An Evaluation of Strategies to Use Indigenous and Imported Sources of Phosphorus to Improve Soil Fertility and Land Productivity in Mali

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The research results and information presented in this report are useful to promote a more productive and sustainable agriculture in Mali. The report is a contribution of IFDC work to the goals of inter-institutional initiatives such as the Soil Water Nutrient Management Initiative of the CGIAR, the Desertification Convention, and the Initiative for Soil Fertility Improvement.

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The report is a methodological approach and involves a comprehensive analysis of the information generated from fertilizer experiments conducted over several years. The report includes relevant data of the multiple information generated through the life of the project. We acknowledge the review of drafts of this document by Dr. H. Breman and Dr. D. T. Hellums. Both of them made valuable suggestions and comments. The ideas, concepts, and conclusions presented in this report are the sole responsibility of the authors.

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Summary of Results

Findings concerning the agronomic and economic performance of phosphate sources in Mali indicate that phosphate fertilizers are indeed needed for the production of food and cash crops and that Tilemsi phosphate rock (TPR) is a suitable indigenous source of phosphorus (P) for the sustainable production of important cropping systems in Mali.

Estimates of private and environmental benefits show that investments in the application of TPR as phosphate fertilizer can be profitable for farmers even when rates of discount are as high as 30%. However, poor rainfall (in some semiarid areas) and the sudden decline in prices of crop output could make this investment unprofitable to farmers. The important magnitude of environmental and social benefits associated with the use of TPR shows that investing in the application of TPR is highly profitable at the community and country levels. These results show that such investment will, in the long run, improve the welfare of farmers and the conservation of natural resources. In the short run, however, drastic fluctuation in prices and climatic conditions can result in short-term financial losses to farmers. Therefore, in areas with greater uncertainty about rainfall and in crops with low price stability, it is more difficult (risky) for farmers to invest in TPR or any other source of P.

Imported triple superphosphate (TSP) is more profitable than TPR as an alternative source for P replenishment investment in Mali, in terms of private and total benefits. Although strategies involving the basal application of TPR supplemented with annual applications of TSP are the most profitable in terms of net present value (NPV), the additional benefit (profit) associated with the use of TPR may not be sufficiently high to provide an incentive for farmers to use a product that is more difficult to handle and apply. Therefore, in the absence of effective activities and interventions to actively promote the use of TPR by farmers, TSP and other soluble sources of P will be preferred and more easily adopted by farmers. However, the use of TPR as an investment becomes more attractive if significant importance is given to foreign exchange savings, the employment and human resource development associated with the exploitation and use of indigenous resources of phosphate rock (PR), the opportunity for a participatory approach involving all beneficiaries, and the strong support indicated at the national level. In this case, a program to promote the use of TPR should be conducted.

Phosphate fertilizer investment is necessary and a crucial component to restore, maintain, and enhance soil fertility and the conservation of natural resources in Mali. However, it is important to emphasize that investments in complementary technologies for erosion control, water conservation, and use of organic and other inorganic fertilizers should be considered as part of investment packages for soil fertility restoration and conservation.

Given the long-term nature of investments in the exploitation of PR deposits and the benefits that PR can provide to the farmers, credit and price policies should be established and maintained for several years as part of any program to promote the sustained use of TPR in Mali.

Serious consideration should be given to the implementation of pilot projects to promote, in properly identified target areas, the use of TPR for direct application as a component of fertilizer use strategies more suitable to the agroecological and socioeconomic circumstances of each location. These strategies will contribute to the enhancement of soil fertility and the conservation of natural resources in the agricultural regions of Mali.

In designing fertilizer use strategies, provisions should be made regarding the effects that adverse fluctuations in climate and market prices may have on profitability and farm income. This is particularly important for investments in phosphate fertilizers because the effects of P fertilizers on soil fertility and crop production take place during several years.

Final Remarks

Profitability is a necessary but not a sufficient condition for farmers to adopt new practices and inputs in agricultural production. In the case of PR or any other source of P for crop production, profitability is determined by the response of crop outputs to the addition of PR, the prices of those outputs, the "farm-gate" price of the PR, and the cost of its application. Biophysical circumstances and agronomic conditions that affect the response of crop outputs to PR are key determinants of (and potential constraints to) the profitability of PR to farmers. Additional key factors affecting the profitability of PR include the policy environment, availability of infrastructure, socioeconomic circumstances affecting the pricing and supply of agricultural inputs and outputs in general and of PR in particular, and the behavior of farmers as producers and consumers. Finally, all factors affecting the cost of producing and supplying PR for direct application to farmers in sufficient quantities and on a timely basis are also important determinants of the profitable use of PR. A very brief summary of the key factors determining the potential economic feasibility of PR use by farmers is presented here.

Biophysical Circumstances – These are mainly associated with the characteristics of the PR and soils and include the following:

1. The inherent **mineralogy and chemistry of the PR** are basic determinants of whether a particular PR can be considered as a potential source of P for improving soil P fertility. Phosphate rocks of sedimentary origin and with considerable levels of carbonate substitution for phosphate are potential sources for building soil P levels over time or for providing the P required by annual crops. The level of carbonate substitution is indicated by chemical extractions (e.g., 2% formic acid, neutral ammonium citrate [2nd extraction]). Assuming that a PR is determined to be reactive enough to supply P for crop production, additional circumstances (indicated below) must be considered.

2. High levels of **potentially hazardous elements** such as cadmium, lead, radium, uranium, etc., within the PR structure can render a PR useless for application to improve soil fertility.

3. The physical **size of PR particles** influences both the rate of dissolution and availability of P following dissolution. The general recommendation is that PR material should be ground so that 80% is -100 mesh. Increases in P availability, particularly for medium-reactive PR such as the TPR-Mali have been obtained using this recommendation. However, shipping and handling difficulties are associated with the finely ground materials. In addition, some farmers have expressed a dislike for such materials due to application problems, particularly in the dry windy conditions of sub-Saharan Africa. For the highly reactive PRs (North Carolina-U.S.A.; Gafsa-Tunisia), which perform well agronomically in their natural state, the additional costs associated with grinding are not justified.

4. There are a number of **soil characteristics, which** in general increase the effectiveness of PR use, and these must be considered. The soil should be acidic (pH <5.5), have considerable P deficiency, and have a low level of available Ca. Phosphate rock dissolution is also increased by the presence of soil organic matter and high soil P retention/fixation. However, increased dissolution resulting from high levels of soil P-retention does not necessarily translate into increased plant-available P. The availability of other primary nutrients (N and K) and micronutrients in the soil also affects positively the effectiveness of PR and other sources of P.

5. Climatic factors, particularly rainfall, influence the effectiveness of PR. The efficiency of reactive PRs improves as annual rainfall increases above 500 mm. Areas with annual rainfall below 500 mm would not be suitable for PR application. Other climatic factors (e.g., temperature) that affect the length of the growing season have an indirect positive effect on PR efficiency.

Agronomic Conditions – These are factors mainly associated with the technology and management of crops, cropping systems, water, and soils and include the following:

1. Some crop species and varieties are capable of enhancing PR dissolution and/or extracting PR due to an extended or perennial growing season, reactions within the plant root rhizosphere, and/or extensive rooting systems (e.g., canola).

2. Production technologies that integrate suitable crop rotations, application of other nutrients deficient in the soil, complementary practices of animal husbandry for livestock production, managed fallows, appropriate tillage practices, water harvesting, and the addition of manure and composts can improve the overall agronomic and economic effectiveness of PR.

Socioeconomic Circumstances – Factors that affect the economics of PR use and the behavior of farmers toward the adoption of improved technology include the following:

1. Availability of farm labor to transport, handle, and apply PR – a more bulky and dusty product than commercially available P fertilizers.
2. Availability of and access to infrastructure facilities to move and distribute PR from production sites to distribution centers and farmers' fields.
3. Land property rights or long-term possession of land by farmers to benefit from the application of PR and other soil amendments.
4. Farmers' level of knowledge and access to information (education and availability of information) on agricultural production technology and farm management.
5. Consequences of recent farmers' experiences with the use of fertilizers, soil amendments, and other external inputs.
6. Magnitude and relative importance of the marketable surpluses of rural households from farming, e.g., outputs and prices of crop and animal production. Sustainable expansion of farmers' marketable surpluses should be associated with expansion in the adoption of PR and other external inputs. The lack of marketable surplus associated with subsistence farming is a serious constraint to the adoption of PR and other external inputs. It is important to note that the sustainable growth of farmers' marketable surplus also depends on the existence of market outlets and the demand for their products that can ensure stable and suitable levels of prices.
7. Availability of credit to purchase PR and complementary inputs that are required for ensuring the profitability of investing in PR and other soil amendments and conservation practices.

8. The price that farmers must pay for PR to cover the cost of PR production and distribution relative to the prices of commercial P fertilizer will affect the farmers' decisions.

Factors Affecting Supply and Farm-Level Price of PR – These are factors that affect the cost of production, distribution, retailing, and transport of the PR to farms relative to commercial P fertilizers on a nutrient basis:

1. Costs associated with production of PR (e.g., mining, beneficiation, capital outlays for processing equipment, maintenance, environmental mitigation, etc.).

2. Costs associated with shipping, handling, distribution and retailing of PR vis-à-vis other sources of P (e.g., transportation, storage, etc.).

As indicated above, there are numerous factors that determine where PR can be economically used, once it is proven to be agronomically effective. Most of these factors are location specific and, therefore, the feasibility of PR use should be evaluated and monitored at the farm level in locations where *a priori* assessment of all circumstances and factors indicate that the use of PR is expected to be successful from the ecological, economic, and social points of view.

Resumé

L’évaluation de l’efficacité agronomique et économique des sources de phosphate (P) au Mali montre que, pour une production durable des principaux systèmes de culture, l’utilisation des engrais phosphatés est nécessaire tant pour les cultures vivrières que pour les cultures de rente, et que le phosphate naturel de Tilemsi (PNT) est une source locale appropriée de P.

L’estimation des bénéfices individuels et environnementaux montre qu’investir dans l’application du PNT en guise d’engrais phosphaté est rentable pour les paysans, même lorsque le taux d’escompte atteint 30%. Cependant, la faible pluviométrie (dans certaines zones semi-arides) et la chute brutale des prix agricoles peuvent compromettre la rentabilité financière d’un tel investissement. Les importants bénéfices sociaux et environnementaux qui découlent de l’utilisation du PNT prouvent que cet investissement est très profitable aussi bien pour les communautés rurales que pour le pays tout entier, car il permet, à long terme, l’amélioration du bien-être des paysans et la conservation des ressources naturelles. Cependant, à court terme, un tel investissement pourrait aboutir à des pertes financières pour les paysans, en raison de la forte fluctuation des prix des denrées alimentaires et des aléas climatiques. Par conséquent, il est plus difficile (risquant) pour les paysans d’investir dans l’utilisation du PNT ou toute autre source de P dans des régions à pluviométrie incertaine et pour des cultures dont les prix sont instables.

L’étude montre par ailleurs qu’au Mali, sur le plan individuel et social, l’utilisation du TSP importé comme source alternative de P est plus rentable que celle du PNT. Bien que les stratégies consistant à effectuer un phosphatage de fond avec le PNT complété par des apports annuels de TSP se révèlent plus rentable en termes de valeur actuelle nette (VAN), les gains additionnels obtenus a cause de l’utilisation du PNT ne sont pas suffisamment incitatifs pour motiver les paysans à recourir à cette source de P dont la manipulation et l’application sont plus difficiles. Par conséquent, en l’absence d’activités et d’interventions efficaces visant à promouvoir l’utilisation du PNT par les paysans, ces derniers préféreront utiliser le TSP et d’autres sources solubles de P. Cependant, si l’on prend en compte l’épargne en devises étrangères, la création d’emplois et la formation des ressources humaines résultant de l’exploitation et de l’utilisation des sources locales de PN, la possibilité de participation de tous les bénéficiaires, et le grand intérêt observé au niveau gouvernemental, l’exploitation des PNT devient un investissement plus attractif. Dès lors, un programme de promotion de l’utilisation du PNT devient nécessaire.

L’investissement dans l’utilisation des engrais phosphatés est une composante nécessaire et cruciale pour la restauration, le maintien et l’amélioration de la fertilité des sols ainsi que la conservation des ressources naturelles au Mali. Il est cependant important de souligner que des investissements sur des technologies complémentaires relatives au contrôle de l’érosion, à la conservation de l’eau, et à l’utilisation des engrais organiques et autres engrais inorganiques devraient être envisagés dans le cadre d’un paquet d’investissements pour la restauration et l’amélioration de la fertilité des sols.

Etant donné que l’exploitation des gisements de phosphate naturel (PN) implique des investissements à long terme et parce que pour les agriculteurs, bien qu’augmentant de manière significative dans le temps, les bénéfices immédiatement qui en résultent ne sont pas assez importants, des politiques de prix et de crédit devraient être mises en place et maintenues pendant plusieurs années pour promouvoir l’utilisation durable du PNT au Mali.

Pour promouvoir l’application directe du PNT dans le cadre d’une stratégie de fertilisation adaptée aux caractéristiques agro-écologiques et socio-économiques des zones d’utilisation, il est important que des projets pilotes soient initiés dans des régions soigneusement identifiées. Une telle stratégie contribuera de manière significative à l’amélioration de la fertilité des sols et à la conservation des ressources naturelles au Mali.

En élaborant des stratégies d’utilisation des engrais, il est nécessaire de prendre en compte les effets potentiels des aléas climatiques et de la fluctuation des prix sur la rentabilité et les revenus agricoles. Ceci est

particulièrement important pour les investissements sur les engrais phosphatés dont les effets sur la fertilité des sols et la protection des plantes s'étalent sur plusieurs années.

Remarques Finales

La rentabilité est une condition nécessaire mais pas suffisante à l'adoption par les paysans de nouveaux intrants et pratiques agricoles. Dans le cas particulier du phosphate naturel (PN) ou de toute autre source de P, la rentabilité est fonction de la production additionnelle obtenue, du prix de vente des produits récoltés, du prix du PN rendu au champ**,** et du coût de son application. Par conséquent, les facteurs biophysiques et agronomiques qui influencent la réponse des cultures à l'apport de P sont les déterminants (et les contraintes potentielles) de la rentabilité financière de l'utilisation du PN. Il en est de même de l'environnement politique, de l'existence d'infrastructures de transport et de stockage, des facteurs socio-économiques qui conditionnent le prix et l'offre des intrants et produits agricoles en général, et ceux du PN en particulier, ainsi que du comportement des paysans en tant que producteurs et consommateurs. Enfin, tous les facteurs qui influencent le coût de production et l'offre de PN en quantité suffisante et en temps opportun sont des déterminants de la rentabilité de l'utilisation de cette source de P. Un bref résumé des principaux facteurs qui influencent la rentabilité économique de l'utilisation du PN est présentée ci-après.

Facteurs Biophysiques – Ces facteurs sont essentiellement liés aux caractéristiques du PN et à celles des sols.

1. La composition minéralogique et chimique détermine si un PN particulier peut être considéré comme une source potentielle de P pour l'amélioration de la fertilité des sols. Les PN d'origine sédimentaire contenant une proportion importante de substitutions de phosphates par des carbonates sont des sources potentielles pour la reconstitution dans le temps du niveau de P des sols ou d'approvisionnement en P pour les cultures annuelles. Le niveau de carbonates de substitution est déterminé par extraction chimique (ex: acide formique à 2%, le citrate d'ammonium neutre [2ème extraction]). Lorsqu'il est établi qu'un PN peut apporter suffisamment de P aux plantes, les facteurs supplémentaires ci-dessus doivent être pris en considération.

2. Des taux élevés d'éléments potentiellement toxiques tels que le calcium, le plomb, le radium, l'uranium etc., dans la composition des PN peuvent les rendre impropres à l'amélioration de la fertilité des sols.

3. La taille des particules de PN influence la vitesse de dissolution et la disponibilité du P. Il est généralement recommandé que le PN soit finement moud (80%) de manière à pouvoir passer à travers un tamis à maille de 0,100 mm. Cette granulométrie a permis d'accroître considérablement la disponibilité du P, en particulier pour ce qui est des PN à réactivité moyenne tels que les PNT. Cependant, la manutention et l'emploi du PN moulu posent des problèmes. En effet, certains paysans déplorent l'incommodité de l'application de la poudre fine, en particulier sur les sols semi-arides de l'Afrique subsaharienne balayés par les vents. Pour les PN les plus réactifs (Caroline du Nord-Etats-Unis, Gafsa-Tunisie) qui montrent une bonne efficacité économique à l'état naturel, le coût supplémentaire lié au broyage n'est pas financièrement justifié.

4. Certaines caractéristiques des sols, qui généralement augmentent l'efficacité des PN doivent être prises en considération. En effet, le sol doit être; (1) acide ($pH<5.5$), (2) fortement déficient en P, et (3) pauvre en Ca disponible. La dissolution des PN est aussi accélérée par la présence de la matière organique et un fort taux de rétention/fixation de P du sol. Il faut cependant noter qu'un taux de rétention de P élevé n'implique pas nécessairement un accroissement de la quantité de P disponible pour les cultures. Enfin, la disponibilité dans le sol d'autres principaux éléments nutritifs (N et K) et d'oligo-éléments influe aussi positivement sur l'efficacité des PN et autres sources de P.

5. Les facteurs climatiques, en particulier la pluviométrie, influencent l'efficacité des PN. Celle-ci s'améliore lorsque la pluviométrie annuelle dépasse 500 mm. En d'autres termes, les localités enregistrant des précipitations annuelles inférieures à 500 mm ne conviennent pas à l'utilisation des PN. D'autres facteurs

climatiques (la température) qui influent sur le cycle végétatif des plantes ont un effet positif indirect sur l'efficacité des PN.

Conditions Agronomiques – Il s'agit principalement des facteurs liés aux types de technologies, à la gestion des cultures, aux systèmes culturaux, ainsi qu'aux conditions hydriques et édaphiques.

1. Certaines espèces et variétés de cultures pérennes ou à cycle végétatif long sont capables d'améliorer la dissolution et/ou l'extraction du P des PN grâce à certaines réactions qui se produisent au niveau de la rhizosphère et/ou à des systèmes racinaires développés (colza).

2. Les technologies intégrant la rotation de cultures, l'apport d'autres éléments nutritifs déficients dans les sols, un élevage complémentaire, une jachère améliorée, un labour approprié, la maîtrise de l'eau, un apport de fumure et composte peuvent améliorer l'efficacité agronomique et économique des PN.

Facteurs socio-économiques – Il s'agit des facteurs qui influencent l'économie de l'utilisation des PN et l'attitude des paysans vis-à-vis des technologies améliorées.

1. La disponibilité de main-d'œuvre pour la manutention et l'application du PN qui est un produit plus volumineux et plus poussiéreux que les engrais phosphatés couramment commercialisés.

2. L'existence et l'accès aux infrastructures de transport (routes) et de stockage, ainsi que des moyens d'acheminement des PN vers les centres de distribution et les champs paysans.

3. Le droit de propriété ou d'usage à long terme permettant aux paysans de bénéficier de l'application des PN et autres types d'amendements du sol.

4. Le niveau de connaissance et d'accès des agriculteurs aux informations concernant les technologies de production et de gestion agricoles.

5. Les résultats d'expériences récentes d'utilisation d'engrais et d'amendements du sol et de tout autre intrant agricole externe, faites par les agriculteurs.

6. L'importance et la valeur relative du surplus commercialisable obtenu par les ménages ruraux. La promotion de l'utilisation des PN et autres intrants agricoles externes devrait être liée à un accroissement durable du surplus commercialisable. Par conséquent, l'absence de surplus commercialisable qui caractérise très souvent les systèmes de production de subsistance est un handicap à l'adoption des PN et autres intrants agricoles externes. Il faut noter que l'accroissement durable du surplus commercialisable dépend en partie de l'existence de marchés des produits et de la demande des consommateurs qui peuvent garantir des niveaux de prix stables et rémunérateurs.

7. La disponibilité d'un système de crédit à l'achat des PN et des intrants complémentaires qui sont nécessaires pour assurer la rentabilité des investissements en PN et autres amendements du sol et celle des techniques de conservation des sols.

8. Le coût des PN aux paysans par rapport à celui des engrais phosphatés commercialisés.

Facteurs influençant l'offre et le prix des PN – Ce sont les facteurs qui influencent les coûts de production de l'unité fertilisante de la distribution, de la vente au détail et du transport des PN jusqu'aux champs paysans, par rapport aux engrais phosphatés commerciaux.

1. Les coûts liés à la production des PN (extraction, enrichissement, maintenance, protection de l'environnement, etc.)

2. Les coûts liés au transport, à la manutention, à la distribution et à la vente au détail des PN par rapport à ceux des autres sources de P.

Tous les éléments cités ci-dessus montrent que plusieurs facteurs entrent en ligne de compte pour déterminer la rentabilité de l'utilisation des PN dont l'efficacité agronomique est établie. Parce que la plupart de ces facteurs sont spécifiques aux lieux d'utilisation, la rentabilité de l'utilisation des PN devrait être évaluée, au champ, dans des régions où une évaluation préalable de toutes les conditions et des facteurs déterminants indique que l'utilisation des PN peut être efficace sur le plan écologique, économique et social.

1. Introduction

The Republic of Mali, a landlocked country without direct access to the sea, has a land area of 1.24 million km^2 or 4.2% of Africa's total area; thus, it is one of the largest Sahel countries. The northern 44% of the country is barren desert without permanent settlement of human population. The south, which includes the Sudano-Guinean zone, is characterized by subhumid to humid environments with more fertile savanna lands.

Over 80% of the population of Mali is dependent on agriculture, which accounts for approximately 70% of the gross domestic product (GDP). Because of the dominant role of agriculture in the country's economy, agriculture continues to receive special attention in development programs. Growth of the agriculture sector, however, has been limited by low land productivity associated with poor rainfall, low soil fertility, and traditional crop management practices. In addition, Mali and other African countries are being affected by the increasing overexploitation of land resources and forests as a result of overgrazing and the rapid growth in demand for foodstuffs and fuelwood. Consequently, the restoration and/or maintenance of soil fertility and the prevention of soil loss and environmental degradation through better management practices and improved technology for sustainable agricultural production have become the greatest challenges facing farmers, institutions, and policymakers.

The present study examines the agronomic and economic effectiveness of the use of the indigenous Tilemsi phosphate rock (TPR) as a source of phosphorus (P) to improve soil fertility and crop production in agricultural regions of Mali. The study is based on extensive field work performed in key agricultural areas of the country. It summarizes seasonal crop responses to phosphorus applied using alternative sources of P and assesses soil phosphorus balances in selected agroenvironments. The study provides valuable information for developing economically sound fertilizer use strategies and for implementing crop production alternatives based on the use of indigenous resources of phosphate rock (PR).

Data and results from the project on Efficient Utilization of Fertilizer in Mali (IFDC, 1989) were used in preparing this report. This project was conducted by the International Fertilizer Development Center (IFDC) in collaboration with IER during 1982 to 1987. The project was financed by the International Development Research Centre (IDRC) of Canada.

The area of study covered sites located in four agroecological zones, namely, the Sahel-North, Sahel-South, Sudanian, and Sudano-Guinea zones. The sites were distributed along the five regions covering the Mali-Sud area: Sikasso, Koulikoro, Kayes, Segou, and Mopti. These regions cover about 55% of the total area of the country of which 29%, about 19.5 million ha, is classified as agricultural land. The agricultural areas comprise a diversity of farming conditions and crop production practices from subsistence production to commercial-scale agriculture. Maps of the Republic of Mali showing administrative divisions and the sites where project activities were conducted and mean annual rainfall amounts prevailing in those areas are presented in Figures 1 and 2.

2. Economy and Population – An Overview

The economy of Mali is largely dependent on its agriculture sector. The country is a net importer of food grains and benefits from continuous food and fertilizer aid. With a per capita income of US $220 (Table 1), Mali is one of the world's poorest and least developed countries. It has very few mineral resources (bauxite, iron ore, manganese, uranium) and a small industrial sector that accounts for only 13%-15% of the country's GDP, with almost no possibility of increasing industrial output. The GDP was US $1,500 million in 1993. Agriculture's share of the GDP was 61% in 1975 and decreased to 42% in 1993. The rate of economic growth in recent decades has declined due to a decrease in agricultural output. In the absence of strong economic growth and no major structural changes, employment patterns have changed very little. Approximately 80% of the labor force works either full or part-time in the nonwage agricultural, livestock, and fishery activities, which are primary sectors in the determination of average incomes.

The decline in economic growth has contributed to the country's precarious financial situation. Mali's budget deficit has remained at a high level; its total external debt amounted to US $2,650 million in 1993, which represented US $300 per capita, 266.8% of total exports, and 58.8% of gross national product (GNP). Mali was among the 22 countries classified by the World Bank as "debt distressed." The per capita external debt exceeds the per capita national income by about 36%. The total debt service was 45% of the exports of goods and services in 1993 (World Bank, 1995).

Figure 1. Mali Administrative Divisions and Main Bioclimatic Zones

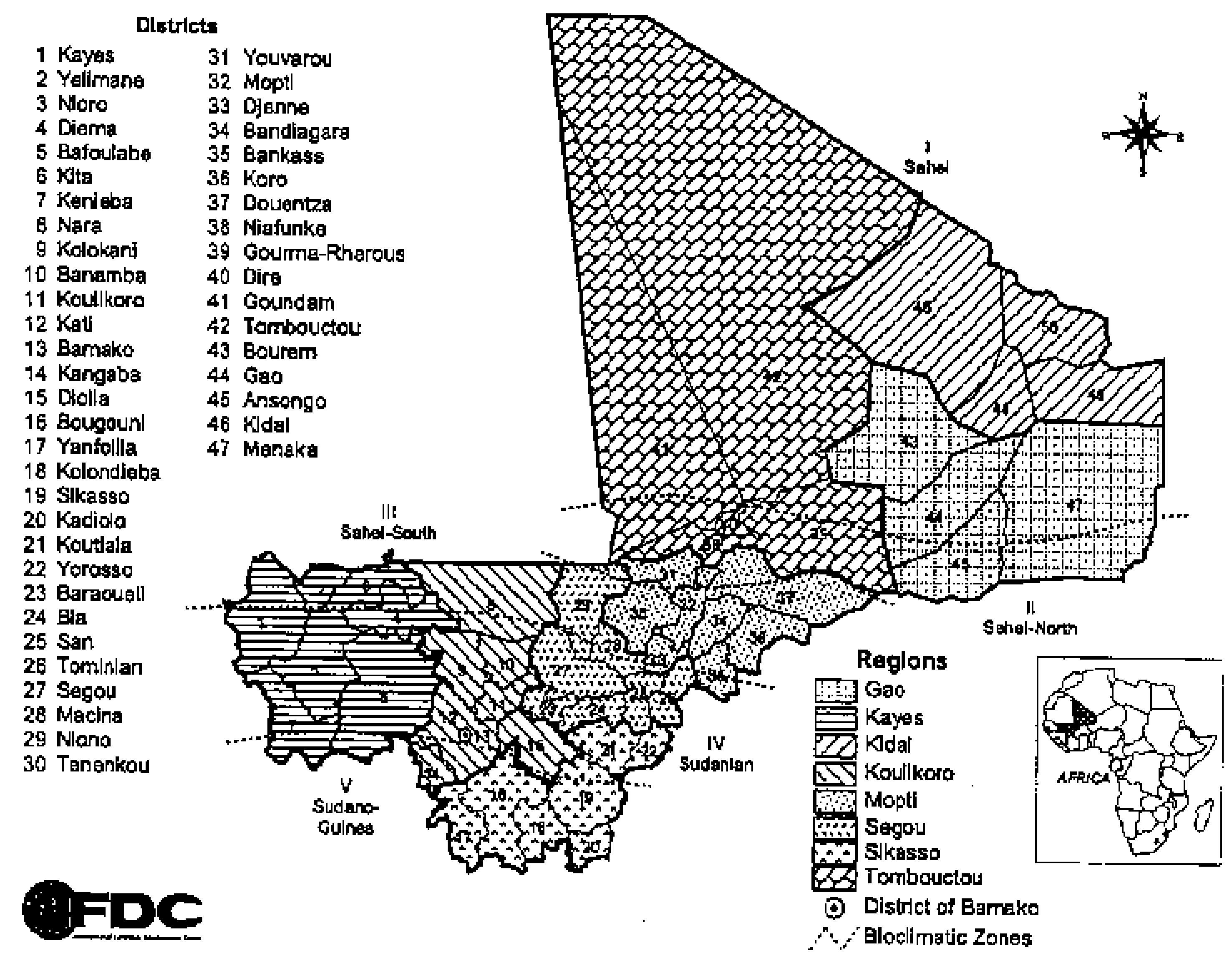


Figure 2. Mean Annual Rainfall

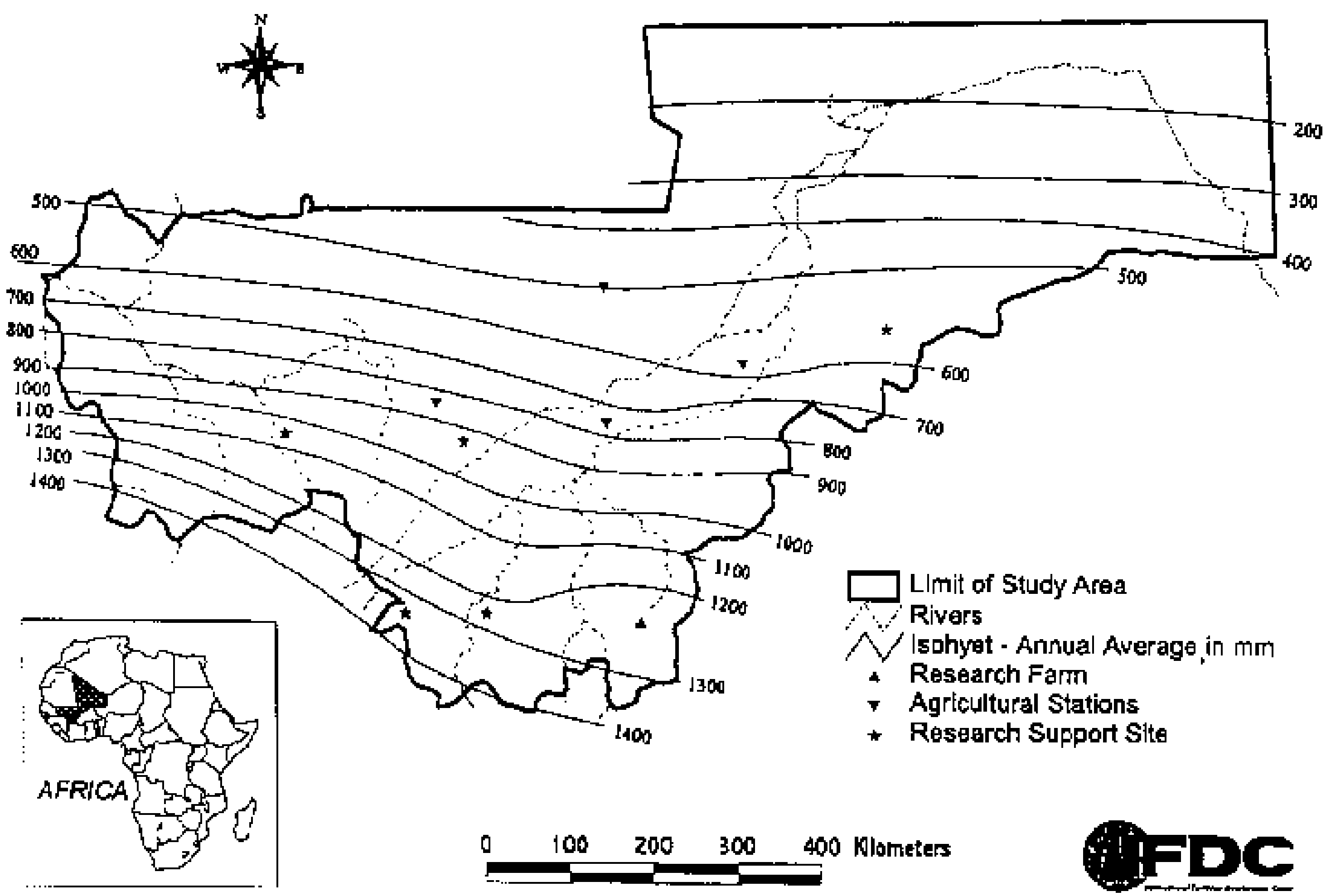


Table 1. Mali Macroeconomic, Demographic, and Land Use Indicators

Indicators	1975	1980	1985	1990	1993
Economic					
Real GDP growth (%)	2.8	3.3	3.5	2.2	2.5
Per capita national income (US $)	110.0	130.0	170.0	180.0	220.0
Average annual inflation rate (%)	7.7	10.7	3.8	1.3	1.8
Average exchange rate (FCFA/US $1)	211.0	211.0	449.3	272.3	371.0
External debt (million US $)	338.1	684.7	1,334.2	2,242.2	2,650.0
Exports (f.o.b. - million US $)	-	-	244.5	337.9	342.6
Imports (c.i.f. - million US $)	-	-	432.4	447.0	496.5
Balance of Trade (million US $)	-	-	-187.9	-109.1	-153.9
Share of GDP (% Based on Current Prices)					
Agriculture	61.0	68.2	53.8	51.6	42.0
Industry	11.7	10.2	10.5	13.0	15.3
Manufacturing	5.0	6.0	6.0	6.0	7.0
Services	22.3	15.6	29.7	28.4	35.7
Labor Force in Agriculture (%)	86.9	85.5	84.2	81.3	80.0
Population					
Total ('000 persons)	6,278	6,880	7,915	9,212	10,462
Annual growth rate (%)	-	1.9	2.2	2.5	2.8
Rural (% of total)	84.5	85.5	83.4	80.9	78.6
Population density (persons/km^2)	5.6	6.0	6.8	7.5	8.0
Per capita food production (1979-81=100)	-	-	94.5	91.3	94.5

Land Use (as at 1993)	('000 ha)	%
Total area	124,019	
Land area	122,019	100.00
Pastoral land	19,580	16.05
Agro-pastoral/agriculture	7,500	6.15
Agro-pastoral/pastoral	8,300	6.80
Agricultural land	19,580	16.05
Bush pastureland	2,300	1.89
Irrigated and naturally flooded land	183	0.15
Other land (desert and rocky areas)	64,576	52.92

The Food and Agricultural Organization of the United Nations, Agricultural Yearbook, 1994, Vol. 48.
IMF, International Financial Statistics, 1994.
African Research Bulletin, Economic, Financial, and Technical Series, Vol. 2, 1993.
Direction Nationale de la Statistique et de L'Informatique, Mali, 1993.
Project d'Inventaire des Resources Terrestres (PIRT), Mali, 1982.

An important factor contributing to the debt burden in Mali is the continuous worsening of its balance of trade. Mali's trade balance is in chronic deficit; exports represent 55%-75% of the value of the imports. Although Mali's agricultural policy aims at food security and diversification of agricultural production and exports, sources of foreign exchange earnings are limited and crop production is not diversified. Most of its foreign exchange is earned by the export of a few commodities (cotton, cattle, groundnut, dried fish, rice, gold, and rubber). Cotton and livestock production each account for 30%-40% of the country's export income. These two commodities have been affected by unstable market prices due, in the cotton case from increased exports by Russia and China, and in the livestock case from subsidized EU meat exports to Mali's traditional markets, which have cost the country about 8% of its foreign-currency earnings (DGIS, 1995).

The total population was 10.5 million in 1993 (World Bank, 1995). The population is increasing by about 3%/year and is expected to reach 15 million by 2010 and about 25 million by 2025; urban population is estimated to be growing at 4.9% per year. The total fertility rate, the average number of children a woman is expected to bear in her lifetime, is 7.3 and results in a population where at least 46% are below the age of 15 years. As long as birth rates remain high, sustainable food security will be increasingly difficult to achieve.

The country needs to increase and accelerate the growth of food production. A recent study (Gerner et al., 1995) has suggested that, although the recent devaluation of the FCFA has increased the profitability of the export crop sector, it has not immediately benefitted the food crop subsector, and food production is expected to continue to be low because of the stagnant low use of modern agricultural inputs, especially mineral fertilizers.

Although the country is sparsely populated with about 8 persons/km^2, the Sahel and Sudan Savannah are overpopulated in view of the low qualitative endowment of available resources. Only a small portion of the total area is suitable for ecologically and economically sound agriculture that depends on external inputs, and the population density may reach up to 230 persons/km^2 in some agricultural areas. The estimated distribution of population by region is shown in Table 2. The Kayes and Koulikoro regions are the least populated with an average density of 7.3 and 10.4 persons/km^2, respectively. Average density is 14 to 18 persons/km^2 in more densely populated regions – Mopti, Sikasso, and Segou. In the other two regions not considered in this study – Bamako and Gao – population densities are 10.4 and 0.8 persons/km^2, respectively.

In Mali, more than 80% of the population is rural. Most of the people depend on small-scale agriculture for their livelihood; the cultivated area per person is about 0.5 ha, and the average household size is 5 persons. Because productivity is very low and unemployment widespread, people have very low incomes. It is this population that has experienced the greatest decrease in food per capita despite substantial food imports and donor support.

More than three quarters of the male and female population in Mali work in agriculture. Men work primarily on cash crops (cotton, groundnut, and rice), and women divide their time to work in activities associated with the production of some food crops and in housework (obtaining water, gathering firewood, and acquiring and preparing food). Because an increasing number of young men migrate to urban centers and coastal countries in search of jobs, the women have increased their role in agricultural production, consequently, increasing household responsibilities.

Population in urban areas is increasing at a rate that is about twice that of the rural areas. It has been projected that by the year 2010, per capita food consumption will increase by more than 30% over the current consumption rate. Urban food demand for millet, sorghum, maize, and rice is expected to increase at a rate over 10,000 mt/year, based on a requirement of 180 kg per person annually. The current population growth and the present levels of nutrition present huge challenges for the agriculture sector.

Rapid population growth and the deterioration of economic and social conditions have produced growing pressure on the resource base for agriculture, particularly on the soil's stock of nutrients. In turn, this threatens the sustainable productive capacity of the land, which is already low. Sustainable production to cope with the demands of a growing population requires appropriate use of the resource base for agriculture, more intensive use of improved seeds and other external inputs including mineral fertilizers to maintain soil fertility, and improved farm management practices.

3. Resource Base for Agriculture

3.1 Land Resources

Nearly one-half of Mali is unsuitable for permanent agricultural production (Tables 1 and 2). The country's

Table 2. Selected Population and Land Use Indicators by Regions

Indicators	Units	Regions				
		Kayes	Koulikoro	Mopti	Segou	Sikasso
Population						
No Rural	%	11.0	10.0	8.0	16.0	11.0
Rural	%	85.0	88.0	84.0	82.0	88.0
Nomads	%	4.0	2.0	8.0	2.0	1.0
Density	#/km^2	7.3	10.4	14.2	17.9	15.3
Population in Agriculture						
Male	%	84.8	85.6	73.7	82.3	86.3
Female	%	94.2	49.8	81.9	47.1	77.2
Female household heads	%	19.1	11.2	15.9	14.4	10.4
Cultivated Area/Person	ha	0.6	0.4	0.3	0.4	0.5
Household Size	# pers.	5.6	5.5	4.4	4.9	5.6
Potential Land Use						
Flood plains and irrigated area	ha	30,600	28,500	165,500	105,100	30,930
	%	0.3	0.3	3.0	1.7	0.4
Alluvial areas	ha	37,500	91,772	19,850	4,700	13,994
	%	0.3	1.0	0.4	0.1	0.2
Permanent annual crops	ha	154,450	528,620	142,400	545,950	599,196
	%	1.3	5.9	2.6	9.0	8.5
Transitory crops with long fallows	ha	420,600	603,894	643,700	890,200	624,810
	%	3.4	6.7	11.8	14.6	8.9
Perennials (fruit trees)	ha	10,000	22,430	0	12,200	10,000
	%	0.1	0.2	0	0.2	0.1
Marginal land	ha	5,000	50,630	0	6000	20,000
	%	0.0	0.6	0	0.1	0.3
Land potentially cultivable	ha	2,915,240	1,668,230	587,000	947,750	2,967,050
	%	23.9	18.5	10.7	15.6	42.1
Land not apt for agriculture	ha	8,625,110	6,025,454	3,902,500	3,570,000	2,774,620
	%	70.7	66.8	71.5	58.7	39.4
Total Area	ha	12,198,500	9,019,530	5,460,950	6,081,900	7,040,600

Project Inventaire des Resources au Mali. Phase B. Synthese Regionale.
CTFT (Department du CIRAD). SYSAME. 1991.

potential agricultural areas are located in the Sahel-South, the Sudanian, and the Sudano-Guinea zones (Figure 1). These agro-ecological zones correspond to semiarid and subhumid zones according to agroclimatic classifications. The northern 44% (54.5 million ha) of the country is barren desert. Of the area receiving measurable annual rainfall, 27% (33.5 million ha) receives between 250 and 600 mm, whereas the southern region, representing 29% of the country (35.9 million ha), has an annual rainfall ranging from 600 to 1,400 mm (Figure 2).

A land resource study of the country (PIRT, 1982) recognizes five primary types of land use in the agricultural areas: pastoral, agropastoral, agricultural, bush-pasture, and irrigated (Figure 3). Very few unused areas were identified. The pastoral areas, which account for 16% (20 million ha) of the total land area, are characterized by severe aridity (<400 mm rainfall/year) and natural vegetation limited to sparse grass. These areas are used almost exclusively for grazing and itinerant animal husbandry. The pastoral zone merges into a zone of agropastoralism with scattered tree vegetation, and receives 400 mm-700 mm of annual rainfall. This area, which occupies 12% of the total land area (15.8 million ha), is characterized by subsistence agriculture and pastoralism where expansion of herds beyond the carrying capacity and overgrazing of rangelands have degraded the soils. The arable land currently in use in this area is approaching the limits of potentially cultivable land. Due to inadequate rainfall and degrading soils, migration accompanied by a concentration of subsistence agriculture occurs. This situation results in increased pressures on the more fertile land and natural vegetation of the southern areas of the country.

Land used for permanent and transitory (bush pastureland) agriculture occupies about 16% of the total land area (19.6 million ha), primarily in the southern part of the country. This land has more abundant natural vegetation and receives 700 mm or more of annual rainfall. The population derives most of its income from subsistence and commercially oriented agriculture complemented with livestock activities. Natural vegetation in this area includes forest, thicket, mixed forest-grassland formations (woodlands, wooded savannas, trees, and shrub savannas), and grass savannas. Although much of the land is degrading, it continues to be the primary source for food, fodder, fuel, and building materials. Irrigated areas, using water control systems or traditional flooding systems, are located along water streams flowing across these areas; particularly important are the catchment areas of the Niger River.

Results of the study performed by The Project d'Inventaire des Ressources Terrestres du Mali (PIRT, 1982) on the potential use of the land per region are presented in Table 2. Between 66% and 72% of the total land in Kayes, Koulikoro, and Mopti is land classified as not suitable for agriculture, whereas 58.7% and 39.4% of the total land is so classified in the Segou and Sikasso regions, respectively. Among the reasons mentioned were degradation of the land due to continuous cropping, overuse of marginal lands, increased deforestation and overgrazing, and very limited use of inputs to replenish nutrients and preserve the fertility of the soils. Only 1.3% of the land in Kayes and 9.0% of the land in Segou is classified as land suitable for continuous cropping. Additionally, 3.4% of the land in Kayes and 14.6% in Segou is classified as cultivable if long fallows or appropriate management practices, including intensive use of mineral and organic fertilizers, are utilized.

3.2 Soil Fertility

The natural fertility of the soils on agricultural lands is inherently poor with low nutrient content, shallow profiles (<125 cm), low water-holding capacity, and low nutrient retention. Mineralogically, the soils are residual systems dominated by quartz/kaolinite/Fe-oxide (goethite); thus, the colloidal fraction of the soils has been formed from coarse materials with limited ability to supply plant nutrients. Malian soils are fragile and highly susceptible to wind and water erosion and have gravel layers; their structure can be easily degraded with continuous farming.

The chemical characteristics of modal soil profiles in the Malian regions (observed during the 1982 cropping season) are presented in Table 3. The organic matter content of most soils is limited (0.3% to 1.6%); cation exchange capacity (CEC) is low (<5 meq/100 g soil); the soils have low buffering capacity and low clay content. The pH of most soils is acidic to strongly acidic, and base saturations are generally less than 40% in the upper horizons. The total phosphorus is low (<200 ppm) as is available phosphorus (2-7 ppm Bray P-1 method). Aluminum saturation percentages tend to be high in superficial and subsoil horizons.

The low fertility and low-based status of the soils have been primary limitations to agricultural production. The most extensive cultivable area, located in the alluvial valleys of the Senegal River, is rich in tropical ferruginous soils (Alfisols) with rapid mineralized organic matter. These soils can only support intensive plantation agriculture or annual crops with appropriate

Figure 3. Mali Existing Land Use

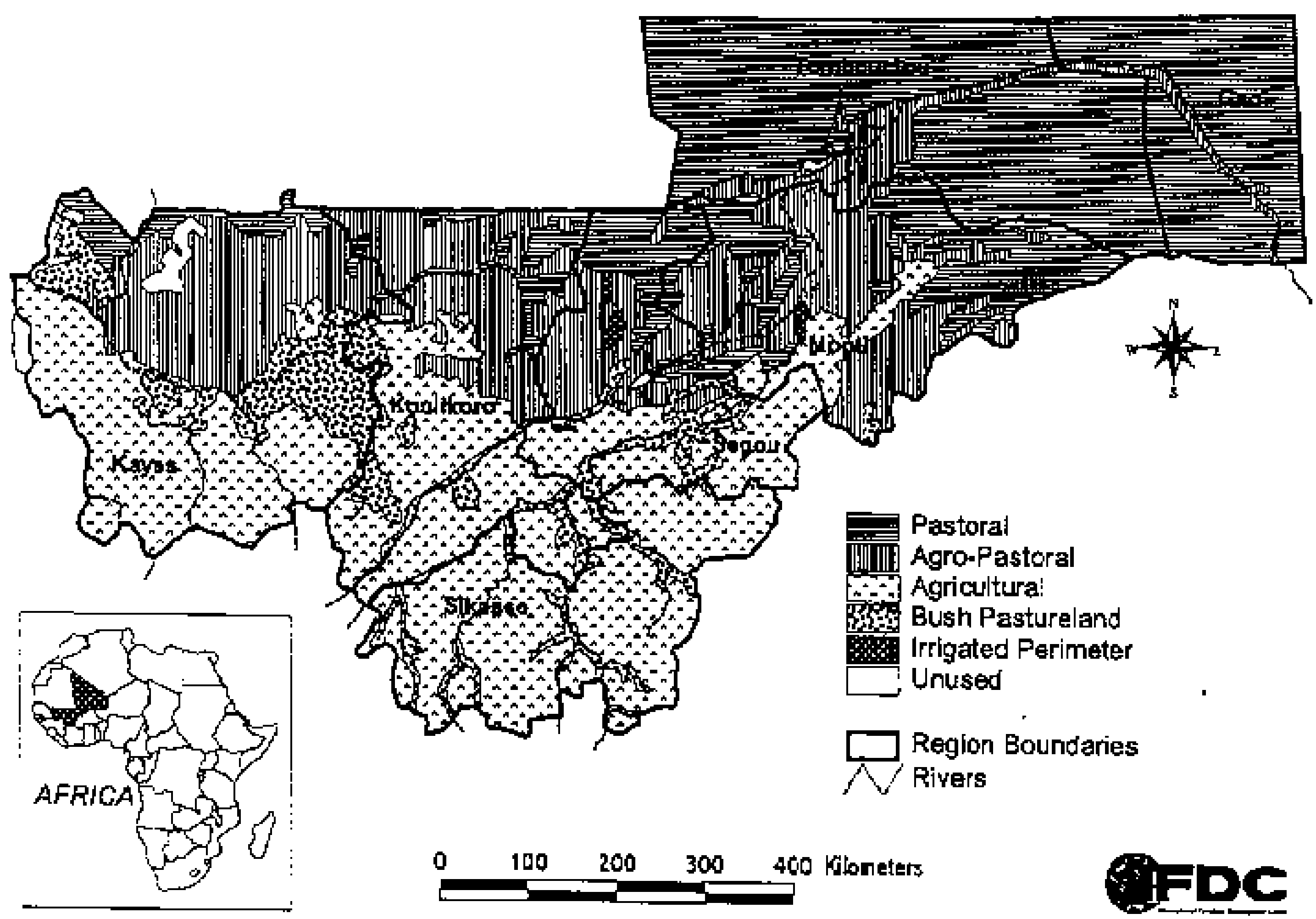


Table 3. Soil Characteristics of the Study Regions

Characteristics		Regions				
		Kayes	Koulikoro	Mopti	Segou	Sikasso
Soil Chemical						
pH (2:1 water:soil)		4.2-5.3	5.1-5.9	5.7-6.8	4.5-5.9	4.3-5.7
pH (2:1 KCL:soil)		3.8-4.8	4.7-5.2	5.3-6.1	4.1-5.3	3.9-5.1
Organic Matter (%)*		0.4-0.8	0.7-1.2	0.3-0.7	0.8-1.4	0.8-1.6
Extractable P						
Bray P-1 mg /kg soil		3.5-6.0	3.0-4.8	2.1-2.9	3.1-3.9	4.2-7.2
Exchangeable Cations (Cmol/kg)						
Na		0.12-0.22	0.10-0.40	0.16-0.28	0.10-0.24	0.10-0.22
K		0.10-0.23	0.12-0.40	0.07-0.25	0.10-0.17	0.19-0.32
Ca		0.85-1.20	0.90-2.00	0.35-1.60	1.15-1.70	1.05-1.21
Mg		0.28-0.80	0.60-0.90	0.21-1.25	0.58-0.65	0.24-0.65
Effective cation exchange capacity (ECEC, Cmol/kg)		1.75-3.25	2.50-5.78	1.15-3.38	2.35-4.80	2.20-4.25
Base saturation (%)		22-49	33-65	39-80	32-58	30-52
AL saturation (%)		15-53	12-45	0-26	10-58	13-45
Total P (mg P/kg soil)		44-93	52-105	22-56	46-125	58-160
Soil Physical						
Depth		Medium	Medium	Shallow	Shallow	Deep
Clay (%)		17.4	14.3	7.3	17.8	24.4
Sand (%)		71.5	64.5	83.9	55.6	54.7
Bulk density (gr/cm^3) **		1.15-1.35	1.35-1.52	1.55-1.82	1.40-1.50	0.80-1.10
Soil Classification	USDA	Alfisols Aqualfs	Alfisols Haplustalfs	Entisols Psamments	Alfisols Haplustalfs	Ultisols Haplustults
	FAO	Nitosols	Planosols	Arenosols	Luvisols	Acrisols
Relief		Sloping	Sloping	Level	Level	Sloping
Present Erosion		Moderate	Moderate	High	Moderate	Moderate
Erodibility		Medium	High	Very High	High	Medium
Erosion (tons/ha per year)		5-20	5-25	10-30	8-25	5-18

* Wet combustion (top 10 cms).
** Soil depth : 10-20 cm.
Project d'inventaire des Resources Terrestres (PIRT). Mali, 1982.
IFDC, 1985 Soil Analysis.

rotation systems and continuous use of mineral fertilizers or long fallows. In the central and northern parts of the Koulikoro, Segou, and Mopti regions, most of the soils are classified as tropical ferruginous (Alfisols and Entisols). They generally have low water-holding capacity and nutrient content, which places severe limits on continuous crop growth and livestock production. These soils tend to be poorly structured, which explains the compaction of the subsoils; they are continuously affected by water/wind erosion of the topsoil. Typical cropping systems prevailing in these types of soils include semi-intensive production of millet, sorghum, and groundnut on which very limited amounts of fertilizers are applied and rudimentary management practices are employed.

The southern parts of the Segou, Koulikoro, and Sikasso regions have better soils, which have considerable pedological diversity. Most of these soils are ferruginous soils leached to hydromorphic types. The use of hydromorphic valley lands (mostly Ultisols) for root crops is quite common, and traditional cultivation systems are practiced in these areas. These soils have low soil fertility and are under continuous cultivation with short rotation and intercrop systems.

4. Soil Degradation

Soil degradation, which occurs because of water and wind erosion, nutrient depletion, and biological degradation (decrease in organic matter), is the main threat to the sustainability of agricultural production and economic development of Mali. Soil degradation through erosion has been aggravated by the present pattern of agricultural and livestock practices. It has been estimated that Mali is losing between 15 and 30 tons/ha/year of soil due to erosion (Lawson, 1991). A study performed by Bishop and Allen in 1989 evaluated the losses of soil productivity due to erosion in Mali. The analysis, which focused on the cultivated land within a north-south swath of Mali – one-third of the country's most productive agricultural land – estimated that the average soil loss was 6.5 tons/ha/year, with higher losses occurring in the South (a maximum of 31 tons/ha/year). Estimates for the whole country showed that the cumulative 10-year loss due to erosion in terms of the monetary value of lost production was about 1.5% of Mali's GDP and about 4% of its Gross Agricultural Product (GAP). Gross estimates of soil erosion by region, calculated by using methods similar to those developed by Bishop and Allen, are presented in Table 3.

As much as 60% of the fertilizer applied can be lost through erosion and leaching, thereby contributing to continuous nutrient depletion. Nutrient depletion estimates calculated using nutrient balance approaches have been determined in Mali as a means of assessing the degradation of soils. The most recent studies conducted by Stoorvogel and Smaling, 1990, and by Van der Pol, 1992, have found that Malian soils lost 8, 2, and 8 kg/ha of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O), respectively, during the 1983 cropping season. The losses projected for the year 2000 were 11, 6, and 12 kg/ha/year for N, P_2O_5, and K_2O, respectively. Given the low natural fertility of Malian soils, the nutrient depletion rate in Mali is a cause for great concern. In these studies, the authors concluded that current farming is based on the mining of nutrients from the soils and that this is a significant threat to the sustainability of agriculture in the country. The authors also observed that if the added value of agricultural production is examined and if the cost of nutrients depleted from the soils was included in the analysis, the viability of agriculture as an economically sound production system could be seriously questioned.

Extensive deforestation to obtain firewood and timber and the removal of crop residue have accelerated soil erosion and, thus, caused a decrease in organic matter and physical degradation of soils (increase in bulk density/decrease permeability). Firewood and crop residue supply almost 90% of the energy consumed in the country. Since there are no adequate reforestation programs, these practices have caused the complete destruction of the forest in some areas. While the immediate supply of firewood may not yet be restricted in Mali, agricultural pressure on deforested land has resulted in soil erosion, which will make it more difficult to carry out reforestation activities that would ensure wood supplies in the future (ISNAR, 1995). Although some cleared land reverts to bush or tree fallow, the natural vegetation is not usually re-established. Although cropping intensity remains low in most agricultural areas, expansion of monocultural agriculture, overgrazing into forest areas, and the commercial exploitation of forests beyond their natural ability to regenerate have had adverse economic, social, and ecological consequences.

Contributing to accelerated land degradation is the farm management system that is practiced in most of the country and is mainly characterized by very low use of inputs and no conservation practices. This is commonly associated with limited extension services, higher input prices, and the present land tenure system.

In the current system, the land is the property of a group (family, village, or ethnic group) and is assigned to individuals for cultivation and usufruct on the basis of fixed rules. Land tenure often changes with the location or physical characteristics of the land and the manner in which it is used. Thus, changes in infrastructure, management, and characteristics of the land, such as irrigation or improved technologies, can cause changes in the land tenure and existing social relationships. The system of land-use rights usually promotes the overuse of commonly owned land and most farmers have neither the incentives nor the financial means to invest in soil conservation practices that preserve soil fertility and sustainable production.

5. Crop Production Systems

While crop production predominates in the southern part of the savanna zones, crop production and animal husbandry are equally important and often complement each other in the northern part. The humid, subhumid, and dry savannas have a wide range of similar food crops although management practices, cropping systems, and yields vary in each zone. The most important crops are sorghum, millet, maize, rice, groundnuts, and cotton. Legumes, root crops, and vegetables are less significant in terms of volume and are confined to humid savannas.

Rainfed agriculture, with the exception of enclaves of irrigated rice, is the predominant production system; thus, the number of crops and crop production systems that are cultivated is highly restricted by the length of the growing season. The length of the growing season in Mali varies from 24 days in the dry areas that are suitable only for pastoralism and itinerant agriculture to 80-120 days in the semiarid or subhumid areas with an isothermic temperature regime, where permanent and semi-intensive agriculture is practiced. In most agricultural areas, of the subhumid zones, the length of the growing season ranges from 80 to 160 days (Table 4), thus an adequate environment is provided for the production of grain crops, vegetables, tobacco, cotton, groundnut, sugarcane, and sesame.

The percentage of the area under cultivation with the primary rainfed crops and cropping systems is presented in Table 4. Food crops such as millet, sorghum, maize, and vegetables are cultivated mainly for household consumption by 80% of the active population in the country, using the traditional practices of subsistence farming. Maize, cultivated principally in the Sikasso region, is becoming an important staple for human and animal consumption. Over the long term, maize has the potential of replacing sorghum and millet to some extent in the humid savannas. Fruits, mainly mangoes, are also grown in this area.

Cotton is grown principally in the Sikasso region, which contributes about 50% of the annual production; the remainder is produced in the inner delta of the Niger River and in some fertile soils of Bamako, Koulikoro, and Segou regions. Most cotton, grown as a rainfed crop and usually in rotation with cereals, is planted in these regions where annual rainfall exceeds 700 mm and its distribution is more favorable.

Groundnuts and vegetables are grown in the alluvial valleys of the Senegal and Niger rivers. The main cash crop in the western part of the Kayes and Koulikoro and some areas in the Segou region is groundnuts. The southernmost regions of the humid savannas and the northern parts of the dry areas are unsuitable for groundnut cultivation. The area in groundnut production has not increased. Most producers are small farmers who grow groundnuts in mixed stands with millet, maize, sorghum, and cowpeas.

Rice, sugarcane, tobacco, and tea are cash crops being cultivated more recently by farmers in the Koulikoro, Sikasso, and Segou regions. Irrigated rice paddy, deep water or floating rice, and upland rainfed rice are all cultivated in Mali. Systems of water control vary greatly, from the total control of water in the area supervised by the Office du Niger (ON), the flooding control practiced by Operation-Riz-Mopti, to essentially no water control and regulation in the traditional systems of natural submersion flooding or recession cultivation. In southern Mali, rice is cultivated in small river basins to supplement cash and cereal crops.

Traditionally, cropping systems based on crop rotation schemes depend, among other factors, on the needs of farmers and the status of soil fertility vis-à-vis the crop nutrient requirements. After land is cleared, a rotation of sorghum, millet, groundnut, and fonio is typical. This sequence reflects the hierarchy of requirements of each crop with respect to nutrients. Groundnut and fonio are planted often at the end of rotation, just prior to the fallow period. The rotation may also include only cereal crops, either sorghum followed by millet or continuous millet or sorghum for about 5 years up to the fallow period.

Crop associations or intercropping of two or three crops is practiced in some regions. The most common association is cowpea and sometimes dah in fields of

Table 4. Average Climate Indicators and Main Cropping Systems in Cropped Land

Factors *	Regions (Stations)				
	Kayes	Koulikoro	Mopti	Segou	Sikasso
Climate					
Average rainfall (mm)	732.7	997.6	531.5	712.6	1,385.0
Standard deviation rainfall (mm)	50.0	120.0	113.0	150.0	250.0
Mean temperature (Celsius)	28.0	26.7	29.7	27.8	27.2
Radiation (Cal/cm/day)	462.0	470.0	486.0	451.0	454.0
Evapotranspiration (mm)	2,218.0	2,865.0	3,011.0	2,367.0	2,003.0
Growing Season					
Dry days	280	278	265	255	206
Humid days	41	43	71	33	52
Wet days	44	44	30	77	107
Main Cropping Season					
Beginning (month/day)	5/31	6/28	6/28	6/17	5/11
Ending (month/day)	10/14	9/23	9/19	10/5	10/17
Length (days)	137	88	80	111	160
Main Crop Production Systems	(% of Cropped Land**)				
Continuous					
Groundnut (Grd)	20	10	5	15	12
Cotton (Cot)	-	4	-	10	14
Millet (Mil)	21	28	35	21	20
Sorghum (Srg)	18	24	18	14	15
Maize (Mai)	10	5	1	-	5
Rice	5	2	20	12	2
Other	6	5	12	6	10
Rotations					
Mai-Grd	10	4	-	-	2
Mil-Grd	4	2	2	11	2
Mai-Cot	-	-	-	6	10
Srg-Grd	2	14	2	2	4
Intercropping					
Mil/Cowpea	2	1	5	1	1
Mai/Cowpea	1	-	-	1	1
Trees (Fruits)	1	1	-	1	2
Total (%)	100	100	100	100	100

* Climate: Annual averages of 30 years
** Includes land in flooded and irrigated areas, alluvial, permanent crop, transitory crops, and perennial and marginal areas.

penicillate millet, sorghum, or maize. Various explanations for the practice of intercropping may be offered. First, in the rural subsistence economy where millet and sorghum are the principal food crops, other crops are used as food and diet complements (e.g., vegetables) or for activities of artisans (cotton, dah). Second, the association of different crops reduces the risk of crop failure due to the different ecological requirements of each crop; in some years, a bad harvest of one crop may be compensated, in part, by the harvest of another. In addition, there may be a specific complementarity in the nutritional needs of the plants grown in intercropping.

The traditional fallow system, although rapidly decreasing, is still practiced in Mali. This system is based on the dependence on fallow periods to restore soil fertility, which diminishes during the cropping cycle, or to suppress weed species. After a number of cropping seasons, when the farmer receives a limited yield, the land is left to fallow for natural regeneration of the soil. Of particular importance to the regeneration process is tree cover such as the preservation by farmers of *Acacia albida, Vitellaria paradoxa, and Pterocarpus spp*. In the central and southern Mali regions, trees have been particularly beneficial in protecting the soil from erosion.

Natural conditions in Mali's savanna lands will support the cultivation of a wide range of important crops and cropping systems. However, specific climatic conditions, climatic variability, and low soil fertility cause the agricultural lands to be extremely susceptible to any type of overuse. Sustained yields are possible with appropriate land use practices and use of inputs based on crop production systems that are suitable for the prevailing fragile ecosystem.

6. Trends in Agricultural Production

Agricultural production in Mali has been low by modern standards and is heavily dependent upon the amount and distribution of rainfall and the fertility of the soils. Most of the literature suggests that institutional shortcomings, low and unstable prices of agricultural output to producers, and recently, the continuous exodus of population to urban areas have also contributed to adversely affect agricultural production in the country.

Production of cereals, mainly millet, sorghum, and maize, reached a total high of 1.8 million tons and occupied an area of 2.0 million ha during the period of 1985-89, while rice production reached an average of 219,000 tons per year in an area of 169,000 ha (Table 5). Output of these cereals was low in 1987/88 because of inadequate rainfall. However, a recovery occurred in 1988/89, when total production reached 2.2 million tons, a self-sufficiency target set by the government in 1988. A lower harvest of food grains was recorded during the 1990-92 cropping seasons; production levels were insufficient to meet domestic requirements. Grain production increases were recorded in 1993/94 with levels of production above 2.0 million tons. Annual growth rate of production for crops from 1990 to 1994 has varied from 4.6% for millet up to 15.1% for rice. However, the high rate of population growth since 1980 has meant that cereal imports (estimated at 90,000 tons in 1992/93) are still required, despite outputs of some 2.3 million tons per year.

Increases in the area cultivated and yield have been observed for the main crops (Table 5). The annual growth rate of area cultivated in food crops for the period, 1990 to 94, has ranged from 1.1% for millet to 5.6% for rice. Annual growth yields have increased from 3.3% for millet to 7.5% for rice. According to DGIS (1995), irrigated rice in the ON region has registered increases in yields from about 1,500 kg/ha in 1985 to about 4,000 kg/ha in 1993.

Cotton, the most important cash crop and the main source of foreign exchange earnings, has increased area harvested sixfold over 30 years and reached a yield of 1,390 kg/ha in 1994. Mali accounted for 0.6% of the world output in 1992, and the country is Africa's second largest cotton producer (after Egypt). About 2.3 million people are engaged in cotton production. Area harvested, production levels, and yields of cotton have increased at rates of 6.9%, 7.8%, and 0.7% per year, respectively, for the period from 1990 to 1994. Production reached 354,000 tons of cotton seed in 1994.

Groundnut production reached a record level of 205,000 tons in 1976 and declined in subsequent years. As a result of favorable weather and management conditions, output increased to 133,000 tons in 1992 and 146,000 tons in 1994. Area harvested and total production have shown some decreases since 1990; yields have shown moderate increases in 1993 and 1994.

Despite increases in cultivated area, production, and yields for food crops since 1990, the country must rely on external food sources. Rainfall to support extensive agriculture occurs in only one-quarter of the country's

Table 5. National Trends in Area Harvested, Production, and Yields of Major Crops

Period	Item*	Millet	Sorghum	Maize	Rice Paddy	Cotton Seed	Groundnuts In Shell	Total
1980-84	Area	753	616	80	145	110	115	1,819
	Production	389	440	85	145	130	75	
	Yield	517	714	1,063	1,000	1,182	652	
1985-89	Area	1,083	774	125	169	145	147	2,443
	Production	842	731	205	219	180	127	
	Yield	777	944	1,640	1,296	1,241	864	
1990	Area	1,213	809	190	197	189	228	2,826
	Production	737	581	227	312	255	180	
	Yield	608	718	1,195	1,584	1,349	789	
1991	Area	1,025	741	186	251	195	250	2,648
	Production	792	770	257	454	285	190	
	Yield	773	1,039	1,382	1,809	1,462	760	
1992	Area	1,027	850	192	257	247	173	2,746
	Production	582	602	193	410	320	133	
	Yield	567	708	1,005	1,595	1,296	769	
1993	Area	1,280	1,006	257	258	201	160	3,162
	Production	708	694	283	428	240	131	
	Yield	553	690	1,101	1,659	1,194	819	
1994	Area	1,280	1,016	226	252	254	177	3,205
	Production	905	903	315	548	354	146	
	Yield	707	889	1,394	2,175	1,394	825	
				Annual Growth (%)				
1990-94	Area	1.1	5.1	3.8	5.6	6.9	-4.5	2.7
	Production	4.6	11.1	7.8	15.1	7.8	-3.8	
	Yield	3.3	4.8	3.3	7.5	0.7	0.9	

* Area: in '000 ha
Production: '000 tons
Yield: kg/ha

The Food and Agricultural Organization of the United Nations, Agricultural Yearbook, Vol. 45, 46, 47, and 48. 1992-94 total area, and only 2% of the land can be used for intensive agriculture. Increases in food production should come as a result of a more intensive use of inputs such as mineral fertilizers and the adoption of improved management practices, including seeds and pesticides, and to some extent from structural adjustment and support services.

7. Actual and Potential Use of Fertilizers

Malian farmers have dealt with the low fertility of their soils by using traditional practices. Some of these practices include the use of organic fertilizers alone or in combination with mineral fertilizers for cash crops. However, according to Breman and Traore (1987), the potential organic fertilizer availability in Mali's agricultural lands can provide only one-third of the nutrients needed to maintain crop production. Therefore, it is important to make the use of mineral fertilizers economically feasible. A significant increase in the use of mineral fertilization has been observed in some areas, principally as a result of the provision of mineral fertilizer complemented with institutional support by donor programs.

Apparent levels of consumption of mineral fertilizer nutrients since 1965 based on fertilizer import data are shown in Table 6. The amount of nutrients ($N+P_2O_5+K_2O$) imported in 1994 was 25,480 tons of which 13,180 tons (52%) was nitrogen, 9,200 tons (36%) phosphorus, and 3,100 tons (12%) potassium. The annual average growth rate of mineral fertilizer use during 1975-84 was about 10.2%; this rate of growth declined to about 3.2% during the period 1985-94. Overall, fertilizer consumption in Mali almost doubled between 1980 and 1990; however, the average fertilizer application rate in 1994 was about 6.29 kg of NPK/ha, which shows that Mali is one of the countries with the lowest consumption of mineral fertilizer in the world.

At present more than 80% of fertilizer consumption is imported and financed through donor programs (Gerner and Harris, 1993; DGIS, 1995). The Netherlands, which has been the primary fertilizer donor, recently eliminated fertilizer aid to Mali; Japan has occasionally supplied it on a significant scale. Others, such as the Canadian International Development Agency (CIDA), have shown interest in financing a project for the production of Tilemsi phosphate rock (TPR) or Phosphate Naturel du Tilemsi (PNT).

Mineral fertilizer products are mainly used in cash crops such as cotton, rice, and groundnut. More recently, fertilizer products are being used in some cereal crop rotations (Table 7). Until 1980, annual consumption of the most widely used special cotton formula, NPKSB, fluctuated around 20,000 tons of product; from 1990 onward it was over 27,000 tons. Consumption of the cereal formula used in maize-cotton rotation increased from 7,000 tons in 1980 to about 15,000 tons per year in 1990. The amounts of urea used have more than doubled, from some 7,000 (3,200 N) to 20,000 (9,200 N) tons per year. Other products including diammonium phosphate (DAP), single superphosphate, and PNT are being used for rice and groundnuts.

Fertilizer use is more concentrated in the development zones supervised by extension and support operations. Extension and advisory services usually recommend the application of mineral fertilizer products on cash crops, assuming that food crops that are planted in the following year will benefit from the residual nutrients left in the soil after cash crops are harvested. Mineral fertilizers are not used in dry cereal-farming areas. Advisory services are concerned with the low economic benefits and high risk of fertilizer use to farmers as a result of relatively high fertilizer/crop price ratios and the uncertainty about the effectiveness of mineral fertilizers in those areas. In the southern regions, organic rather than mineral fertilization is encouraged for millet, sorghum, and maize; with the adoption of improved varieties, the use of mineral fertilizers on these crops is becoming more common.

Research activities have been conducted to evaluate crop response to fertilizer at experimental stations and on farmers' fields in different production areas with significant yield responses to fertilizers being observed for a variety of crops and cropping systems. These potential gains in yields have not been fully realized at the farm level. On the basis of experimental data, nutrient uptake by crops, nutrient availability of soils under cultivation, agricultural land area, and potential crop nutrient requirements, it was estimated that to increase production levels by 30% on main food and cash crops and contribute to the restoration and maintenance of the nutrient status of the soils, Mali will need to use at least 76,000 tons of NPK ($N+P_2O_5+K_2O$) per year or an average of 25-35 kg/ha.

Strategies to use mineral fertilizers to increase production and restore and maintain the nutrient status of the soils should include as a key component the

Table 6. Use of Main Mineral Fertilizer Nutrients in Mali

Year	Quantities of Nutrients in Metric Tons				Use of NPK (kg/ha)
	N	P_2O_5	K_2O	Total NPK	
1965	56	141	0	197	0.06
1970	693	1,797	57	2,547	0.80
1975	2,657	3,241	1,079	6,977	1.86
1980	6,704	4,446	3,044	14,194	3.78
1981	3,935	2,814	1,955	8,704	2.32
1982	5,559	3,047	2,642	11,248	2.99
1983	3,348	3,674	3,143	10,165	2.70
1984	10,267	5,041	3,130	18,438	4.91
1985	11,188	4,999	3,519	19,706	4.87
1986	8,043	3,738	3,519	15,300	3.78
1987	9,009	3,837	2,768	15,614	3.86
1988	9,000	3,400	2,390	14,790	3.65
1989	8,700	9,100	3,219	21,019	5.19
1990	9,200	6,000	3,359	18,559	4.59
1991	9,500	5,500	3,206	18,206	4.50
1992	10,700	7,800	3,000	21,500	5.31
1993	12,000	8,500	3,000	23,500	5.81
1994	13,180	9,200	3,100	25,480	6.29
			Annual Growth (%)		
1975-84	14.47	4.52	11.24	10.21	10.19
1985-94	1.65	6.29	-1.28	2.60	3.20

Estimates using area under cultivation.

IFDC, West Africa Fertilizer Study. Vol. 3. Mali, 1976.
Direction Nationale de L'agriculture (DNA).
Cited by Bumb, B. L., Teboh, J. F., and Mariko, F. 1992. (Unpublished report).

The Food and Agricultural Organization of the United Nations, Fertilizer Yearbook. Vol. 42, 43, and 44. 1992-94.

Table 7. Fertilizer Recommendations for Main Cropping Systems

Fertilizer Type	Crop	Composition (%) N	P_2O_5	K_2O	Use ** (%)	Recommended Dose (kg/ha)	Application (tonnes) 1980	1990
Cotton Complex	Cotton	14.0	22.0	12.0	95.9	150-200	20,296	27,739
Cereal Complex	Maize/sorghum	15.0	15.0	15.0	65.5	100-200	7,000	15,186
Urea	Cotton/cereals	46.0	-	-	84.3	50-100	7,048	20,496
SSP	Groundnut	-	20.0	-	0.4	75.0	1,855	127
TPR	Groundnut	-	28.0	-	3.0	300.0	840	9,535
DAP	Rice	18.0	46.0	-	10.0	100.0	2,326	2,625
Animal dung with straw	Cotton/maize	1.1	0.4	1.8	25.0	15,000 *		
Animal dung mixed with soil	Cotton/maize	1.2	0.5	1.9	25.0	15,000 *		

Complex Cotton: NPKSB (12-22-12-7-1).
Complex Cereal: NPK (15-15-15).
SSP: Single Superphosphate.
TPR: Tillemsi Phosphate Rock.
DAP: Diammonium Phosphate.

* Basic application for three years.
** Percent based on cultivated area in 1990.

Source:
Direction Nationale de L'Agriculture. Annual Reports.
CMDT: Compagnie Malienne Pour le Developpement dex Textiles. Mali.

adoption of complementary crop management practices, including the use of organic fertilizers. It has been suggested by some researchers (Pieri, 1989, 1992; Bationo and Mokwunye, 1991) that additional plant nutrients that are necessary to maintain the nutrient status of Malian soils at a level acceptable for crop production should come from a diverse set of sources that are potentially available in Mali and include:

1. Crop residues, which can be effective in maintaining soil moisture, increasing organic matter, and recycling some nutrients to the soil. However, crop residues are not additional sources of nutrients and are not likely to correct nutrient imbalances or deficiencies that prevail in many of these soils. An important factor in recycling crop residues in Mali is the competing demands for its use by livestock and as a source of energy. Mulching with crop residues (straw) and the application of mineral fertilizers are particularly beneficial in areas where water is not readily available.

2. Animal manures, like crop residue, vary in nutrient composition, and the quantities available are very small, especially in dry areas where manure is used as a substitute for firewood. The use of manures is also affected by its cost, feed management, and method of application to soils. Alternatives such as composting (millet straw, cow dung, and rock phosphate) have significant potential benefits for improving phosphorus availability, changing soil structure, and increasing organic matter content of the soils.

   Animal manure is usually applied to crops grown in the immediate proximity of villages near family compounds, which also benefit from the application of organic household refuse. Use of manure is preponderant in the agro-pastoral zone in villages located along the routes of livestock farmers. This practice is widespread northeast of Mopti and in the zones of Nara and Nioro. In the south of Mali, where cash crops often benefit from the application of mineral fertilizers, there is still an important use of manures. In this region, manure is applied to 20% of the cotton area in the entire southern zone and to as much as 40% of the cotton area in the Sikasso Region.

3. Green manuring, particularly with legumes, is not widely practiced by Malian farmers; however, including leguminous annual crops in rotations is beneficial for improving soil conditions, reducing weeds, and breaking the cereal disease-pest cycles. Significant quantities of nitrogen (N) can be provided by legumes through biological nitrogen fixation; the quantities of N fixed vary with the crop, soil, and climatic conditions (IAEA, 1984). Thus, this practice can be limiting in many areas in Mali where soil acidity, low soil phosphorus levels, and water availability are not uncommon. Alternatives such as the use of perennial crops in crop production systems would also be beneficial and will improve nutrient recovery (Teme et al., 1996) and contribute to maintaining soil moisture content.

Malian farmers originally began to use mineral fertilizers because of the work done by the extension services, donor-supported fertilizer aid, and technical assistance provided to farmers. However, the increase in use of mineral fertilizer has been largely determined by the pattern of fertilizer and crop prices and the crop response to fertilizers. Some of the measures that should be taken to achieve the goals of increased crop production and nutrient use include the following:

1. Promote more effective crop management by facilitating the use of improved seed and soil conservation practices and by promoting more productive crop rotation systems and the recycling of crop residues.

2. Increase the supply and use of mineral fertilizers. Efforts must be made to promote, in areas where it is feasible, the use of indigenous resources such as phosphate rock and limestone supplemented with on-farm resources such as animal and green manures.

3. Implement policies to increase efficiency in the supply of fertilizers and other inputs and in the marketing of agricultural outputs. Favorable fertilizer/crop price ratios are necessary for the profitability and adoption of fertilizers. Malian farmers are clearly aware of the different levels of profitability involved in applying fertilizers to various crops. Policies should be designed to facilitate the availability of credit to finance the supply of fertilizers (procurement and marketing) and the marketing of agricultural outputs.

4. Establish programs to monitor the environmental impact of a more productive agriculture involving the increased use of fertilizers and agricultural intensification in general.

8. Phosphate Rock Use in Mali

Numerous studies have been conducted to determine if West African phosphate rocks can be used as sources of P to improve soil fertility and crop production. Truong et al., 1978, summarized some of the earlier results of several experiments comparing several West African phosphate rocks from Togo, Burkina Faso (Kodjari), Niger (Tahoua), and Mali (Tilemsi). The authors concluded that the Tahoua and Tilemsi rocks could be suitable for direct application as sources of P. A review of the use of phosphate rocks in the tropics completed by Hammond et al., 1986; emphasized the importance of using phosphate rocks as a supplemental low-cost fertilizer that should be targeted for use in areas with high risk of production, low fertility levels, and soils with low pH and P retention where appropriate cropping systems can be established.

Mali is endowed with a phosphate ore deposit with reserves of 20 million mt of phosphate ore containing about 27% P_2O_5 located in the Tilemsi Valley north of Gao. The Tilemsi deposits have been mined on a pilot scale by the Société Nationale de Recherche Geologiques et d'Exploitation Miniére (SONAREM), a state-owned organization within the framework of Malian-German technical cooperation. Mining is relatively easy, because the overburden is only 1.5-2.0 m thick. The mined phosphate rock is finely ground, concentrated through cycloning, bagged at Bourem and transported on the Niger River to the agricultural areas.

Tilemsi phosphate rock (TPR) is a medium reactive rock suitable for direct application. TPR has a solubility of 61% in formic acid. This reactivity is attributable to a relatively high degree of carbonate substitution for phosphate in the rock minerals. Chemical and mineral composition of the rock from Tilemsi Valley and the solubility of some phosphate products derived from TPR are presented in Table 8.

The entire production of TPR is used within the country. Production of ground TPR was estimated as: 4,529 tons in 1981, 8,092 tons in 1988, 11,000 tons in 1989, and 18,560 tons in 1990. The plant was often closed between 1991 and 1994 as a result of political unrest in the mine area. The estimated potential production is 36,000 tons per year.

The use of TPR as a P fertilizer has been suggested by many researchers. Review of earlier research conducted in Mali (Pieri, 1973; Poulain, 1976; Thibout et al., 1980) shows that TPR could be used for direct application on crops and recommended rates ranging from 20-80 kg P_2O_5/ha (70-290 kg/ha of TPR). The TPR is to be applied on the fallow and incorporated by a late plowing at the end of the rainy season. An internal review paper of the Division de la Recherche Agronomique (DRA) in 1982 recommended 200 kg/ha of TPR applied on the fallow and incorporated by plowing later. Additional work conducted by the Semi-Arid Food Grain Research and Development (SAFGRAD) in farmers' fields recommended that TPR be used at a rate of 300 kg/ha. CMDT has recommended for cotton, maize, sorghum, or groundnut rotation the application of 300 kg/ha of Tilemsi phosphate rock (TPR) on the fallow, incorporated by plowing at the end of the rainy season. For rice, the Office du Niger (ON) recommends applications of 500 kg/ha of TPR, but farmers are very reluctant to use TPR on rice.

The Government of Mali has promoted through the extension service the use of TPR in their crop production programs; however, only the Company for the Development of Textiles (CMDT) has sold significant quantities of TPR to farmers. The supply of TPR in the CMDT zone, in southern Mali, was estimated as 4,024 tons in the 1989/90 cropping season, 11,227 tons in the 1990/91 cropping season, and 11,086 tons in the 1991/92 cropping season. CMDT reported that during the 1991/92 season most of the TPR was used in 0.6% of the areas planted with cotton and maize and in 1% of the areas planted with millet and sorghum.

Phosphorus fertilization alternatives in Mali, based on TPR, include direct application of TPR either basal or annual, application of TPR supplemented with low amounts of P soluble fertilizers, and application of TPR combined with organic manures. Generally, TPR is applied manually and incorporated into the soil prior to planting; mechanized spreading using animal traction has been tested at the experimental station level.

8.1 Evaluation of Phosphate Fertilizer Alternatives

The agronomic evaluation used data from research stations and farm-level trials that included several cropping systems and P fertilizer sources at several rates of application. Exploratory surveys and case studies were used to estimate farm budgets and evaluate fertilizer management. Experiments on experimental stations were conducted during the 1982 to 1987 cropping seasons in each of the five regions, namely, Sikasso, Segou, Kayes, Koulikoro, and Mopti.

Soil samples were taken from each site at the beginning of the trials in 1982 and again in 1984 to evaluate

Table 8. Solubility of Phosphate Products and TPR Characterization

Phosphate Product*	P_2O_5 Content (%)				Particle Size (mm)
	Total	Citrate-Solubility	Water-Solubility	Availability	
TSP: Triple Superphosphate	46.0	6.7	38.3	45.0	2.0 - 3.5
TPR : (finely ground)	27.6	4.2	<1	4.2	0.2 - 0.4
PAPR - 30% (run-of pile)	24.2	4.9	5.1	10.0	2.0 - 3.5
PAPR - 30% (granular)	22.8	4.2	6.1	10.3	0.5 - 1.0

Tilemsi Phosphate Rock Characterization

Item	Composition	Weight (%)
1. Mineral Composition		
Apatite (Francolite)	$Ca_{9.64}\ Na_{0.12}\ Mg_{0.05}\ (PO_4)_{5.51}\ F_{2.19}\ (CO_3)_{0.49}$	77.00
Quartz	SiO_2	8.00
Montmorillonite	$Ca_{0.24}\ Na_{0.01}\ Mg_{0.36}\ Fe_{0.02}\ Al_{1.25}\ Si_{3.87}\ O_{10}\ (OH)_{2.0}\ H_2O$	7.00
Goethite	$FeO(OH)$	8.00
Total		100.00
2. Chemical Composition		
CaO		39.20
P_2O_5		27.60
F		2.50
CO_2		2.00
MgO		0.44
Na_2O		0.32
K_2O		0.13
Fe_2O_3		7.10
Al_2O_3		2.70
SiO_2		13.90
Total S		0.30
3. Beneficiation Potential		
CaO		53.70
P_2O_5		38.00
F		3.40
R_2O_3		3.90
SiO_2		2.40

* PAPR: Tilemsi phosphate rock (TPR) partially acidulated with H_2SO_4.
McClellan, G. 1982. International Fertilizer Development Center (IFDC).

changes in soil fertility. Rainfall and temperature measurements were obtained from daily observations recorded at experimental stations and at meteorological stations close to the experimental sites. Average monthly and annual rainfall distributions for each area during the evaluation period are presented in Appendix Tables A1 to A5.

Crop management and fertilizer practices used were those considered most suitable to the regions and recommended by the extension service and crop production operations. The proposed mineral fertilization practices include annual applications of nitrogen (N) in the form of prilled urea (46% N) at a rate recommended by the extension service and operations providing technical assistance. Potassium sulfate (K_2SO_4) was also applied to provide the potassium and sulfur requirements of the crops. The following phosphate fertilizer sources were evaluated in this study:

1. Finely ground TPR – represents the lowest level of technology available for the production of a phosphate fertilizer from the Tilemsi deposits of PR.

2. Triple superphosphate (TSP) – commercial fertilizer imported by Mali as a source of water-soluble P_2O_5.

3. Partially acidulated TPR (PAPR) – fertilizer produced by using less sulfuric acid than is required to produce single superphosphate (SSP). A range of PAPR products can be produced with varying levels of water-soluble P_2O_5.

The PAPR product chosen for these experiments was prepared by acidulating the TPR with 30% of the sulfuric acid required to produce SSP with TPR. The PAPR products were prepared in granular form to match the imported products in physical quality; a run of pile (ROP) or semi-granular material, which is not dusty, was also produced. Chemical and physical analyses of these fertilizers are provided in Table 8. The fertilizer use strategies that were evaluated are presented in Table 9.

The effect of P fertilizer on crop yields was assessed through the estimation of empirical response function models. The models were specified to account for the fact that, generally, in soils deficient in phosphorus, crop response to P increases at a decreasing rate up to a point where no significant increase in yield occurs to additions of P. This response is restricted by water availability and other limiting factors including other plant nutrients. The crop responses to fertilizer phosphorus, at constant rates of N and K_2O, for each region and cropping system were calculated for each year and fertilizer use strategy by estimating and then evaluating the following response function model:

$$Y_{ij} = \alpha + ß\ Ln(TPR) + \theta\ Ln(F_j) + \delta\ (TPR)\ (F_j) + \varepsilon_{ij} \qquad (1)$$

Where:

Y_{ij} = yield of grain and/or stover in kg/ha;

TPR = basal application (one time application) of Tilemsi phosphate rock;

F_j = quantity of fertilizer j (TSP or PAPR) applied annually;

α = intercept of response function;

ß, θ, δ = parameter estimates of the response function; and

ε_{ij} = random error.

Estimates of nutrient uptake and crop yield responses to fertilizer use strategies for various cropping systems and years calculated by evaluating model (1) are summarized in Appendix Tables B1 to B11. These results show that basal applications of TPR, supplemented with annual applications of PAPR or a more soluble P source such as TSP, increased yields significantly in all sites, particularly in areas with very intensive agriculture such as Sikasso, Segou, and Koulikoro. Applications of TPR supplemented with low amounts of a more soluble P source can sustain high yields in monoculture or rotation systems (Figure 4). Yields and responses to P applied using annual applications of TSP without TPR also were very significant, but average yields were somewhat lower than those obtained when basal applications of TPR were made. Cropping systems based on crop rotations sustain higher yields than systems based on continuous cropping of a single crop. Basal applications of 120 kg P_2O_5/ha as TPR (450 kg/ha of TPR), broadcast and incorporated at the start of the cropping sequence, produce significant yield increases and can effectively reduce the rate required for subsequent annual applications of P fertilizer in the crop production system.

It was observed that fertilizer strategies combining applications of basal TPR supplemented with annual applications of PAPR generally resulted in lower crop yields than those with applications of TSP. Experimental results also indicated that granule size influenced PAPR effectiveness. In the humid zone, granular PAPR products (size to 2-3.5 mm) produced crop yields that were approximately 15% lower than those obtained with run-of-pile (ROP) PAPR products (size 0.5-1 mm).

Table 9. Fertilizer and Crop Management Strategies Evaluated in Mali Agricultural Areas

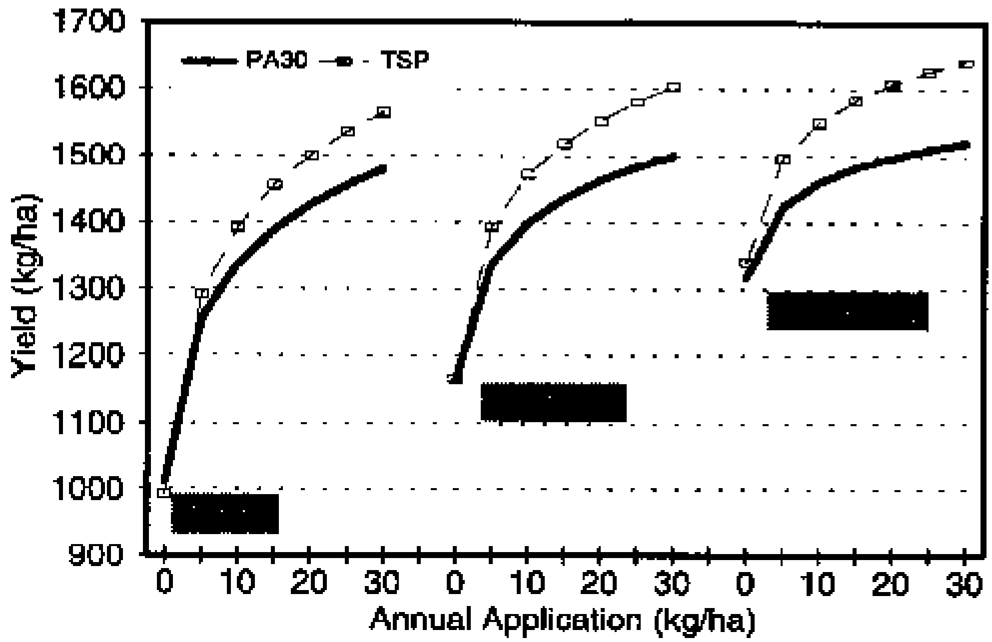
Code	Strategy	Nitrogen N (kg/ha)	Potassium K_2O (kg/ha)	P_2O_5 (kg/ha) Basal TPR	Annual TPR	Annual TSP
	Fertilizer Practices					
1	No fertilization (Abs)	0	0	0	0	0
2	N and K applied (PCont)	60-80	15-25	0	0	0
	One time application of TPR					
3	TPR-60B	60-80	15-25	60	0	0
4	TPR-120B	60-80	15-25	120	0	0
	One initial application of TPR plus annual doses of P_2O_5					
5	60TPR-15PAPR	60-80	15-25	60	15	0
6	60TPR-15TSP	60-80	15-25	60	0	15
7	120TPR-15PAPR	60-80	15-25	120	15	0
8	120TPR-15TSP	60-80	15-25	120	0	15
	Annual applications of P_2O_5					
9	30PAPR	60-80	15-25	0	30	0
10	30TSP	60-80	15-25	0	0	30
	Crop Management					
1	Continuous maize		MaMa			
2	Continuous cotton		CoCo			
3	Rotation maize-cotton		MaCo			
4	Continuous millet		MIMI			
5	Continuous groundnut		GrGr			
6	Rotation millet-groundnut		MiGr			
7	Rotation groundnut-maize		GrMa			
8	Continuous sorghum		SrSr			
9	Rotation sorghum-groundnut		SrGr			
10	Continuous rice		RiRi			

TPR: Tilemsi phosphate rock (26.7 % of P_2O_5).
TSP: Triple superphosphate (45% of P_2O_5).
PAPR: TPR acidulated to 30% sulfuric acid base (24.2% of P_2O_5).
N: Nitrogen application (applied as urea with 46% of N).
K_2O: Potassium applied as potassium sulfate (50% K_2O, 18% S).
Note:
TPR, applied 1 or 2 weeks before planting.
PAPR, TSP, and K_2O applied at planting time.
Urea, split applications (at planting time and 2 months after planting).

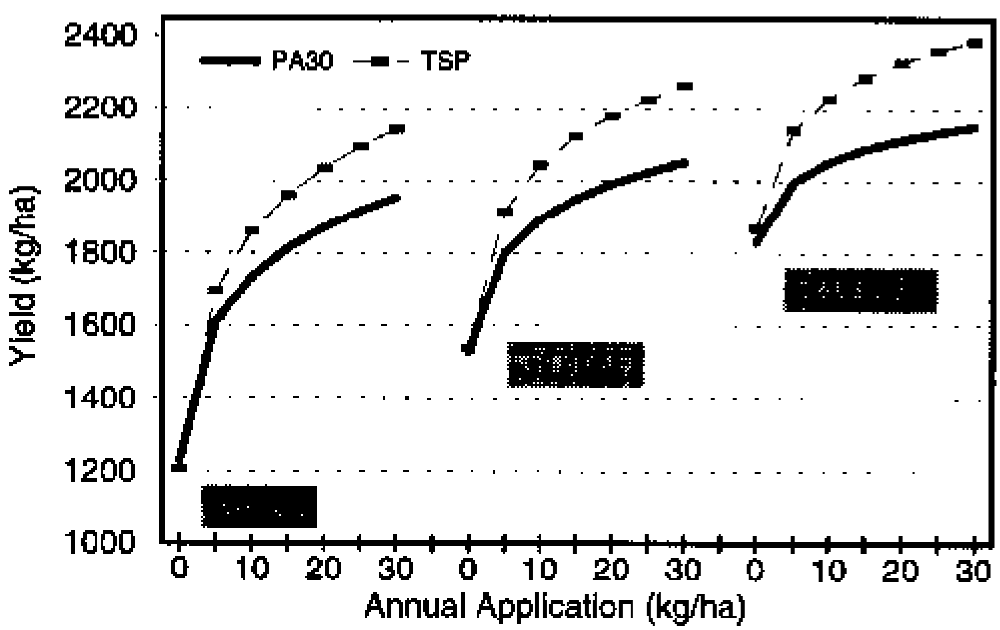
Figure 4. Average Crop Response to Annual and Basal Phosphate Applications

AEZ: Sudanian - Sudano-Guinea
Average Rainfall: 1200 mm/year
Region: Sikasso

Crop: Continuous Cotton (Six-year period)



Crop: Continuous Maize (Six-year period)



Large variability in yields among sites is explained mainly by variability in rainfall and soil moisture conditions. To account for the effect of rainfall variability on crop yields, the following modified form of model (1) was estimated for the semiarid and the subhumid areas:

$$Y_{ij}^* = \alpha + \beta^*(1+R)\ Ln(TPR) + \theta^*(1+R)\ Ln(F_j) + \delta^*(TPR)\ (F_j) + \varepsilon_{ij} \qquad (2)$$

Where:

Y_{ij}^* = yield of grain in kg/ha for agroclimatic area i and fertilizer product j;

R = is the total amount of rainfall in mm during the cropping season; and

ε_{ij} = random error.

Estimates of model (2) are summarized in Appendix Table B12. Highly significant interactions were observed between TPR response and the amount of rainfall after planting. Sites with basal applications of TPR in semiarid and subhumid areas, receiving at least 50 mm of rainfall during the first month after planting, produced about 30%-40% higher yields of maize, cotton, and groundnut than sites receiving less rainfall. The effectiveness of basal applications of TPR supplemented with annual applications of TSP or PAPR can be seriously affected by low rainfall during the cropping season. Results summarized in Figure 5 show that, on the average, crop yields in the Sudanian zone of Mali can be reduced by 20% in sorghum-, millet-, and groundnut-cropping systems and by about 40% for maize in cotton-maize cropping systems when annual rainfall is reduced from 900 to 500 mm; if seasonal rainfall is lower than 500 mm, yield reductions can be about 25% for sorghum, millet, and groundnut systems to more than 50% for maize in cotton-maize production systems. Yield reductions in cotton amount to about 30% when rainfall reduces from 900 to 500 mm.

A substantial part of the benefits of P applications on crop yields occurs during several years after the application of phosphate fertilizers. An assessment of the amount of P in the soils was made through a gross estimation of the P balance in the soils after 6 years of cropping by subtracting the P uptake in grain and stover and the estimated P loss due to soil erosion from the amount of P added as fertilizer. The P balance equation used has the form:

$$Pbal = Pa - (\Sigma(Y_{ij}^*Pg) + \Sigma(TDM_{ij} - Y_{ij}^*)\ Ps + Po) \qquad (3)$$

Where:

Pbal = total P in kg/ha left in soil fertilized after 6 years of P fertilizer applications;

Pg = amount of P_2O_5 in grain yield (kg per kg of grain);

Ps = amount of P_2O_5 in stover yield (kg per kg of stover);

Pa = amount of P_2O_5 additions (fertilizers) in kg/ha;

Po = P_2O_5 losses due to water and wind erosion;

TDM = total dry matter yield in kg/ha; and

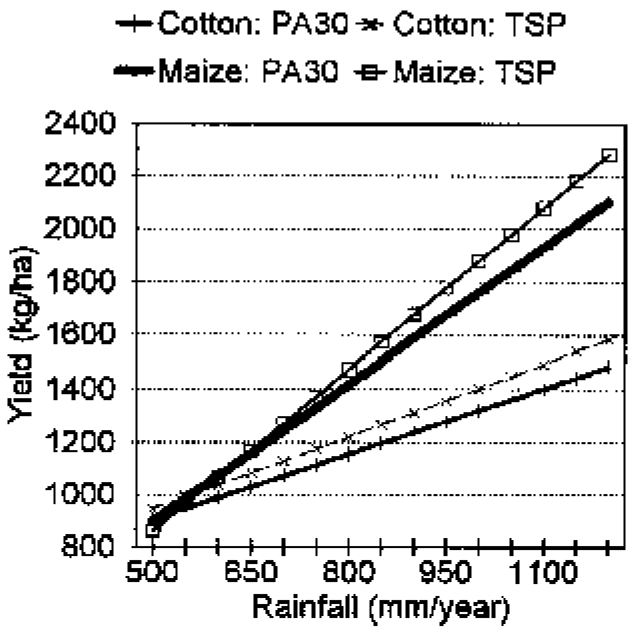
Y_{ij}^* = grain yield obtained from model (1) in kg/ha.

Phosphorus balance estimates are presented in Figures 6 to 10. It was observed that with no application of fertilizers, a common situation in many areas in Mali, the decrease of phosphorus in soils averaged 6.0 kg of P/ha over a 6-year period. By using fertilizer applications containing nitrogen and potassium and no phosphorus, P in soils was reduced by an average of 10 kg of P/ha after 6 years. Alternatively, basal applications of 120 kg of P_2O_5/ha of TPR (strategy 4) increased the amount of P in the soil up to 20 kg/ha. The estimated maximum amount of P remaining in the soil after 6 years was about 50 kg of P/ha with basal applications of 120 kg P_2O_5/ha as TPR supplemented with annual applications of 15 kg of P_2O_5/ha as PAPR (strategy 7).

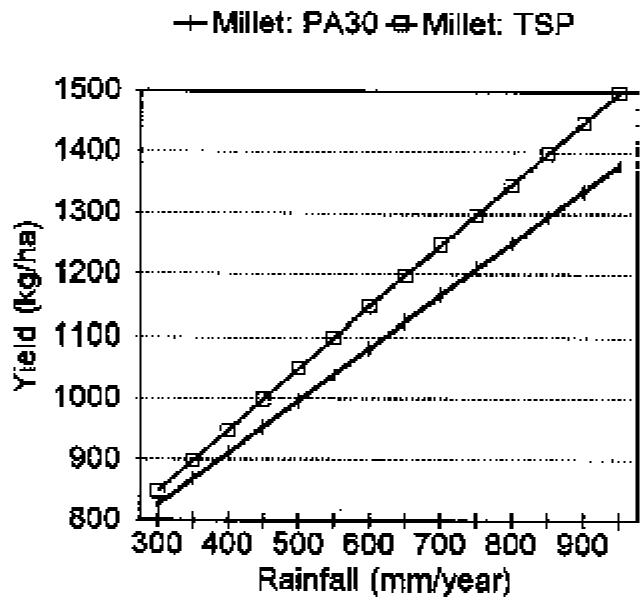
Estimates of soil reversion of applied P after 3 years of fertilization are presented in Table 10. Quantities of PO_4^{-3} in various successive extracts (Chang and Jackson, 1957) represent phosphorus fractions linked to aluminum (Al), iron (Fe), and calcium (Ca). Many analyses of widely differing soils have shown a good relationship between the distribution of these extractable phosphorus fractions and soil physical and chemical properties (Chang and Juo, 1963). As shown in Table 10, it is estimated that a basal application of 120 kg of P_2O_5/ha as TPR increased the average amount of Al-P and Fe-P by 3.9 ppm and 18.9 ppm, respectively. An increase of about 4.2 ppm in the Ca-P fractions of the soils was observed as a result of annual applications of 120 kg of P_2O_5/ha as TPR. Applications of TPR supplemented with TSP and PAPR also showed increases in the amounts of Al-P, Fe-P, and Ca-P. Due to the acidic nature of the soils, the sum of the increases in the fraction of Al-P and Fe-P was consistently greater than the increase in the Ca-P fraction for the fertilizer strategies. Soil analysis by the Bray P1 method, which extracts Al-P and some Ca-P fractions, showed an increase in extractable P with applications of TPR alone and in combination with TSP or PAPR. Similar results were obtained with alkaline extractions of soil P by the Olsen method (0.5 N of $NaHCO_3$), which extracts mainly Al-P and Fe-P (data not shown). However, previous studies have shown that Bray P1 can overestimate or underestimate available P from PR with respect to TSP, whereas Olsen P underestimates available P from PR

Figure 5. Rainfall Effect on Crop Response to PR Applications

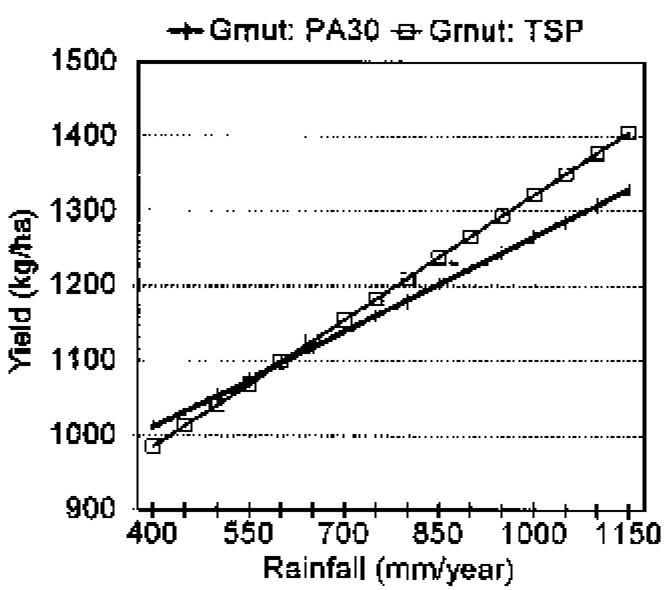
AEZ: Sudanian - Sudano-Guinea
Region: Sikasso



AEZ: Sudanian
Region: Segou



AEZ: Sudanian
Region: Kayes



AEZ: Sudanian - Sahel-South
Region: Koulikoro

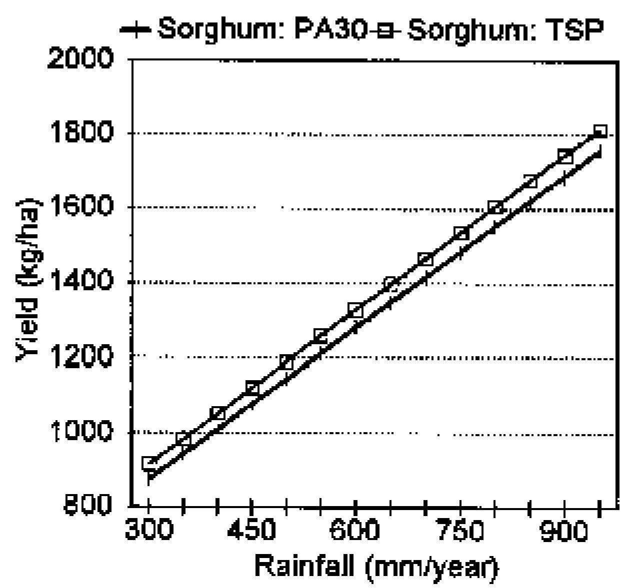
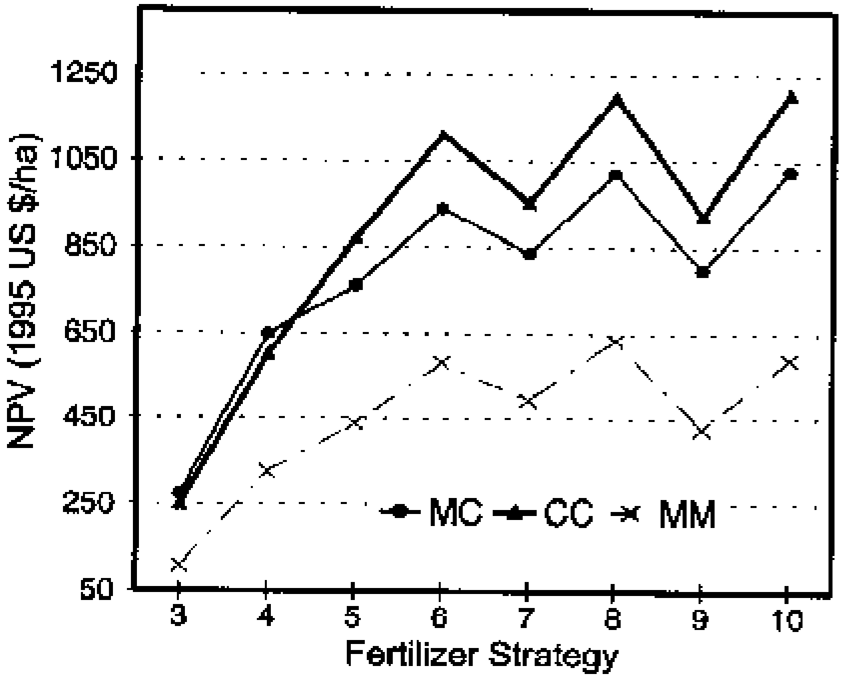


Figure 6. Assessment of Private Benefits and Phosphorus Balance — Region, Sikasso

(a) Private Benefits



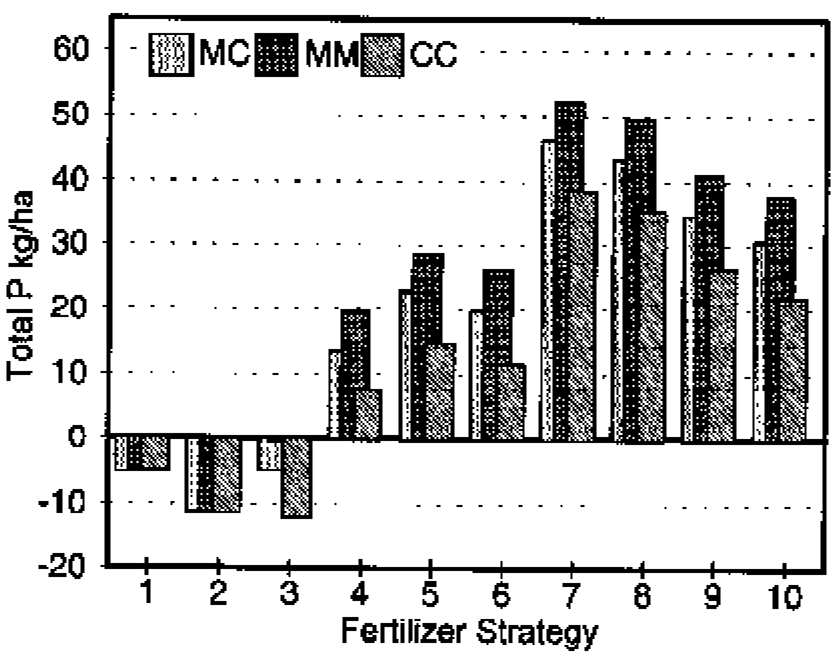
Fertilizer Strategy

	Basal	Annual	
1	0	0	Abs
2	0	0	Pcont
3	60	0	TPR
4	120	0	TPR
5	60	15	PA30
6	60	15	TSP
7	120	15	PA30
8	120	15	TSP
9	0	30	PA30
10	0	30	TSP

Discount Rate: 10%

Crop Sequence
MC: Maize-Cotton
MM: Maize-Maize
CC: Cotton-Cotton

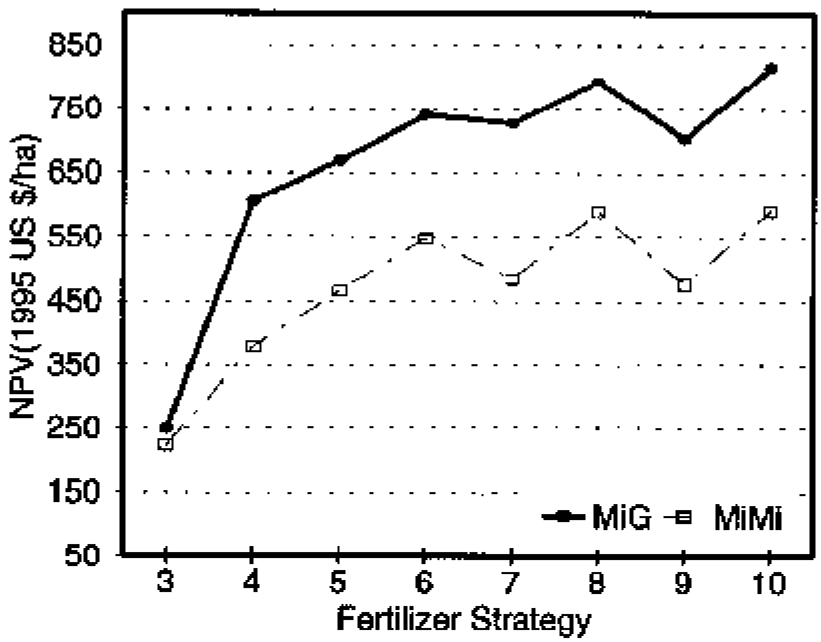
(b) Phosphorus Balance



* Estimate of total P left in soil after six years of fertilizer applications

Figure 7. Assessment of Private Benefits and Phosphorus Balance — Region, Segou

(a) Private Benefits



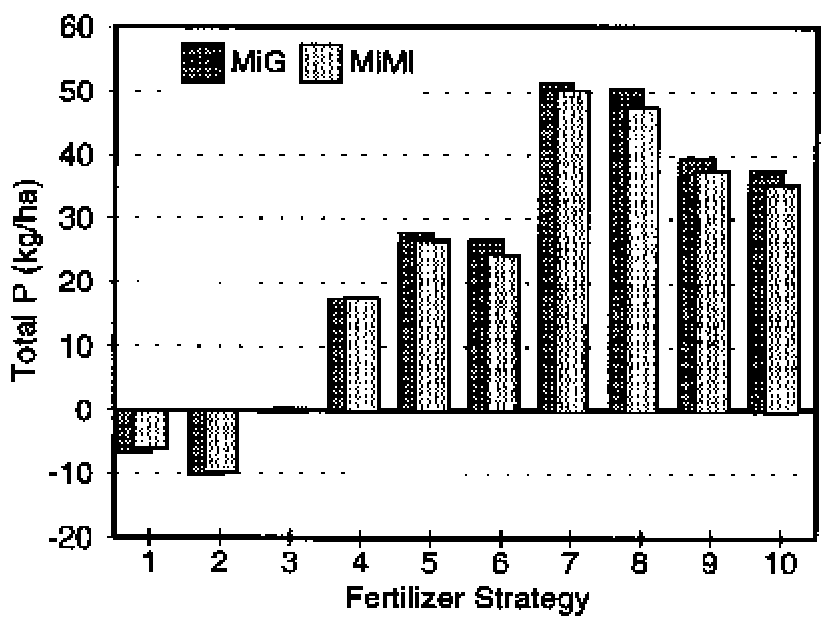
Fertilizer Strategy

	Basal	Annual	
1	0	0	Abs
2	0	0	Pcont
3	60	0	TPR
4	120	0	TPR
5	60	15	PA30
6	60	15	TSP
7	120	15	PA30
8	120	15	TSP
9	0	30	PA30
10	0	30	TSP

Discount Rate: 10%

Crop Sequence
MiG: Millet-Groundnut
MiMi: Millet-Millet

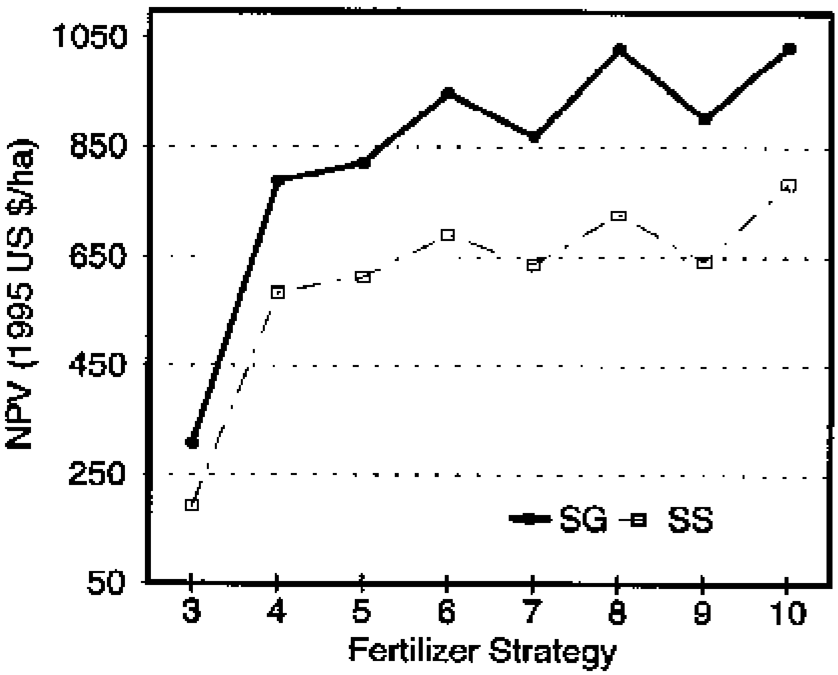
(b) Phosphorus Balance



* Estimate of total P left in soil after six years of fertilizer applications

Figure 8. Assessment of Private Benefits and Phosphorus Balance — Region, Koulikoro

(a) Private Benefits



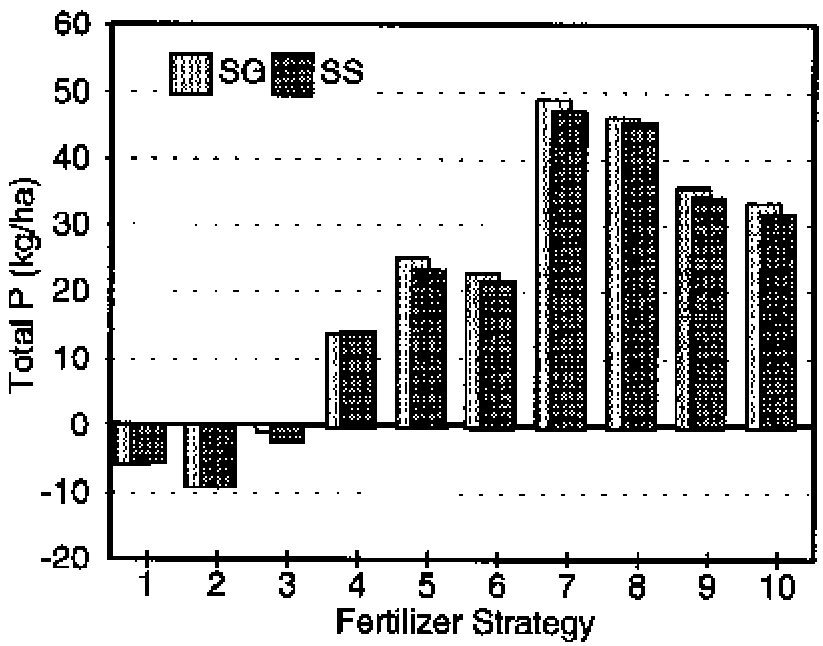
Fertilizer Strategy

	Basal	Annual	
1	0	0	Abs
2	0	0	Pcont
3	60	0	TPR
4	120	0	TPR
5	60	15	PA30
6	60	15	TSP
7	120	15	PA30
8	120	15	TSP
9	0	30	PA30
10	0	30	TSP

Discount Rate: 10%

Crop Sequence
SG: Sorghum-Groundnut
SS: Sorghum-Sorghum

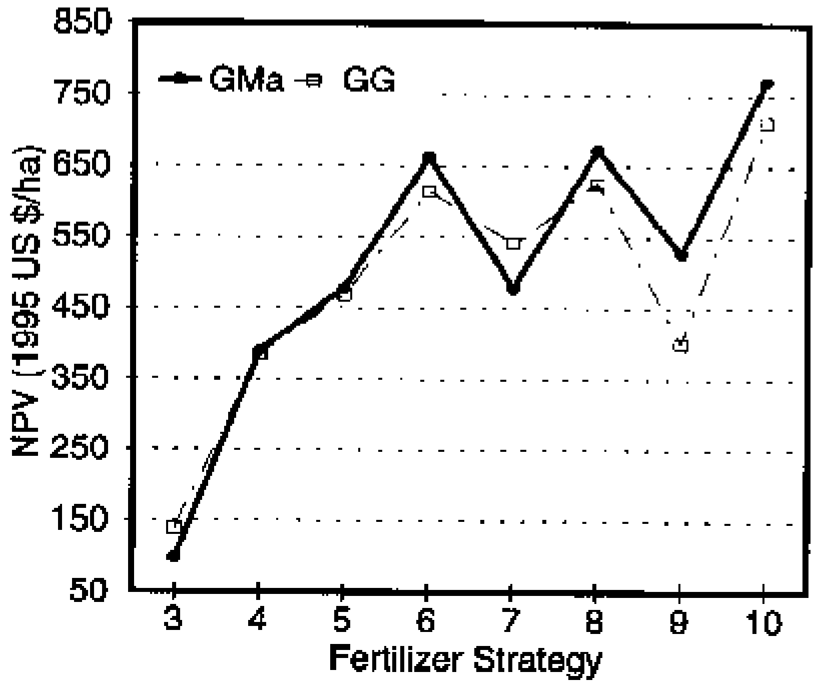
(b) Phosphorus Balance



* Estimate of total P left in soil after six years of fertilizer applications

Figure 9. Assessment of Private Benefits and Phosphorus Balance — Region, Kayes

(a) Private Benefits



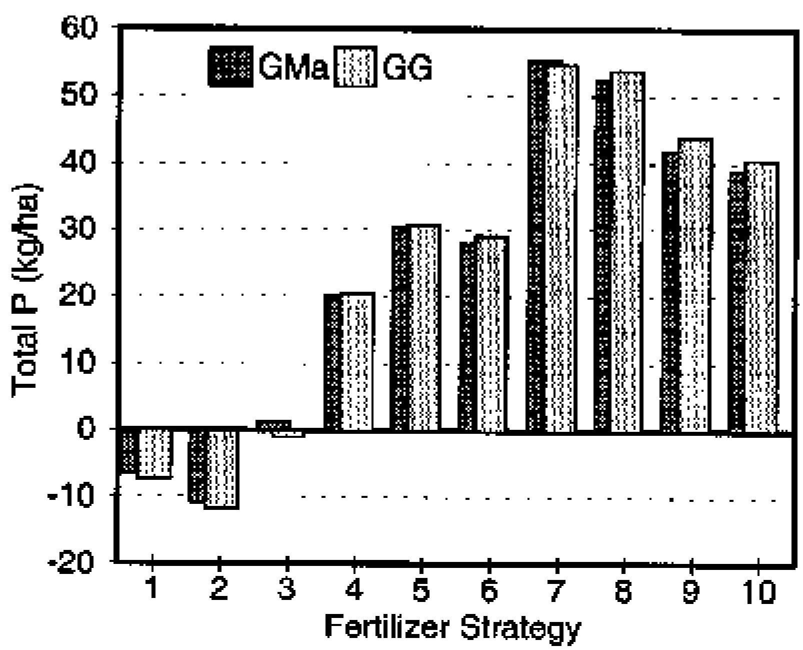
Fertilizer Strategy

	Basal	Annual	
1	0	0	Abs
2	0	0	Pcont
3	60	0	TPR
4	120	0	TPR
5	60	15	PA30
6	60	15	TSP
7	120	15	PA30
8	120	15	TSP
9	0	30	PA30
10	0	30	TSP

Discount Rate: 10%

Crop Sequence
GMa: Groundnut-Maize
GG: Grdnut-Grdnut

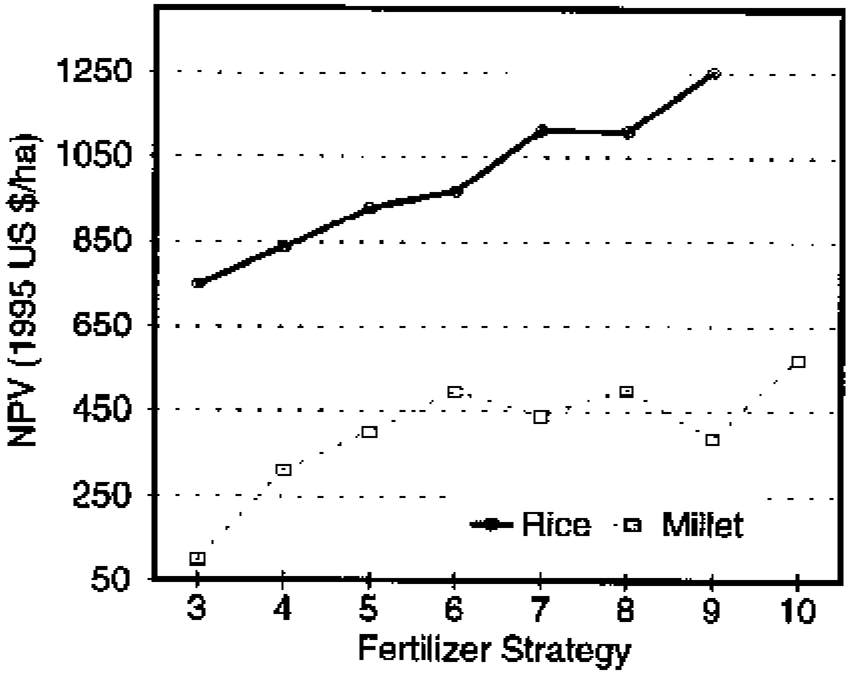
(b) Phosphorus Balance



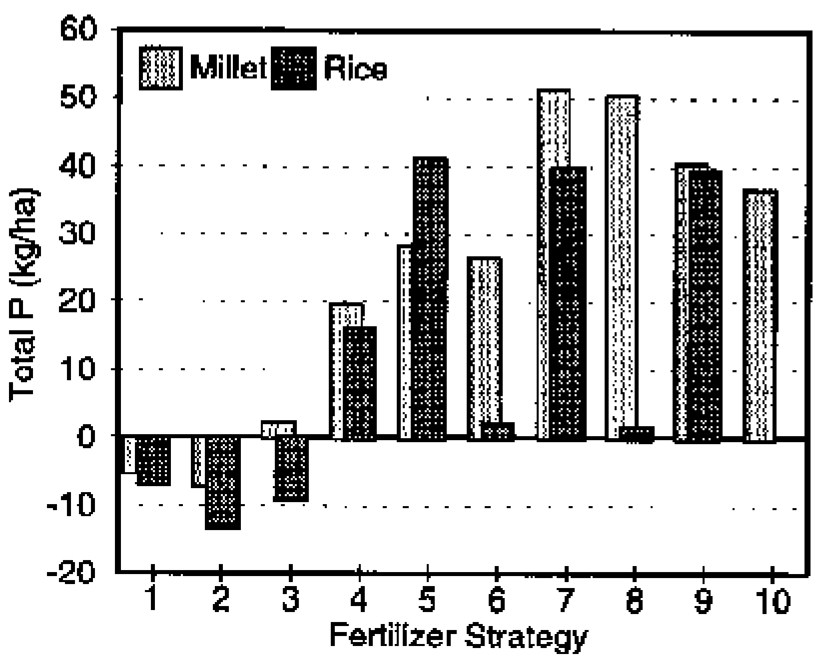
* Estimate of total P left in soil after six years of fertilizer applications

Figure 10. Assessment of Private Benefits and Phosphorus Balance — Region, Mopti

(a) Private Benefits



(b) Phosphorus Balance



Fertilizer Strategy

Crop Sequence
Millet-Millet

	Basal	Annual	
1	0	0	Abs
2	0	0	Pcont
3	60	0	TPR
4	120	0	TPR
5	60	15	PA30
6	60	15	TSP
7	120	15	PA30
8	120	15	TSP
9	0	30	PA30
10	0	30	TSP

Crop Sequence
Rice-Rice

1	0	0	Abs
2	0	0	Pcont
3	60	0	TPR
4	120	0	TPR
5	0	30	TPR
6	0	15	PA30
7	0	30	PA30
8	0	15	TSP
9	0	30	TSP

Discount Rate: 10%

* Estimate of total P left in soil after six years of fertilizer applications

Table 10. Increases in Soil P Fractions and Available Soil P after Three Cropping Seasons

Region	Fertilizer Basal	Fertilizer Annual	Al-P[a]	Fe-P[a]	Ca-P[a]	Bray P[b]
	(kg P_2O_5/ha)		(mg P/kg)			
Sikasso	TPR:120		5.5	21.0	4.1	4.8
	TPR:120	TSP:15	10.3	24.5	3.5	6.3
	TPR:120	PAPR:15	8.8	32.3	3.3	5.2
Segou	TPR:120		3.2	12.5	2.5	4.2
	TPR:120	TSP:15	8.1	18.5	3.1	5.4
	TPR:120	PAPR:15	6.3	31.0	6.2	4.7
Koulikoro	TPR:120		3.3	19.0	4.1	4.2
	TPR:120	TSP:15	9.3	22.0	3.5	5.2
	TPR:120	PAPR:15	7.5	36.0	8.3	4.9
Mopti	TPR:120		2.8	21.0	4.9	4.8
	TPR:120	TSP:15	5.1	24.5	5.2	6.1
	TPR:120	PAPR:15	3.6	32.3	8.7	7.2
Kayes	TPR:120		4.6	21.0	5.2	4.6
	TPR:120	TSP:15	11.4	24.5	3.8	7.1
	TPR:120	PAPR:15	10.6	32.3	9.2	6.3
Average of Three Cropping Seasons						
	TPR:120		3.9	18.9	4.2	4.5
	TPR:120	TSP:15	8.8	22.8	3.8	6.0
	TPR:120	PAPR:15	7.4	32.8	7.1	5.7

Method: a. Chang, S. C. and M. L. Jackson (1958).
b. Bray, R. H. and L. T. Kurtz (1945).

(Hammond, 1977; Chien, 1978; Yost et al., 1982). These conventional soil tests are more suitable for measuring available P from water-soluble P fertilizers. Two new soil tests, cation and anion exchange resin membrane and iron-oxide impregnated paper (Pi test), show promise for use on soils treated with PR and water-soluble P fertilizer (Chien, 1996; Habib et al., 1998). These results support the findings that reaction products due to TPR applications and soluble P sources contributed to the increase in the fertility of the soils and provided residual P for crop responses in successive years.

8.2 Economic Evaluation

Economic considerations ultimately determine the feasibility of phosphate rock use by farmers. In this study, special attention is given to the assessment of the long-term economic benefits of various TPR strategies in terms of their effects on sustainable increases in crop yields and the prevention of land degradation. Because the effects of P applications take place over several years and benefit farmers and society as a whole, the economics of P applications should be analyzed from the point of view of both farmers, representing the private interest, and society as a whole, representing the social interest, respectively (Gerner and Baanante, 1995). This is particularly important in the case of P fertilizers because higher profits for individual farmers may be associated with additional benefits (prevention of land degradation) and costs (pollution) to society as a whole.

The economic evaluation included (1) determination of the profitability of using alternative sources of phosphorus suited to Malian agricultural lands and (2) identification of fertilizer strategies that use TPR and are economically beneficial to farmers and the region in general. The profitability of each fertilizer use strategy was calculated by estimating the flow and present values of the benefits, costs, and net added returns associated with each strategy. Calculations of the flows of benefits, costs, and net added returns were based on the following considerations:

1. Crop yield responses to fertilizers applied in each crop period were used in conjunction with prices of crop outputs and fertilizers to calculate the flow of net benefits to farmers. The flows of added benefits to farmers (BN) over the 6-year crop rotation period are the values of the increments in crop yields that are associated with the use of fertilizers for basal and annual applications and are determined by estimates of the response function (1) and the fertilizer rates (F_{ij}) as follows:

Added benefit in the crop season i is

$$BNi = Py*(Y_{ij} - \alpha); \text{ and} \qquad (4)$$

added cost is

$$CF_{ij} = PF_{ij}*F_{ij}.$$

Where Py and PF are the prices of crop output (grain and residues) and fertilizer, respectively.

2. Prices of crop outputs were the average farm-gate prices received by farmers for average quality product expressed in 1995 constant U.S. dollars (Table 11). Crop residue was quantified as a benefit, based on its value as fodder. When only the market price was available, it was adjusted to account for the marketing costs per unit of output. Such costs include on-farm processing costs, selling costs, transportation costs, etc. Adjustments were made for income from plant residue. Similarly, fertilizer prices, expressed in terms of P_2O_5 price, were also calculated farm-gate prices that farmers would have to pay (Table 12). The total unit cost of P_2O_5 at the farm level included: (1) unit cost of P_2O_5 at the point of production or importation, (2) average unit cost of storage of P_2O_5 from the time it is imported (or produced) until it is used, (3) cost of transport per unit of P_2O_5 from place of production or importation to the farm gate, and (4) application cost per unit of P_2O_5 estimated for the method of application used for each source. Because PAPR products are not produced and available to farmers in Mali, preliminary cost estimates of the domestic production of PAPR were calculated. Since the Government of Mali does not have a policy at present to subsidize imported fertilizers, it was assumed that farmers would pay the full price for all phosphate fertilizers.

3. Flows of added benefits and costs associated with the use of fertilizer in each strategy show the profitability of fertilizer use for the six crops in the crop rotation sequence. Because there are differences in the patterns and magnitudes of the flows of benefits and costs among strategies, these flows cannot be used to compare the profitability of one strategy with another. Simple addition of the flow of added benefits, costs, and profits for each strategy would be appropriate to compare the profitability of various strategies if the time opportunity cost (cost associated with the use of borrowed money) of money was zero. However, because the time opportunity cost

Table 11. Calculation of Import Parity Prices of Selected Crops

Item	Region	Units	Maize	Sorghum Millet	Rice	Groundnut	Cotton
International price		$/ton	70	80	340	180	300
Quality adjustment factor			0.9	0.99	0.8	0.9	0.9
Quality adjusted price		$/ton	63	79.2	272	162	270
Ocean freight and insurance		$/ton	20	20	30	-	-
C.I.f. – Dakar		$/ton	83	99.2	302	162	270
Transportation and handling -- Dakar - Bamako		$/ton	15	25	30	25	-
C.i.f price - Bamako		$/ton	98	124.2	332	187	270
Marketing costs		$/ton	10	10	20	20	-
Wholesale price (inland market)		$/ton	108	134.2	352	207	270
		FCFA/kg	54	67	176	104	135
Farmgate prices by region							
	Kayes	$/ton	76	94	334	186	257
		FCFA/kg	38	47	167	93	128
	Koulikoro	$/ton	72	101	334	176	243
		FCFA/kg	36	50	167	88	122
	Mopti	$/ton	-	87	352	-	-
		FCFA/kg	-	44	176	-	-
	Sikasso	$/ton	70	101	324	166	243
		FCFA/kg	35	50	162	83	122
	Segou	$/ton	71	101	334	166	248
		FCFA/kg	36	50	167	83	124
Crop residue prices		$/ton	32	36	53	41	41
		FCFA/kg	16	18	26	21	20

Exchange rate used: US $1 = 500 CFA.
1995 prices as follows:
Maize, sorghum, and millet f.o.b., U.S. Gulf.
Rice 5% broken f.o.b. Bangkok.
Groundnut c.i.f. north-east Europe.
Cotton Mexican c.i.f. north-east Europe.
Cotton fiber price: US $1,900/ton; seed price of US $310/ton. Fiber:seed = 60:40 composition.

Grain and Feed Market News, Agricultural Marketing Service Livestock and Seed Division. USDA, 1995. Food Outlook,Statistical Supplement, Food and Agriculture Organization of the United Nations. Rome. 1994.

Table 12. Derivation of Prices of Phosphate Fertilizers

Item	Region	Units	TSP[a,e]		TPR[b,c]		PAPR 30NG[b,d]	
			Prod.	P_2O_5	Prod.	P_2O_5	Prod.	P_2O_5
International price (bulk)		$/ton	160	-	80	-	100	-
Handling and transportation to markets		$/ton	65	-	40	-	55	-
Marketing markup		$/ton	30	-	30	-	30	-
Wholesale price		$/ton	255	554	150	562	165	764
		FCFA/kg	128	277	75	281	83	343
Total costs[f]	Kayes	$/ton	265	577	155	579	178	734
		FCFA/kg	133	259	77	260	89	330
	Koulikoro	$/ton	273	593	156	584	179	741
		FCFA/kg	136	267	78	263	90	334
	Mopti	$/ton	283	615	150	562	176	727
		FCFA/kg	142	277	75	253	88	327
	Sikasso	$/ton	273	593	155	579	179	741
		FCFA/kg	136	267	77	260	90	334
	Segou	$/ton	275	599	156	584	178	734
		FCFA/kg	138	269	78	263	89	330

Other Fertilizer Products (Price: FCFA/kg)

Cotton complex	160 (14-22-12-6S-1B)
Cereal complex	150 (15-15-15)
Urea (bagged)	135
SSP	115
Diammonium phosphate	208 DAP
Muriate of potash	50 KCl

a. Current 1995 prices. Bulk f.o.b. Dakar, Senegal (Exchange rate: US 1$=500 FCFA).
b. Represent production costs at a rate of 10,000 mt/year (estimate).
c. Tilemsi Phosphate Rock with average P_2O_5 content of 27%.
d. Tilemsi Phosphate Rock 30% partially acidulated (Average P_2O_5 content: 24.2%).
e. Triple Superphosphate (TSP) with average P_2O_5 content of 46%.
f. Iincluding transportation, retailing, and application costs.

Food and Agriculture Organization of the United Nations. Food Outlook. Vol. 7, 1995.
African Fertilizer Market (AFM). Nov. 1994. Cited by Dahoui Kossi IN Use of Phosphate Rock for Sustainable Agriculture in West Africa. (IFDC-A). Marketing Study in Mali (First Draft). 1995.

of money is greater than zero, the benefits, costs, and profits that occur in the future (second to sixth year) have less value than those occurring in the present (first crop period). Therefore, it is necessary to calculate the present value of the flows of benefits and costs by using a rate of discount (r) that is representative of the time opportunity cost of money for farmers in the different regions of Mali. Hence, for a given fertilizer use strategy (k), the present values of the flows of benefits (PVB_k), costs (PVC_k), and added profits to farmers (private benefit, NPV_k) are calculated as follows:

$$PVB_k = \Sigma_i(BN_i)/(1+r)^i \qquad (5)$$
$$PVC_k = \Sigma_i(C_i)/(1+r)^i$$
$$NPV_k = \Sigma_i(BN_i-C_i)/(1+r)^i$$
$$i = 0,1,2,..........5.$$

Annual rates of discount of 5%, 10%, 15%, and 20% were used to calculate the present values of benefits and costs. It is difficult to identify a rate of discount that represents properly the time opportunity cost of money for all farmers in Mali because all of them do not experience the same financial constraints and do not face the same circumstances and risks. A higher discount rate should be used to calculate the present value of future benefits for resource-poor farmers, living in risky and unstable environments, than for large-scale farmers operating in low-risk environments.

The net present values (NPVs) of benefits or added profits are calculated to determine the profitability of each fertilizer use strategy and compare and rank strategies by profitability to farmers. Any fertilizer strategy with an NPV greater than zero is economically acceptable: properly discounted long-term benefits exceed long-term costs. A limitation of NPV as criteria for evaluation and ranking of investment alternatives is that the NPV figure by itself provides no information about the amount of capital invested in each strategy which, if substantial, becomes a serious constraint for most Malian farmers. A proposed strategy may have a larger net present value than an alternative one, but it may also require a much larger capital investment.

4. Changes in the economic value of natural resources (land, water, etc.) that are used in crop production as a result of investments in P fertilizer use are benefits or costs to the owners of those resources and to the community and society as a whole. To determine the economic feasibility of phosphate fertilizer use strategies as an investment by the society as a whole, the benefit cost analysis (BCA) is modified to explicitly include environmental benefits and costs. Thus, the rule for the potential acceptance of a strategy should be:

$$NPV_k = \Sigma_i[(BN_i-C_i) + (B_{ei}-C_{ei})]/(1+r)^i > 0 \qquad (6)$$

where B_{ei} and C_{ei} are environmental benefits and costs. The inclusion of environmental benefits and costs involves the monetary valuation of those benefits and costs. Environmental and indirect economic and social benefits and costs are often neither obvious nor easy to quantify, especially in the short term.

5. Because uncertainties are always present about future prices of inputs and outputs, the selection of the discount rate, rainfall and climatic factors, and expected crop outputs at harvest, sensitivity analyses are used to determine how the outcomes of BCA will be affected as a result of changes in some of these variables and assumptions. The results can then be presented and discussed in the form of ranges of possible outcomes and associated probabilities. It is unrealistic to base economic evaluations on the assumptions of near-perfect knowledge and complete price stability (Gittinger, 1982).

8.2.1 Valuation of Environmental Benefits and Costs – The continuous use of mineral fertilizer such as TPR may affect the area or influence other activities in the region; benefits and costs to other farmers or to the community will result. The following environmental effects may be observed:

1. **Prevention of Land Degradation** – Increasing the use of mineral fertilizers and improving crop management practices will (1) increase vegetative cover and biomass production in Mali; (2) reduce water erosion; (3) reduce nutrient losses; and (4) prevent soil nutrient mining. Soil erosion and P loss due to erosion for the regions and cropping systems were assessed by using a modified version of the Universal Soil Loss Equation (USLE). An exponential model that relates soil loss to erosion (Bishop and Allen, 1989) was modified to estimate P losses due to soil erosion. Nutrient mining due to plant uptake was assessed from plant nutrient uptake in the plots without fertilizers. Estimates of model parameters are presented in Appendix Table B13. Based on nutrient mining and losses by erosion, it was estimated that soils will be highly degraded in about 10 years

of cultivation if no mineral fertilizer and proper management practices are applied. Estimates of land degradation components are presented in Table 13. The value of prevention of land degradation per hectare was assessed by the foregone income estimated using farm budgets for each region and cropping system.

2. **Carbon Sequestration** – This phenomenon is a beneficial externality that results from preventing deforestation and increasing vegetative cover. Carbon losses for each year and region were estimated by using an empirical model that relates carbon losses to soil erosion (Appendix Table B13). Because phosphate applications and crop management may prevent the loss of at least one hectare of cropland in 10 years, the amount of soil organic matter (SOM) and soil C losses prevented after 10 years was calculated for each region by estimating the amount of SOM and C in the arable layer in one hectare. A value of US $10 was assumed for one ton of C. Also, estimates of soil carbon losses and monetary benefits of carbon sequestration associated with preventing deforestation are presented in Table 13.

3. **Prevention of Pollution (Phosphogypsum) and High Energy Consumption** – This situation is associated with the manufacturing of wet-process-based P fertilizers and results in a beneficial externality of the direct application of TPR and sulfuric acid-based PAPR. These products can be manufactured without the disadvantages of point pollution associated with the manufacturing of water-soluble fertilizers such as TSP and DAP. Benefits of pollution prevention are estimated on the basis of a cost estimate of about US $40/ton P_2O_5 to dispose of phosphogypsum. Estimates of the value (Table 13) of disposing it for each region were assumed to be about US $0.8/ha/year (IFDC, 1997).

4. **Eutrophication in Water Bodies** – Phosphorus losses due to erosion can cause eutrophication in water bodies. Generally, total phosphorus concentrations in excess of 100 µg P/liter have a high probability of becoming eutrophic, and in some agricultural areas levels as low as 30 µg P/liter may be necessary to avoid it (*Phosphorus & Potassium*, 1995). In Mali, excessive use of P fertilizers in areas close to the rivers could result in this negative externality. Given the limited extent of agriculture in these areas and the low rates of P fertilizers that are required, this type of contamination is expected to be insignificant in Mali even if average rates of P applied are increased substantially.

5. **Accumulation of Heavy Metals** – Possible accumulation of heavy metals in soils may occur as a result of long-term and continuous use of P fertilizers at high application rates. Of particular interest is cadmium (Cd), which is very toxic to animals and humans and is present at different levels of concentration in some phosphate rocks, particularly those of sedimentary origins. Studies to date indicate that most of the Cd added to the soil in phosphate fertilizers remains in the top 7-15 cm of soil with the amounts recovered by most crops being below the levels that are considered safe by the World Health Organization (Johnston and Jones, 1992). Because of the low rates of P fertilizers recommended for agriculture in Mali, this type of contamination is expected to be negligible.

8.2.2 Distribution of Benefits – The use of mineral fertilizers benefits farmers by increasing their incomes and also benefits society as a whole by preventing soil nutrient depletion and land degradation. Most of the environmental benefits will, in the short and long term, benefit the village, the region, and the country. Thus, they are called positive or beneficial externalities. To estimate, in the short and long term, the flow of the private and environmental benefits, the fertilizer strategies were simulated for a period of 18 years, and the flow of net benefits were discounted to calculate present values.

Net present values (NPV) of the stream of private benefits calculated for the agricultural regions using a 10% discount rate are presented in Figures 6 to 10 and in Appendix Tables C1 to C11. Several observations follow from these results.

Investments in phosphate fertilizers, in any form, provide significantly positive returns to farmers in Mali. Application of phosphate as TPR appear to be an economic alternative for all agricultural areas in Mali; the benefits for local farmers in terms of net present values varied from US $96.7/ha for basal applications of 60 kg /ha as TPR in the rotation groundnut-maize in Kayes to US $1,200/ha with applications of 120 kg P_2O_5/ha as basal TPR, supplemented with annual applications of 15 kg P_2O_5/ha as TSP in continuous cotton for the Sikasso region. The net present values for private benefits generally increase when basal applications of TPR are supplemented with a soluble source of P such as TSP or PAPR for all cropping systems in the country.

Table 13. Environmental Benefits and Costs

Item	Region/Cropping System[a]										
	Sikasso			Segou		Mopti		Koulikoro		Kayes	
	MaCo	MaMa	CoCo	MiGr	MiMi	MiMi	RiRi	SrSr	SoGr	GrMa	GrGr
1. Prevention of Land Degradation											
Nutrient mining (kg P/ha/year)	2.0	2.1	2.2	2.3	1.8	1.6	2.1	1.7	1.8	2.4	2.6
Soil erosion (ton/ha/year)	12	14	10	12	18	22	27	15	18	17	14
Soil P loss by erosion (kg/ha/year)	2.2	2.6	1.8	1.8	2.7	1.2	1.4	1.9	2.3	2.3	1.9
Estimated value (US $/ha/year)	16.8	14.0	18.0	14.0	12.0	12.0	18.0	15.0	15.6	17.0	14.0
Land value (US $/ha)	168	140	180	140	120	120	180	150	140	140	160
Years to degrade	10	10	10	10	10	10	10	10	10	10	10
2. Carbon Sequestration											
Soil organic carbon loss (ton C/ha/year)	0.64	0.69	0.58	0.55	0.72	0.59	0.71	0.63	0.70	0.58	0.50
Estimated Value (US $/ha/year)	6.4	6.9	5.8	5.5	7.2	5.9	7.1	6.3	7.0	5.8	5.5
Organic C cost (US $/ton)	10	10	10	10	10	10	10	10	10	10	10
3. Prevention of Deforestation (US $/ha)	59.4	59.4	59.4	57.4	57.4	62.5	62.5	54.5	54.5	58.5	58.5
4. Prevention of Industrial Pollution											
Phosphogypsum US $/ha/year	0.80	0.80	0.80	0.80	0.80	0.80	0.60	0.80	0.80	0.80	0.80

[a] Ma= maize; Co= cotton; Mi= millet; Ri= rice; Sr= sorghum; Gr= groundnut.
Sources: Bishop and Allen, 1989. The On-Site Costs of Soil Erosion in Mali.
The World Bank Policy Planning and Research Staff Report.
Project d'Inventaire des resources terrestres (PIRT), Mali, 1982.

Basal applications of 120 kg P_2O_5/ha as TPR in subhumid areas of Sikasso produced net present values that varied from US $325/ha for continuous maize to US $648/ha for the rotation maize-cotton. In more risky areas, such as the semiarid areas in Koulikoro, the returns varied from US $583 for continuous sorghum to US $789/ha for the rotation sorghum-groundnut. In Segou, an agricultural area with high risk due to rainfall variability, farmer returns varied from US $380/ha for continuous millet to US $606/ha for rotations millet-groundnut. In the Kayes region, areas suitable for intensive food and cash crops, farmer returns for groundnut-maize rotations or continuous groundnut production were about US $390/ha.

Basal applications of 120 kg in P_2O_5/ha as TPR combined with 15 kg P_2O_5/ha as TSP produced higher benefits than basal applications of TPR alone. This fertilizer alternative can be considered in food crops if TSP is available in the country and prices are maintained at about the level used in this study. For food crops, returns to farmers vary from US $589/ha for continuous millet in Segou to US $1,200/ha for continuous cotton in Sikasso. It is important to note that annual applications of 30 kg P_2O_5/ha as TSP generally produced the highest returns to farmers and should be considered as the best alternative in cash crops, principally in continuous cotton. Also, this strategy is one of the most profitable in all regions.

A summary of the distribution of net benefits is presented in Table 14. Besides the benefits on soil fertility, the use of TPR, either basal or supplemented with TSP, generates positive environmental benefits to the regions. The environmental benefits for the best TPR alternatives varied from 51% of the total benefit in the subhumid area of Sikasso with continuous maize to 25.7% for continuous cotton in the same area. Basal applications of TPR tend to provide lower private benefits than alternatives that include the use of more soluble sources. The use of organic sources of nutrients in combination with a basal application of TPR is an option that can benefit farmers directly by increasing crop yields and incomes, while providing benefits to the community and country through the conservation of land resources and protection of the environment. It should be noted that if this distribution of benefits is used as a guide to share the cost of TPR investments, then it is possible to suggest that the regional or national community should pay about one-third of the cost due to the environmental benefits. This approach will help to reduce the burden of initial high investments that are generally incurred when applying basal applications of TPR.

8.2.3 Sensitivity Analysis – The effect of changing the discount rate on net present values is presented in Appendix Tables C1 to C11. In all cases, fertilizer strategies show a positive net present value and follow similar trends. As expected, increasing the discount rate of private benefits from 5% to 20% decreased private and total benefits. Because capital and credit are scarce and there is a great deal of uncertainty on crop production and prices received by farmers for some crops, the rates at which farmers in Mali discount future benefits are probably much higher than 20%. These circumstances in addition to uncertainty on long-term land possession seriously reduce and often eliminate the economic incentive for farmers to use TPR or any other fertilizer. This analysis illustrates the great difficulty of transferring these practices to farmers in risky areas and in areas where farmers are not applying TPR or other mineral fertilizer because of high fertilizer-crop price ratios.

Table 14. Distribution of Benefits for Selected Fertilizer Strategies

Region	Cropping System	Fertilizer Basal (kg/ha)	Fertilizer Annual (kg/ha)	Benefits * Private (US $/ha)	Benefits * Environmental (US $/ha)	Benefits * Total (US $/ha)	Benefits * Environmental %
Sikasso	MC	TPR:120		647.8	403.5	1,051.3	38.4
		TPR:120	TSP:15	1,021.3	403.5	1,414.9	28.5
	MM	TPR:120		325.6	344.2	669.8	51.4
		TPR:120	TSP:15	633.5	344.2	967.8	35.6
	CC	TPR:120		600.1	412.8	1,012.9	40.8
		TPR:120	TSP:15	1,200.3	412.8	1,603.2	25.7
Segou	MiG	TPR:120		605.7	351.0	956.7	36.7
		TPR:120	TSP:15	793.7	351.0	1,134.8	30.9
	MiMi	TPR:120		380.4	345.2	725.6	47.6
		TPR:120	TSP:15	599.8	345.2	925.1	37.3
Kayes	GMa	TPR:120		390.3	377.8	768.1	49.2
		TPR:120	TSP:15	672.9	377.8	1,040.8	36.3
	GG	TPR:120		386.1	399.0	785.1	50.8
		TPR:120	TSP:15	626.5	399.0	1,015.7	39.3
Koulikoro	SG	TPR:120		788.6	370.9	1,159.5	32.0
		TPR:120	TSP:15	1,032.3	370.9	1,393.4	26.6
	SS	TPR:120		582.7	365.6	948.3	38.6
		TPR:120	TSP:15	726.9	365.3	1,084.6	33.7
Mopti	Rice	TPR:120		836.9	433.0	1,269.9	34.1
		TPR:120	TSP:15	1,111.9	433.0	1,545.0	28.0
	Millet	TPR:120		311.8	356.2	667.9	53.3
		TPR:120	TSP:15	499.8	356.2	846.1	42.1

* Discount Rate:
Private benefits = 10%
Environmental benefits = 3%

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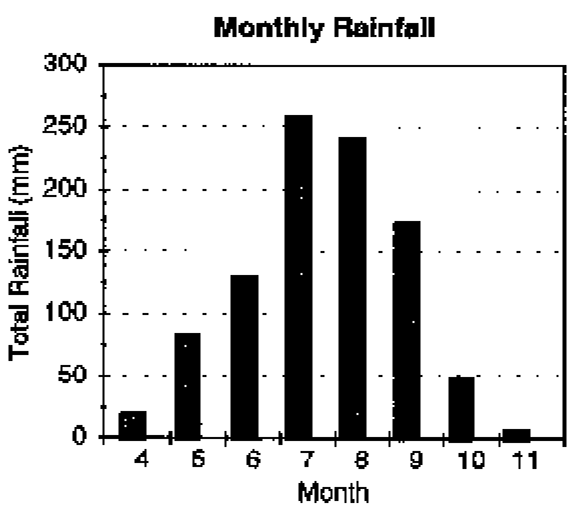
Appendixes

Appendix Tables A1-A5
Appendix Tables B1-B13
Appendix Tables C1-C11

Table A1. Average Rainfall during 1982 to 1987. Experimental Sites — Region, Sikasso

Yr.	Month	Total	Min.	Max.	Prob:0	CV	Yr.	Month	Total	Min.	Max.	Prob:0	CV
		mm	mm	mm	%	%			mm	mm	mm	%	%
82	5	67	0	78	2.9	60.8	83	5	92	0	125	0.7	40.2
	6	158	0	256	5.0	68.2		6	121	0	159	0.4	44.4
	7	324	0	447	0.6	47.0		7	282	0	387	0.1	37.4
	8	248	0	376	1.9	55.9		8	246	0	311	0.1	38.7
	9	217	0	247	0.1	37.8		9	206	0	265	0.2	41.5
	10	102	0	132	0.9	50.0		10	43	0	79	10.6	63.6
	11	15	0	5	32.5	139.2		11	0	0	0	.	.
	Year	1151	0	1537	0.0	63.3		Year	991	0	1325	0.0	50.4
84	5	63	0	108	0.6	47.3	85	5	57	0	105	4.7	67.2
	6	114	0	206	0.8	48.9		6	131	0	215	0.6	47.6
	7	149	0	255	0.2	40.2		7	228	0	385	0.0	33.2
	8	170	0	312	0.8	49.4		8	187	0	348	0.1	37.3
	9	101	0	158	0.2	41.2		9	184	0	357	1.7	55.3
	10	68	0	98	1.7	65.0		10	82	0	115	4.4	66.1
	11	11	0	23	32.5	111.4		11	14	0	30	32.5	111.4
	Year	668	0	1159	0.0	51.0		Year	871	0	1553	0.0	54.6
86	4	74	0	126	5.7	70.4	87	4	53	0	112	6.5	75.0
	5	84	0	138	3.8	64.1		5	123	0	145	3.8	62.1
	6	131	0	210	2.8	60.4		6	128	0	166	3.1	46.3
	7	321	0	468	0.5	45.7		7	250	0	456	0.5	47.2
	8	289	0	345	0.1	38.4		8	302	0	334	0.1	33.1
	9	153	0	245	1.7	55.3		9	178	0	225	1.7	51.2
	10	18	0	35	32.6	92.8		10	5	0	46	85.0	96.0
	11	0	0	0	.	.		11	0	0	0	.	.
	Year	1075	0	1566	0.0	69.2		Year	1039	0	1504	0.0	66.4



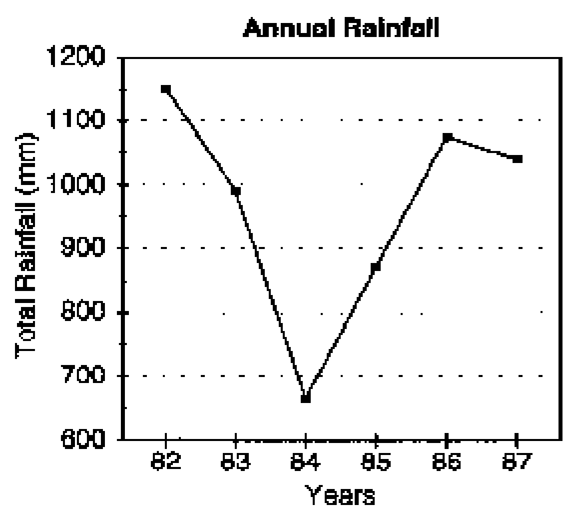
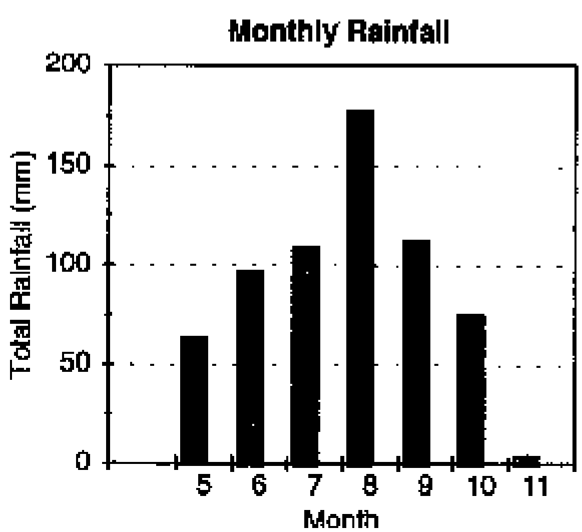


Table A2. Average Rainfall during 1982 to 1987. Experimental Sites — Region, Segou

Yr.	Month	Total	Min.	Max.	Prob:0	CV	Yr.	Month	Total	Min.	Max.	Prob:0	CV
		mm	mm	mm	%	%			mm	mm	mm	%	%
82	5	78	0	158	8.0	102.5	83	5	65	0	117	8.5	79.4
	6	98	0	173	4.4	68.1		6	53	0	85	6.2	61.1
	7	162	0	246	0.3	56.9		7	123	0	172	0.5	40.2
	8	248	0	325	0.1	37.6		8	202	0	278	0.3	37.6
	9	128	0	213	4.4	66.1		9	105	0	159	4.9	51.1
	10	110	0	263	19.2	136.9		10	102	0	208	23.4	104.2
	11	7	0	4	33.0	.		11	2	0	2	.	.
	Year	829	0	1382	0.0	67.5		Year	652	0	1021	0.0	75.0
84	5	39	0	70	9.1	79.8	85	5	59	0	113	6.2	71.7
	6	66	0	102	1.6	54.3		6	83	0	168	3.1	82.9
	7	78	0	114	1.2	46.2		7	124	0	220	0.4	59.4
	8	139	0	219	0.3	57.8		8	148	0	239	0.1	46.0
	9	66	0	115	1.8	73.7		9	122	0	206	1.7	52.6
	10	15	0	39	23.5	55.0		10	68	0	119	4.4	75.4
	11	0	0	0	.	.		11	3	0	9	32.5	.
	Year	403	0	659	0.0	51.0		Year	607	0	1074	0.0	54.6
86	5	72	0	117	5.8	83.0	87	4	65	0	112	6.5	73.0
	6	145	0	259	2.1	79.0		5	132	0	214	2.1	61.0
	7	89	0	136	2.8	52.8		6	78	0	186	1.9	45.3
	8	185	0	298	0.5	61.3		7	145	0	312	0.6	42.7
	9	122	0	173	0.1	42.0		8	134	0	256	1.1	42.0
	10	90	0	160	3.4	67.0		9	66	0	225	1.7	51.2
	11	4	0	9	32.5	106.6		10	5	0	46	35.0	96.0
	Year	707	0	1142	0.0	61.4		Year	625	0	1351	0.0	56.0



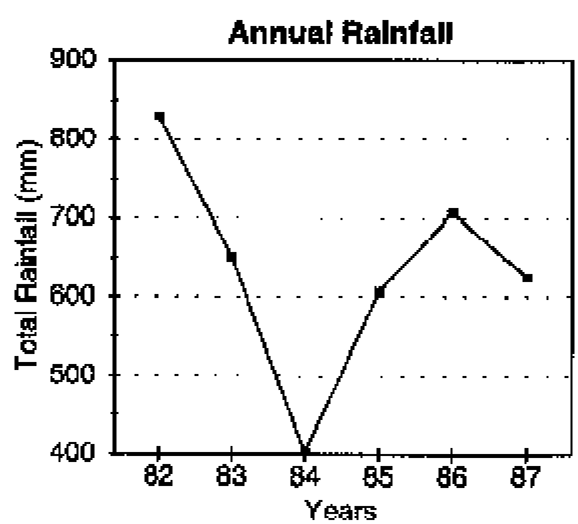
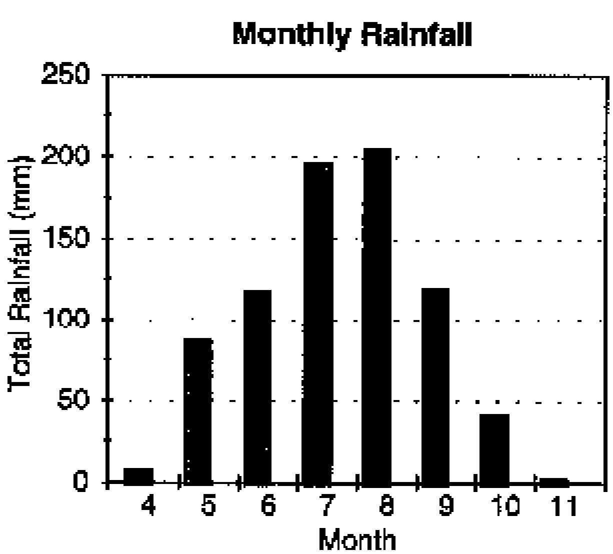


Table A3. Average Rainfall during 1982 to 1987. Experimental Sites — Region, Kayes

Yr.	Month	Total	Min.	Max.	Prob:0	CV	Yr.	Month	Total	Min.	Max.	Prob:0	CV
		mm	mm	mm	%	%			mm	mm	mm	%	%
82	5	102	0	163	2.7	59.8	83	5	92	0	155	3.2	68.3
	6	123	0	179	0.8	49.1		6	113	0	176	1.1	56.1
	7	238	0	339	1.4	53.2		7	189	0	315	1.4	66.5
	8	196	0	288	0.6	47.2		8	167	0	252	0.9	51.0
	9	159	0	229	0.4	45.1		9	159	0	242	0.8	52.2
	10	85	0	161	16.8	96.6		10	89	0	173	19.3	93.9
	11	10	0	4	39.0	.		11	0	0	4	42.0	.
	Year	913		1363		61.0		Year	809		1317		69.7
84	5	35	0	66	13.2	89.8	85	5	15	0	36	12.3	71.7
	6	72	0	119	3.9	64.6		6	101	0	186	5.6	82.9
	7	158	0	243	1.5	53.8		7	213	0	365	0.8	59.4
	8	166	0	265	2.7	59.8		8	199	0	358	0.5	46.0
	9	127	0	201	2.6	58.5		9	144	0	248	0.7	52.6
	10	2	0	5	32.4	123.4		10	20	0	33	4.3	75.4
	11	0	0	0	.	.		11	3	0	9	43.4	.
	Year	560	0	699	0.0	81.5		Year	694		1234		54.6
86	4	17	0	45	13.6	111.6	87	4	23	0	123	8.4	92.0
	5	145	0	221	7.4	82.7		5	132	0	234	5.3	75.0
	6	172	0	271	1.2	60.1		6	123	0	223	3.5	67.0
	7	190	0	230	0.5	45.9		7	169	0	306	0.6	64.0
	8	277	0	312	0.4	35.2		8	223	0	278	1.1	49.0
	9	38	0	71	6.1	96.8		9	90	0	303	3.9	51.2
	10	19	0	33	22.6	73.5		10	34	0	86	14.8	106.0
	11	1	0	9	39.0			11	3	.0	10	39.5	
	Year	857		1192		77.2		Year	817		1665		56.0



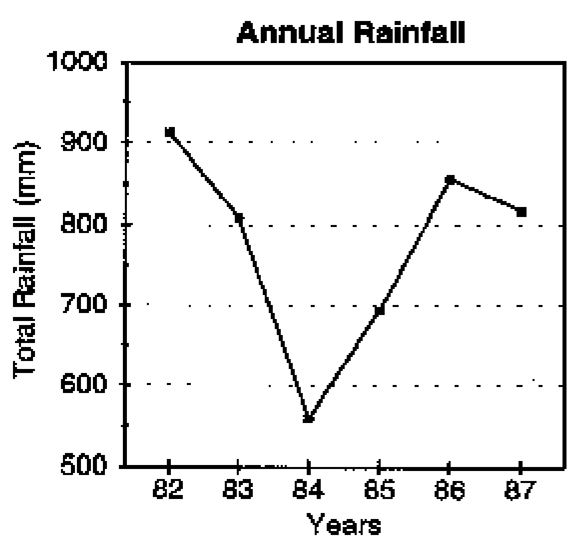
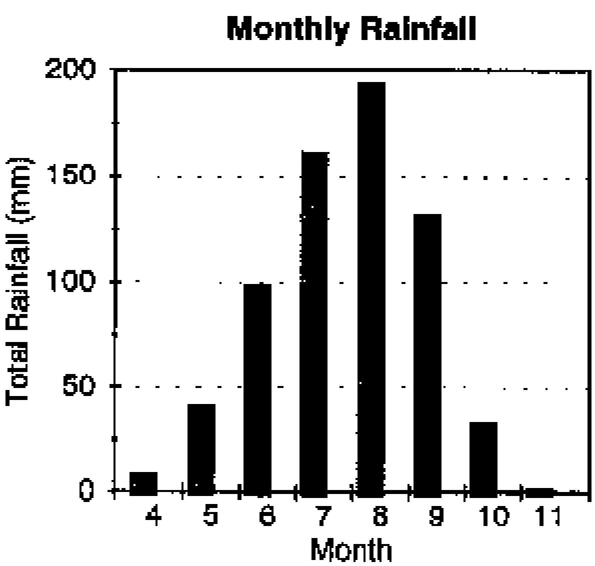


Table A4. Average Rainfall during 1982 to 1987. Experimental Sites — Region, Koulikoro

Yr.	Month	Total	Min.	Max.	Prob:0	CV	Yr.	Month	Total	Min.	Max.	Prob:0	CV
		mm	mm	mm	%	%			mm	mm	mm	%	%
82	5	77	0	143	3.8	85.7	83	5	33	0	69	9.6	108.2
	6	121	0	203	4.9	68.0		6	79	0	151	5.1	91.4
	7	152	0	222	0.0	46.2		7	175	0	269	1.5	53.7
	8	200	0	297	0.7	48.3		8	171	0	255	0.8	48.9
	9	162	0	245	1.1	51.1		9	163	0	266	3.5	63.0
	10	63	0	118	10.2	87.2		10	10	0	23	18.1	93.9
	11	0	0	0	.	.		11	0	0	0	.	.
	Year	775		1228		68.5		Year	631		1033		74.5
84	5	26	0	46	13.2	69.2	85	5	17	0	57	9.3	81.7
	6	65	0	114	7.7	75.9		6	70	0	206	6.3	62.9
	7	133	0	197	1.6	48.0		7	177	0	311	1.4	49.4
	8	150	0	222	1.4	48.2		8	225	0	428	1.2	46.2
	9	112	0	160	8.3	53.0		9	151	0	208	4.6	36.9
	10	18	0	132	23.3	103.5		10	20	0	73	12.8	75.4
	11	1	0	7	56.9	.		11	3	0	12	33.5	.
	Year	506	0	678	0.0	72.6		Year	663		1293		56.8
86	4	22	0	45	23.8	111.6	87	4	30	0	89	11.8	90.0
	5	42	0	77	10.1	82.7		5	50	0	123	8.9	79.0
	6	136	0	304	3.9	60.1		6	120	0	216	3.5	53.0
	7	173	0	288	1.5	46.9		7	160	0	267	0.8	56.0
	8	207	0	300	0.4	35.2		8	211	0	289	0.5	51.0
	9	113	0	256	6.1	96.8		9	90	0	189	4.1	65.0
	10	35	0	87	14.6	73.5		10	47	0	95	14.8	86.0
	11	2	0	9	33.0			11	2	0	5	39.5	
	Year	729		1366		75.1		Year	710		1273		66.0



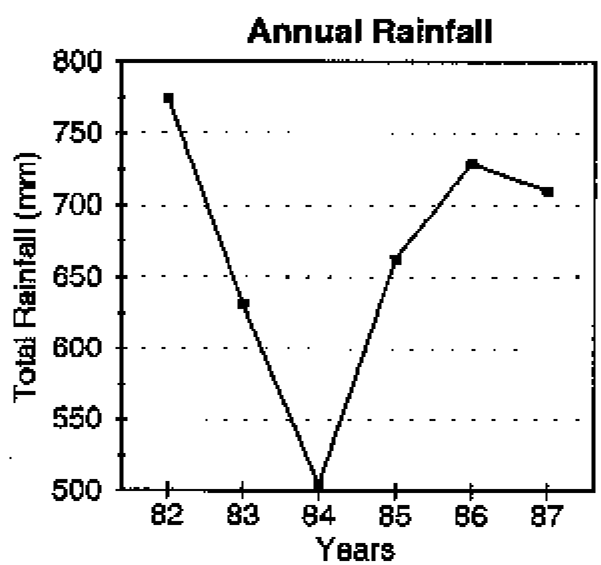
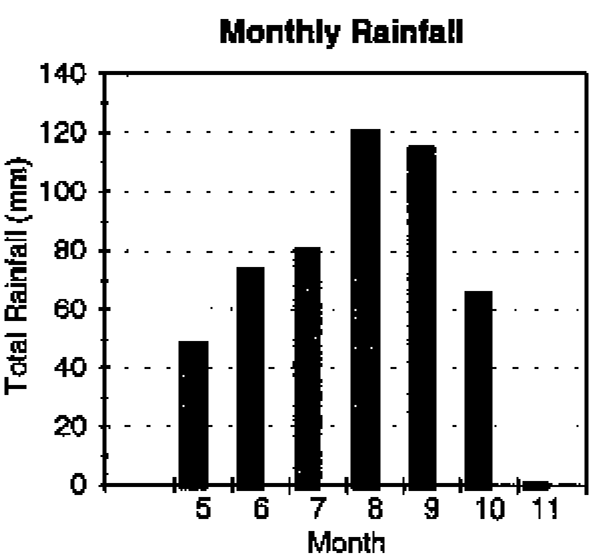


Table A5. Average Rainfall during 1982 to 1987. Experimental Sites — Region, Mopti

Yr.	Month	Total	Min.	Max.	Prob:0	CV	Yr.	Month	Total	Min.	Max.	Prob:0	CV
		mm	mm	mm	%	%			mm	mm	mm	%	%
82	5	75	0	154	12.3	105.9	83	5	54	0	98	10.1	80.9
	6	83	0	169	4.6	94.8		6	42	0	71	7.4	68.6
	7	102	0	153	0.6	50.3		7	56	0	61	0.8	45.2
	8	134	0	189	0.4	42.6		8	112	0	158	0.4	41.4
	9	112	0	208	4.8	58.0		9	123	0	189	4.8	53.6
	10	78	0	189	16.5	142.6		10	96	0	201	23.1	109.2
	11	0	0	0	.	.		11	0	0	0	.	.
	Year	584	0	1063		72.3		Year	483	0	798		85.0
84	5	12	0	31	10.3	77.3	85	5	45	0	110	8.1	74.2
	6	45	0	68	7.2	50.0		6	68	0	145	4.5	90.1
	7	54	0	103	3.4	56.2		7	84	0	199	1.2	61.9
	8	78	0	155	2.1	64.5		8	122	0	230	0.8	51.0
	9	65	0	167	1.8	93.7		9	82	0	153	1.3	50.3
	10	15	0	48	24.6	133.6		10	36	0	68	15.9	77.8
	11	0	0	0	.	.		11	2	0	6	32.5	.
	Year	269	0	572		66.5		Year	449	0	911		71.9
86	5	55	0	85	7.8	61.0	87	4	52	0	110	7.7	77.0
	6	98	0	220	5.2	82.0		5	106	0	155	3.1	58.0
	7	104	0	133	2.8	54.3		6	83	0	176	1.4	63.0
	8	134	0	216	1.3	63.0		7	144	0	237	0.8	55.0
	9	144	0	205	0.8	44.0		8	137	0	226	1.1	50.0
	10	67	0	112	16.0	75.0		9	103	0	145.	12.4	43.9
	11	2	0	6	32.5			10	3	0	12	28.0	
	Year	805	0	977	0.0	63.0		Year	627	0	1081	0.0	58.0



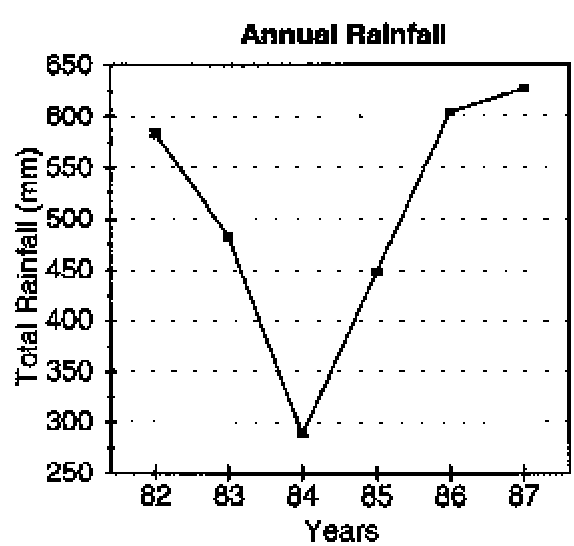


Table B1. Response of Maize-Cotton Rotation to Fertilizer Strategies — Region, Sikasso

Strat.	Basal PR Rate P_2O_5/ha	Annual App. Rate P_2O_5/ha	Annual App. Source	Production by Year Maize 1982	Cotton 1983	Maize 1984	Cotton 1985	Maize 1986	Cotton 1987	Total P_2O_5 Removed
				Grain Yield Production (kg/ha)*						
1	0	0	Abs.	650	523	285	363	163	280	
2	0	0	Pcont.	1332	985	457	584	704	518	
3	60	0	TPR	1600	1193	657	866	1035	771	
4	120	0	TPR	1867	1401	858	1148	1365	1023	
5	60	15	PA30	1842	1364	1040	1157	1512	1266	
6	60	15	TSP	1996	1456	1090	1206	1747	1337	
7	120	15	PA30	1932	1399	1118	1255	1615	1364	
8	120	15	TSP	2152	1513	1149	1277	1868	1408	
9	0	30	PA30	1853	1411	1084	1174	1578	1323	
10	0	30	TSP	1960	1498	1168	1267	1846	1444	
				Stover Yield Production (kg/ha)						
1	0	0	Abs.	1040	889	456	617	261	442	
2	0	0	Pcont.	1998	1675	686	993	1056	881	
3	60	0	TPR	2399	2088	986	1516	1552	1349	
4	120	0	TPR	2801	2452	1287	2009	2048	1791	
5	60	15	PA30	2948	2456	1664	2083	2419	2276	
6	60	15	TSP	3193	2621	1744	2171	2796	2407	
7	120	15	PA30	3091	2519	1788	2259	2584	2455	
8	120	15	TSP	3443	2723	1839	2298	2989	2535	
9	0	30	PA30	2965	2540	1734	2113	2524	2381	
10	0	30	TSP	3137	2696	1869	2281	2954	2599	
				P_2O_5 Removed From Soil Due to Grain and Stover Harvesting (kg/ha) **						
1	0	0	Abs.	3.4	2.6	1.2	2.0	0.7	1.4	11.4
2	0	0	Pcont.	6.8	5.3	2.3	3.1	4.5	2.6	24.8
3	60	0	TPR	10.9	16.3	5.4	14.0	9.8	14.3	70.7
4	120	0	TPR	12.7	19.1	7.0	16.5	13.0	19.0	89.3
5	60	15	PA30	12.8	18.8	8.7	18.9	14.7	23.6	97.6
6	60	15	TSP	13.8	20.1	9.1	19.7	17.0	25.2	104.8
7	120	15	PA30	13.4	19.3	9.3	20.5	15.7	25.7	103.6
8	120	15	TSP	14.9	20.9	9.6	20.8	18.2	26.5	110.8
9	0	30	PA30	12.9	19.5	9.0	19.1	15.3	24.9	100.7
10	0	30	TSP	13.6	20.7	9.7	20.7	17.9	27.2	109.8

* Cotton yield in kg/ha of seed.
** Assumed 70% of stover harvested and 30% left as crop residue.

Table B2. Response of Continuous Maize to Fertilizer Strategies — Region, Sikasso

Strat.	Basal PR Rate P_2O_5/ha	Annual App. Rate P_2O_5/ha	Annual App. Source	Production by Year: Maize 1982	1983	1984	1985	1986	1987	Total P_2O_5 Removed
				Grain Yield Production (kg/ha)						
1	0	0	Abs.	600	491	400	423	311	208	
2	0	0	PCont	1308	1163	501	753	900	731	
3	60	0	TPR	1580	1425	700	1006	1248	1067	
4	120	0	TPR	1853	1686	899	1258	1596	1403	
5	60	15	PA30	1814	1726	1109	1388	1764	1702	
6	60	15	TSP	2063	1788	1222	1417	1938	1802	
7	120	15	PA30	1917	1854	1205	1504	1906	1820	
8	120	15	TSP	2202	1907	1265	1516	2095	1902	
9	0	30	PA30	1806	1705	1135	1395	1845	1788	
10	0	30	TSP	2070	1790	1341	1450	1992	1934	
				Stover Yield Production (kg/ha)						
1	0	0	Abs.	960	786	640	677	498	333	
2	0	0	PCont	2158	1919	827	1242	1485	1206	
3	60	0	TPR	2608	2351	1155	1659	2059	1761	
4	120	0	TPR	3057	2782	1484	2076	2633	2315	
5	60	15	PA30	3084	2937	1886	2359	3034	2894	
6	60	15	TSP	3507	3040	2078	2409	3295	3063	
7	120	15	PA30	3259	3153	2049	2557	3241	3094	
8	120	15	TSP	3744	3241	2151	2581	3562	3233	
9	0	30	PA30	3074	2899	1930	2372	3136	3039	
10	0	30	TSP	3520	3044	2280	2465	3386	3287	
				P_2O_5 Removed From Soil Due to Grain and Stover Harvesting (kg/ha)*						
1	0	0	Abs.	2.5	2.1	1.4	1.8	1.3	0.9	9.9
2	0	0	PCont	6.2	5.5	2.4	3.6	4.3	3.5	25.3
3	60	0	TPR	11.1	11.0	5.9	9.2	12.2	11.2	60.6
4	120	0	TPR	13.0	13.0	7.6	11.5	15.7	14.6	75.4
5	60	15	PA30	12.8	13.5	9.4	12.8	17.7	18.1	84.3
6	60	15	TSP	14.6	13.9	10.4	13.0	19.2	19.1	90.3
7	120	15	PA30	13.6	14.4	10.2	13.8	18.9	19.3	90.3
8	120	15	TSP	15.6	14.8	10.7	14.0	20.8	20.2	96.1
9	0	30	PA30	12.8	13.3	9.6	12.8	18.3	19.0	85.8
10	0	30	TSP	14.7	13.9	11.4	13.3	19.7	20.5	93.6

* Assumed 70% of stover harvested and 30% left as crop residue.

Table B3. Response of Continuous Cotton to Fertilizer Strategies — Region, Sikasso

Strat.	Basal PR Rate P_2O_5/ha	Annual App. Rate P_2O_5/ha	Annual App. Source	Production by Year: Cotton 1982	1983	1984	1985	1986	1987	Total P_2O_5 Removed
				Seed Yield Production (kg/ha)						
1	0	0	Abs.	510	342	314	242	194	144	
2	0	0	PCont	1151	965	547	698	750	600	
3	60	0	TPR	1266	1118	665	864	950	828	
4	120	0	TPR	1380	1250	823	1032	1150	1056	
5	60	15	PA30	1370	1332	985	1104	1333	1285	
6	60	15	TSP	1477	1421	1082	1153	1397	1384	
7	120	15	PA30	1397	1380	1083	1154	1388	1347	
8	120	15	TSP	1522	1461	1122	1202	1467	1484	
9	0	30	PA30	1390	1356	968	1139	1404	1373	
10	0	30	TSP	1499	1476	1161	1203	1465	1473	
				Stover Yield Production (kg/ha)						
1	0	0	Abs.	867	581	534	411	330	245	
2	0	0	PCont	1957	1675	930	1183	1275	1020	
3	60	0	TPR	2215	1956	1199	1512	1662	1449	
4	120	0	TPR	2415	2188	1440	1806	2012	1848	
5	60	15	PA30	2467	2398	1773	1987	2400	2314	
6	60	15	TSP	2658	2558	1948	2076	2515	2492	
7	120	15	PA30	2514	2484	1950	2077	2499	2425	
8	120	15	TSP	2739	2629	2020	2163	2641	2636	
9	0	30	PA30	2502	2441	1743	2051	2528	2471	
10	0	30	TSP	2699	2658	2090	2165	2637	2651	
				P_2O_5 Removed From Soil Due to Grain and Stover Harvesting (kg/ha) *						
1	0	0	Abs.	3.0	2.0	1.8	1.4	1.1	0.8	10.3
2	0	0	PCont	6.2	5.3	2.9	3.7	4.0	3.2	25.4
3	60	0	TPR	15.7	15.2	10.2	13.9	16.5	15.4	86.9
4	120	0	TPR	17.1	17.1	12.2	16.6	20.0	19.6	102.6
5	60	15	PA30	17.2	18.4	14.8	18.0	23.4	24.2	116.0
6	60	15	TSP	18.5	19.6	16.3	18.8	24.5	26.0	123.8
7	120	15	PA30	17.5	19.0	16.3	18.8	24.4	25.3	121.4
8	120	15	TSP	19.1	20.1	16.9	19.6	25.8	27.5	129.0
9	0	30	PA30	17.4	18.7	14.6	18.6	24.7	25.8	119.7
10	0	30	TSP	18.8	20.4	17.5	19.6	25.7	27.7	129.7

* Assumed 70% of stover harvested and 30% left as crop residue.

Table 84. Response of Millet-Groundnut Rotation to Fertilizer Strategies — Region, Segou

Strat.	Basal PR Rate P_2O_5/ha	Annual App. Rate Source P_2O_5/ha	Production by Year Millet 1982	Grdnut. 1983	Millet 1984	Grdnut. 1985	Millet 1986	Grdnut. 1987	Total P_2O_5 Removed
			Grain Yield Production (kg/ha)						
1	0	0 Abs.	383	503	230	333	283	303	
2	0	0 PCont	769	728	255	517	545	404	
3	60	0 TPR	1005	953	525	791	833	732	
4	120	0 TPR	1242	1178	795	1065	1121	1060	
5	60	15 PA30	1236	1187	899	1090	1233	1114	
6	60	15 TSP	1295	1225	928	1121	1264	1138	
7	120	15 PA30	1286	1246	1011	1167	1341	1189	
8	120	15 TSP	1353	1282	1037	1181	1350	1218	
9	0	30 PA30	1286	1224	914	1133	1262	1190	
10	0	30 TSP	1348	1273	955	1192	1330	1213	
			Stover Yield Production (kg/ha)						
1	0	0 Abs.	586	770	352	509	433	464	
2	0	0 PCont	1177	1114	390	791	834	618	
3	60	0 TPR	1508	1553	788	1290	1250	1193	
4	120	0 TPR	1925	1920	1232	1737	1738	1728	
5	60	15 PA30	2040	2018	1483	1854	2034	1894	
6	60	15 TSP	2137	2082	1532	1906	2086	1934	
7	120	15 PA30	2123	2118	1668	1983	2212	2022	
8	120	15 TSP	2233	2179	1711	2007	2228	2071	
9	0	30 PA30	2122	2081	1508	1926	2083	2023	
10	0	30 TSP	2224	2164	1575	2026	2195	2063	
			P_2O_5 Removed From Soil Due to Grain and Stover Harvesting (kg/ha)*						
1	0	0 Abs.	2.9	3.3	1.7	2.2	2.1	2.0	14.2
2	0	0 PCont	5.8	4.7	1.9	3.4	4.1	2.6	22.6
3	60	0 TPR	10.9	9.6	6.8	9.4	12.6	10.0	59.3
4	120	0 TPR	13.6	11.8	10.5	12.6	17.2	14.5	80.3
5	60	15 PA30	13.9	12.1	12.1	13.1	19.4	15.4	86.1
6	60	15 TSP	14.6	12.4	12.5	13.5	19.9	15.8	88.7
7	120	15 PA30	14.5	12.7	13.7	14.0	21.1	16.5	92.4
8	120	15 TSP	15.2	13.0	14.0	14.2	21.3	16.9	94.6
9	0	30 PA30	14.5	12.4	12.3	13.6	19.9	16.5	89.2
10	0	30 TSP	15.2	12.9	12.9	14.3	21.0	16.8	93.1

* Assumed 70% of stover harvested and 30% left as crop residue.

Table B5. Response of Continuous Millet to Fertilizer Strategies — Region, Segou

Strat.	Basal PR Rate P_2O_5/ha	Annual App. Rate P_2O_5/ha	Source	Production by Year: Millet 1982	1983	1984	1985	1986	1987	Total P_2O_5 Removed
Grain Yield Production (kg/ha)										
1	0	0	Abs.	436	381	206	248	270	212	
2	0	0	Pcont	816	636	210	363	452	380	
3	60	0	TPR	1020	866	465	645	706	643	
4	120	0	TPR	1224	1097	720	927	961	906	
5	60	15	PA30	1193	1148	792	983	1120	1020	
6	60	15	TSP	1290	1167	832	1027	1183	1129	
7	120	15	PA30	1231	1230	911	1080	1222	1008	
8	120	15	TSP	1365	1236	946	1116	1258	1192	
9	0	30	PA30	1235	1166	784	1010	1154	1187	
10	0	30	TSP	1310	1208	840	1075	1265	1229	
Stover Yield Production (kg/ha)										
1	0	0	Abs.	667	583	315	379	413	324	
2	0	0	Pcont	1265	986	326	563	701	589	
3	60	0	TPR	1632	1386	744	1032	1130	1028	
4	120	0	TPR	1958	1755	1152	1483	1537	1449	
5	60	15	PA30	2028	1951	1347	1671	1905	1734	
6	60	15	TSP	2193	1984	1415	1746	2011	1919	
7	120	15	TSP	2093	2091	1549	1837	2077	1714	
8	120	15	PA30	2321	2101	1608	1897	2139	2026	
9	0	30	PA30	2100	1985	1333	1718	1962	2018	
10	0	30	TSP	2227	2054	1428	1828	2151	2090	
P_2O_5 Removed From Soil Due to Grain and Stover Harvesting (kg/ha)*										
1	0	0	Abs.	3.3	2.9	1.6	1.9	2.0	1.6	13.3
2	0	0	Pcont	6.2	4.8	1.6	2.8	3.4	2.9	21.7
3	60	0	TPR	11.3	10.6	6.2	9.3	11.0	10.7	59.1
4	120	0	TPR	13.6	13.4	9.6	13.4	14.9	15.1	80.0
5	60	15	PA30	13.6	14.4	10.8	14.6	17.9	17.5	88.8
6	60	15	TSP	14.7	14.6	11.4	15.2	18.9	19.3	94.2
7	120	15	PA30	14.0	15.4	12.5	16.0	19.5	17.3	94.7
8	120	15	TSP	15.6	15.5	12.9	16.5	20.1	20.4	101.1
9	0	30	PA30	14.1	14.7	10.7	15.0	18.4	20.3	93.2
10	0	30	TSP	14.9	15.2	11.5	15.9	20.2	21.0	98.8

* Assumed 70% of stover harvested and 30% left as crop residue.

Table B6. Response of Sorghum-Groundnut Rotation to Fertilizer Strategies — Region, Koulikoro

Strat.	Basal PR Rate P_2O_5/ha	Annual App. Rate Source P_2O_5/ha	Production by Year Sorg. 1982	Grdnut. 1983	Sorg. 1984	Grdnut. 1985	Sorg. 1986	Grdnut. 1987	Total P_2O_5 Removed
			Grain Yield Production (kg/ha)						
1	0	0 Abs.	509	439	324	360	326	256	
2	0	0 Pcont	1038	617	520	422	495	360	
3	60	0 TPR	1287	934	824	684	889	711	
4	120	0 TPR	1536	1251	1128	945	1283	1062	
5	60	15 PA30	1586	1178	1166	1012	1379	1123	
6	60	15 TSP	1662	1242	1218	1100	1465	1168	
7	120	15 PA30	1659	1243	1251	1057	1462	1186	
8	120	15 TSP	1720	1354	1291	1202	1557	1245	
9	0	30 PA30	1626	1230	1215	1096	1487	1227	
10	0	30 TSP	1739	1252	1295	1135	1584	1266	
			Stover Yield Production (kg/ha)						
1	0	0 Abs.	713	659	454	540	456	384	
2	0	0 Pcont	1453	926	728	633	693	540	
3	60	0 TPR	1802	1401	1154	1025	1245	1067	
4	120	0 TPR	2688	1876	1975	1418	2246	1593	
5	60	15 PA30	2775	1884	2041	1619	2413	1797	
6	60	15 TPS	2908	1987	2132	1760	2565	1869	
7	120	15 PA30	2903	1989	2189	1691	2559	1898	
8	120	15 TSP	3009	2166	2260	1923	2725	1992	
9	0	30 PS30	2845	1968	2127	1754	2602	1963	
10	0	30 TSP	3044	2003	2266	1816	2771	2026	
			P_2O_5 Removed From Soil Due to Grain and Stover Harvesting (kg/ha)*						
1	0	0 Abs.	2.8	2.8	1.8	2.3	1.8	1.6	13.0
2	0	0 Pcont	5.7	3.9	2.8	2.7	2.7	2.3	20.1
3	60	0 TPR	12.8	9.2	9.8	8.0	12.3	9.5	61.6
4	120	0 TPR	16.7	12.3	14.8	11.0	19.6	14.3	88.7
5	60	15 PA30	17.3	11.8	15.3	12.0	21.0	15.3	92.6
6	60	15 TSP	18.1	12.4	15.9	13.0	22.4	15.9	97.8
7	120	15 PA30	18.1	12.4	16.4	12.5	22.3	16.2	97.8
8	120	15 TSP	18.7	13.5	16.9	14.2	23.8	17.0	104.1
9	0	30 PA30	17.7	12.3	15.9	13.0	22.7	16.7	98.3
10	0	30 TSP	19.0	12.5	16.9	13.4	24.2	17.3	103.3

* Assumed 70% of stover harvested and 30% left as crop.

Table B7. Response of Continuous Sorghum to Fertilizer Strategies — Region, Koulikoro

Strat.	Basal PR Rate P_2O_5/ha	Annual App. Rate Source P_2O_5/ha	Production by Year						Total P_2O_5 Removed
			Sorghum						
			1982	1983	1984	1985	1986	1987	
			Grain Yield Production (kg/ha)						
1	0	0 Abs.	509	445	322	381	298	220	
2	0	0 Pcont.	975	670	380	496	607	505	
3	60	0 TPR	1236	983	686	839	911	747	
4	120	0 TPR	1497	1296	992	1182	1214	989	
5	60	15 PA30	1577	1305	1096	1147	1407	1227	
6	60	15 TSP	1653	1414	1114	1196	1443	1268	
7	120	15 PA30	1647	1393	1197	1214	1475	1284	
8	120	15 TSP	1729	1499	1238	1263	1529	1283	
9	0	30 PA30	1634	1346	1084	1220	1515	1328	
10	0	30 TSP	1720	1486	1170	1280	1537	1430	
			Stover Yield Production (kg/ha)						
1	0	0 Abs.	814	712	419	495	477	352	
2	0	0 Pcont.	1560	1072	494	645	971	806	
3	60	0 TPR	1978	1573	960	1175	1457	1195	
4	120	0 TPR	2545	2204	1488	1774	2064	1681	
5	60	15 PA30	2681	2218	1645	1721	2393	2086	
6	60	15 TSP	2810	2404	1670	1794	2454	2155	
7	120	15 PA30	2800	2368	1798	1821	2507	2183	
8	120	15 TSP	2939	2549	1857	1895	2600	2182	
9	0	30 PA30	2779	2288	1626	1829	2575	2258	
10	0	30 TSP	2924	2526	1755	1920	2613	2432	
			P_2O_5 Removed From Soil Due to Grain and Stover Harvesting (kg/ha)*						
1	0	0 Abs.	3.0	2.6	1.7	2.0	1.7	1.3	12.2
2	0	0 Pcont.	5.7	3.9	2.0	2.6	3.5	2.9	20.6
3	60	0 TPR	13.0	11.3	8.2	7.1	13.4	11.7	64.7
4	120	0 TPR	16.1	15.3	12.1	10.1	18.3	16.0	88.0
5	60	15 PA30	17.0	15.4	13.4	9.5	21.2	19.6	96.7
6	60	15 TSP	17.8	16.7	13.6	10.2	21.7	20.5	100.6
7	120	15 PA30	17.7	16.5	14.7	10.4	22.2	20.7	102.2
8	120	15 TSP	18.6	17.7	15.2	10.8	23.0	20.7	106.1
9	0	30 PA30	17.6	15.9	13.3	10.4	22.8	21.4	101.5
10	0	30 TSP	18.5	17.6	14.3	11.0	23.2	23.1	107.6

* Assumed 70% of stover harvested and 30% left as crop residue.

Table B8. Response of Groundnut-Maize Rotation to Fertilizer Strategies — Region, Kayes

Strat.	Basal PR Rate P_2O_5/ha	Annual App. Rate Source P_2O_5/ha	Production by Year						Total P_2O_5 Removed
			Grdnut. 1982	Maize 1983	Grdnut. 1984	Maize 1985	Grdnut. 1986	Maize 1987	
			Grain Yield Production (kg/ha)						
1	0	0 Abs.	620	553	453	412	396	193	
2	0	0 Pcont	966	1041	561	705	695	406	
3	60	0 TPR	1122	1249	663	971	887	886	
4	120	0 TPR	1276	1466	785	1236	979	1384	
5	60	15 PA30	1261	1392	996	1265	1175	1386	
6	60	15 TSP	1314	1510	1130	1250	1279	1452	
7	120	15 PA30	1296	1422	1020	1347	1206	1482	
8	120	15 TSP	1346	1531	1176	1440	1321	1571	
9	0	30 PA30	1269	1439	1041	1296	1252	1506	
10	0	30 TSP	1359	1595	1205	1392	1306	1554	
			Stover Yield Production (kg/ha)						
1	0	0 Abs.	667	940	646	700	566	326	
2	0	0 Pcont.	1449	1562	672	1056	1043	612	
3	60	0 TPR	1683	1673	1025	1166	1256	1063	
4	120	0 TPR	1917	2476	1176	2104	1469	2319	
5	60	15 PA30	2016	2366	1576	2151	1660	2360	
6	60	15 TSP	2103	2566	1609	2294	2046	2469	
7	120	15 PA30	2074	2417	1632	2290	1929	2520	
8	120	15 TSP	2153	2602	1681	2447	2114	2671	
9	0	30 PA30	2063	2446	1665	2206	2002	2560	
10	0	30 TSP	2174	2711	1926	2366	2165	2642	
			P_2O_5 Removed From Soil Due to Grain and Stover Harvesting (kg/ha)*						
1	0	0 Abs.	3.9	2.4	2.6	1.6	2.5	0.8	14.1
2	0	0 Pcont.	6.1	4.8	3.7	3.2	4.4	1.9	24.1
3	60	0 TPR	10.6	10.1	7.8	8.6	11.1	9.0	57.2
4	120	0 TPR	12.1	12.3	8.9	12.4	13.0	15.7	74.4
5	60	15 PA30	12.2	11.8	11.4	12.6	15.9	16.0	79.8
6	60	15 TSP	12.7	12.7	13.1	13.5	17.3	16.7	86.0
7	120	15 PA30	12.5	12.0	11.8	13.4	16.3	17.1	83.1
8	120	15 TSP	13.0	12.9	13.6	14.4	17.9	18.1	89.8
9	0	30 PA30	12.4	12.1	12.1	12.9	16.9	17.3	83.6
10	0	30 TSP	13.1	13.5	14.0	13.9	18.5	17.9	90.8

* Assumed 70% of stover harvested and 30% left as crop residue.

Table B9. Response of Continuous Groundnut to Fertilizer Strategies — Region, Kayes

Strat.	Basal PR Rate P_2O_5/ha	Annual App. Rate Source P_2O_5/ha	Production by Year: Groundnut 1982	1983	1984	1985	1986	1987	Total P_2O_5 Removed
			Grain Yield Production (kg/ha)						
1	0	0 Abs.	500	457	453	403	380	366	
2	0	0 Pcont.	900	750	481	645	768	702	
3	60	0 TPR	1088	936	638	837	911	837	
4	120	0 TPR	1276	1122	794	1029	1054	972	
5	60	15 PA30	1140	1093	978	1075	1142	1130	
6	60	15 TSP	1255	1154	1042	1130	1188	1153	
7	120	15 PA30	1258	1157	1103	1146	1200	1156	
8	120	15 TSP	1311	1193	1066	1173	1243	1193	
9	0	30 PA30	1051	1094	942	1090	1159	1198	
10	0	30 TSP	1269	1201	1147	1194	1221	1211	
			Stover Yield Production (kg/ha)						
1	0	0 Abs.	715	654	648	576	543	523	
2	0	0 Pcont.	1350	1125	722	968	1152	1053	
3	60	0 TPR	1632	1404	956	1256	1366	1256	
4	120	0 TPR	1913	1683	1191	1544	1580	1458	
5	60	15 PA30	1824	1748	1565	1720	1827	1807	
6	60	15 TSP	2008	1846	1667	1809	1901	1844	
7	120	15 PA30	2013	1852	1765	1833	1920	1850	
8	120	15 TSP	2098	1909	1705	1876	1989	1909	
9	0	30 PA30	1682	1751	1507	1745	1855	1917	
10	0	30 TSP	2031	1921	1835	1910	1954	1937	
			P_2O_5 Removed From Soil Due to Grain and Stover Harvesting (kg/ha)*						
1	0	0 Abs.	3.1	2.9	2.8	2.5	2.4	2.3	16.0
2	0	0 Pcont.	5.5	4.6	2.9	3.9	4.7	4.3	25.9
3	60	0 TPR	10.3	9.8	7.3	10.3	12.1	11.9	61.6
4	120	0 TPR	12.1	11.7	9.0	12.7	14.0	13.8	73.3
5	60	15 PA30	11.0	11.6	11.3	13.5	15.4	16.4	79.2
6	60	15 TSP	12.1	12.2	12.1	14.2	16.1	16.7	83.3
7	120	15 PA30	12.1	12.3	12.8	14.4	16.2	16.7	84.5
8	120	15 TSP	12.7	12.7	12.3	14.7	16.6	17.3	86.4
9	0	30 PA30	10.1	11.6	10.9	13.7	15.7	17.3	79.4
10	0	30 TSP	12.3	12.7	13.3	15.0	16.5	17.5	87.3

* Assumed 70% of stover harvested and 30% left as crop residue.

Table B10. Response of Continuous Millet to Fertilizer Strategies — Region, Mopti

Strat.	Basal PR Rate P_2O_5/ha	Annual App. Rate Source P_2O_5/ha	Production by Year						Total P_2O_5 Removed
			Millet						
			1982	1983	1984	1985	1986	1987	
			Grain Yield Production (kg/ha)						
1	0	0 Abs.	478	396	225	268	303	285	
2	0	0 Pcont	735	520	270	303	402	359	
3	60	0 TPR	885	745	446	579	696	605	
4	120	0 TPR	1035	970	622	855	990	851	
5	60	15 PA30	1067	992	808	962	1066	1004	
6	60	15 TSP	1120	1053	859	1007	1099	1080	
7	120	15 PA30	1146	1081	924	1042	1150	1082	
8	120	15 TSP	1170	1115	929	1077	1162	1115	
9	0	30 PA30	1050	995	792	1021	1119	1061	
10	0	30 TSP	1149	1104	914	1088	1188	1202	
			Stover Yield Production (kg/ha)						
1	0	0 Abs.	717	594	338	402	455	428	
2	0	0 Pcont	1139	806	419	470	623	556	
3	60	0 TPR	1416	1192	713	926	1114	968	
4	120	0 TPR	1708	1601	1026	1411	1634	1404	
5	60	15 PA30	1815	1686	1373	1636	1811	1706	
6	60	15 TSP	1904	1791	1461	1712	1869	1836	
7	120	15 PA30	1948	1837	1570	1771	1955	1839	
8	120	15 TSP	1989	1896	1578	1830	1975	1896	
9	0	30 PA30	1784	1691	1347	1735	1903	1803	
10	0	30 TSP	1954	1876	1554	1850	2019	2044	
			P_2O_5 Removed From Soil Due to Grain and Stover Harvesting (kg/ha)*						
1	0	0 Abs.	2.9	2.4	1.4	1.6	1.8	1.7	11.9
2	0	0 Pcont	4.5	3.2	1.7	1.9	2.5	2.2	16.0
3	60	0 TPR	9.9	9.2	6.0	8.5	10.9	10.2	54.7
4	120	0 TPR	11.8	12.1	8.5	12.6	15.8	14.5	75.3
5	60	15 PA30	12.3	12.6	11.2	14.4	17.2	17.3	84.9
6	60	15 TSP	12.9	13.3	11.9	15.1	17.7	18.7	89.5
7	120	15 PA30	13.2	13.7	12.8	15.6	18.5	18.7	92.4
8	120	15 TSP	13.5	14.1	12.8	16.1	18.7	19.3	94.5
9	0	30 PA30	12.1	12.6	10.9	15.3	18.0	18.3	87.2
10	0	30 TSP	13.2	14.0	12.6	16.3	19.1	20.8	96.0

* Assumed 70% of stover harvested and 30% left as crop residue.

Table B11. Response of Continuous Rice to Fertilizer Strategies — Region, Mopti

Strat.	Basal PR Rate P_2O_5/ha	Annual App. Rate Source P_2O_5/ha	Production by Year						Total P_2O_5 Removed
			Rice						
			1982	1983	1984	1985	1986	1987	
			Grain Yield Production (kg/ha)						
1	0	0 Abs.	1375	1152	920	815	789	620	
2	0	0 TCont	1900	1750	1670	1687	1550	1400	
3	60	0 TPR	2112	1967	1793	1861	1967	1836	
4	120	0 TPR	2146	2027	1814	1890	2060	1911	
5	0	30 TPR	2067	2065	1776	1895	2096	2054	
6	0	15 PA30	2174	2082	1755	1890	2021	1956	
7	0	30 PA30	2240	2161	1776	1938	2133	2089	
8	0	15 TSP	2247	2145	1735	1909	2043	1978	
9	0	30 TSP	2330	2239	1751	1962	2161	2116	
			Stover Yield Production (kg/ha)						
1	0	0 Abs.	1925	1613	1288	1141	1105	868	
2	0	0 Pcont	2660	2450	2338	2362	2170	1960	
3	60	0 TPR	3169	2981	2690	2792	2981	2757	
4	120	0 TPR	3222	3040	2721	2835	3090	2866	
5	0	30 TPR	3307	3336	2841	3032	3354	3286	
6	0	15 PA30	3479	3330	2809	3024	3233	3130	
7	0	30 PA30	3584	3457	2841	3102	3413	3343	
8	0	15 TSP	3596	3432	2777	3055	3269	3165	
9	0	30 TSP	3729	3582	2802	3140	3458	3386	
			P_2O_5 Removed From Soil Due to Grain and Stover Harvesting (kg/ha)*						
1	0	0 Abs.	3.8	3.2	2.5	2.2	2.2	1.7	15.5
2	0	0 Pcont	5.7	5.2	5.0	5.0	4.6	4.2	29.7
3	60	0 TPR	11.8	12.2	12.1	13.6	15.6	15.4	80.7
4	120	0 TPR	12.0	12.5	12.2	13.8	16.2	16.1	82.7
5	0	30 TPR	11.9	13.2	12.2	14.1	16.8	17.7	85.9
6	0	15 PA30	12.5	13.1	12.1	14.1	16.2	16.8	84.9
7	0	30 PA30	12.9	13.6	12.2	14.5	17.1	18.0	88.3
8	0	15 TSP	12.9	13.5	12.0	14.2	16.4	17.0	86.1
9	0	30 TSP	13.4	14.1	12.1	14.6	17.4	18.2	89.8

* Assumed 70% of stover harvested and 30% left as crop residue.

Table B12. Model Estimates for Crop Response to P Rates and Rainfall Variations

Model Estimates		Regions: Sikasso		Segou	Kayes	Koulikoro
		Cotton	Maize	Millet	Groundnut	Sorghum
1. Response to Basal TPR Supplemented With Annual PAPR Applications						
Intercept		-152.60	-510.64*	-401.68**	-146.08	-458.28
		-208	-244.12	-128.14	-114.09	-328.84
Rain	R	0.97**	1.45**	1.38**	1.10**	1.59**
		-0.21	-0.25	-0.19	-0.14	-0.49
Basal P	Bp	3.46*	2.62	5.57**	3.39**	7.23*
		-2.23	-2.62	-1.38	-1.22	-3.51
R*Bp		-0.0008	0.0021	-0.0023	-0.0008	-0.0035
		-0.0023	-0.0026	-0.0021	-0.0015	-0.0052
Annual P	Ln(Ap)	160.25**	203.08*	236.43**	274.29**	176.04
		-72.34	-84.81	-44.69	-39.59	-113.86
R*Ln(Ap)		-0.02	0.007	-0.091	-0.21**	0.06
		-0.07	-0.086	-0.067	-0.05	-0.17
Bp*Ln(Ap)		-0.64**	-0.99**	-1.06**	-0.54**	-1.29**
		-0.23	-0.27	-0.17	-0.11	-0.29
	n	36	36	36	36	36
	Sy	104.64	122.67	77.84	53.37	130.90
	R2	0.83	0.91	0.92	0.92	0.85
2. Response to Basal TPR Supplemented With Annual TSP Applications						
Intercept		-75.23	-424.70**	-383.47**	-77.26	-440.72
		-211.67	-246.26	-115.61	-96.25	-350.18
Rain	R	0.89**	1.36**	1.35**	1.01**	1.56**
		-0.22	-0.25	-17	-0.12	-0.52
Basal P	BR	2.06	1.07	5.24**	2.14*	6.86*
		-2.26	-2.54	-1.24	-1.03	-3.74
R*BR		0.0007	0.0037	-0.0017	0.0008	-0.0029
		-0.0023	-0.0027	-0.0019	-0.0013	-0.0055
Annual P	Ln(AR)	194.30*	175.05*	230.79**	299.76**	201.77
		-73.53	-85.55	-40.33	-33.39	-121.24
R*Ln(AR)		-0.023	0.081	-0.052	-0.198**	0.060
		-0.074	-0.086	-0.061	-0.042	-0.178
BR*Ln(AR)		-0.66**	-1.01**	-1.01**	-0.745**	-1.33**
		-0.23	-0.27	-0.16	-0.1	-0.31
	n	36	36	36	36	36
	Sy	106.36	123.75	70.23	45.02	139.39
	R2	0.86	0.93	0.95	0.96	0.85

* and ** Significant at 0.05 and 0.01 probability levels, respectively.

Table B13. Estimates for Models used in Evaluation of Environmental Factors

Model Estimates		Region				
		Sikasso	Segou	Koulikoro	Mopti	Kayes
1. Estimates of P Losses in kg/ha Per Year						
Intercept		-1.65	-1.87	-2.056	-2.784	-1.942
		(-0.051)	(-0.052)	(-0.061)	(-0.37)	(-0.09)
Erosion	Ln (Er)	0.988	0.988	0.988	0.949	0.986
		(-0.016)	(-0.016)	(-0.017)	(-0.121)	(-0.03)
	n	24	24	24	14	22
	R2	0.97	0.93	0.95	0.85	0.92
2. Estimates for Organic C Losses in kg/ha Per Year						
Intercept		5.14	4.59	4.93	3.52	4.31
		(-0.079)	(-0.311)	(-0.204)	(-0.393)	(-0.26)
Erosion	Ln (Er)	0.526	0.679	0.558	0.916	0.724
		(-0.03)	(-0.118)	(-0.077)	(-1.32)	(-0.098)
	n	24	24	24	14	22
	R2	0.94	0.85	0.91	0.82	0.89

* Numbers in parentheses are standard errors of estimates.

Table C1. Benefits and Sensitivity Analysis of Fertilizer Strategies — Region, Sikasso

Years	TPR 60B	TPR 120B	60TPR 15PAPR	60TPR 15TSP	120TPR 15PAPR	120TPR 15TSP	30PAPR	30TSP
Crop Rotation: Maize-Cotton Net Returns (1995 US $/ha)								
1	-16.2	-19.3	7.2	28.0	-16.6	12.2	32.2	49.6
2	54.6	120.1	100.1	131.4	111.2	149.4	103.8	135.8
3	10.6	34.3	48.0	56.3	57.4	63.5	42.2	56.9
4	77.0	165.7	159.9	177.6	190.8	200.0	154.0	188.0
5	26.0	65.0	76.1	106.8	88.5	121.5	72.9	109.9
6	67.6	147.1	214.9	239.7	245.9	262.3	221.9	264.7
7	-16.2	-19.3	7.2	28.0	-16.6	12.2	32.2	49.6
8	54.6	120.1	100.1	131.4	111.2	149.4	103.8	135.8
9	10.6	34.3	48.0	56.3	57.4	63.5	42.2	56.9
10	77.0	165.7	159.8	177.6	190.8	200.0	154.0	188.0
11	26.0	65.0	76.1	106.8	88.5	121.5	72.9	109.9
12	67.6	147.1	214.9	239.7	245.9	262.3	221.9	264.7
13	-16.2	-19.3	7.2	28.0	-16.6	12.2	32.2	49.6
14	54.6	120.1	100.1	131.4	111.2	149.4	103.8	135.8
15	10.6	34.3	48.0	56.3	57.4	63.5	42.2	56.9
16	77.0	165.7	159.9	177.6	190.8	200.0	154.0	188.0
17	26.0	65.0	76.1	106.8	88.5	121.5	72.9	109.9
18	67.6	147.1	214.9	239.7	245.9	262.3	221.9	264.7
Private Benefits Net Present Values (1995 US $/ha)								
Annual Rate r1								
0.05	408.6	960.8	1130.2	1389.2	1253.9	1514.1	1176.0	1515.2
0.10	273.5	647.8	759.2	940.3	836.1	1021.3	795.5	1028.5
0.15	194.9	465.0	543.6	676.5	593.9	734.3	573.0	744.5
0.20	145.8	350.8	409.5	515.2	443.6	555.3	435.8	567.3
Total Benefits. Sensitivity Analysis Net Present Values (1995 US $/ha)								
Annual Rate r1 r2								
0.05 0.03	812.1	1364.3	1523.8	1782.8	1647.5	1907.7	1569.6	1906.8
0.10 0.03	677.0	1051.3	1152.9	1333.9	1229.6	1414.9	1189.1	1422.1
0.15 0.03	598.4	868.6	937.3	1072.2	987.6	1127.9	987.5	1138.2
0.20 0.03	549.3	754.3	803.2	908.9	837.2	949.0	829.5	961.0

Environmental Benefits
Net Present Values (1995 US $/ha)

Land Degradation		231.1
Carbon Sequestration		162.6
Prevention of Pollution		9.9
	Total	403.5

r1 and r2: Annual discount rates for private and environmental benefits.

Table C2. Benefits and Sensitivity Analysis of Fertilizer Strategies — Region, Sikasso

Years	TPR 60B	TPR 120B	60TPR 15PAPR	60TPR 15TSP	120TPR 15PAPR	120TPR 15TSP	30PAPR	30TSP
Crop Sequence: Maize-Maize Net Returns (1995 US $/ha)								
1	-14.3	-15.6	6.2	39.4	-15.7	22.0	29.1	66.1
2	19.1	51.2	48.0	57.7	63.8	72.5	34.1	49.1
3	11.5	35.9	52.3	68.6	64.3	74.0	44.5	74.5
4	18.0	49.0	56.0	61.9	70.5	74.5	45.9	57.1
5	29.7	72.5	87.4	108.7	102.5	128.2	83.7	78.9
6	28.3	69.5	97.9	112.5	112.6	124.9	97.4	120.0
7	-14.3	-15.6	6.2	39.4	-15.7	22.0	29.1	66.1
8	19.1	51.2	48.0	57.7	63.8	72.5	34.1	49.1
9	11.5	35.9	52.3	68.6	64.3	74.0	44.5	74.5
10	18.0	49.0	56.0	61.9	70.5	74.5	45.9	57.1
11	29.7	72.5	87.4	108.7	102.5	128.2	83.7	78.9
12	28.3	69.5	97.9	112.5	112.6	124.9	97.4	120.0
13	-14.3	-15.6	6.2	39.4	-15.7	22.0	29.1	66.1
14	19.1	51.2	48.0	57.7	63.8	72.5	34.1	49.1
15	11.5	35.9	52.3	68.6	64.3	74.0	44.5	74.5
16	18.0	49.0	56.0	61.9	70.5	74.5	45.9	57.1
17	29.7	72.5	87.4	108.7	102.5	128.2	83.7	78.9
18	28.3	69.5	97.9	112.5	112.6	124.9	97.4	120.0
Private Benefits Net Present Value (1995 US $/ha)								
Annual Rate r1								
0.05	167.8	487.5	650.1	850.3	738.6	933.8	628.8	852.7
0.10	109.5	325.6	437.7	580.6	493.4	633.5	426.1	588.4
0.15	75.9	231.5	314.0	422.8	351.0	456.0	308.0	433.0
0.20	55.1	172.9	236.9	323.9	262.3	348.3	234.4	335.4
Total Benefits. Sensitivity Analysis Net Present Values (1995 US $/ha)								
Annual Rate r1 r2								
0.05 0.03	512.0	831.7	984.4	1184.6	1072.9	1268.2	963.1	1187.0
0.10 0	453.7	669.8	772.0	915.0	827.8	967.8	760.4	922.7
0.15 0	420.1	575.6	648.3	757.1	685.3	792.3	642.4	767.3
0.20 0	399.3	517.0	571.2	658.2	596.6	682.5	568.7	669.7

Environmental Benefits
Net Present Values (1995 US $/ha)

Land Degradation		165.0
Carbon Sequestration		169.3
Prevention of Pollution		9.9
	Total	344.2

r1 and r2: Annual discount rates for private and environmental benefits.

Table C3. Benefits and Sensitivity Analysis of Fertilizer Strategies — Region, Sikasso

Years	TPR 60B	TPR 120B	60TPR 15PAPR	60TPR 15TSP	120TPR 15PAPR	120TPR 15TSP	30PAPR	30TSP
			Crop Sequence: Cotton-Cotton Net Returns (1995 US $/ha)					
1	-9.3	-8.0	15.3	51.3	-11.0	39.6	45.2	79.8
2	30.8	72.5	89.9	120.3	105.0	132.8	86.3	124.5
3	31.6	75.0	117.0	150.0	148.0	162.6	100.5	161.5
4	41.3	94.2	107.9	125.9	123.7	141.2	108.1	128.2
5	47.9	114.3	163.7	186.2	181.2	208.4	175.1	194.3
6	60.0	131.8	195.5	229.1	215.0	254.4	212.0	243.7
7	-9.3	-8.0	15.3	51.3	-11.0	39.6	45.2	79.8
8	30.8	72.5	89.9	120.3	105.0	132.8	86.3	124.5
9	31.6	75.0	117.0	150.0	148.0	162.6	100.5	161.5
10	41.3	94.2	107.9	125.9	123.7	141.2	108.1	128.2
11	47.9	114.3	163.7	186.2	181.2	208.4	175.1	194.3
12	60.0	131.8	195.5	229.1	215.0	254.4	212.0	243.7
13	-9.3	-8.0	15.3	51.3	-11.0	39.6	45.2	79.8
14	30.8	72.5	89.9	120.3	105.0	132.8	86.3	124.5
15	31.6	75.0	117.0	150.0	148.0	162.6	100.5	161.5
16	41.3	94.2	107.9	125.9	123.7	141.2	108.1	128.2
17	47.9	114.3	163.7	186.2	181.2	208.4	175.1	194.3
18	60.0	131.8	195.5	229.1	215.0	254.4	212.0	243.7
			Private Benefits Net Present Values (1995 US $/ha)					
Annual Rate r1								
0.05	374.5	894.3	1290.1	1630.6	1420.7	1768.6	1364.3	1768.8
0.10	249.5	600.1	869.8	1110.5	953.6	1200.3	922.9	1210.0
0.15	177.0	428.8	624.8	806.1	681.7	868.1	665.7	882.5
0.20	131.9	322.1	472.1	615.6	512.2	660.4	505.3	677.2
			Total Benefits . Sensitivity Analysis Net Present Values (1995 US $/ha)					
Annual Rate r1 r2								
0.05 0.03	787.2	1307.0	1693.0	2033.5	1823.6	2171.5	1767.2	2171.7
0.10 0.03	662.3	1012.9	1272.7	1513.4	1356.5	1603.2	1325.8	1612.9
0.15 0.03	589.7	841.6	1027.7	1209.0	1084.6	1271.0	1068.6	1285.4
0.20 0.03	544.6	734.8	875.0	1018.5	915.1	1063.3	908.2	1080.1

Environmental Benefits
Net Present Values (1995 US $/ha)

Land Degradation		247.6
Carbon Sequestration		155.3
Prevention of Pollution		9.9
	Total	412.8

r1 and r2: Annual discount rates for private and environmental benefits.

Table C4. Benefits and Sensitivity Analysis of Fertilizer Strategies — Region, Segou

Years	TPR 60B	TPR 120B	60TPR 15PAPR	60TPR 15TSP	120TPR 15PAPR	120TPR 15TSP	30PAPR	30TSP
				Crop Rotation: Millet-Groundnut Net Returns (1995 US $/ha)				
1	-14.3	-12.7	14.7	25.6	-12.8	-0.6	46.2	59.7
2	42.4	94.8	89.3	100.2	103.1	113.7	87.0	102.6
3	26.2	66.9	74.3	80.6	91.2	97.2	65.5	75.8
4	53.0	116.8	114.7	124.0	132.7	138.1	113.7	131.6
5	28.5	72.4	82.1	88.9	98.5	101.9	75.6	89.9
6	65.1	141.5	146.1	153.8	163.9	172.7	153.1	162.6
7	-14.3	-12.7	14.7	25.6	-12.8	-0.6	46.2	59.7
8	42.4	94.8	89.3	100.2	103.1	113.7	87.0	102.6
9	26.2	66.9	74.3	80.6	91.2	97.2	65.5	75.8
10	53.0	116.8	114.7	124.0	132.7	138.1	113.7	131.6
11	28.5	72.4	82.1	88.9	98.5	101.9	75.6	89.9
12	65.1	141.5	146.1	153.8	163.9	172.7	153.1	162.6
13	-14.3	-12.7	14.7	25.6	-12.8	-0.6	46.2	59.7
14	42.4	94.8	89.3	100.2	103.1	113.7	87.0	102.6
15	26.2	66.9	74.3	80.6	91.2	97.2	65.5	75.8
16	53.0	116.8	114.7	124.0	132.7	138.1	113.7	131.6
17	28.5	72.4	82.1	88.9	98.5	101.9	75.6	89.9
18	65.1	141.5	146.1	153.8	163.9	172.7	153.1	162.6
				Private Benefits Net Present Values (1995 US $/ha)				
Annual Rate r1								
0.05	372.8	898.4	983.4	1066.1	1079.7	1171.8	1028.4	1186.8
0.10	249.1	605.7	668.2	741.1	727.8	793.7	704.6	816.2
0.15	177.1	434.9	483.8	538.9	522.3	572.5	514.7	598.3
0.20	132.3	328.1	368.3	412.0	393.9	434.2	395.5	461.4
				Total Benefits . Sensitivity Analysis Net Present Values (1995 US $/ha)				
Annual Rate r1 r2								
0.05 0.03	723.7	1249.3	1324.5	1427.2	1420.8	1512.9	1369.5	1527.9
0.10 0.03	600.0	956.7	1009.3	1082.2	1068.9	1134.8	1045.7	1157.2
0.15 0.03	528.1	785.8	824.9	880.0	863.4	913.6	855.8	939.4
0.20 0.03	483.2	679.1	709.4	753.1	735.0	775.3	736.6	802.5

Environmental Benefits
Net Present Values (1995 US $/ha)

Land Degradation		192.5
Carbon Sequestration		148.5
Prevention of Pollution		9.9
	Total	351.0

r1 and r2: Annual discount rates for private and environmental benefits.

Table C5. Benefits and Sensitivity Analysis of Fertilizer Strategies — Region, Segou

Years	TPR 60B	TPR 120B	60TPR 15PAPR	60TPR 15TSP	120TPR 15PAPR	120TPR 15TSP	30PAPR	30TSP
Crop Sequence: Millet-Millet Net Returns (1995 US $/ha)								
1	-16.2	-20.7	2.7	19.6	-26.5	-4.0	33.2	48.6
2	41.7	56.9	57.4	62.4	70.0	72.9	49.4	59.7
3	25.5	63.6	66.0	74.1	84.2	91.5	53.8	66.3
4	53.1	71.9	72.6	81.3	87.4	94.9	65.7	79.7
5	25.8	63.8	80.4	92.1	95.9	103.5	74.6	95.6
6	48.6	66.2	75.7	94.4	74.0	104.0	90.3	100.7
7	-16.2	-20.7	15.7	19.6	-26.5	-4.0	33.2	48.6
8	41.7	56.9	57.4	62.4	70.0	72.9	49.4	59.7
9	25.5	63.6	66.0	74.1	84.2	91.5	53.8	66.3
10	53.1	71.9	72.6	81.3	87.4	94.9	65.7	79.7
11	25.8	63.8	80.4	92.1	95.9	103.5	74.6	95.6
12	48.6	66.2	75.7	94.4	74.0	104.0	90.3	100.7
13	-16.2	-20.7	15.7	19.6	-26.5	-4.0	33.2	48.6
14	41.7	56.9	57.4	62.4	70.0	72.9	49.4	59.7
15	25.5	63.6	66.0	74.1	84.2	91.5	53.8	66.3
16	53.1	71.9	72.6	81.3	87.4	94.9	65.7	79.7
17	25.8	63.8	80.4	92.1	95.9	103.5	74.6	95.6
18	48.6	66.2	75.7	94.4	74.0	104.0	90.3	100.7
Private Benefits Net Present Values (1995 US $/ha)								
Annual Rate r1								
0.05	332.8	564.9	686.1	803.1	721.4	870.9	697.5	860.0
0.10	223.2	380.4	465.7	548.0	485.9	589.8	477.7	591.4
0.15	159.3	272.4	338.3	398.3	347.9	425.1	348.7	433.5
0.20	119.3	204.7	255.2	304.4	261.5	321.9	267.8	334.2
Total Benefits . Sensitivity Analysis Net Present Values (1995 US $/ha)								
Annual Rate r1 / r2								
0.05 / 0.03	678.0	910.1	1021.5	1138.4	1056.7	1206.3	1032.9	1195.3
0.10 / 0.03	568.4	725.6	801.0	883.3	821.2	925.1	813.0	926.7
0.15 / 0.03	504.5	617.6	671.7	733.6	683.3	760.4	684.0	768.8
0.20 / 0.03	464.5	549.9	590.5	639.7	596.8	657.3	603.1	669.5

Environmental Benefits
Net Present Values (1995 US $/ha)

Land Degradation	165.0
Carbon Sequestration	170.3
Prevention of Pollution	9.9
Total	345.2

r1and r2: Annual discount rates for private and environmental benefits.

Table C6. Benefits and Sensitivity Analysis of Fertilizer Strategies — Region, Koulikoro

Years	TPR 60B	TPR 120B	60TPR 15PAPR	60TPR 15TSP	120TPR 15PAPR	120TPR 15TSP	30PAPR	30TSP
Crop Rotation: Sorghum-Groundnut Net Returns (1995 US $/ha)								
1	-12.5	6.2	37.8	51.8	14.1	25.7	67.9	89.9
2	62.2	137.5	113.8	131.6	129.7	158.7	115.4	125.1
3	30.4	87.2	81.9	92.2	95.0	103.5	78.4	95.1
4	49.1	111.3	120.1	143.6	131.0	168.2	129.4	143.3
5	43.2	114.7	118.4	133.9	131.2	148.1	123.9	143.3
6	70.4	153.7	161.7	174.9	177.0	193.4	175.7	189.7
7	-12.5	6.2	37.8	51.8	14.1	25.7	67.9	89.9
8	62.2	137.5	113.8	131.6	129.7	158.7	115.4	125.1
9	30.4	87.2	81.9	92.2	95.0	103.5	78.4	95.1
10	49.1	111.3	120.1	143.6	131.0	168.2	129.4	143.3
11	43.2	114.7	118.4	133.9	131.2	148.1	123.9	143.3
12	70.4	153.7	161.7	174.9	177.0	193.4	175.7	189.7
13	-12.5	6.2	37.8	51.8	14.1	25.7	67.9	89.9
14	62.2	137.5	113.8	131.6	129.7	158.7	115.4	125.1
15	30.4	87.2	81.9	92.2	95.0	103.5	78.4	95.1
16	49.1	111.3	120.1	143.6	131.0	168.2	129.4	143.3
17	43.2	114.7	118.4	133.9	131.2	148.1	123.9	143.3
18	70.4	153.7	161.7	174.9	177.0	193.4	175.7	189.7
Private Benefits Net Present Values (1995 US $/ha)								
Annual Rate r1								
0.05	455.0	1156.2	1202.6	1386.2	1279.8	1511.9	1316.6	1503.8
0.10	306.9	788.6	822.4	951.1	870.3	1032.3	904.7	1036.6
0.15	220.4	572.9	599.4	695.4	630.5	750.9	662.9	761.8
0.20	166.4	437.5	459.5	534.6	480.3	574.3	511.0	589.0
Total Benefits . Sensitivity Analysis Net Present Values (1995 US $/ha)								
Annual Rate r1 r2								
0.05 0.03	825.9	1527.2	1563.7	1747.3	1640.9	1873.0	1677.7	1864.9
0.10 0.03	677.8	1159.5	1183.5	1312.2	1231.4	1393.4	1265.8	1397.7
0.15 0.03	591.4	943.8	960.5	1056.5	991.6	1112.0	1023.9	1122.9
0.20 0.03	537.3	808.4	820.6	895.8	841.4	935.4	872.1	950.1

Environmental Benefits
Net Present Values (1995)

Land Degradation		206.3
Carbon Sequestration		154.8
Prevention of Pollution		9.9
	Total	370.9

r1 and r2: Annual discount rates for private and environmental benefits.

Table C7. Benefits and Sensitivity Analysis of Fertilizer Strategies — Region, Koulikoro

Years	TPR 60B	TPR 120B	60TPR 15PAPR	60TPR 15TSP	120TPR 15PAPR	120TPR 15TSP	30PAPR	30TSP
Crop Sequence: Sorghum-Sorghum Net Returns (1995 US $/ha)								
1	-9.0	35.0	36.2	49.9	11.8	26.6	68.8	86.3
2	33.8	85.0	75.1	94.1	68.7	107.1	70.4	96.2
3	31.9	78.9	83.1	87.8	97.8	106.0	70.1	87.1
4	37.6	90.6	74.3	83.7	84.1	93.5	73.8	87.1
5	32.4	81.8	100.3	108.0	110.6	121.1	105.6	113.4
6	23.1	62.6	87.9	96.4	96.7	98.8	92.3	112.3
7	-9.0	35.0	49.2	49.9	11.8	26.6	68.8	86.3
8	33.8	85.0	75.1	94.1	88.7	107.1	70.4	96.2
9	31.9	78.9	83.1	87.8	97.8	106.0	70.1	87.1
10	37.6	90.6	74.3	83.7	84.1	93.5	73.8	87.1
11	32.4	81.8	100.3	108.0	110.6	121.1	105.6	113.4
12	23.1	62.6	87.9	96.4	96.7	98.8	92.3	112.3
13	-9.0	35.0	49.2	49.9	11.8	26.6	68.8	86.3
14	33.8	85.0	75.1	94.1	68.7	107.1	70.4	96.2
15	31.9	78.9	83.1	87.8	97.8	106.0	70.1	87.1
16	37.6	90.6	74.3	83.7	84.1	93.5	73.8	87.1
17	32.4	81.8	100.3	108.0	110.6	121.1	105.6	113.4
18	23.1	62.6	87.9	96.4	96.7	98.8	92.3	112.3

Private Benefits
Net Present Values (1995 US $/ha)

Annual Rate r1	TPR 60B	TPR 120B	60TPR 15PAPR	60TPR 15TSP	120TPR 15PAPR	120TPR 15TSP	30PAPR	30TSP
0.05	283.7	838.4	890.5	999.8	930.6	1056.2	926.5	1126.2
0.10	193.1	582.7	613.1	692.5	636.7	728.9	643.0	784.7
0.15	139.7	431.0	449.4	510.9	463.8	534.5	475.7	582.6
0.20	106.1	334.9	346.3	396.2	355.0	411.9	370.1	454.8

Total Benefits . Sensitivity Analysis
Net Present Values (1995 US $/ha)

Annual Rate r1	r2	TPR 60B	TPR 120B	60TPR 15PAPR	60TPR 15TSP	120TPR 15PAPR	120TPR 15TSP	30PAPR	30TSP
0.05	0.03	649.2	1203.9	1246.2	1355.5	1286.3	1413.9	1282.2	1481.9
0.10	0.03	558.6	948.3	968.8	1048.2	992.4	1084.6	998.7	1140.4
0.15	0.03	505.3	796.6	805.1	866.6	819.5	890.2	831.4	938.3
0.20	0.03	471.6	700.5	702.0	751.9	710.7	767.6	725.8	810.5

Environmental Benefits
Net Present Values (1995 US $/ha)

Land Degradation		192.5
Carbon Sequestration		163.2
Prevention of Pollution		9.9
	Total	365.6

r1 and r2: Annual discount rates for private and environmental benefits.

Table C8. Benefits and Sensitivity Analysis of Fertilizer Strategies — Region, Kayes

Years	TPR 60B	TPR 120B	60TPR 15PAPR	60TPR 15TSP	120TPR 15PAPR	120TPR 15TSP	30PAPR	30TSP
Crop Rotation: Groundnut-Maize Net Returns (1995 US $/ha)								
1	-18.3	-23.6	5.6	22.0	-27.2	-11.5	39.8	64.3
2	16.5	57.0	34.4	56.2	38.8	59.4	28.4	60.2
3	10.2	33.4	70.2	107.8	78.0	118.4	69.9	116.4
4	13.8	72.1	63.2	80.0	75.4	93.5	55.0	77.5
5	19.4	51.7	88.0	116.3	95.2	126.1	92.7	127.6
6	44.8	133.2	123.8	137.5	137.8	155.3	128.3	144.0
7	-18.3	-23.6	5.6	22.0	-27.2	-11.5	39.8	64.3
8	16.5	57.0	34.4	56.2	38.8	59.4	28.4	60.2
9	10.2	33.4	70.2	107.8	78.0	118.4	69.9	116.4
10	13.8	72.1	63.2	80.0	75.4	93.5	55.0	77.5
11	19.4	51.7	88.0	116.3	95.2	126.1	92.7	127.6
12	44.8	133.2	123.8	137.5	137.8	155.3	128.3	144.0
13	-18.3	-23.6	5.6	22.0	-27.2	-11.5	39.8	64.3
14	16.5	57.0	34.4	56.2	38.8	59.4	28.4	60.2
15	10.2	33.4	70.2	107.8	78.0	118.4	69.9	116.4
16	13.8	72.1	63.2	80.0	75.4	93.5	55.0	77.5
17	19.4	51.7	88.0	116.3	95.2	126.1	92.7	127.6
18	44.8	133.2	123.8	137.5	137.8	155.3	128.3	144.0
Private Benefits Net Present Value (1995 US $/ha)								
Annual Rate r1								
0.05	152.5	592.5	715.0	978.0	728.1	1005.8	777.8	1122.7
0.10	96.7	390.3	478.1	662.8	479.0	672.9	526.8	770.2
0.15	64.9	273.7	340.7	478.6	335.2	479.2	380.7	563.3
0.20	45.6	201.7	255.3	363.4	246.3	358.7	289.6	433.5
Total Benefits . Sensitivity Analysis Net Present Values (1995 US $/ha)								
Annual Rate r1 / r2								
0.05 / 0.03	530.4	970.3	1083.0	1346.0	1096.0	1373.7	1145.6	1490.7
0.10 / 0.03	474.5	768.1	846.1	1030.7	846.9	1040.8	894.8	1138.2
0.15 / 0.03	442.8	651.5	708.7	846.6	703.2	847.2	748.6	931.3
0.20 / 0.03	423.4	579.5	623.3	731.4	614.3	726.7	657.6	801.5

Environmental Benefits
Net Present Values (1995 US $/ha)

Land Degradation	213.9
Carbon Sequestration	154.0
Prevention of Pollution	9.9
Total	377.8

r1 and r2: Annual discount rates for private and environmental benefits.

Table C9. Benefits and Sensitivity Analysis of Fertilizer Strategies — Region, Kayes

Years	TPR 60B	TPR 120B	60TPR 15PAPR	60TPR 15TSP	120TPR 15PAPR	120TPR 15TSP	30PAPR	30TSP
				Crop Sequence: Groundnut-Groundnut				
				Net Returns (1995 US $/ha)				
1	-11.1	-9.2	-7.5	23.2	-21.0	-4.5	-0.2	58.7
2	29.3	71.6	56.4	74.8	71.4	83.9	43.8	76.9
3	22.6	58.3	91.1	110.1	120.0	115.6	69.7	125.6
4	30.7	74.4	76.3	93.2	92.6	103.0	66.8	99.1
5	19.5	52.0	63.8	78.7	77.2	91.3	54.8	77.4
6	17.7	48.4	75.9	85.5	82.1	94.8	78.8	90.1
7	-11.1	-9.2	5.5	23.2	-21.0	-4.5	-0.2	58.7
8	29.3	71.6	56.4	74.8	71.4	83.9	43.8	76.9
9	22.6	58.3	91.1	110.1	120.0	115.6	69.7	125.6
10	30.7	74.4	76.3	93.2	92.6	103.0	66.8	99.1
11	19.5	52.0	63.8	78.7	77.2	91.3	54.8	77.4
12	17.7	48.4	75.9	85.5	82.1	94.8	78.8	90.1
13	-11.1	-9.2	5.5	23.2	-21.0	-4.5	-0.2	58.7
14	29.3	71.6	56.4	74.8	71.4	83.9	43.8	76.9
15	22.6	58.3	91.1	110.1	120.0	115.6	69.7	125.6
16	30.7	74.4	76.3	93.2	92.6	103.0	66.8	99.1
17	19.5	52.0	63.8	78.7	77.2	91.3	54.8	77.4
18	17.7	48.4	75.9	85.5	82.1	94.8	78.8	90.1
				Private Benefits				
				Net Present Values (1995 US $/ha)				
Annual Rate r1								
0.05	205.7	563.4	688.8	891.8	797.8	918.3	590.5	1021.4
0.10	139.7	386.1	467.6	614.7	541.7	626.5	400.1	711.5
0.15	100.9	281.4	337.6	451.0	391.0	454.7	288.6	527.6
0.20	76.4	215.3	255.9	347.6	296.3	346.6	218.8	411.0
				Total Benefits . Sensitivity Analysis				
				Net Present Values (1995 US $/ha)				
Annual Rate r1 r2								
0.05 0.03	604.7	962.4	1078.0	1281.0	1187.0	1307.5	979.7	1410.6
0.10 0	538.8	785.1	856.8	1003.9	930.8	1015.7	789.3	1100.7
0.15 0	499.9	680.5	726.8	840.2	780.2	843.9	677.8	916.8
0.20 0	475.4	614.3	645.1	736.8	685.4	735.8	607.9	800.2

Environmental Benefits

Net Present Values (1995 US $/ha)

Land Degradation		244.5
Carbon Sequestration		144.7
Prevention of Pollution		9.9
	Total	399.0

r1 and r2: Annual discount rates for private and environmental benefits.

Table C10. Benefits and Sensitivity Analysis of Fertilizer Strategies — Region, Mopti

Years	TPR 60B	TPR 120B	60TPR 15PAPR	60TPR 15TSP	120TPR 15PAPR	120TPR 15TSP	30PAPR	30TSP
Crop Sequence: Millet-Millet Net Returns (1995 US $/ha)								
1	-29.5	-45.4	-11.5	0.0	-39.5	-32.3	12.9	35.2
2	21.1	56.0	48.3	61.1	61.7	70.5	35.9	59.5
3	13.4	40.4	56.8	68.2	74.3	78.6	41.7	67.2
4	28.2	70.4	75.3	85.7	87.4	96.2	71.3	88.7
5	31.0	76.1	76.5	85.2	89.3	94.7	71.8	92.7
6	23.9	61.7	73.4	88.6	85.2	93.8	69.2	97.8
7	-29.5	-45.4	-11.5	0.0	-39.5	-32.3	12.9	35.2
8	21.1	56.0	48.3	61.1	61.7	70.5	35.9	59.5
9	13.4	40.4	56.8	68.2	74.3	78.6	41.7	67.2
10	28.2	70.4	75.3	85.7	87.4	96.2	71.3	88.7
11	31.0	76.1	76.5	85.2	89.3	94.7	71.8	92.7
12	23.9	61.7	73.4	88.6	85.2	93.8	69.2	97.8
13	-29.5	-45.4	-11.5	0.0	-39.5	-32.3	12.9	35.2
14	21.1	56.0	48.3	61.1	61.7	70.5	35.9	59.5
15	13.4	40.4	56.8	68.2	74.3	78.6	41.7	67.2
16	28.2	70.4	75.3	85.7	87.4	96.2	71.3	88.7
17	31.0	76.1	76.5	85.2	89.3	94.7	71.8	92.7
18	23.9	61.7	73.4	88.6	85.2	93.8	69.2	97.8
Private Benefits Net Present Values (1995 US $/ha)								
Annual Rate r1								
0.05	156.5	474.6	595.7	731.8	662.9	747.2	569.9	838.7
0.10	99.2	311.8	400.3	495.7	440.7	499.8	386.2	574.4
0.15	66.4	217.3	286.2	357.4	311.3	355.5	278.8	419.2
0.20	46.1	158.7	214.9	270.8	230.7	265.4	211.6	321.8
Total Benefits, Sensitivity Analysis Net Present Values (1995 US $/ha)								
Annual Rate r1 / r2								
0.05 / 0.03	512.6	830.7	942.0	1078.1	1009.2	1093.5	916.2	1185.0
0.10 / 0.03	455.4	667.9	746.6	841.9	787.0	846.1	732.5	920.7
0.15 / 0.03	422.5	573.5	632.5	703.7	657.6	701.8	625.1	765.5
0.20 / 0.03	402.3	514.8	561.2	617.1	577.0	611.7	557.9	668.0

Environmental Benefits
Net Present Values (1995 US $/ha)

Land Degradation	185.7
Carbon Sequestration	160.6
Prevention of Pollution	9.9
Total	356.2

r1 and r2: Annual discount rate for private and environmental benefits.

Table C11. Benefits and Sensitivity Analysis of Fertilizer Strategies — Region, Mopti

Years	TPR 60B	TPR 120B	TPR 30A	PA30 15A	PA30 30A	TSP 15A	TSP 30A
			Crop Sequence: Rice-Rice Net Return (1995 US $/ha)				
1	43.9	18.6	55.4	107.3	121.7	141.3	159.4
2	93.3	109.6	123.8	129.6	149.7	159.5	182.3
3	46.1	54.5	27.8	26.4	22.0	21.7	11.7
4	67.1	79.0	70.4	75.5	82.8	87.1	92.7
5	164.0	204.5	209.7	185.6	219.5	198.5	231.0
6	173.9	203.9	253.1	219.7	262.1	232.4	273.3
7	43.9	18.6	55.4	107.3	121.7	141.3	159.4
8	93.3	109.6	123.8	129.6	149.7	159.5	182.3
9	46.1	54.5	27.8	26.4	22.0	21.7	11.7
10	67.1	79.0	70.4	75.5	82.8	87.1	92.7
11	164.0	204.5	209.7	185.6	219.5	198.5	231.0
12	173.9	203.9	253.1	219.7	262.1	232.4	273.3
13	43.9	18.6	55.4	107.3	121.7	141.3	159.4
14	93.3	109.6	123.8	129.6	149.7	159.5	182.3
15	46.1	54.5	27.8	26.4	22.0	21.7	11.7
16	67.1	79.0	70.4	75.5	82.8	87.1	92.7
17	164.0	204.5	209.7	185.6	219.5	198.5	231.0
18	173.9	203.9	253.1	219.7	262.1	232.4	273.3
			Private Benefits Net Present Values (1995 US $/ha)				
Annual Rate r1							
0.05	1104.8	1247.2	1382.4	1414.0	1626.8	1608.8	1816.0
0.10	748.5	838.9	931.7	970.3	1114.1	1111.9	1253.0
0.15	541.0	598.8	670.5	710.9	814.9	820.4	923.2
0.20	411.8	451.0	508.3	548.8	628.0	637.7	716.7
			Total Benefits Net Present Values (1995 US $/ha)				
Annual Rate r1 r2							
0.05 0.03	1537.8	1680.2	1815.4	1837.2	2059.8	2041.9	2249.0
0.10 0.03	1181.5	1269.9	1364.8	1393.5	1547.2	1545.0	1686.1
0.15 0.03	974.0	1031.9	1103.5	1134.1	1247.9	1253.5	1356.3
0.20 0.03	844.8	884.1	941.3	971.9	1061.1	1070.7	1149.7

Environmental Benefits. Sensitivity Analysis
Net Present Values (1995 US $/ha)

Land Degradation		247.6
Carbon Sequestration		175.6
Prevention of Pollution		9.9
	Total	433.0

r1 and r2: Annual discount rates for private and environmental benefits.

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