explain farmers' behavior and to anticipate possible impacts of policy interventions. By explicitly incorporating in the production process the dynamic effects of soil quality represented here by soil nutrient replenishment at the farm level, it explains how optimal i.e expected income-maximizing fertilizer use decisions by farmers involve considering the incremental production flows in different time periods (as a result from its application) and also the intertemporal tradeoff between current versus future output. The magnitude of the tradeoff depends on the discount rate. Farmers with high discount rates are more likely to mine the soil of its nutrients to get increased output in the short term at the expense of tomorrow's output. In contrast, those with lower discount rates are more likely to adopt soil-replenishing practices that maintain or increase future output.

References

Adesina, A.A., P.C. Abbott and J.H. Sanders. 1988. Ex-ante Risk Programming Appraisal of New Agricultural Technology: Experiment Station Fertilizer Recommendations in Southern Niger. *Agricultural Systems*, 27:23-35.

Anderson, J. R., J. L. Dillon and J. B. Hardaker.1977 Agricultural Decision Analysis. Ames, Iowa: The Iowa State University Press.

Binswanger, H. 1990. Attitudes Toward Risk: Experimental Measurement in Rural India. *American Journal of Agricultural Economics* 62:395-407.

Burt, O. R. 1981. "Farm level Economics of Soil Conservation in the Palouse Area of the Northwest". *American Journal of Agricultural Economics*, 63: 83-91.

Coulibaly, O., J. Vitale and J. Sanders. 1998. Expected Effects of Devaluation on Cereal Production in the Sudanian Region of Mali. *Agricultural Systems*, 57, no.4.

Chiao, Y. and A Gillingham. 1989. The Value of Stabilizing Fertilizer under Carry-Over Conditions. *American Journal of Agricultural Economics*. May,352-362.

Dalton, Timothy. 1996. Soil Degradation and Technical Change in Southern Mali. Ph.D Dissertation. Department of Agricultural Economics, Purdue University, West Lafayette, IN.

Delgado, C., J. Hopkins and V. Kelly. 1994. Agricultural growth linkages in sub-Saharan Africa: A synthesis. p. 22-26. *In* Proc. of a Workshop on Agricultural Growth Linkages in Sub-Saharan Africa, Washington, DC. 26 May 1994. Int. Food Policy Res. Inst., Washington, DC.

Diagana, Bocar, V. Kelly and A. A. Fall. 1995. " Dévaluation du Franc CFA et Décisions de Production Agricole: Une Analyse Empirique de l'Impact de la Dévaluation du Franc CFA sur les Choix de Culture et de Technologies de Production par les Ménages Ruraux du Bassin Arachidier du Sénégal" paper presented at PRISAS regional workshop "Impact de la Dévaluation du Franc CFA sur les Revenus et la Securité Alimentaire en Afrique de l'Ouest", Bamako, Mali, June.

Dillon, J and P. Scandizzo. 1978. Risk Attitudes of Subsistence Farms in Northeast Brazil: A Sampling Approach. *American Journal of Agricultural Economics*. 60:425-435.

Honfoga, B.G. 1999. Farmers Perceptions of Soil Fertility Resulting from Adoption of Improved Farm Technologies in Southern Togo. *in* Debrah, S.K. and W. G. Koster (eds). Linking Soil Fertility Management to Agricultural Input and Output Market Development: the key to Sustainable Agriculture in West Africa. IFDC-Africa, Lome, Togo.

Kelly, V., T. Reardon, B. Diagana, A. Fall and L. Mcneilly.1993. "Final Report for the IFPRI/ISRA Study of Consumption and Supply Impacts of Agricultural Price Policies in the Peanut Basin and Senegal Oriental" (2 volumes), submitted to USAID/Senegal, September.

Larson, B.A. and G.B. Frisvold. 1996. Fertilizers to Support Agricultural Development in Sub-Saharan Africa: What is needed and Why? *Food Policy*, vol. 21, no. 6: 509-525.

McConnell, K. 1983. "An Economic Model of soil conservation." *American Journal of Agricultural Economics*. 65: 83-89.

McIntire, J. 1986. Constraints to Fertilizer Use in sub-Saharan Africa. In *Management of Nitrogen and Phosphorus Fertilizers in sub-Saharan Africa*. eds A. U. Mokwunye and P. L.G. Vlek Proceedings of a symposium. Martinus Nijhoff Publishers.

Moscardi, E. and A. de Janvry. 1977. Attitudes Toward Risk among Peasants: An Econometric Approach . *American Journal of Agricultural Economics*. 59: 710-716.

Reardon, T., E. Crawford and V. Kelly. 1994. Links Between Nonfarm Income and Farm Investment in African Households: Adding the Capital Market Perspective. *American Journal of Agricultural Economics*. 76(5):264-296.

Sadoulet, E. and A. de Janvry. 1995. Quantitative Development Policy Analysis. The John Hopkins University Press. Baltimore and London.

Saha, Atanu. 1994. A Two-Season Agricultural Household Model of Output and Price Uncertainty. *Journal of Development Economics*. 45: 245-269.

Sanchez, P.A, K. Shepherd, M. Soule, F. Place, R. Buresh, A-M. Izac, U. Mokwunye, F. Kwesiga, C. Ndiritu and P. Woomer. 1997. Soil fertility Replenishment in Africa: An Investment in Natural Resource Capital. In *Replenishing Soil Fertility in Africa* eds R. Buresh, P. Sanchez and F. Calhoun SSSA Special Publication Number 51. Madison, Wisconsin, USA: Soil Science Society of America and American Society of Agronomy.

Savadogo, K., T. Reardon, and K. Pietola.1994. Farm Productivity in Burkina Faso:Effects of Animal Traction and Nonfarm Income. *American Journal of Agricultural Economics*. 76: 608-612.

Scherr, S. J. 1999. "Soil Degradation: A Threat to Developing-Country Food Security by 2020?" IFPRI, Food, Agriculture and The Environment Discussion Paper 27, February..

Shapiro, B. and J. Sanders. 1998. Fertilizer Use in Semiarid West Africa: Profitability and Supporting Policy. *Agricultural Systems*, 56, no.4.

Singh, I., L. Squire and J. Strauss (eds). 1986. Agricultural Household Models. Baltimore: John Hopkins University Press.

Young, D.L. 1979. Risk Preferences of Agricultural Producers: Their Use in Extension and Research. *American Journal of Agricultural Economics*. 61(Dec.):1063-1070.

Van Kooten, G.C., W. P. Weisensel and D. Chinthammit. 1990. "Valuing trade-offs between net returns and stewardship practices: The case of soil conservation in Saskatchewan." *American Journal of Agricultural Economics*. 72: 676-680.

ESSAY II:

LAND AND QUALITY PRODUCTIVITY OF SELECTED CROPPING PRACTICES: AN APPLICATION OF BIOPHYSICAL MODELING TO THE SAHELIAN CONTEXT OF SENEGAL

1. Introduction

Agriculture production in SSA, especially in its ecologically fragile regions, has been plagued by low productivity and declining soil fertility levels. These two factors are interrelated. According to a CIMMYT report (1990),

> Soil fertility is determined by a combination of several factors including soil depth, texture, organic matter content, and nutrient replenishment (Speirs and Olsen, 1992). The most important components of soil fertility are the nutrients nitrogen, phosphorus, and potassium. Crop yields cannot increase without necessary nutrient levels, nor can yields be sustained over time or respond to other inputs such as new seeds and management practices without adequate levels of soil fertility.

Thus, a key farm-level issue determinant in stopping soil fertility decline and making cropping systems sustainable is how to economically replenish soil nutrients mined by crops (Coulibaly *et al.*, 1998). Three questions emerge from this key issue. The first one is the extent of soil nutrient mining or depletion without replacement. A second one deals with the alternative techniques or cropping practices available and/or used by farmers to replenish lost soil nutrients. The third one concerns the profitability of these practices under the uncertain physical environment of crop production in SSA.

Soil mining or nutrient depletion has been widely reported as a source of reduced crop yields in SSA agriculture (Stocking, 1987, Bishop and Allen, 1989; Cleaver and Schreiber, 1992; Speirs and Olsen, 1992), and also as a result of certain cropping practices or land uses.

In the empirical farm production literature in SSA, attempts have been made to measure the extent of soil nutrient mining, using conventional research methods of soil surveys and sample analyses (Stoorvogel *et al.*, 1993; Van der Pol *et al.*, 1993). But, a more comprehensive assessment of that problem should account for the close interactions between crop plant, weather, soil and management decisions through biological processes that govern plant growth and development (Hanks and Ritchie, 1991; Tsuji *et al.*, 1998). Keeping track of these dynamic processes under variable rainfall, soil condition, and management conditions requires tools with broader scope than conventional research methods. Fortunately, simulation models such as crop growth models are designed to handle such interactions, and provide an appropriate research tool for estimating crop yield and soil nutrient impacts of alternative cropping practices.

However, use of crop simulation models in SSA is still rare in the regional literature. Few applications are the calibration of QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) using data from maize fertilizer trials in Kenya (Smaling and Janssen, 1993), the use of EPIC (Erosion Productivity Impact Calculator) to assess the impacts of technological change in southern Mali (Dalton, 1996), and the use of CMKEN, a locally adapted version of CERES-Maize and a subset of DSSAT in Kenya to simulate crop yields subject to variable plant populations, cultivars, sowing dates and nitrogen fertilizer rates (Wafula, 1995). Moreover, the performance of most of these models under the extreme climatic conditions (total rainfall amount and its spatial and temporal distribution) of the Western Sahel has seldom been validated to date.

The range of technical options available to farmers to improve land quality and productivity is limited. Crop rotation helps smooth macronutrient consumption across crops, and leads to higher crop yields than monocropping (Bationo and Lompo, 1999), in addition to reduced soil erosion, less negative environmental externalities, better soil fertility and less need for commercial fertilizer (Gebremedhin and Schwab, 1998). However, with the breakdown of fallow systems under demographic pressure (Speirs and Olsen, 1992; Gaye *et al.*, 1996; Dalton, 1996), and the incapacity of manure alone to provide the key for attaining sustainable yield levels (Williams *et al.*, 1995), fertilization remains the only option. It has even been argued that substantial growth in external inputs use in the form of inorganic fertilizers is needed to sustain crop production and agricultural growth in SSA (Breman, 1990; McIntire and Powell, 1995; Larson and Frisvold, 1996), and to prevent mining of soil nutrients (Seckler *et al.*, 1991).

But, considering historically low levels of inorganic fertilizer use by farmers in these regions, between 12-15 kg/ha, one should rightly wonder whether inorganic fertilizer use is seen by farmers as less profitable than alternative crop production practices, hence explaining its nonuse. Mixed evidence exists on this question, which has experienced renewed interest and urgency in policy and research circles after the lackluster results of the 1980s Structural Adjustment Programs and the challenge to reverse the downward agricultural productivity trend and the man-caused soil fertility decline of already nutrient-poor soils.

In Senegal, which lies in the arid western Sahelian area of SSA, observed farming practices include rotating millet and peanut crops grown usually without fertilizer and with different plant densities. One of these practices that allegedly aggravates the soil mining problem is the practice of higher than recommended levels of seeding density for peanut cropping with no fertilization at all. Farmers justify it mostly by the desire to dampen yield reduction due to soil fertility or seed quality decline or lack of fertilizer (Gaye *et al.*, 1996). But, agronomists argue it reduces crop yields and soil nutrient levels in the long run (Kelly *et al.*, 1996). Despite works by Kumar and Venkatachari (1971) who found that closer intra-row spacings, thus higher seeding densities, led to higher peanut yields than farther spacings in India, the magnitude of the yield and soil fertility effects of these practices in the Sahelian areas of West Africa is generally unknown. As Freud *et al.* (1997) pointed out in their study of the 'peanut crisis' in Senegal, there is a dearth of research on the evolution of soil fertility in the areas under peanut cropping and its effects on peanut yields.

2. Research Objectives and Questions

Our research objective is to fill the empirical knowledge gap on the three questions described above. They all require measuring the long term yield and soil nutrient impacts of different cropping practices. These measures depend upon a well-calibrated and validated crop simulation model. This study will specifically seek a) to modify and validate a particular crop growth model to the sahelian context of Senegal, and b) to use the model results to answer the following research questions:

1. What are the average long term effects of millet-peanut crop rotation under different cropping practices (fertilizer application rates and seeding densities) on crop yields and soil nutrients in the Senegalese Peanut Basin?

2. Which of these crop rotation practices is financially more profitable in the long run under the risky conditions of crop production?

The main hypothesis to be tested is whether the practice of using fertilizer on millet-peanut rotation is financially more profitable in the long run than other cropping practices under the variable weather and agricultural production conditions existing in western Sahel.

3. Cropping Systems in the Senegalese Peanut Basin

Most of the agricultural output in Senegal comes from the Peanut Basin, which is "a vast (sahelian) area of rainfed peanut and millet production that represents 33% of Senegal's land area, 65% of its rural population, 80% of its exportable peanut production, and 70% of its cereal production" (Kelly *et al.*, 1996). Agricultural production is mainly done by smallholding farmers that use traditional cropping practices characterized by continuous cultivation of soils without fertilization. Yields for millet(a food crop) and peanut (the main source of cash income) are low and highly variable following the vagaries of rainfall (see figure 1.1) and policy environment. During the last decade, they seem to have turned downward for peanut and at best stayed stable for millet (see figure 1.2). Most varieties grown in the Peanut Basin are short cycle. Dry planting before the first useful rain[7] is common for millet as it frees labor for peanut cropping; re-seeding is done when no rains of 7 mm or more fall in the same week. Seeding for peanut is done the day after the first useful rain. Observed seeding densities for peanut can vary up to twice the recommended 60 kg/ha of grains.

---

1 Defined as the first rain of 20-25 mm not followed by a 25-30 day drought period.

Rural household incomes are very low, ranging from CFA 30 to 60,000 ($50-100 US)[2] per adult equivalent per year across agroclimatic zones (Kelly *et al.*, 1993). World Bank Living Standard Measurement Survey results showed that more than half (58%) of rural households live below the poverty line and most of these poor are located in the Peanut Basin (Republic of Senegal/MA/GRS, 1997). One consequence of these low incomes and of the limited cash flows is that they constrain farmers' capacity to make capital investments to restore soil fertility and allow a transition from traditional systems to more productive/intensive systems.

During the last three decades, input distribution and price policies in Senegal have been characterized by frequent episodic and incoherent changes that added to the instability of the production environment (Diagana *et al.*, 1996). The 1980 Structural Adjustment Program contained a progressive elimination of subsidies (especially for inputs). As a result, fertilizer use followed a downward trend at the national (annual growth rate of -1.8% from 1965 to 1996; more pronounced decline between 1980 and 1986; see figure 1.3) and farm levels (Kelly *et al.*, 1996).

An outcome of the interaction of factors above has been the declining fertility status of most of Senegalese soils: 70% of them are rated from 'poor' to 'very poor' in terms of suitability to agriculture (Mbodj, 1987). These tropical ferruginous soils are poor in physical and chemical characteristics. Their topsoil and subsoil textures are characterized by sandy or clay-sandy layers, high kaolinite dominance in the clay fractions, low water holding capacity, low organic matter and low cation exchange capacity (Sheldon, 1987; Mbodj, 1987), all of which affect crop response.

---

2 $1.0 US = CFA 600

Figure 1.1: Total annual rainfall in Senegal

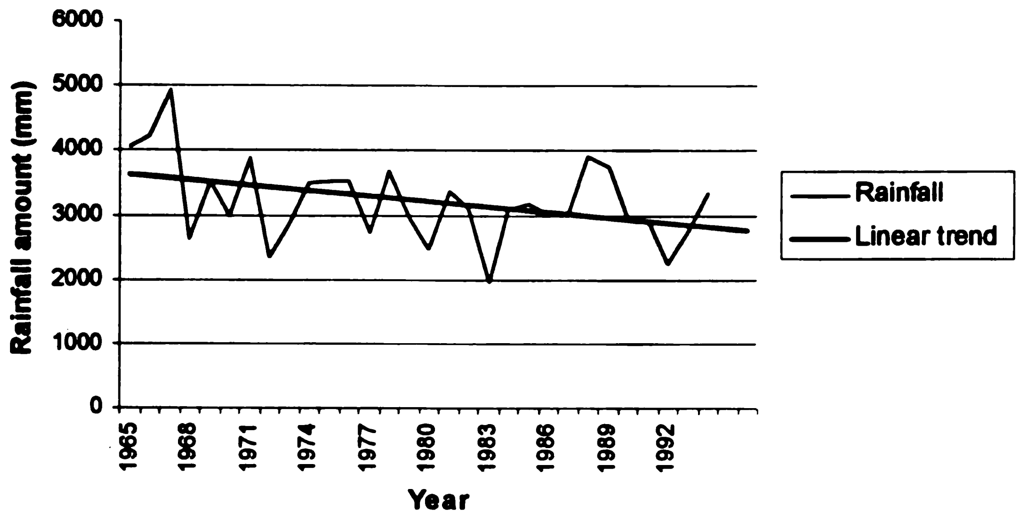


Figure 1.2: Average millet and peanut yields in Senegal

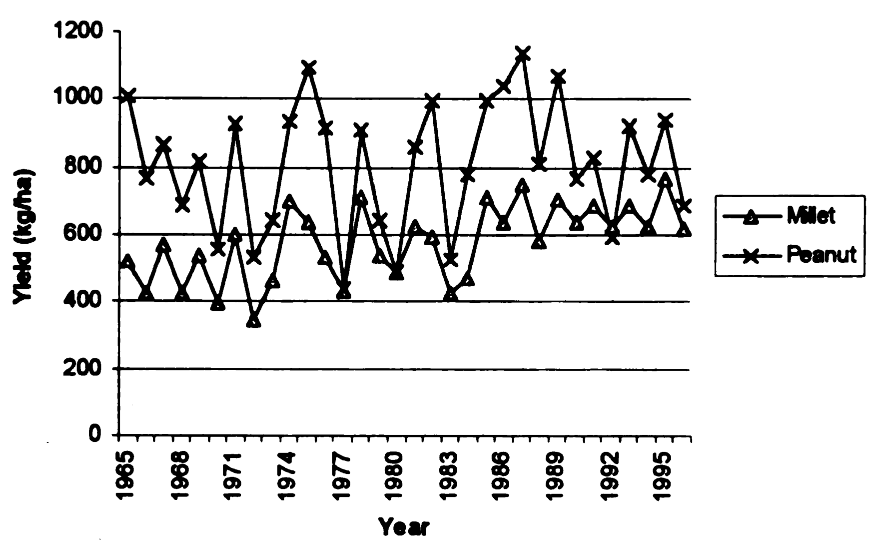
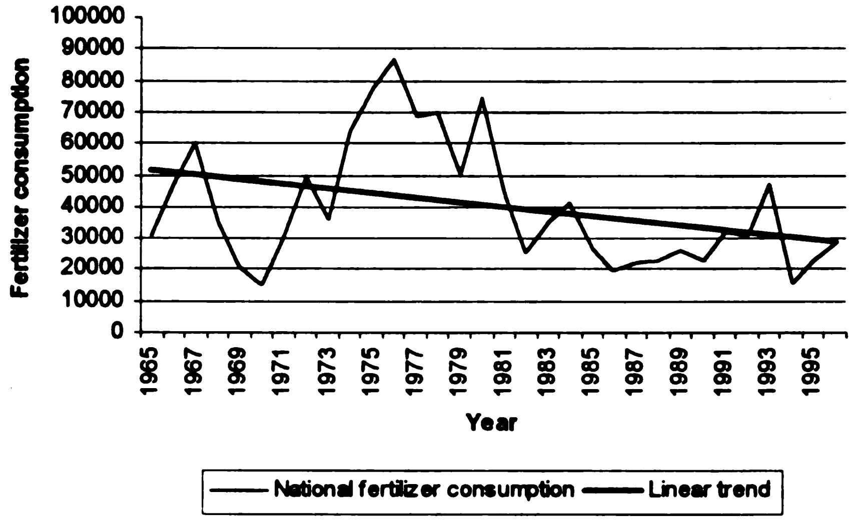


Figure 1.3: Total inorganic fertilizer (all formulas) consumption in Senegal (in metric tons)



Around 70-75% of the 2.25 million ha of cropped lands in 1995 were soil nutrient deficient (Republic of Senegal/ICS/SENCHIM, 1996). Particularly serious is the high phosphorus (P) deficiency of most Senegalese soils (Republic of Senegal/MA/"Bureau Pédologie", 1995; 1997), as levels of total P in soils are in general low. Where total P is higher, it is not easily available to plants because of the high fixation capacity of soils. Regressing or disappearing fallow systems in most areas limit the effectiveness of natural soil nutrient replenishment mechanisms. This places the P-deficiency as the most important biophysical constraint to increased agricultural production that needs to be addressed (Republic of Senegal/MA, 1996).

4. Materials and Methods

4.1 Materials:

Two zones of the Peanut Basin, center and southeast, have been chosen for this study because of the importance of rainfed millet and peanut production, their different weather and soil characteristics, and the availability of data. A 20-year long (1977-96) series of daily minimum and maximum temperature, sunshine hours and rainfall data for two locations in Senegal was collected from the ISRA (Senegalese Agricultural Research Institute) Bioclimatology Center in Bambey, Senegal. The two weather stations, Bambey and Nioro, respectively lie in the heart of the center and southeast Peanut Basin[9] (see tables 1.1a,b for their weather characteristics). Rainfall is one of the most limiting factors to agricultural production in the arid areas of the Senegalese Peanut Basin. The rainy season lasts from June to October when peanut and millet crops are grown; annual total rainfall averaged 497 mm in Bambey and 674 mm in Nioro over the 1977-96 period and was highly variable.

Soil laboratory analysis results collected from the "Bureau Pédologie" of Senegal characterize soils from two sites: Colobane in the center and Dioly in the southeast. These sites are close to the weather stations above. Common soils are tropical ferruginous type: as

3 These two stations are the only ones located in the two studied zones of the Peanut Basin for which a complete series of climatic data are available.

Table 1.1a: Weather Characteristics, Center Peanut Basin, Senegal (Bambey station: latitude: 14.7N, longitude: -16.5)

MONTHLY AVERAGES (1977-96)					
Month	Solar Radiation	Temperature		Total Rainfall	
	MJ/m2	Max.(°C)	Min.(°C)	Amount (mm)	Days
January	17.8	32.4	16.6	1.6	0.3
February	20.4	34.9	17.9	1.2	0.2
March	22.2	35.8	18.8	0.1	0.1
April	24.0	35.8	19.3	0.2	0.1
May	23.1	36.8	20.7	0.3	0.2
June	20.9	36.2	22.9	31.6	2.5
July	20.8	34.4	24.0	87.5	8.1
August	20.2	33.0	23.8	196.1	14.0
September	19.9	33.4	23.6	155.2	11.9
October	20.3	36.3	22.4	21.0	3.6
November	18.8	36.1	19.2	1.4	0.2
December	16.9	33.3	17.3	0.6	0.4

Table 1.1b: Weather Characteristics, Center Peanut Basin, Senegal (Nioro station: latitude: 14.1N, longitude: -16.1)

MONTHLY AVERAGES (1977-96)					
Month	Solar Radiation	Temperature		Total Rainfall	
	MJ/m2	Max.(°C)	Min.(°C)	Amount (mm)	Days
January	17.7	34.0	15.1	0.0	0.0
February	20.4	36.3	16.4	0.0	0.0
March	22.7	37.2	18.8	0.0	0.1
April	23.5	38.0	20.4	0.0	0.0
May	22.8	38.0	22.3	3.5	0.8
June	19.6	36.4	23.9	62.7	5.2
July	20.5	33.4	24.0	166.7	11.9
August	20.3	32.1	23.5	235.4	15.8
September	19.6	32.5	23.2	153.9	12.7
October	20.0	34.7	22.5	47.2	4.8
November	18.6	36.4	18.2	2.8	0.2
December	16.7	34.2	15.3	1.4	0.3

Source: Calculated by DSSAT3.5 weather using data from ISRA Bioclimatology Center, Bambey, Senegal.

illustrated by their physical and chemical characteristics (tables 1.2a,b), their soil fertility status is generally rated as low.

A major problem for model validation is the dearth of good quality crop yield data series. The only source we found available was the "Amelioration Fonciere" research trial yield data sets[10] on the same two zones of the Peanut Basin. Since they concern peanut millet rotation under different rates of NPK fertilization for different years between 1973 and 1982, they will be used to validate the simulation model and their limits discussed.

4.2 Simulation Experiments:

For validation purposes, three N and P fertilizer treatments similar to those used in the collected experimental data are considered for each crop of the millet-peanut rotation: 0-0, 61-14 and 84-14 kg/ha of N and P for millet and 0-0, 12-12 and 16-16 kg/ha of N and P for peanut.

Three NPK fertilizer treatments were considered. The control treatment receives no fertilizer at all and reflects traditional cropping practices. The semi-intensive treatment involves applying 75 kg of 6-20-10 NPK on peanut and 150 kg of 14-7-7 and 100 kg of urea on millet. The intensive treatment consists of 150 kg of 6-20-10 on peanut and 200 kg of 14-7-7 and of urea on millet. Other specifications such as seeding and spacing are described in tables A.1.a and A.1.b (in appendix) which summarize agronomic information on these two crops in Senegal. Based on combinations of these three treatments, six scenarios to be simulated in each of the two zones of the Peanut Basin are:

---

4 See Kelly, 1988 for a detailed description of these data sets.

Table 1.2a: Soil Characteristics, Center Peanut Basin, Senegal (site: Colobane)

Layer	Water Limit			Bulk Density	Organic carbon	Content		Nitrogen	pH	CEC
	Lower	Drained upper	Saturated			Clay	Silt			
cm	%	%	%	g/cm3	%	%	%			
5	10.5	23.7	32.0	1.61	0.17	6.9	36.2	0.019	4.7	1.53
15	10.5	23.7	32.0	1.61	0.17	11.4	31.0	0.019	4.7	1.53
30	10.5	23.7	33.1	1.66	0.16	17.0	9.6	0.017	4.7	1.83
45	10.5	23.7	33.2	1.54	0.16	16.7	11.6	0.017	4.7	1.83
60	10.5	23.7	33.2	1.54	0.16	19.5	10.8	–	4.6	1.53
90	18.0	29.0	33.1	1.57	0.16	28.5	9.8	–	4.6	1.35
150	18.0	29.0	33.1	1.55	0.16	27.7	9.6	–	4.6	1.35

Table 1.2b: Soil Characteristics, South Peanut Basin, Senegal (site: Dioly)

Layer	Water Limit			Bulk Density	Organic carbon	Content		Nitrogen	pH	CEC
	Lower	Drained upper	Saturated			Clay	Silt			
cm	%	%	%	g/cm3	%	%	%			
5	10.5	23.7	32.0	1.62	0.29	6.9	36.2	0.020	6.4	3.95
15	10.5	23.7	32.0	1.62	0.26	11.4	31.0	0.020	5.9	4.30
30	10.5	23.7	33.1	1.58	0.70	17.0	9.6	0.050	5.4	7.22
45	10.5	23.7	33.2	1.58	0.29	16.7	11.6	0.030	5.7	6.37
60	10.5	23.7	33.2	1.54	0.30	19.5	10.8	–	6.0	7.12
90	18.0	29.0	33.1	1.57	0.30	28.5	9.8	–	6.1	8.62
120	18.0	29.0	33.1	1.55	0.30	27.7	9.6	–	6.0	5.37

Source: Bureau Pedologie, Senegal, 1991-3 for organic C, clay, silt content, N, pH, CEC variables; bulk density is from Sene, 1995; soil water content variables were calculated using Ratliff *et al.* (1983) indications. Note that clay and silt content data are identical for both sites; they were missing for the Colobane site and we used those from the Dioly site.

- no fertilizer on either crop (MP-00),

- no fertilizer on either crop, and high seeding density on peanut (MP-HSD0),

- no fertilizer on millet, but intensive scheme on peanut (MP-02),

- semi-intensive on both crops (MP-11),

- intensive on both crops (MP-22), and

- intensive on both crops, but with an initial one-time basal application of a 50-50 blend of 400 kg/ha of tri calcium phosphate and phosphogypsum (MP-2PP).

The first three scenarios are observed practices while the last three are recommended, but seldom observed in the Peanut Basin. Soil conditions are initialized as of 1991 for the center and 1993 for the south of the Peanut Basin. Replications are each of the 20-year actual historical weather sequence (1977-96) that displays a wide range of good and also very severe climatic conditions, allowing to capture variability in rainfall, temperature and sunlight that influences year-to-year crop yield outcomes.

4.3 Simulation Methods:

4.3.1 Description of the crop growth simulation model:

The Decision Support System for Agrotechnology Transfer (DSSAT, version 3.5 with P) model, a product of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) is used. DSSAT3.5P contains a set of crop growth simulation models. The CERES models simulate cereal crops (Jones and Kiniry, 1986) whereas the CROPGRO models handle legume crops (Wilkerson *et al.*, 1983). Parsch *et al.* (1991) describe the CERES models as a family of physiologically-based crop growth models that simulate the effects of management and environmental variables on daily dry-matter growth, vegetative and reproductive development, and crop yield. Type of cultivars, planting time and density, fertilizer levels are among the user-specified management variables. Environmental variables also specified by the user range from daily weather data to parameters showing the basic characteristics of the soil profile. Both CERES-Millet and CROPGRO-Peanut models of DSSAT3.5P will be used in this research.

DSSAT3.5P has been credited with two advantages over other crop growth simulation models. First, it provides a more detailed accounting of phenological development and stresses encountered in each phenological stage than other models (Kiniry, 1991; Jones *et al.*, 1991), hence enabling a more accurate prediction of variation in crop yields from year to year under different planting dates. Second, it requires only moderate amounts of input data (Krause, 1992; Chu, 1997). Moreover, initially built with a nitrogen (N) focus, the addition of a P-component has made it suitable for our purpose of simulating both N and P dynamics in a country where P is deficient in most soils while significant phosphate deposit reserves exist.

4.3.2 Model modification and testing:

Three main modifications were made to DSSAT3.5P. One concerned some of the soil parameters. Soil water parameter estimates were not available from the aforementioned collected soil data sets. Thus, drained upper limit and lower limit were determined on the basis of textural characteristics of soils in the two zones, following indications in Ratliff *et al.*, (1983). Adjustments were then made to the chemical parameters that control the pace at which P from the applied NPK fertilizer flows in to the labile P pool, and also the flows between the labile P and the active and stable P pools. In the experiment files, the harvest mode was changed to vary the level of crop residues carry-over between periods. It was set to 100% to make all grain and top plant residues harvested, which is consistent with the observed use of crop residues by farmers for purposes (animal feed, fuel, construction, etc.) other than their reincorporation in the soil.

Test of millet model: To calibrate the CERES-Millet model, we started with its ICRISAT, Niger local adaptation to similar sahelian conditions. It was modified and then tested under different NPK fertilizer levels described earlier, using the 1977 weather year and soil conditions in the two zones of the Peanut Basin.

One specific modification was to revise the genetic coefficients of cultivars used in the Niger-adaptation of the model in order to reflect the characteristics of those grown in Senegal (IBV 8001 and 8004). After many model runs, we adjusted the growth genetic characteristics, using observed cycle length (physiological maturity date minus planting date) and yield as calibration tools.[11] The thermal time from seedling emergence to the end of the juvenile phase during which the plant is not responsive to changes in photoperiod, P1, was set equal to 75 degree days, the thermal time from beginning of grain filling to physiological maturity or P5 to 400 degree days and PHINT, the Phylochron interval or the interval in thermal time between successive leaf tip appearances to 60 degree days. All other characteristics were kept similar to those of the IB00044-CIVT cultivar used in Niger.

Test of peanut model: The same procedure was also applied to the CROPGRO-Peanut model. Unfortunately, no Sahel adaptation of the model was found as the CROPGRO

---

5 After a sensitivity analysis to get harvest maturity date and yield estimates reasonably close to observed in 1977, changes were finally made first on P1 and P5, and then on PHINT.

model was developed for conditions very different from those in Senegal in terms of cultivar, weather and soil type. Modification was made on the cultivars by adjusting some of the characteristics of the Spanish and Virginia cultivars that appear to be the closest to the ones grown in Senegal.[12]

4.4 Data Analysis Methods:

First, for validation purpose, the sequential mode of DSSAT3.5P designed for crop rotations is used to carry out runs of CERES-Millet and CROPGRO-Peanut under the same fertilizer treatments as are in the observed experimental crop yield data sets described earlier, using historical weather data from 1977 to 1982 in each of the two zones in the Peanut Basin. A graphical analysis of these results is done to demonstrate the model performance.

Second, the validated model is run again for 20 years, but under the six scenarios described earlier. Under each scenario, the model simulates a 20-year long series of crop yields and soil nutrient balances. Descriptive statistics of these modeling outputs are calculated to answer the first research question.

Third, these simulated yields data are used along with historical input and output prices to construct cumulative probability distribution curves of gross margins over variable costs per ha for each of the six scenarios.[13] Gross margins are defined here as total value of

---

6 Based on personal communication by O. Ndoye (peanut plant breeder, ISRA/Senegal, doctoral candidate, Texas, A&M, USA), Spanish could be used to approximate either 55-437 or Fleur 11 or 73-30; by the same token, Virginia can mirror either 28-206 or GH119-20.

7 Using either the gross margins or the net returns criterion has been found to lead to consistent results in terms of ranking different cropping practices (Gebremedhin and

yield output minus seed and chemical input (fertilizer, urea, fungicides) costs. In the distribution of these gross margins are embedded production risks due to weather, hence yield variability. These probability distributions of the different scenarios or cropping practices are then ranked using stochastic dominance (SD) ordering method[14] to determine risk-return tradeoffs and answer the second research question.

5. Results and Discussion

5.1. Model Validation Results:

Overall, the model does a reasonable job of simulating crop yields for millet and peanut in the two zones of the Senegalese Peanut Basin over the 1977-82 period. Plotted observed versus simulated yield points are scattered from the bottom left to the upper right corner in figure 1.4, suggesting a 1:1 relationship between predicted and measured observations. Regressing predicted on observed yield values gave a statistically significant coefficient of predicted yield equal to .97. A t-test of this coefficient being equal to 1 could not be rejected at 95%.

The curves depicting the cumulative sum of mean yields of the millet-peanut rotation under each of the three fertilization levels over the 1977-82 period are shown in figure 1.5.

Schwab, 1998; Paudel *et al.*, 1998).

8 As a risk efficiency criterion, SD incorporates information on risk and expected returns in identifying a management strategy (cropping practice) that maximizes expected utility (here gross margins) and is preferred by decisionmakers with a known risk attitude (King and Robison, 1981; Boisvert and McCarl, 1990; Parsch *et al.*, 1991).

Figure 1.4: Observed vs simulated yields (kg/ha) of a hectare of millet-peanut rotation in the Senegalese Peanut Basin: 1977-82

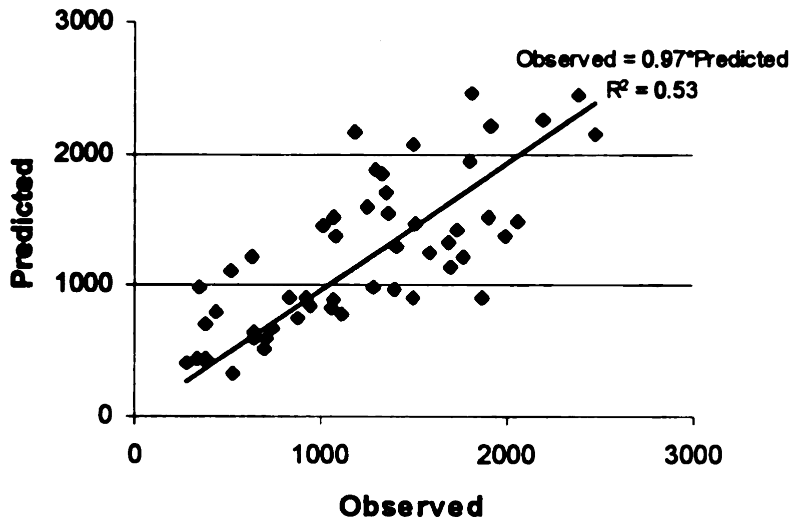
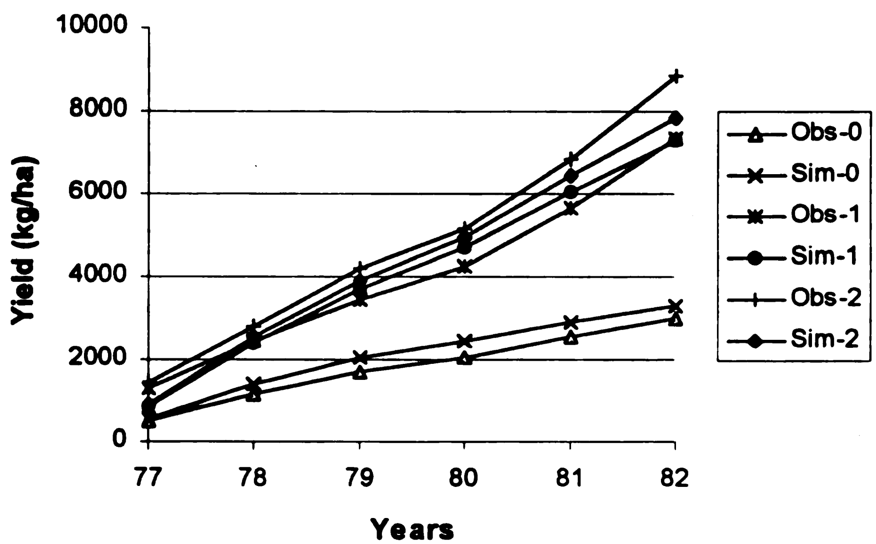


Figure 1.5: Cumulative sum of mean millet-peanut yields in the observed and simulated experiments at three levels of NPK fertilization in the Center Peanut Basin, Senegal



In general, the model estimated the yields accurately at all fertilization levels. A very good job was done for the control plot yield, with estimates (Sim-0) consistently close to measured (Obs-0) yields. The medium treatment predictions (Sim-1) show some overestimation in mid years, but converge to the observed (Obs-1) at the end. The high fertilization level (Obs-2 vs Sim-2) exhibits some overestimation in the last years. In light of this, the following points ought to be mentioned about both the measured and predicted data used for validation:

(i). Few extremes, i.e predictions for millet well below observed levels are observed in 1977. Low rainfall during that year and a period of drought of 2-3 weeks during critical periods of the millet plant's growth caused a serious water stress (.3 to .7 on a scale of 0 to 1, 1 being the maximum) which has significantly depressed biomass production, hence millet yields for all fertilizer treatments. This highlights the sensitivity of the model to water stress, a conditioner of the effects of nutrients on plant growth.

(ii). There is some uncertainty in the measured yield data illustrated by the absence of replications in the experiments, and some oddity observed in 1980 (very low yields for all treatments, especially for higher NPK fertilizer levels), due maybe to some problems (e.g., pest attack) that the model does not consider.

(iii). Distance between weather stations and crop experiment sites, though not substantial, may also have introduced some spatial variation that may explain differences between predicted and measured yields.

5.2. Simulation Results:

5.2.1. Long term biophysical outcomes of cropping practices:

5.2.1.1 Yield effects[15]:

Simulated yields of six cropping practices in both zones of the Senegalese Peanut Basin are compared in table 1.3. First, predicted yields from these zones seem consistent with national averages shown in figure 1.2, mostly between 400-800 kg for millet and 600-1000 kg for peanut in the 1977-96 period. As expected, the rainier southern zone has higher yields than the drier center under all cropping practices but non-fertilized millet.

Long-term average yields increase with fertilization levels for both crops in the two zones. Under no fertilization, increasing the peanut seed density adds very little to the peanut yield compared to the control plot in the long run. Allocating all acquired fertilizer to peanut, the cash crop for which input credits are more readily available than millet, is a common practice that also benefits the millet crop following the fertilized peanut with a gain of 239-266 kg over the control treatment. Results also indicate that participating in the phosphate distribution program under the recommended conditions, i.e using also NPK fertilizer, generates a combined millet-peanut yield gain of 125-159 kg/ha over the intensive treatment.

---

15 Simulated results on the water balance components are presented in appendices.

Table 1.3: Simulated long-term yield effects of selected millet-peanut cropping practices in the Senegalese Peanut Basin: 1977-96 (kg/ha/year)

		No fertilization		Semi intensive fertilization		Intensive fertilization		No fertilizer on either crop; HSD(b) on pn		No fertilizer on ml, intensive fertilizer on pn		Intensive fertilizer with PP(c)	
		ml(a)	pn(a)	ml	pn	ml	pn	ml	pn	ml	pn	ml	pn
Center	mean	306	332	669	690	793	950	301	352	545	849	853	1015
	stdev	190	184	227	168	266	211	189	192	195	204	326	286
	max	794	908	1113	1262	1223	1504	775	949	933	1535	1584	1867
	min	105	195	149	508	98	466	98	202	119	608	93	436
South	mean	294	533	686	1118	839	1556	290	554	560	1370	902	1652
	stdev	224	231	270	283	321	350	224	239	232	305	396	432
	max	977	1264	1281	1773	1380	2147	975	1316	1124	1917	1837	2674
	min	116	255	167	487	170	699	116	254	116	640	170	724

Legend:
(a) ml: millet; pn: peanut
(b) HSD: high seeding density
(c) PP: one-time basal application of phosphate products under the phosphate distribution program.

5.2.1.2. Soil nutrient effects:

The impacts of the cropping practices on selected characteristics of the soils are shown in tables 1.4a and 1.4b. Traditional non fertilizer-using cropping practices (MP-00 and MP-HSD0) contribute more to depleting pools of soil nutrients than other practices. For plant-available labile P and active P pool, the average annual rate of depletion is higher when no fertilizer is used. In contrast, the stable P pool is being replenished faster under fertilizer-using cropping practices as the latter give more yields, thus more roots returned to the soil that increase organic matter decomposition.

Inorganic N is being replenished under all practices, but faster when more N is externally applied and more is being fixed by the peanut plant. By contrast, the organic N pool is decreasing under all practices, and at a faster rate when no fertilizer is used, probably because of higher mineralization to release the necessary N required by the millet crop plant.

Comparing the two zones, one can note that average annual changes in the stock of P in the three different pools are almost the same while being very different for organic N. The organic N pool is decreasing almost twice as fast in the rainier south as the drier center zone. For the inorganic N, the replenishment is faster under almost all practices in the center than in the south.

Table 1.4a: Simulated average long-term effects of millet-peanut cropping practices on key soil nutrient pools* in the Center Peanut Basin, Senegal: 1977-96 (in kg/ha/year)

		CENTER					
		No fertilizer on either crop MP00	Semi-intensive fertilizer on both MP11	Intensive fertilizer on both crops MP22	No fertilizer on either; high seed density on peanut MPHSD0	No fertilizer on millet; intensive on peanut MP02	Intensive fertilizer on both with phosphate program MP2PP
P	Labile	-1.5	0.9	2.4	-1.5	0.9	2.6
	Inorganic active	-2.5	-2	-1.8	-2.5	-2	-1.7
	Organic active	-3.3	-3	-3	-3.3	-3.1	-3
	Inorganic stable	1.6	3.6	4.8	1.5	3.7	5.6
	Organic stable	0.9	1.6	2	0.9	1.6	2.2
N	Inorganic N	3.5	10	14.9	3.7	4.4	14.8
	Organic N	-46	-35	-31.5	-44.6	-35.2	-30.5

Notes: * All figures refer to annual changes in kg/ha (level at end-harvest minus level at beginning-planting) averaged over the simulation period.

. Initial levels in the Center of the Peanut Basin are respectively:

for labile P, 34 kg/ha;
for inorganic P in the active pool, 71 kg/ha;
for organic P in the active pool, 86 kg/ha;
for inorganic P in the stable pool, 278 kg/ha;
for organic P in the stable pool, 204 kg/ha;
for inorganic N (sum of ammonium and nitrate), 33.5kg/ha;
for organic N, 3333 kg/ha.

Table 1.4b: Simulated average long-term effects of millet-peanut cropping practices on key soil nutrient pools* in the South Peanut Basin, Senegal: 1977-96 (in kg/ha/year)

		SOUTH					
		No fertilizer on either crop	Semi-intensive fertilizer on both	Intensive fertilizer on both	No fertilizer on either, high seed density on peanut	No fertilizer on millet; intensive on peanut	Intensive fertilizer on both with phosphate program
		MP00	MP11	MP22	MPHSD0	MP-02	MP-2PP
P	Labile	-1.5	0.2	1	-1.7	-0.1	1.7
	Inorganic active	-2.5	-2.1	-1.9	-2.15	-2.1	-1.8
	Organic active	-4	-3.7	-3.6	-4	-3.7	-3.6
	Inorganic stable	1.1	2.9	4	1	3	4.7
	Organic stable	1.4	2.2	2.7	1.45	2.3	2.9
N	Inorganic N	3.2	5.9	7.6	3.3	2.7	7.6
	Organic N	-89.7	-80.6	-76.5	-88.2	-79.7	-75.5

Notes: * All figures refer to annual changes in kg/ha (level at end-harvest minus level at beginning-planting) averaged over the simulation period.

. Initial levels in the South of the Peanut Basin are respectively:

for labile P, 26 kg/ha;
for inorganic P in the active pool, 70 kg/ha;
for organic P in the active pool, 104 kg/ha;
for inorganic P in the stable pool, 274 kg/ha;
for organic P in the stable pool, 245 kg/ha;
for inorganic N (sum of ammonium and nitrate), 30.35 kg/ha;
for organic N, 6348 kg/ha.

5.2.2. Stochastic dominance analysis of cropping practices:

The cumulative probability density curves of gross margins over variable costs (labor not included) of the six cropping practices in the two zones of the Senegalese Peanut Basin are shown in figures 1.6 and 1.7. Using first-degree stochastic dominance (FSD) analysis, the graphs clearly indicate that non fertilizer-using practices (Cump-0 and Cump-hi0) are dominated by the others. In effect, at any level of gross margins per ha of millet-peanut used here as a crude measure of financial profitability, the probability of getting that level or less is always higher when no fertilizer is used at all. For any practice, this probability is measured as the vertical distance between any point on the X-axis and the corresponding curve. This means that, for farmers seeking to minimize the downside risk of getting low gross margins, FSD ordering suggests using fertilizer over not using it. For example, the likelihood of getting less than CFA 30,000 per ha of millet-peanut is almost certain (close to 100%) in the two zones when one does not use fertilizer.

Moreover, in both zones, using the intensive scheme on either the peanut crop only or on both crops (Cump-02, 22, 2PP) is financially more interesting in the long run than applying the semi-intensive scheme (Cump-1). Among the intensive fertilizer uses, no dominance is clearly exhibited by any scheme in neither zone . Finally, without fertilization, practicing high seeding density on peanut is dominated by applying the recommended seeding rate for gross margins per ha up to CFA 25,000 /ha in the Center and CFA 40,000 /ha in the South.

Figure 1.6: Cumulative probability distribution curve of gross margins over variable costs of a ha of millet-peanut rotation grown under selected management practices in Center Peanut Basin, Senegal: 1977-96

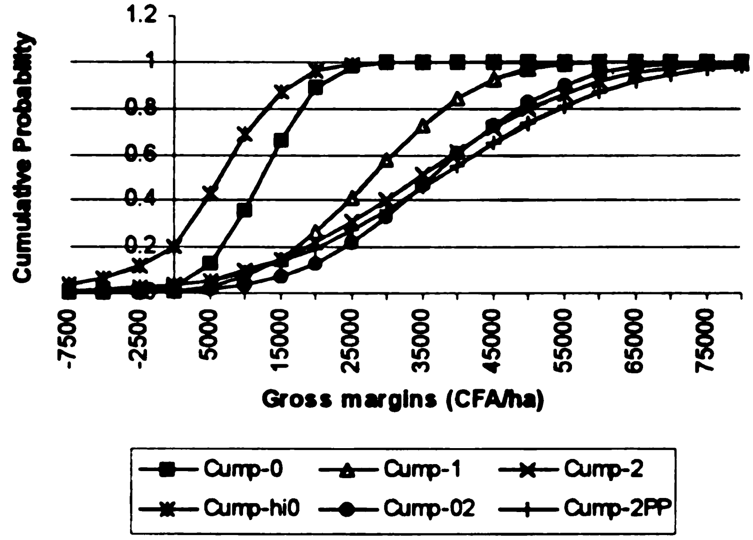
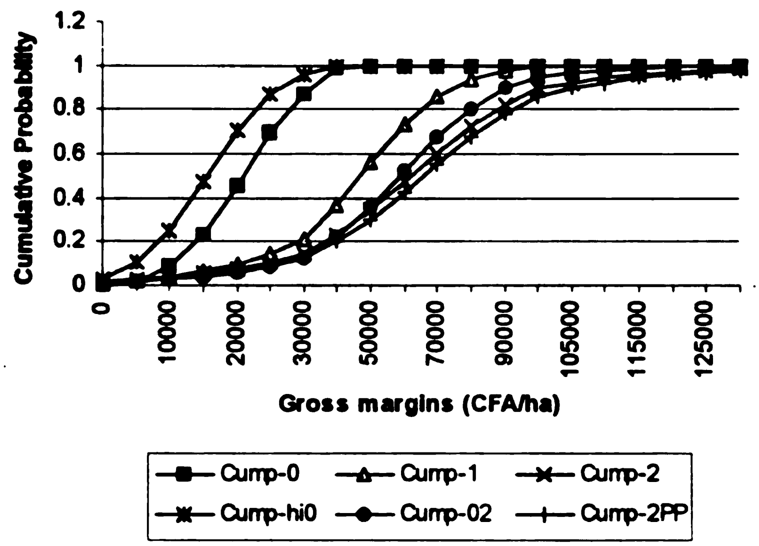


Figure 1.7: Cumulative probability distribution curve of gross margins over variable costs of a ha of millet peanut rotation grown under selected management practices in South Peanut Basin, Senegal: 1977-96



In sum, given variability in weather conditions and of yield outcomes, using fertilizer on millet-peanut rotation is a financially more attractive long term cropping alternative than not using it at all. In financial terms, practicing high seeding density on peanut is not supported in the long run by the results of this analysis. This lends some support to the argument that high peanut seeding density under no fertilization as done by farmers, while financially profitable in the short-run, is financially less interesting than other practices in the long term (Kelly *et al.*, 1996; 1998).

6. Conclusions

Crop simulation models provide a good research tool to study the land productivity as well as the environmental consequences of various cropping practices. The system approach upon which they are based to link biophysical conditions with behavioral crop management decisions in order to predict outcomes must, however, be shown to be as close to real situations as possible to gain wider acceptance in applied research. This study has shown that a modified, calibrated and validated version of the DSSAT model has performed reasonably well for millet and peanut cropping under the extreme conditions of western Sahel prevailing in the Senegalese Peanut Basin. However, more should be done to improve model adaptation to other areas it was not originally designed for. To accomplish this, the serious data constraint is to be overcome, and conducting research trials in areas such as those of western Sahel on major crops under variable physical and management conditions is a good and necessary step in that direction.

Modeling results clearly indicate as expected that, in the long run, observed and widespread practices of not using fertilizer on millet-peanut rotation:

(i) lead to low crop output,

(ii) contribute more to depleting the soil of the necessary macronutrients N and P, and

(iii) are financially less attractive to farmers than fertilizer-based practices in the Senegalese Peanut Basin.

These analyses done at the plot level highlight some strong incentives to use fertilizer and lend support to the view that financially and environmentally sustainable land uses in semi arid areas are possible through increased inorganic fertilizer use. However, another determinant of the use of this productivity-enhancing and soil nutrient-replenishing input is the capacity of farmers to get access to fertilizer at low cost, in a timely manner and when other competing needs for scarce liquidities are urgent. Going beyond this plot-level analysis by considering the overall environment in which the farmer operates (which is influenced by policymaking), his/her resource constraints and other objectives will shed more light on the financial attractiveness of this input. This can be done in a linear programming farm household model.

References

Bishop, J. and J. Allen. 1989.On-Site Costs of Soil Erosion in Mali. Environment Department Working Paper No. 21, World Bank, Washington DC, November.

Boisvert, R.N.and B. McCarl, 1990. Agricultural Risk Modeling Using Mathematical Programming. Southern Cooperative Series, bulletin No. 356, July.

Breman, H. 1990. No Sustainability Without External Inputs. p. 124-134. *In* sub-Saharan Africa beyond adjustment. Africa seminar, Maastricht. Project Group Africa. Directorate General for Int. Coop., Ministry of Foreign Affairs, the Hague, the Netherlands.

Chu, M.C. 1997. Designing Production Contracts to Reduce Agricultural Nonpoint Source Pollution. Ph.D dissertation. Dpt of Ag. Economics, Michigan State University, East Lansing, MI.

CIMMYT. 1990. CIMMYT World Maize Facts and Trends: Realizing the Potential of Maize in Sub-Saharan Africa. CIMMYT, Harare, Zimbabwe.

Cleaver, K. and G. Schreiber. 1992. The Population, Agriculture and Environment Nexus in Sub-Saharan Africa. Agriculture and Rural Development Series No. 1, Technical Department, African Region, World Bank, Washington, DC.

Coulibaly, O., J. Vitale and J. Sanders. 1998. Expected Effects of Devaluation on Cereal Production in the Sudanian Region of Mali. *Agricultural Systems*, vol. 57, no.4.

Dalton, T. 1996. Soil Degradation and Technical Change in Southern Mali. Ph.D Dissertation. Department of Agricultural Economics, Purdue University, West Lafayette, IN.

Diagana, B., V. Kelly and M. Kébé. 1996. "L'Offre Agricole Suite à la Dévaluation: Pourquoi Une Réponse Si Faible Au Sénégal?" ISRA/PASE-CILSS/PRISAS Note, October .

Freud, C., E. H. Freud, J. Richard and P. Therein. 1997. "La Crise de l'Arachide Au Senegal: Un Bilan-Diagnostic" CIRAD report, January.

Gaye, M and V. Kelly. 1996. L'Utilisation des Terres Agricoles dans le Bassin Arachidier du Senegal: Facteurs Determinants des Combinaisons Culturales et des Systemes de

Rotation. Michigan State University Department of Agricultural Economics Staff Paper no. 96-32, April.

Gaye M., M. Sene and V. Kelly. 1996. Facteurs Determinants des Densites de Semis de l'Arachide. Michigan State University Department of Agricultural Economics Staff Paper no. 96-29, April.

Gebremedhin, B. and G. Schwab. 1998. The Economic Importance of Crop Rotation Systems: Evidence From the Literature. Michigan State University Department of Agricultural Economics Staff Paper no. 98-13, August.

Hanks, J. and J. T. Ritchie (eds). 1991. Modeling Plant and Soil Systems. Number 31 in the series of Agronomy. American Society of Agronomy, Inc. Madison, Wisconsin.

Jones, C. A. and J.R. Kiniry (eds). 1986. CERES-Maize: A simulation model of Maize Growth and Development. College Station, TX: Texas A&M University Press.

Jones, C.A., K.J. Boote, S.S. Jagtap, and J.W. Mishoe. 1991. "Soybean Development" Ch. 5 *In* J. Hanks and J. T. Ritchie (eds). Modeling Plant and Soil Systems. Number 31 in the series of Agronomy. American Society of Agronomy, Inc. Madison, Wisconsin. 1991: 71-90.

Kelly, V., B. Diagana, M. Gaye, T. Reardon and M. Sène . 1998. "L'Ajustement Structurel Est-il Incompatible Avec Une Gestion Durable de la Fertilité des Sols: L'Experience Senegalaise dans le Bassin Arachidier" *in* G. Renard, A. Neef, K. Becker and M. Von Oppem (eds) "Soil Fertility Management in West African Land Systems" Proceedings of the University of Hohenheim (Germany), ICRISAT Sahelian Center and INRAN regional workshop, 3-8 March 1997 Niamey, Niger. Werkersheim: Margraf Verlag, 1998.

Kelly, V., B. Diagana, T. Reardon, M. Gaye and E. Crawford. 1996. Cash Crop and Foodgrain Productivity in Senegal: Historical View, New Survey Evidence, and Policy Implications, Michigan State University International Development Paper no. 20.

Kelly, V., T. Reardon, B. Diagana, A. Fall and L. Mcneilly. 1993. "Final Report for the IFPRI/ISRA Study of Consumption and Supply Impacts of Agricultural Price Policies in the Peanut Basin and Senegal Oriental" (2 volumes), submitted to USAID/Senegal, September.

Kelly, V..1988. Factors Affecting the Demand for Fertilizer in Senegal's Peanut Basin. Unpublished PhD thesis dissertation, Dpt of Agricultural Economics, Michigan State University, East Lansing, MI.

King R. P. and L. Robison. 1981. Implementation of the Interval Approach to the Measurement of Decision Maker Preference. Research Report 418, Michigan State University Agricultural Experiment Station, Michigan State University, November.

Kiniry, J.R.1991. "Maize Phasic Development". Ch. 4 *In* J. Hanks and J. T. Ritchie (eds). Modeling Plant and Soil Systems. Number 31 in the series of Agronomy. American Society of Agronomy, Inc. Madison, Wisconsin. 1991: 55-70.

Krause, M. A. 1992. Optimal adoption strategies for conservation tillage technology in Michigan. Ph.D dissertation. Dpt of Ag. Economics, Michigan State University, East Lansing, MI.

Kumar, M.A. and A. Venkatachari. 1971. Studies on the Effects of Intra Row Spacings and Fertility Levels on the Yield and Quality of two Varieties of Groundnut (*Arachis Hypogaea L.*)". *Indian J. of Agric. Res.* 5(2):67-73.

Larson, B.A. and G.B. Frisvold. 1996. Fertilizers to Support Agricultural Development in Sub-Saharan Africa: What is needed and Why? *Food Policy*, vol. 21, no. 6: 509-525.

Mbodj, M.1987. L'Utilisation des Engrais et la Production Agricole: Fertilisation des Cultures au Senegal et dans les Autres Pays de l'Afrique de l'Ouest. Mimeo, Ministry of Rural Development, Dakar, Senegal.

McIntire, J., and J.M. Powell. 1995. African Semi-arid Tropical Agriculture Cannot Grow Without External Inputs. p. 539-554. *In* J.M. Powell *et al.*, (eds.) Livestock and sustainable nutrient cycling in mixed farming systems of sub-Saharan Africa. Vol. II. Tech. Pap. Int. Livestock Ctr. for Africa, Addis Ababa, Ethiopia.

Parsch, L.D., M.J. Cochran, K.L. Trice, and H. D. Scott. 1991. "Biophysical Simulation of Wheat and Soybean to Assess the Impacts of Timeliness on Double-Cropping Economics". Ch. 22 *In* J. Hanks and J. T. Ritchie (eds). Modeling Plant and Soil Systems. Number 31 in the series of Agronomy. American Society of Agronomy, Inc. Madison, Wisconsin. 1991: 511-533.

Paudel, K., N. Martin, G. Wehtje, and T. Grey. 1998. "Economic Decision Making Using Enterprise Budgeting and Statistical Analysis: An Illustration in Weed Control Practices in Peanut Production." *Journal of Production Agriculture*, 11(1):48-73.

Ratliff , L.F., J. T. Ritchie and D. K. Cassel.1983. Field-Measured Limits of Soil Water Availability as Related to Laboratory-Measured Properties. *Soil Science Society of America Journal*, vol. 47, no. 4, July-August.

Seckler D., D. Collin and P. Antoine. 1991. Agricultural Potential of "Mid Africa": A Technological Assessment *in* Agricultural Technology in Sub-Saharan Africa, eds S. Gnaegy and J.R. Anderson, pp. 61-103, World Bank Discussion Paper 126, World Bank, Washington, DC.

Sene, M. 1995. Influence de l'Etat Hydrique et du Comportement du Sol sur l'Implantation et la Fructification de l'Arachide. These doctorat en Agronomie. Ecole Nationale Superieure Agronomique, Montpellier, Institut National de la Recherche Agronomique, Laon, France.

Senegal, Republic of, Ministry of Agriculture. 1996. Programme Agricole 1997/98. December.

Senegal, Republic of, Ministry of Agriculture, "Groupe de Reflexion Strategique". 1997. Rapport sur La Politique Agricole au Senegal.

Senegal, Republic of, Ministry of Agriculture, Bureau Pédologie. 1997. Programme de Restauration de la Fertilité des Sols du Sénégal. Avril.

Senegal, Republic of, Ministry of Agriculture, Bureau Pédologie. 1995. Rapport Annuel.

Senegal, Republic of, ICS/SENCHIM. 1996. Projet de Restauration de la Productivite des Sols au Senegal. Mimeo, Octobre.

Senegal, Republic of, Ministry of Energy, Mines and Industry. 1996. Projet de Fertilisation des Sols et d'Utilisation des Engrais Phosphates. October.

Sheldon, V.1987. Fertility Status of African Soils: a Handbook for Non Agronomists. Curriculum Publications Clearinghouse, Western Illinois University.

Smaling E.M.A. and B.H. Janssen. 1993. Calibration of QUEFTS, A Model Predicting Nutrient Uptake and Yield from Chemical Soil Fertility Indices. *Geoderma*. 59:1-4, 21-44.

Speirs M. and O. Olsen. 1992. Indigenous Integrated Farming Systems in the Sahel. World Bank Technical Paper No. 179, Africa Technical Department Series, World Bank, Washington, DC.

Stocking, M. 1987. Measuring Land Degradation. *In* Land Degradation and Society, eds. P. Blackie and H. Brookfield, Methuen, London.

Stoorvogel, J.J., E.M.A. Smaling and B.H. Janssen. 1993. Calculating Soil Nutrient Balances in Africa at Different Scales. I. Supra-national Scale. *Fertilizer Research*. 35(3): 227-235.

Tsuji, G.Y. *et al.*, (eds). 1998. Understanding Options for Agricultural Production. Kluwer Academic Publishers.

Van Der Pol, F. 1992. Soil Mining: an Unseen Contributor to Farm Income in Southern Mali. Royal Tropical Institute, Amsterdam.

Wafula, B.M. 1995. Applications of Crop Simulation in Agricultural Extension and Research in Kenya. *Agricultural Systems*, 49: 399-412.

Wilkerson, G. G., J.W. Jones, K.J. Boote, K.T. Ingram, and J.W. Mishoe. 1983. "Modeling Soybean Growth for Crop Management." *Trans. ASAE*, 26(1983):63-73.

Williams, T.O., J.M. Powell and S. Fernandez-Rivera. 1995. Manure Availability in Relation to Sustainable Food Crop Production in Semi-Arid West Africa: Evidence from Niger. *Quarterly-Journal-of-International-Agriculture*. 34:3, 248-258.

APPENDIX A2

Table A.2.a: Agronomic characteristics of millet production in the Peanut Basin (PB)

Millet Cultivar	Souna 3	IBV 8001	IBV 8004
Cycle length (days)	85 - 95	75 - 95	75 - 95
Seeding density (plant/ha)	30 000	30 000	30 000
Plant spacing (cm)	100 x 100	100 x 100	100 x 100
Rainfall zones (mm)	≥ 400 center & south PB	≥400 center & south PB	300 - 400 north PB

Source: M.Sene, agronomist, ISRA/Bambey, Senegal, personal communication, January 1998.

Table A.2.b: Agronomic characteristics of peanut production in the Peanut Basin (PB)

Peanut Cultivar	28-206 & GH119-20	73-33	Fleur 11	55-437 & 73-30
Cycle length (days)	120	110	90	90
Seeding density (plant/ha)	110 000	130 000	135 000	166 000
Plant spacing (cm)	60 x 15	50 x 15	50 x 15	40 x 15
Rainfall zones (mm)	≥700 Southwest PB	400 - 700 South PB	300 - 500 Center PB	300 - 500 Center north & north PB

Source: M. Sene, agronomist, ISRA/Bambey, Senegal, personal communication, January 1998.

APPENDIX A3

Table A3.1.a: **Summary of simulated water balance component results in Center Peanut Basin for no-fertilizer treatment**

Year	Total rainfall mm	Rain in crop season %	Total . runoff mm	Total drainage mm	Total Evapotransp. mm	Change in stored water mm
77	389	83.3	22	0	297	70
78	794	78.3	105	62	525	102
79	445	90.8	35	47	405	-42
80	404	93.8	32	83	309	-20
81	504	97.6	112	34	350	8
82	454	96.5	37	72	357	-12
83	434	58.9	56	0	318	60
84	342	96.5	39	37	323	-57
85	390	94.1	15	21	337	17
86	425	84.9	61	62	290	12
87	378	62.7	13	45	317	3
88	648	94.3	123	204	315	6
89	799	93.1	165	289	350	-5
90	392	88.2	36	18	376	-38
91	371	85.2	37	33	268	33
92	339	98.2	32	67	273	-33
93	500	93.2	85	126	255	34
94	484	90.1	79	94	344	-33
95	587	94.9	66	171	319	31
96	310	100	21	22	281	-14
Mean	469.4	88.7	58.55	74.35	330.45	6.1

Source: DSSAT3.5P outputs.

Table A3.1.b: **Summary of simulated water balance component results in Center Peanut Basin for semi-intensive fertilizer treatment.**

Year	Total rainfall mm	Rain in crop season %	Total runoff mm	Total drainage mm	Total Evapotransp. mm	Change in stored water mm
77	389	83.3	22	0	309	58
78	832	75.3	110	66	545	111
79	407	89.9	32	29	395	-49
80	429	88.3	33	64	334	-2
81	479	97.5	112	26	360	-19
82	529	82.8	60	45	385	39
83	359	50.4	32	0	329	-2
84	373	88.5	39	3	370	-39
85	359	93.6	15	0	358	-14
86	425	96.7	62	22	286	55
87	378	62.7	13	0	364	1
88	710	86	134	180	365	31
89	737	92.5	160	254	365	-42
90	392	88.3	37	0	412	-57
91	371	85.2	37	0	271	63
92	340	97.9	33	31	326	-50
93	499	93.2	85	66	295	53
94	565	77.2	104	81	390	-10
95	507	94.1	46	110	341	10
96	305	100	22	8	320	-45
Mean	469.2	86.2	59.4	49.25	356	4.6

Source: DSSAT3.5P outputs

Table A3.2.a: **Summary of simulated water balance component results in South Peanut Basin for no-fertilizer treatment**

Year	Total rainfall mm	Rain in crop season %	Total runoff mm	Total drainage mm	Total Evapotransp. mm	Change in stored water mm
77	567	60.5	46	80	299	142
78	772	81.9	79	127	563	3
79	709	86.7	82	167	485	-25
80	519	92.9	66	47	462	-56
81	782	83.4	66	218	442	56
82	545	91.4	33	47	500	-35
83	510	69.2	74	10	383	43
84	442	99.1	52	35	420	-65
85	531	78.9	32	36	406	57
86	876	90.2	168	193	489	26
87	833	68.8	91	337	432	-27
88	956	95.1	178	294	452	32
89	795	81.2	79	268	469	-21
90	536	90.5	52	67	480	-63
91	545	67.5	47	104	319	75
92	695	97.4	99	173	466	-43
93	789	79.7	111	246	403	29
94	721	94.7	88	179	468	-14
95	696	81.7	77	246	371	2
96	487	100	67	64	405	-49
Mean	665.3	84.5	79.3	146.9	435.7	3.3

Source: DSSAT3.5P outputs

Table A3.2.b: **Summary of simulated water balance component results in South Peanut Basin for semi-intensive fertilizer treatment**

Year	Total rainfall mm	Rain in crop season %	Total runoff mm	Total drainage mm	Total Evapotransp. mm	Change in stored water mm
77	567	60.5	45	79	300	143
78	772	81.9	82	125	564	1
79	709	86.7	84	152	497	-24
80	519	92.9	69	40	472	-62
81	782	83.4	67	196	456	63
82	545	91.4	36	40	511	-42
83	510	69.2	72	0	408	30
84	442	99.1	53	12	433	-56
85	531	78.9	33	0	452	46
86	876	90.2	175	155	499	47
87	833	68.8	92	286	480	-25
88	956	95.1	186	283	456	31
89	795	81.2	80	217	517	-19
90	536	90.5	55	46	506	-71
91	545	67.5	46	63	353	83
92	695	97.4	106	139	495	-45
93	789	79.7	113	191	453	32
94	721	94.7	94	167	480	-20
95	696	81.7	80	202	406	8
96	487	100	70	40	440	-63
Mean	665.3	84.5	81.9	121.6	458.9	2.8

Source: DSSAT3.5P outputs

ESSAY III:

MICROECONOMICS OF SOIL NUTRIENT REPLENISHMENT IN SUBSAHARAN AFRICA: EVIDENCE FROM SENEGAL AND PROSPECTS FOR A SUSTAINABLE FARM INTENSIFICATION

1. Introduction

Under adverse agroecological conditions, especially low and erratic rainfall, nutrient-poor and degraded soils, water and soil erosion, agricultural production in Sub-Saharan Africa (SSA) has grown very sluggishly in the last three decades, well under the rapid pace of demographic growth at around 3% per year. To meet soaring food and fiber needs from a fast growing population, it has been argued that agricultural production should grow at an estimated rate of 4% per annum. This would then require an annual increase of 1.5% for labor productivity and of 3% for land productivity (Delgado *et al.*,1987; Cleaver and Schreiber, 1992; Larson and Frisvold, 1996).

The debate about production path options to meet this serious agricultural productivity growth challenge has raised several issues. First, extensification onto new and marginal lands offers limited potential to increase production, and is even likely to put further pressure on forested areas and resources, leading to more land degradation and deforestation (Marter and Gordon, 1996). Second, intensification paths which involve using more productivity-enhancing inputs per unit of land area (improved seeds, chemical inputs, labor) can be of various types differentiated by their productivity and soil fertility impacts (Reardon *et al.*, 1997;1999). Whatever the production path, there is a growing consensus that the appropriate one capable of meeting the productivity challenge must be also sustainable, i.e with a real potential to increase crop yields, to ensure a concomitant and appropriate replenishment of soils and to generate profits to the farmer.

Despite all existing evidence underscoring the fact that inorganic fertilizer is a key element for sustainable land use and crop production (Mudahar, 1986; Padwick, 1983; Larson and Frisvold, 1996; Shapiro *et al.*, 1998), resource-poor farmers in SSA use this input very sparsely, at levels (12-15 kg/ha) well below world standards. Justification for this behavior can be sought in general through the lack of strong incentives and/or capacity to acquire and use this input. Both of these two causes can be altered thru policymaking informed by sound and relevant research. Under market-oriented reforms, changes in the structure of product and factor prices, credit conditions and capital transfers are made to affect incentives faced by and the capacity of farmers to invest in this input. An example is the 'Agricultural Program' launched in Senegal in 1997/98 which contained among others the following policy measures: peanut output price increases, reduction of downpayment requirements on input credits, distribution of phosphate products to farmers to remedy their deficiency in the phosphorus (P) nutrient.

Also affecting fertilizer use are two factors of concern to the farmer, soil quality and uncertainty, with important behavioral implications. In so far as the quality of land is reflected in how future crop output from that piece of land evolves and is subsequently valued by the farmer, concerns for it then influences adoption of fertilizer. This concern, based on farmers' observations made over time of the trend of output obtained per unit area, also depends on how much they trade present for future output, i.e on their discount rate. The more they value tomorrow's output relative to today's, the former depending, among other things, on maintaining the fertility status of the cropped soils, the more likely they are to use fertilizer to restore the soil's productive capacity, other things being equal.

Uncertainty due to variable weather, unstable prices and unpredictable input distribution policies makes farming activities risky in SSA. Farmers deal with this situation by adopting different risk management strategies that are reflected in their crop, input and technological choices. It is often suggested that the typical farmer in developing countries is risk averse (Moscardi and DeJanvry, 1977; Dillon and Scandizzo, 1978; Binswanger, 1980). Evidence exists that risk aversion deters adoption of fertilizer. Adesina *et al.* (1988), using a MOTAD risk programming model, found that the more risk averse farmers in Southern Niger applied fertilizer only on a limited crop area, and the less risk averse would use more fertilizer, even though cash and seasonal labor constraints would limit it.

However, the available evidence on the dynamic effects of policies on the farm profitability of cropping practices that condition production paths has so far been scarce and, above all, inconclusive. Moreover, in the empirical literature, fertilizer profitability studies in SSA have usually considered the positive effect of fertilizer use on current production and returns to land while paying little attention to the very often important effects on future production flows due to maintained or improved land quality. The empirical neglect of land quality outcomes in these analyses has limited the extent of their contributions to the sustainable agricultural intensification policy debate in SSA. Freud *et al.*, (1997) point to the same flaw when they deplore the lack of empirical evidence about the "consequences of the elimination of the fertilizer distribution program on soil fertility and crop yields in Senegal". Crucial to determining these dynamic effects is deciphering how they are mediated through the farmer's response (in terms of activity and technological choices) to policy-driven market signals.

The main objective of this article is to bridge the empirical knowledge gap highlighted above. It first attempts to build a farm household model that includes various cropping practices and their dynamic effects on soil fertility and then uses the model to shed light on two important policy questions.

(i)Will recent price, credit and capital transfer policy changes in Senegal encourage farmers in the Peanut Basin in the long run to intensify crop production by adopting fertilizer-using cropping practices or not?

(ii) Subsequently from the model solution, what will the corresponding effects of the optimal crop production practices be on soil fertility, here proxied by the soil macronutrient (N and P) stocks?

We contend that, if current policies mentioned above stand in Senegal during the next decade with the same trend for input and output prices, incremental yields due to increased fertilizer use would increase profits to farmers, hence offering them incentives to invest in this input. But, initial capital constraints would have to be overcome to increase its use, and hence to improve soil fertility conditions. Ways to ease capital constraints and finance fertilizer acquisition can be increased access to nonfarm activity and less restrictive formal credit requirements (for example reduced downpayment). Increased participation in nonfarm activity, a source of cash income, can influence long term crop and input choices (especially fertilizer use) by severely cash-constrained farmers, but it can also limit the available farm household labor supply to farming.

The paper is organized along the analytical steps described in figure 1 presented earlier in the general introduction. First, a set of cropping practices is identified in the study zones and their impacts on crop yields and nutrient stocks are estimated in Senegal with a crop growth simulation model using weather and soil condition inputs. Then, these simulated results are plugged in a multi-period farm household model as production coefficients. This household model also incorporates information on policy variables such as prices and credit requirements along with the household nonfarm activities and its resource endowment set. Finally, linear programming (LP) is used to solve the multi-period household problem for the optimal set of cropping and nonfarm activities that maximizes the farm household's objective function.

2. Cropping Practices in the Senegalese Peanut Basin

2.1 Context:

Farmers in the Senegalese Peanut Basin are mainly millet and peanut producers under rainfed conditions. This sahelian area represents 33% of Senegal's land area, 65% of its rural population, 80% of its exportable peanut production, and 70% of its cereal production. Rainfall is a serious limiting factor to agricultural production. The rainy season lasts from June to October when peanut and millet crops are grown. Annual total rainfall averaged 497 mm in the center and 674 mm in the south of the Peanut Basin over the 1977-96 period and was highly variable. Yields for millet (a food crop) and peanut (the main source of cropping income) are low and fluctuate a lot with the vagaries of rainfall and the instability of the policy environment. Low rural household incomes between CFA 30 to 60,000 (around $50-100 US) per adult equivalent per year across agroclimatic zones (Kelly *et al.*, 1993) and limited cash flows constrain farmers' capacity to make capital investments to restore soil fertility and allow a transition from traditional systems to more productive/intensive systems.

During the last three decades, instability in input distribution and price policies in Senegal has compounded the uncertainty of the production environment (Diagana *et al.*, 1996). Added to the progressive elimination of subsidies (especially for inputs) under the 1980s Structural Adjustment Program, this has led to a decline of fertilizer use at the national (annual growth rate of -1.8% from 1965 to 1996) and farm levels (Kelly *et al.*, 1996).

Most Senegalese soils have low soil fertility status: 70% of them are rated from 'poor' to 'very poor' in terms of suitability to agriculture (Mbodj, 1987). Their topsoil and subsoil textures are characterized by sandy or clay-sandy layers, high kaolinite dominance in the clay fractions, low water holding capacity, low organic matter and low cation exchange capacity (Sheldon, 1987; Mbodj, 1987), all of which affect crop response. In addition, three-quarters of the 2.25 million ha cropped in 1995 were said to be nutrient deficient (Republic of Senegal/ICS/SENCHIM, 1996). Particularly serious is the high P-deficiency of these soils (Republic of Senegal /MA/Bureau Pédologie, 1995; 1997), a problem diagnosed as the most important biophysical constraint to increased agricultural production (Republic of Senegal/MA, 1996).

2.2 Cropping practices:

Peanut and millet are usually grown in rotation in the Peanut Basin and most varieties are short cycle. Dry planting before the first useful rain is common for millet as it frees labor for peanut cropping. Seeding for peanut is done the day after the first useful rain. Observed seeding densities for peanut can vary up to twice the recommended 60 kg/ha of grains. Farmers justify this high seeding density for peanut by the desire to dampen yield reduction due to soil fertility or seed quality decline or lack of fertilizer (Gaye *et al.*, 1996). But, agronomists argue that, without fertilizer, high seeding density would depress crop yields and soil nutrient levels in the long run (Kelly *et al.*, 1996).

Farmers, mostly smallholders, predominantly use traditional cropping practices characterized by continuous cultivation of soils without fertilization. Research- recommended fertilizer application rates are 75 kg of 6-20-10 NPK on peanut and 150 kg of 14-7-7 NPK and 100 kg of urea on millet (semi-intensive scheme) and 150 kg of 6-20-10 NPK on peanut and 200 kg of 14-7-7NPK and of urea on millet (intensive scheme). When farmers do use fertilizer, it is usually on the peanut cash crop. Moreover, a phosphate program has been recently launched: phosphate products are being distributed nationally and free of charge to farmers to apply to their fields in addition to using NPK fertilizer in order to correct the soil P-deficiency mentioned earlier.

2.3 Simulated biophysical outcomes:

Using these observed or recommended practices on millet-peanut rotation, we have simulated with the DSSAT[16] model their long-term yield and soil nutrient effects under six scenarios in two zones of the Peanut Basin:

- no fertilizer on either crop (MP-00),
- no fertilizer on either crop, but high seeding density on peanut (MP-HSD0),
- no fertilizer on millet, but intensive scheme on peanut (MP-02),
- semi intensive on both crops (MP-11),
- intensive on both crops (MP-22), and
- intensive on both crops, but with an initial one-time basal application of a 50-50 blend of 400 kg/ha of tri-calcium phosphate and phosphogypsum (MP-2PP).

Results are summarized in table 3.1 below. Long term average yields increase with fertilization levels for both crops in the two zones. Under no fertilization, increasing the peanut seed density adds very little to the peanut yield compared to the no-fertilizer case in the long run. Allocating all acquired fertilizer to peanut benefits the millet crop following the fertilized peanut with a gain of 239-266 kg over the no-fertilizer case. Also, participating in the phosphate distribution program under the recommended conditions, i.e using also NPK

3 DSSAT, the Decision Support System for Agrotechnology Transfer, a product of the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) is a set of crop growth simulation models. Its CERES models simulate cereal crops whereas the CROPGRO models handle legume crops (Hanks and Ritchie, 1991).

fertilizer, generates a combined average millet-peanut yield gain of 125-159 kg/ha which is probably not enough to cover the full P costs to the farmer.

Another overall result from this table is that, as expected, traditional non fertilizer-using cropping practices (MP-00 and MP-HSD0) deplete the stocks of soil nutrients more than the fertilizer-using practices. For the plant-available labile P pool, the stock is being depleted when no fertilizer is used, and replenished faster with increased levels of fertilizer application. In contrast, the active pool of P is being depleted by net flows of P into the labile pool, but at a slower pace when fertilizer is used. Inorganic N is being replenished under all practices, but faster when more N is externally applied. By contrast, the stock of organic N is going down under all practices, and more rapidly when no fertilizer is used, probably because of higher mineralization to release the necessary N required by the millet crop plant.

Table 3.1: 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)

		No fertilizer on either crop		Semi-intensive fertilizer use on both crops		Intensive fertilizer use on both crops		No fertilizer; high seeding density on peanut		No fertilizer on millet; intensive fert. on peanut		Intensive fert. use on both crops with phosphate program	
		ml	pn	ml	pn	ml	pn	ml	pn	ml	pn	ml	pn
Center	yield	306	332	669	690	793	950	301	352	545	849	853	1015
	labile P	-1.5		0.9		2.6		-1.5		0.9		2.6	
	Inorganic active P	-2.5		-2		-1.8		-.2.5		-2		-1.7	
	Organic active P	-3.3		-3		-3		-3.3		-3.1		-3	
	Inorganic N	3.5		10		14.9		3.7		4.4		14.8	
	Organic N	-46		-35		-31.5		-44.6		-35.2		-30.5	
South	yield	294	533	686	1118	839	1556	290	554	560	1370	902	1652
	labile P	-1.5		0.2		1		-1.7		-0.15		1.7	
	Inorganic active P	-2.5		-2.1		-1.9		-2.2		-2.1		-1.8	
	Organic active P	-4		-3.7		-3.6		-4		-3.7		-3.6	
	Inorganic N	3.2		5.9		7.6		3.3		2.7		7.6	
	Organic N	-90		-81		-77		-88		-80		-76	

Legend: Millet-peanut rotation: ml=millet; pn=peanut.
For labile P, inorganic and organic P in the active pool, inorganic and organic N, figures are average annual changes: positive indicate a build-up, and negative a depletion of nutrient stocks.

3. Method and Data

3.1 Method:

To address the aforementioned policy question, linear programming (LP) is used to solve a farm household model. Since time is a key factor here to capture changes in soil fertility over time and how they are valued according to the discount rate, multiperiod LP can be used (Baffoe *et al.*, 1987).

As said earlier (figure 1), the LP model uses the simulated yield and soil nutrient impacts presented above as model coefficients. Treating soil fertility impacts as parameters in optimization models is one of the approaches used in the literature to do a balanced economic and environmental analysis of alternative systems (Roberts and Swinton, 1996; Teague *et al.*, 1995).

Bioeconomic models that link biophysical simulation to intertemporal optimization models have been increasingly used during the last decade to measure and compare the effects of farming practices: crop rotation, technologies, management decisions, etc. (Oriade and Dillon, 1997). An early example is provided by Baffoe *et al.*, (1987) who used multiperiod LP techniques and the Universal Soil Loss Equation (USLE) to determine how several representative crop rotational systems compare with each other and with monocultural corn systems in Ontario from an economic and a land degradation (soil erosion and subsequent effects on productivity) point of view. More recently, Barbier (1996) used a combination of a recursive LP and an Erosion Productivity Impact Calculator (EPIC) model of soil conditions and plant growth for two different agroclimatic zones of Burkina Faso under various (population, market, prices, soil fertility) assumptions to test Boserup's hypothesis of the effect of population pressure on agricultural intensification. Dalton (1996) adapted EPIC to the Southern Mali context and linked it to a farm household model to study the long run impacts of technical change (improved cultivars, crop residue management, organic fertilization) and of policy alternatives (taxes) on crop production and land degradation.

In our work, like Baffoe *et al.*, (1987), we compare different crop management practices of a millet-peanut rotation from the profitability and soil fertility point of view, but use DSSAT instead of USLE for the land quality impact estimation. Second, our analysis differs from the ones above on (1) the type of crop simulation model used (DSSAT instead of EPIC), (b) the inclusion of nonfarm activities as choice variables for the farm household, and of (c) a soil capital reserves shock to mimic the effects of the phosphate distribution program in Senegal.

Choice of DSSAT in our research has been justified by two advantages it holds over other crop growth simulation models. First, it provides a more detailed accounting of phenological development and stresses encountered in each phenological stage than other models (Kiniry, 1991; Jones *et al.*, 1991), hence enabling a more accurate prediction of variation in crop yields from year to year under different planting dates. Second, it requires only moderate amounts of input data, and thus is relatively user-friendly. Moreover, initially built with a nitrogen focus, the addition of a phosphorus component has made it suitable for our purpose of simulating both N and P dynamics in a country with important rock phosphate deposits and where P-deficiency in soils is said to seriously limit agricultural production.

3.2 Data:

Our main source of household data is the ISRA/IFPRI baseline data set collected from a sample of 140 rural households in different zones of the Peanut Basin of Senegal during the October 1988 - December 1991 period. It includes production, income and expenditure variables. Added to that is another more recent data set collected under the 1995/96 ISRA/PRISAS/MSU single-visit farm survey and which covers basic characteristics (resource endowments, crop mix, input use) of a 120-household sample from the same zones of the Peanut Basin. Both data sets are used to determine the typical characteristics of farm households in the two study zones (table 3.2).

Table 3.2: Selected characteristics of the typical farm household in the Senegalese Peanut Basin

Characteristics	Center Peanut Basin	South Peanut Basin
Household size (adult equivalent)	10	11
Farm size (ha)	8	11
Labor force (man equivalent)	4	4
Ag equipment: animal traction (#)	1 hoe, seeder, horse	1 hoe, seeder, horse
Share of non farm income in total household income (%)	24	29
Annual income (CFA/AE)	56000	72000

Source: ISRA/IFPRI and ISRA/MSU surveys (1988-92; 1996).

Partial crop budgets for millet and peanut under different cropping practices are calculated with data collected in 1997/98 from ISRA (Senegal Agricultural Research

Institute) and CSA (National Grain Market Information System) grain price series of millet and peanut in the Peanut Basin and input prices for seed, fertilizer, urea, etc. Production coefficients (human and animal labor needs, seed, etc) are obtained from Martin (1991)[17].

4. Empirical Farm Household Model

The farm household model is mathematically specified as follows:

$$\mathbf{Max}\ E[U(Y_t)] = \Sigma_t (1+\delta)^{-t} E\{Y_t\}$$

$$= \Sigma_t \Sigma_i \Sigma_j \Sigma_k (1+\delta)^{-t} E\{p_{jt}*(A_{jt}* q_{jtk})P_k - r_{it} * a_{jit} + w_{nt} * n_{nt} - (1+i)*Cr_t\} \quad (1)$$

subject to:

$$\Sigma_j (a_{jit} * A_{j,t}) \leq b_{it} \quad (2)$$

$$\Sigma_{jt} A_{jt} NB_{jt} \geq 0 \quad (3)$$

$$\Sigma_k \Sigma_j [E(A_{jt} * q_{jtk}) P_k] \geq GC_t \quad (4)$$

$$LIV_t - \alpha E[Y_t] \leq 0 \quad (5)$$

$$w_{nt} * n_{nt} - \beta E[Y_t] \leq 0 \quad (6)$$

$$Dwn_t - \gamma Cr_t = 0 \quad (7)$$

$$a_{jit}, ..., Cr_t \geq 0 \quad (8)$$

where

Y_t is the net farm returns to crop and off-farm activities in the t period;

A_{jt} is the level of the jth crop activity in the t period;

4 ISRA agronomists were also consulted to check the validity of these coefficients: no major changes were detected, or if any, no empirical data are currently available.

$\mathbf{q_{jkt}}$ is the average yield of the jth crop activity under the kth state of nature in the t period;

$\mathbf{a_{ijt}}$ is the quantity of the ith resource used per unit of the jth crop activity in the t period;

$\mathbf{p_{jt}}$, $\mathbf{r_{it}}$ are respectively the output and input price vectors in the t period;

$\mathbf{n_{nt}}$ is the amount of labor devoted to nonfarm activities in the t period;

$\mathbf{w_{nt}}$ is the net returns to a day of nonfarm activity in the t period;

i is the interest rate;

$\mathbf{Cr_t}$ is the amount of credit received at time t;

δ is the discount rate;

$\mathbf{b_{it}}$ is the endowment level of the ith resource in the t period;

$\mathbf{NB_{jt}}$ is the average annual changes in the level of soil nutrients for a hectare of land devoted to the jth crop activity;

P reads probability of occurrence of the kth state of nature;

$\mathbf{GC_t}$ are the household food grain requirements in the t period;

α, β, γ are percentage values between 0 and 1;

$\mathbf{LIV_t}$ are the household total living expenditures in the t period; and

$\mathbf{Dwn_t}$ is the amount of downpayment required on the received credit in the t period.

The model is constructed for the typical household in each of the two zones covered in this study (Center and Southeast of Peanut Basin). These two zones are selected because they are the main producers of the most important cash crop (namely peanut) in the country.

Also, spatially, they represent two agroclimatically different zones which are expected to induce differential land quality and productivity impacts of cropping practices.

4.1 Activities:

Equation (1) contains the different activities to be undertaken by the farm household to maximize the objective function. Major activities are crop production and nonfarm activities, input credit borrowing and grain purchases if necessary to cover food needs. Crop production activities in the LP model are the millet-peanut cropping practices described in the previous section. Nonfarm activities are also incorporated in the model. In addition, provision is made for buying inputs on short-term formal credits to be reimbursed at the end of the period during which they are contracted.

4.2. Constraints:

Constraints are shown in equations (2) to (8). Per period physical constraints are placed on the human and animal labor, on cultivated land (equation 2) and on soil nutrients (equation 3). Labor is supplied entirely from the household to carry out on and off-farm activities during different sub-periods (seasons) of the year, and there is no hiring of outside labor.

Financial constraints are imposed on starting capital, credit available and amount of nonfarm income using empirical observations in the study zones. The credit market in the Peanut Basin is active as it involves most farm households as borrowers and/or lenders; it is also segmented: sources for production loans are formal while consumption loans are informal (Warning and Sadoulet, 1998). Consequently, only formal production credit usually for peanut cropping is included here and is limited by the required downpayment (equation 7).

Limited employment opportunities in rural areas constrain nonfarm income earnings. To reflect this, we use empirical estimates of the share of nonfarm in total household income in the two different zones (Fall, 1991) to put an upper bound on to how much nonfarm income can be earned (equation 6). Changes in both financial and soil nutrient capital resources across periods are monitored in the model.

For food security, grain consumption requirements must be satisfied by own production and/or purchases by the household. The 'safety-first' model is chosen to specify risk that is present in farming decisions made in this uncertain environment described earlier. This simple and general risk specification is chosen over alternative ones for mainly two reasons. First, the biophysical modeling of crop production used here already captures most if not all production risks. Second, we did not find that more sophisticated specification of risk (e.g., a chance-constrained model) gave satisfactory results, given the nature of the simulated data produced by the biophysical model.

The failure to cover food grain needs because of production shortfalls is a common worry for a subsistence risk averse farmer. To shield the household against the risk of insufficient coverage of food needs following production downfall due to weather, hence yield variability, a 'safety first' constraint is set to allow the food security objective to be achieved under different states of nature (equation 4). Using the simulated yield results, three states of nature ('bad', 'average' and 'good') are defined for each crop and level of fertilization on the basis of the mean and standard deviation of the yield distribution (table 3.3). Afterwards, their corresponding probabilities are calculated. Thus, equation (4) ensures that expected production plus purchases if necessary meet grain needs under all states of nature.

Table 3.3: Simulated mean millet and peanut yields (kg/ha) by state of nature

Zone	State of nature	Millet			Peanut		
		No fertilizer	Semi-intensive	Intensive	No fertilizer	Semi-intensive	Intensive
Center	**'Bad'**	197	425	492	237	563	754
	'Average'	287	729	885	309	687	982
	'Good'	747	1041	1139	749	1089	1339
South	**'Bad'**	206	443	524	434	970	1359
	'Average'	213	741	962	488	1098	1585
	'Good'	767	1166	1313	949	1573	2004

Source: DSSAT3.5P simulation outputs.

In equation (5), living expenditures for other foods and needs are allowed to vary positively with earned income. This specification makes total consumption expenditures endogenous to farm income, which is consistent with economic theory (Adesina *et al.*, 1988). One could argue about including a minimum level of living expenditures, regardless of income levels. We found in the analysis that this minimum level was always below the living expenditures given by the model.

4.3. Right-hand side (RHS) values:

Average cultivated land is 8 ha/year in the center and 11 ha/year in the south. Household size is respectively 10 and 11 adult equivalents in the two zones. Initial soil nutrient stocks for N and P are set to observed levels in collected soil data sets: 34 and 26 kg/ha for labile P, 71 and 70 kg/ha for inorganic active P, 86 and 104 kg/ha for organic active P, 33 and 30 kg/ha for inorganic N and 3333 and 6348 kg/ha for organic N respectively in the center and the south. Starting cash capital amounts to respectively CFAF 62,500 and 75,000 in the two zones. Grain consumption requirements for the whole household are calculated on the basis of the national norms of 185 kg of cereals per capita and per year. A summary of the corresponding LP matrix is presented in table 3.4.

4.4. Other assumptions and scenarios:

The model covers 5 periods, each 2 years long (because of the two-year millet peanut rotation), hence a total of 10 years. Other assumptions are: based on trends from historical input and output price data from 1977 to 1996, product price and returns to nonfarm are allowed to increase by 6% per period while input costs increase by 8% per period. Living expenditures (exclusive of grain consumption, handled by equation 5) amount to 80% (α=.8) of net household cash income which is farm revenues net of input costs, grain purchases and credit repayment and the balance of income is transferred to the next period. The share of nonfarm income in total income, β, is initially set respectively at .25 in the center and .3 in the south. The interest rate is set at 10% and downpayment on formal credit is 20% (γ =.2).

Different scenarios of the LP model are run, each representing an observed or hypothetical policy situation under which the typical farm household operates. Alternative situations range from the less restrictive conditions of the current policy program (phosphate program, access to credit and nonfarm activities, called scenario A) to a very restricted access to cash income (no credit or nonfarm; scenario D) through intermediate situations (no participation in the phosphate distribution program or scenario B; either credit or nonfarm being available or scenario C), all scenarios being run with and without a soil replenishment requirement (i.e ending levels of nutrient stocks being higher their beginning levels).

Table 3.4: Summary of the LP farm model (one period only)

CONSTRAINT	RHS	ACTIVITIES														
		Cropping practices 1 —— 6	Millet states 1 2 3	Min grain needs	Grain deficit 1 2 3	Buy millet	Sell millet	Peanut states 1 2 3	Sell pea nut	Input fund1	Input Cred1	End fin. cap1	Living exp1	Cash transfers 1-2	Pcarry 1-2	Ncarry 1-2
Start fin. cap	≤ 100M					pam				1						
Input fund1	= 0	variable cost/ha								-1	-1	1				
Initial P stock	=544	change/period:													1	
Initial N stock	=536	(DSSAT results)														1
Land	≤16	2 ——— 2														
Labor per season	≤L0-6	Labor req coeff.														
millet state 1	≤ 0	yield per crop	1													
" state 2	≤ 0	activity per state	1													
" state 3	≤ 0	of nature for	1													
peanut state 1	≤ 0	millet and peanut						1								
" state 2	≤ 0	(DSSAT results)						1								
" state 3	≤ 0							1								
Millet in/out	≤ 0		p1 p2 p3	1		-1	1									
Grain needs	≥3700			1												
Gr.needs state1	≥ 0		1	-1	-pd											
Gr.needs state2	≥ 0		1	-1	-pd											
Gr.needs state.3	≥ 0		1	-1	-pd											
Gr. prod. state1	≥ 0		1	-1	1											
Gr. prod. state2	≥ 0		1	-1	1											
Gr. prod. state3	≥ 0		1	-1	1											
Peanut in/out	≤ 0							p1,2,3	1							
Endcap1	= 0						-pm		-ppn		-(1+i)	-1	1	1		
Living exp1	≤ 0												-.25			
Fin. cap1-2	= 0													-1		
P carry 1-2	= 0														-1	
N carry 1-2	= 0															-1

Note: to reduce table size, nonfarm and downpayment activities and constraints are not included in this summary table, but are in the run programs.
Legend: pam: purchase price of millet; pm: selling price of millet; ppn: selling price of peanut;
p1,2,3: probability of state of nature 1 (bad), 2 (average), 3 (good) calculated using DSSAT simulated crop yields; pd: percentage of coverage of food grain deficit i.e production - needs, if any (1=all grain deficits are covered); P: phosphorus; N: nitrogen; L0-6: stock of family labor in sub-periods 0 to 6.

5. Results

Table 3.5 summarizes the results of the LP model where only optimal cropping practices under each of the four scenarios are presented. The following salient points can be made.

(i). No traditional i.e non-fertilizer-using practices with and without recommended seeding densities for peanut are present in the 10-year optimal plan, under any scenario. In contrast, in all periods, all scenarios and all zones, the adoption of fertilizer-based practices is optimal, given the farm household's resource constraints and food security needs.

(ii). The optimal land allocation shows a diversified set of cropping practices that include different schemes of fertilizer use: full intensification of millet-peanut under the phosphate program (MP2PP), semi-intensification (MP-11) and full intensification on peanut only followed by non-fertilized millet (MP-02).

(iii). The full intensification scheme (MP-22) enters the optimal plan only under scenario B, i.e outside the phosphate program. Under this scenario, the optimal solution in the Center indicates a shifting from allocating land equally to semi-intensified (MP-11) and intensified millet-peanut (MP-22) in the first period to cropping more land with intensified millet- peanut than with the semi-intensive practice in the last four periods. Contrastingly, in the South, the shift (in terms of land allocation) from rotating fully fertilized peanut with non-fertilized millet toward semi and full intensification of both crops is also taking place.

(iv). Land and capital resources are used up under all scenarios in the Center whereas family labor is binding only during weeding times. As expected, there is some idle labor when nonfarm activities are not available or accessible to the household (scenario C). Land and

Table 3.5: Optimal long-term cropping plan (in ha/year) for the typical farm household in the Senegalese Peanut Basin under different scenarios.

	A: credit, NF, PP		B:credit, NF, no PP		C: Credit and PP		D: No credit, no NF*	
	Center	South	Center	South	Center	South	Center	South
Period 1								
MP-11	.1	2.4	3.9	2.3	.1	3.4	-	-
MP-22	-	--	.05	-	-	-	-	-
MP-02	6.2	5.8	4.0	5.8	6.2	5.1	2.5	3.2
MP2PP	1.7	-	-	-	1.7	-	-	-
Period 2								
MP-11	1.8	4.3	2.8	4.4	1.8	4.3	-	-
MP-22	-	-	4.8	3.5	-	-	-	-
MP-02	1.4	.5	.4	-	1.4	.5	1.9	3.8
MP2PP	4.8	3.6	-	-	4.8	3.6	-	-
Period 3								
MP-11	1.8	4.3	2.8	4.4	1.8	4.3	-	-
MP-22	-	-	4.8	3.5	-	-	-	-
MP-02	1.4	.5	.4	-	1.4	.5	1.4	4.4
MP2PP	4.8	3.6	-	-	4.8	3.6	-	-
Period 4								
MP-11	1.8	4.3	2.8	4.4	1.8	4.3	-	-
MP-22	-	-	4.8	3.5	-	-	-	-
MP-02	1.4	.5	.4	-	1.4	.5	1.1	5.0
MP2PP	4.8	3.6	-	-	4.8	3.6	-	-
Period 5								
MP-11	1.8	4.3	2.8	4.4	1.8	4.3	-	-
MP-22	-	-	4.8	3.5	-	-	-	-
MP-02	1.4	.5	.4	-	1.4	.5	.2	.8
MP2PP	4.8	3.6	-	-	4.8	3.6	-	-
Nutrients								
Lab P chg.	18	5	16	3.3	18	5	1.7	-.5
In. P_a chg.	-19	-15	-19	-15	-19	-15	-3.5	-7
Org P_a chg	-30	-28	-30	-27	-30	-28	-5.5	-12
In. N chg.	109	45	116	43	109	45	7.8	9
Org N chg	-327	-597	-333	-569	-327	-602	-62	-250
Objective function: (000 CFA)	259	685	177	573	179	493	24	183

Notes: MP11:semi-intensification on millet-peanut rotation; MP22: full intensification; MP02: full intensification on peanut only; MP2PP: full intensification under phosphate program.

Lab P, In P_a, Org P_a (active pool), In N and Org N chg 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 and are in kg/ha; positive (negative) numbers indicate build up (depletion) of soil nutrients.

* Results for this scenario are obtained when food security requirements are dropped in both zones.

labor constraints are not binding under the very restrictive (no credit or nonfarm) D-scenario In the South, it is worth noting that land is never binding under any scenario: there are around 2-3 ha of land left unused by the model, as a result of the capital constraint, the only resource that is always binding in this zone.

(v). Under the D scenario, which reflects the situation of the poorest of the poor farmers, meeting grain consumption needs is unfeasible under initial resource constraints. The consumption constraint was then dropped to allow a feasible solution to the model. Also, most of the available land is unused in the last period of the optimal plan, because of the lack of surplus income made in previous periods and carried over to following periods to finance farm production. Millet production under this scenario varies over the different periods between 2 and 36% of food grain needs in the Center and 11 and 67% in the South.

(vi). Removing nonfarm activity from the model to leave only credit (scenario C) has almost no effects on the optimal hectarage plan compared to scenario A in both zones, the only difference being observed in the first period in the south. This similar land allocation stems from the fact that in A, all labor is used up for farm first and the rest for nonfarm. Thus, removing the possibility of using labor for nonfarm does not change the optimal land allocation, but only decreases the level of cash income made and also increases the amount of credit needed. Overall, the most binding constraint is that of initial capital which conditions the path (based on optimal cropping practices) to be taken in later periods.

(vii). Sensitivity analyses were done on all scenarios but D. Capital constraints were eased by reducing credit downpayment requirements from 20% to 12.5%. This change allowed farmers to afford early investments in capital-demanding cropping practices such as

MP-22; more interesting, credit needs can even be lessened in later periods because of higher cash income net of production costs and credit reimbursement being carried over to the next period to finance input acquisition.

(viii). The effect of these optimal cropping practices is, under all scenarios, a replenishment or, even better, 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, organic N) are being 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.

(ix). Lastly, in terms of overall profitability, the A scenario with credit, nonfarm and phosphate program yields the highest discounted net income level after ten years, followed by B (no phosphate program) and C (no-nonfarm, credit-only). These income levels are always higher in the south than in the center of the Peanut Basin, because of higher yields and more land being cropped.

6. Conclusions

The LP modeling results show that the 'Agricultural Program' policy measures, if maintained, offer good incentives to push farm households in the Senegalese Peanut Basin towards an intensification of millet and peanut production. Such an intensification path is made possible by the farm profitability of fertilizer use. The positive impact on soil fertility is illustrated by the build up of the plant-available soil macronutrients, namely inorganic N and labile P and the slower depletion of the other nutrient pools. By enabling soil nutrient replenishment, fertilizer use helps prevent future production losses or maintain future production flows, controlling for other factors. These positive biological (production), economic (profitability) and ecological (soil nutrient replenishment) impacts of optimal cropping practices contribute altogether to making this intensification path sustainable. Moreover, they provide needed evidence confirming that increased fertilizer use is a key element in establishing a sustainable intensification of agricultural production in semi arid areas of SSA. For example, one can recall from table 3.1 that not using fertilizer at all on millet peanut rotation leads on average to a depletion of the plant-available labile P pool by 1.5 kg/ha/year in both studied zones. In contrast, the LP solution in table 3.5 suggests a combination of fertilizer-based practices that replenish the same P pool under the A scenario by 1.8 kg/ha/year in the Center and by .5 kg/ha/year in the South. .

Hence, results suggest some interesting prospects for promoting policies to ensure easier availability and accessibility to this input. One policy implication of these results is the necessity to ease initial capital constraints. Within the context of our model, cash and formal credit constraints, especially in the initial periods, drive the crop production intensification process. Results suggest that measures such as reducing downpayment requirements (or other equivalent ones that would expand input credits or improve access to them) have a potential for helping capital-deprived farmers make the necessary investments in productivity-enhancing and soil nutrient-replenishing inputs. But, this model is restrictive in many senses (formal credit only, no migratory income or other income transfers, etc). Thus, a question is how well it is reflecting the reality of credit constraints in rural Senegal. How really binding these constraints are constitutes a research issue that needs to be empirically established.

Another implication for policy is that programs to remedy the P-deficiency of soils through the distribution of phosphate products can be important because of their production effects compared to currently observed no-fertilizer using practices. However, for them to have any chance to reach the production and nutrient replenishment objectives, the necessary accompanying conditions must be satisfied, i.e annual fertilizer use by farmers, and timely and correct incorporation of P-products in the soil. Soil fertility management is complementary to soil amendments. Consequently, further extension and monitoring efforts should be deployed to inform and convince farmers of the need to correctly undertake these complementary actions. If not, leakage instances like the resale of P-products or their use for other purposes (e.g. construction bricks), their inappropriate application on the soil surface and after the first rains will be more common, and will place this program among the numerous theoretically sound but unfortunately ill-implemented agricultural policy programs.

Finally, this study did not incorporate organic fertilizer, mainly because of data limitation problems. Despite that, it should be understood, as mentioned in the general introduction, that a combination of both organic and inorganic fertilizers is necessary to achieve land productivity and quality goals. Hence, further research efforts should include both forms of fertilization in biophysical and economic modeling.

References

Adesina, A.A., P.C. Abbott and J.H. Sanders. 1988. Ex-ante Risk Programming Appraisal of New Agricultural Technology: Experiment Station Fertilizer Recommendations in Southern Niger. *Agricultural Systems*, 27(1988):23-35.

Baffoe, J.K., D.P. Stonehouse and B.D. Kay. 1987. Methodology for Farm-level Economic Analysis of Soil Erosion Effects under Alternative Crop Rotational Systems. *Canadian Journal of Agricultural Economics* 35:55-74.

Barbier, B. 1996. "Impacts of Market and Population Pressure on Production, Incomes and Natural Resources in the Dryland Savannas of West Africa: Bioeconomic Modeling at the Village Level" Intl. Food Policy Research Institute: EPTD Discussion Paper No. 21.

Binswanger, H. 1990. Attitudes Toward Risk: Experimental Measurement in Rural India. *American Journal of Agricultural Economics* 62:395-407.

Cleaver, K. and G. Schreiber. 1992. The Population, Agriculture and Environment Nexus in Sub-Saharan Africa. Agriculture and Rural Development Series No. 1, Technical Department, African Region, World Bank, Washington, DC.

Dalton, T.. 1996. Soil Degradation and Technical Change in Southern Mali. Ph.D Dissertation. Purdue University, Department of Agricultural Economics, West Lafayette, IN.

Diagana, B., V. Kelly and M. Kébé. 1996. L'Offre Agricole Suite à la Dévaluation: Pourquoi Une Réponse Si Faible Au Sénégal. ISRA/PASE-CILSS/PRISAS Note, October.

Delgado, C., J. Hopkins and V. Kelly. 1994. Agricultural growth linkages in sub-Saharan Africa: A synthesis. p. 22-26. *In* Proc. of a Workshop on Agricultural Growth Linkages in Sub-Saharan Africa, Washington, DC. 26 May 1994. Int. Food Policy Res. Inst., Washington, DC.

Fall, A.A. 1991. Composition Multisectorielle et Distribution du Revenu du Menage Rural: Cout d'Opportunite, Remuneration des Facteurs Capital et Travail. ISRA/IFPRI Project Document V, January.

Freud, C., E. H. Freud, J. Richard and P. Therein. 1997. "La Crise de l'Arachide Au Senegal: Un Bilan-Diagnostic" CIRAD report, January.

Gaye M., M. Sene and V. Kelly. 1996. Facteurs Determinants des Densites de Semis de l'Arachide. Michigan State University Department of Agricultural Economics Staff Paper no. 96-29.

Hanks, J. and J. T. Ritchie (eds). 1991. Modeling Plant and Soil Systems. Number 31 in the series of Agronomy. American Society of Agronomy, Inc. Madison, WI, 71-90.

Jones, C.A., K.J. Boote, S.S. Jagtap, and J.W. Mishoe. 1991. "Soybean Development" Ch. 5 *In* J. Hanks and J. T. Ritchie (eds). Modeling Plant and Soil Systems. Number 31 in the series of Agronomy. American Society of Agronomy, Inc. Madison, WI, 71-90.

Kelly, V., T. Reardon, B. Diagana, A. Fall and L. Mcneilly. 1993. "Final Report for the IFPRI/ISRA Study of Consumption and Supply Impacts of Agricultural Price Policies in the Peanut Basin and Senegal Oriental" (2 volumes), submitted to USAID/Senegal, September.

Kiniry, J.R. 1991. "Maize Phasic Development". Ch. 4 *In* J. Hanks and J. T. Ritchie (eds). Modeling Plant and Soil Systems. Number 31 in the series of Agronomy. American Society of Agronomy, Inc. Madison, Wisconsin. 1991: 55-70.

Larson, B.A. and G.B. Frisvold. 1996. Fertilizers to Support Agricultural Development in Sub-Saharan Africa: What is needed and Why? *Food Policy*, vol. 21, no. 6: 509-525.

Marter, A. and A. Gordon. 1996. Emerging Issues Confronting the Renewable Natural Resources Sector in SSA. *Food Policy* 21(2), pp. 229-241, May.

Martin, F. 1991. Budgets de Culture au Senegal. ISRA/Michigan State University, Department of Agricultural Economics, vol. 4, no. 5.

Mbodj, M. 1987. L'Utilisation des Engrais et la Production Agricole: Fertilisation des Cultures au Senegal et dans les Autres Pays de l'Afrique de l'Ouest. Mimeo, Ministry of Rural Development, Dakar, Senegal.

Mudahar, M. S. 1986. Fertilizer Problems and Policies in sub-Saharan Africa. In *Management of Nitrogen and Phosphorus Fertilizers in sub-Saharan Africa*. eds A. U. Mokwunye and P. L.G. Vlek Proceedings of a symposium. Martinus Nijhoff Publishers.

Oriade, C.A., and C.R. Dillon. 1997. Developments in Biophysical and Bioeconomic Simulation of Agricultural Systems: A Review. *Agricultural Economics*. 17: 45-58.

Padwick, G.W. 1983. The Maintenance of Soil Fertility in Tropical Africa: A Review. *Experimental Agriculture*. vol. 19: 293-310.

Reardon, T., C. Barrett, V. Kelly and K. Savadogo. 1999. Policy Reforms and Sustainable Agricultural Intensification in Africa. *Development Policy Review*, forthcoming.

Reardon, T., V. Kelly, E. Crawford, B. Diagana, J. Dione, K. Savadogo and D. Boughton. 1997. Promoting Sustainable Intensification and Productivity Growth in Sahel Agriculture after Macroeconomic Policy Reform. *Food Policy*, 22(4): 317-327.

Roberts, W. S. and S.M. Swinton. 1996. Economic Methods for Comparing Alternative Crop Production Systems: A Review of Literature. Reprint from *American Journal of Alternative Agriculture*, vol.11, no.1.

Shapiro, B. and J. Sanders. 1998. Fertilizer Use in Semiarid West Africa: Profitability and Supporting Policy. *Agricultural Systems*, 56(1998), no.4.

Senegal, Republic of, Ministry of Agriculture. 1996. Programme Agricole 1997/98. December .

Senegal, Republic of, Ministry of Agriculture, Bureau Pédologie. 1997. Programme de Restauration de la Fertilité des Sols du Sénégal. April.

Senegal, Republic of, Ministry of Agriculture, Bureau Pédologie. 1995. Rapport Annuel.

Senegal, Republic of, ICS/SENCHIM. 1996. Projet de Restauration de la Productivite des Sols au Senegal. Mimeo, October.

Sheldon, V. 1987. Fertility Status of African Soils: a Handbook for Non Agronomists. Curriculum Publications Clearinghouse, Western Illinois University.

Teague, M.L., D.J. Bernardo and H.P. Mapp. 1995. Farm-Level Economic Analysis Incorporating Stochastic Environmental Risk Assessment. *American Journal of Agricultural Economics*. 77(1995): 8-19.

Warning, M. and E. Sadoulet. 1998. The Performance of Village Intermediaries in Rural Credit Delivery under Changing Penalty Regimes: Evidence from Senegal. *Journal of Development Studies*, 35(1), October, pp.115-138.