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Agricultural Production and Soil Nutrient Mining in Africa: Implications for Resource Conservation and Policy Development

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Agricultural Production and Soil Nutrient Mining in Africa: Implications for Resource Conservation and Policy Development

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by
Julio Henao
and
Carlos Baanante

IFDC—An International Center for Soil Fertility and Agricultural Development
P.O. Box 2040
Muscle Shoals, Alabama 35662, U.S.A.

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IFDC—An International Center for Soil Fertility and Agricultural Development
P.O. Box 2040
Muscle Shoals, AL 35662 (U.S.A.)

Telephone: +1 (256) 381-6600
Telefax: +1 (256) 381-7408
E-Mail: general@ifdc.org
Web Site: www.ifdc.org

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Foreword

The economic development of Africa depends on growth of the agricultural and agro-industry sectors, which are affected by productivity of the land. Food security in Africa has deteriorated significantly over the past two decades. With a 3% population growth, Africa is projected to import more than 60 million tons of cereals yearly by 2020. As food security worsens, population pressure on limited land forces farmers to use agricultural land more intensively, and to bring less fertile soils on marginal land into cultivation. Declining soil fertility, caused mainly by increasing soil nutrient mining, is a key source of decreasing crop yields and per capita food production in Africa and of land and environmental degradation.

This paper is a significantly enhanced update of a 1999 publication produced by IFDC, an International Center for Soil Fertility and Agricultural Development. The study is part of IFDC's efforts to help develop and implement policies and investment strategies for improved crop production and resource conservation in Africa. Information in this document is crucial for the design and implementation of policy interventions to slow or prevent the continuous mining of nutrients from African farm land. This is important for the establishment of development assistance programs for increased agricultural production, food security, economic development, land conservation, and environmental protection.

We hope that donors, international development agencies, policy makers, the private sector, and other stakeholders find this document useful for agricultural development programs that will eventually improve the lives of both rural and urban Africans who suffer from poverty and malnutrition.

Amit H. Roy
IFDC President and
Chief Executive Officer

Preface

Agriculture accounts for more than 25% of the gross domestic product (GDP) of most African countries, and is the main source of income and employment for at least 65% of sub-Saharan Africa's population of 750 million. Agricultural development is vital to Africa's economic growth, food security, and poverty alleviation. Agricultural production in much of Africa is, however, hampered by the predominance of fragile ecosystems, low inherited soil fertility, low use of modern inputs such as mineral fertilizers and improved crop varieties, and soil nutrient mining that affects more than 85% of agricultural lands. The declining fertility of African soils because of soil nutrient mining is a major cause of decreased crop yields and per capita food production and, in the mid to long term, a key source of land degradation and environmental damage.

African countries today face not only the challenge of increasing agricultural production with scarce overall resources, but must raise productivity in a way that conserves the natural resource base and prevents further degradation. Information about the extent and intensity of soil nutrient mining and a better understanding of its main causes are essential to the design and implementation of policy measures and investments to reverse the mining and subsequent decline in soil fertility. Restoration of soil fertility is necessary to increase crop yields and food production in order to combat the worsening food security situation in Africa. In this context, policy measures and investment strategies that must be implemented should be viewed as key contributors to the joint goals of increased agricultural production, food security, economic development, land conservation, and environmental protection.

In this publication we assess the status of food production associated with land degradation and estimate indicators of soil nutrient mining by country and region. We examine factors and circumstances that affect nutrient mining in predominant crop production systems of key agro-ecological zones and regions, and suggest policy measures and strategies that can reverse current trends in nutrient mining and increase land productivity in a sustainable way. We also evaluate evolving trends in crop productivity in different regions, and in land degradation caused by nutrient mining.

This publication results from years of IFDC experience in agricultural development in Africa. We acknowledge the cooperation of many national agricultural institutions and international centers. They provided useful information on crop production, crop areas, fertilizer consumption, soil fertility characteristics, rural and urban populations, and livestock. They facilitated publications, maps, geographic information, and methodology that have been valuable to assess nutrient mining across countries in Africa. The authors thank all for this collaboration. Special mention goes to IFDC personnel who collected detailed information, reviewed reports, developed the geographic analysis, established database management systems, provided analytical insight, and revised and edited the reports. The authors are solely responsible for the opinions and for the errors and omissions in this publication.

The work presented in this report was conducted with financial support from the United States Agency for International Development (USAID).

Agricultural Production and Soil Nutrient Mining in Africa: Implications for Resource Conservation and Policy Development

Executive Summary

The economic development of Africa, more than any other region, depends on the development of the agricultural sector and the agro-industry, which is fundamentally affected by the productivity of land resources. This is particularly true for countries in sub-Saharan Africa.

Agriculture accounts for more than 25% of the gross domestic product (GDP) of most African countries, and is the main source of income and employment for at least 65% of Africa's population of 750 million. Thus, agricultural development is vital to Africa's economic growth, food security, and poverty alleviation.

By 2020 Africa is projected to import more than 60 million metric tons (t) of cereal yearly to meet demand. Africa's food security situation has deteriorated significantly over the past two decades. With population growth of about 3% yearly, the number of malnourished people in Africa has grown from about 88 million in 1970 to more than 200 million in 1999–2001.

Agricultural production in much of Africa is also hampered by the predominance of fragile ecosystems, low inherited soil fertility, and low use of modern inputs such as mineral fertilizers and improved crop varieties.

Crop production in a region can increase through higher production per unit of land, or by increasing the area cultivated. The dramatic increases in agricultural production in Asia—known as the Green Revolution—were mostly through higher yields. But Africa's far lower increases have mostly been through expansion of the cultivated land (Figures 2 and 3).

Farmers in sub-Saharan Africa have traditionally cleared land, grown crops for a few cropping cycles, then moved on to clear more land, leaving the land fallow to restore soil nutrients and regain fertility. But population pressure now forces farmers to grow crop after crop, "mining" and gradually depleting the soil of nutrients. With little access to fertilizers, the farmers are forced to bring less fertile soils on marginal land into production, at the expense of Africa's wildlife and forests.

The fact that fertilizer use in Africa is less than 10% of that in Asia explains much of the contrasting trends in these regions.

The declining fertility of African soils because of soil nutrient mining is a major cause of decreased crop yields and per capita food production in Africa and, in the mid to long term, a key source of land degradation and environmental damage.

Methodology

The methodology for monitoring of nutrient mining is based on the estimation of soil nutrient balances. We determine the sum of nutrient inputs such as through fertilization, use of organic residues and manures, nitrogen fixation, and sedimentation. We then subtracted nutrient losses such as through erosion, leaching, and volatilization. Crop uptake is another important loss of nutrients which are then

exported from farmers' fields for human and animal consumption. Balances are evaluated at spatial scales that range from small soil aggregates to regions, countries, and even the African continent. The evaluation process includes use of spatial analysis through geographic information systems to identify crop areas, analyze and classify production, predict erosion and leaching, interpolate nutrient mining, and display regional assessments. Simulated modeling and transfer functions were used to evaluate nutrient losses in soils, assess current yields, and estimate and predict potential yields and nutrient uptake across Africa. Management information systems allowed the interaction and consolidation of data series with primary and secondary information on soils and crops, input consumption and use, and crop production.

In this paper we assess the status of food production associated with land degradation and estimate indicators of soil nutrient mining by country and region. We examine factors and circumstances that affect nutrient mining by predominant crop production systems in key agro-ecological zones and regions, and we review policy measures and investment strategies that can reverse current trends in nutrient mining and increase land productivity in a sustainable way. We also evaluate evolving trends in crop productivity in different regions and in land degradation caused by nutrient mining.

Agricultural Production, Soil Nutrient Mining, and Land Conservation

Soil nutrient mining, the result of overexploitation of agricultural land, is in fact consumption of a key component of the soil's natural capital. The propensity for nutrient mining of Africa's agricultural land and the severity of its consequences are the highest in the world. Soil nutrient mining is usually associated with low agricultural production and land productivity under severe constraints of poverty in terms of physical capital (infrastructure) and human capital (health and education). Continued nutrient mining of soils would mean a future of even increased poverty, food insecurity, environmental damage, and social and political instability.

The findings and conclusions of this paper result from the monitoring of nutrient mining in agricultural lands of key agro-ecological regions and countries of Africa, and have implications for policy development. Sound policies and investment strategies are key contributors to the joint goals of increased agricultural production, food security, economic development, land conservation, and environmental protection.

African countries today face not only the challenge of increasing agricultural production with scarce overall resources but must raise productivity in a way that conserves the natural resource base and prevents further degradation that has characterized African soils for generations.

Agricultural production has particularly stagnated or declined in important food crops such as cereals, tubers, and legumes. Crop yields and productivity in most African countries are about the same as 20 years ago. African cereal yields, particularly in the Sudano-Sahelian region, are the world's lowest (Figure 10). In 1998, cereal yields in sub-Saharan Africa averaged 1 ton per hectare (t/ha)—15% lower than the world average of 1.2 t/ha in 1965. Africa's low crop productivity, especially in densely populated areas, is seriously eroding its economic development and the competitiveness of its agriculture in the world market. Africa's share of the total world agricultural trade has fallen from 8% in 1965 to 3% in 1999–2000.

During the 2002–2004 cropping season, about 85% of African farmland (185 million ha) had nutrient mining rates of more than 30 kg/ha of nutrients yearly, and 40% (95 million ha) had rates greater than 60 kg/ha yearly. These 95 million ha are reaching such a state of degradation that to make them productive again would frequently require investments so large that it will not be economically feasible to implement.

Escalating rates of soil nutrient mining make nutrient losses highly variable in agricultural areas in the Sub-Humid and Humid savannahs of West and East Africa, and in the forest areas of Central Africa. Depletion rates range from moderate, about 30 to 40 kilograms (kg) of nitrogen, phosphorus, and potassium (NPK)/ha yearly in the Humid forests and wetlands of Southern Central Africa and Sudan to more than 60 kg NPK/ha yearly in the Sub-Humid savannahs of West Africa and the highlands and Sub-Humid areas of East Africa. The lands in these areas are typical for the tropics: weathered soil, with low productivity.

Estimates by country show that nutrient mining is highest (more than 60 kg NPK/ha yearly) in agricultural lands of Guinea, Congo, Angola, Rwanda, Burundi, and Uganda (Figure 5, Table 7). Fertilizer use is low in those countries, and the high nutrient losses are mainly the result of soil erosion and leaching. Other regions, such as most countries of the North Africa region and South Africa, although constrained by harsh climate, have lower nutrient depletion rates, varying from 0 to 30 kg NPK/ha per year. Agriculture in the coastal areas of Libya, Egypt, Tunisia, and Algeria is characterized by high mineral fertilizer use and appropriate crop management.

Nutrient mining across Africa ranges from 9 kg NPK/ha per year in Egypt to 88 kg in Somalia in East Africa. Nitrogen losses range from 4.1 kg/ha yearly in South Africa to 52.3 kg/ha in Somalia in the Sudano-Sahelian of East Africa. Losses of phosphorus range from none or minor losses in the Mediterranean and Arid North Africa to 9.2 kg/ha per year in Burundi and Somalia in East Africa. Potassium losses range from 6.5 kg/ha per year in Algeria to 30.4 kg/ha in Equatorial Guinea and Gabon in Humid Central Africa.

The main factors contributing to nutrient depletion are loss of nitrogen and phosphorus through soil erosion by wind and water, and leaching of nitrogen and potassium. Nutrient losses due only to erosion in African soils range from 10 to 45 kg of NPK/ha per year. If erosion continues unabated, yield reductions by 2020 could be from 17% to 30%, with an expected decrease of about 10 million t of cereals, 15 million t of roots and tubers, and 1 million t of pulses.

Based on nutrient mining estimated by country, total annual mining of nutrients (NPK) is about 800,000 t for Humid Central Africa; 3.0 million t for the Humid and Sub-Humid West Africa; 600,000 t for the Mediterranean and Arid North Africa; 1.5 million t for the Sub-Humid and Mountain East Africa; 1.7 million t in the Sudano-Sahel; and 1.4 million t in Sub-Humid and Semi-Arid Southern Africa. Total nutrient mining in the sub-Saharan region may be about 8 million t of NPK per year.

The evidence leaves no doubt that the very resources on which African farmers and their families depend for welfare and survival are being undermined by soil degradation caused by nutrient mining and associated factors such as deforestation, use of marginal lands, and poor agricultural practices. About 50,000 ha of forest and 60,000 ha of Africa’s grassland are lost to agriculture yearly. Intensification of agriculture with low fertilizer use and the clearing of forest lands are the main causes of nutrient mining and land degradation in the tropical forests and savannahs that are characteristic of the Humid and Sub-Humid regions that predominate in Cameroon, Ghana, Nigeria, Gabon, Congo, Sudan, and parts of Uganda. Most soils are fragile and low in plant nutrients. The nutrient recycling mechanisms that sustain soil fertility are insufficient to support increased production without fertilizers. Land is being degraded, and soil fertility is declining to levels unsuitable to sustain economic production.

Indicators of Soil Nutrient Mining, Population, and Nutrition

Population growth and migration associated with drought, food shortages and land overuse have accelerated degradation of agricultural land. Figure 11 gives estimates of the actual supporting capacity of land, calculated by use of crop suitability data and assuming limited use of inputs (rainfed production without mechanization, mineral fertilizers, and conservation practices). The average estimates of population density range from less than 0.1 to 5.0 persons/ha. This means that high population density in many countries already exceeds the long-term population carrying capacity of the land.

Variation in population density is highest in the very fragile soils in the Semi-Arid areas of West and East Africa. Population density varies from as low as 5 persons/ha in Semi-Arid areas of East Africa to as high as 150 persons/ha in some Semi-Arid areas of West Africa. Population densities are also high in Humid and Sub-Humid areas in the west coastal areas and in some east fertile areas in Ethiopia, Kenya, Uganda, Mozambique, Tanzania, Burundi, Rwanda, Namibia, and Angola. Correspondingly, these areas have high rates of nutrient mining. The production of cereals expressed in kilograms per hectare is particularly low in countries with high rates of nutrient depletion such as the Sudano-Sahelian and the Humid and Sub-Humid areas in west central and east Africa. Countries such as Congo, Gabon, Liberia, Sierra Leone, Eritrea, Rwanda, and Botswana continue importing large quantities of cereal food.

Africa imported about 43 million t of cereals at a cost of $7.5 billion in 2003. The sub-Saharan African countries (excluding South Africa) imported 19 million t at a cost of $3.8 billion. Assuming that the current situation in agricultural land management will not change dramatically, Africa is projected to import about 60 million t of cereals, at a cost of about $14 billion, by 2020. The sub-Saharan countries (excluding South Africa) will import about 34 million t of cereal at a cost of $8.4 billion by 2020.

A part of the imports is used as animal feed, but most is to satisfy demands of an increasing population. The imports of cereals, along with imports of other food, have a great impact on economies of African countries, and make food security strategies difficult to accomplish.

The influence of nutrient mining on the land’s capacity to sustain population and production has long-term impacts besides loss of soil productivity and the consequent exodus of farmers. About 33% of the sub-Saharan population is undernourished compared with about 6% in North Africa and 15% in Asia. Most of the undernourished are in East Africa, where nutrient mining rates are high. Malnutrition rates in these regions are from 10% to 50%. The nutritional level as measured in calories per person/day is lower than the basic level of 2,500 kilocalories. Crop cereals provide more than 60% of these calories in the Semi-Arid and Sub-Humid areas, while animal products provide 5% to 30%. Roots, tubers, and plantation crops provide most of the calories in Humid regions. Low yields in nutrient-mined areas seem to contribute to poverty and malnutrition.

Soil Nutrient Mining and Policy Development

Information about the extent and intensity of soil nutrient mining and a better understanding of its main causes are essential to design and implement policy measures and investments to reverse the mining and subsequent decline in soil fertility. Restoration of soil fertility is necessary to increase crop yields and food production in order to combat the worsening food security situation in Africa. Thus, these policy measures and investment strategies must be viewed as key contributors to the joint goals of increased agricultural production, food security, economic development, land conservation, and environmental protection.

A better understanding of the economics of nutrient mining and of the agro-climatic and socioeconomic factors that explain why farmers mine and deplete the soil of nutrients provides the rationale for designing effective policy and investment strategies to reverse current trends. The main goal of such strategies is to prevent soil nutrient mining by making the use of external plant nutrient sources, particularly mineral and organic fertilizers, more economically attractive. This implies implementation of policies and investments that increase the cost of mining plant nutrients from the soil while decreasing the cost and increasing the profitability of mineral and organic fertilizer use. These sources of essential plant nutrients, and other improved technologies, must be made available to farmers efficiently and timely.

Key factors determining the extent of nutrient mining in many areas of sub-Saharan Africa are prevailing land tenure arrangements and the lack of plant nutrients as mineral or organic fertilizers. There are differences between the cost of nutrient mining to individual farmers and to society as a whole caused mainly by land tenure arrangements that make the farmers indifferent to the loss of future economic returns to land. When the farmers' possession of agricultural land is well established through property rights or land tenure arrangements, and there is a functioning market for agricultural land, farmers internalize costs associated with the loss of the land's productive capacity. That significantly increases the cost to farmers of the mined soil nutrients. The opposite occurs when land tenure rights are not well established and there is no functioning market for agricultural land. Then, costs associated with the loss of the land's productive capacity become an externality and thus, a social rather than a private cost. Then, from the farmer's point of view, soil mining is perceived as the least expensive source of plant nutrients. This is particularly true for farmers who practice shifting cultivation. They often perceive that they are not significantly affected by the declining land productivity associated with nutrient mining.

Design and Implementation of Policy and Investment Strategies—Policies and investment strategies to reverse soil nutrient mining should be designed and implemented nationally, and sometimes locally, but always in context, and as a key part, of a comprehensive policy approach to economic development. To facilitate the selection of a set of policy measures and investments as key components of an effective strategy to reverse soil nutrient mining, it is useful to describe and pre-assess them in terms of (1) expected outcomes; (2) impacts on the countries' capital endowments (their natural capital, physical man-made capital, and human capital); and (3) change in the incentives or disincentives to mine soil nutrients. Summaries of key policies follow:

1. **Broad Scope Development Policies.** These include investments in roads and associated infrastructure, investments in schools and education, and measures to control corruption and promote good governance. Expected outcomes of these broad scope development policies are increased availability and lower costs of fertilizers and other agricultural inputs and significantly improved access of farmers to information and markets for their products.

2. **Land Tenure Policy**. Measures or legislation to improve farmers' long-term rights to own the land they use can significantly affect the importance of the benefit streams that farmers receive as a result of the long-term use of the land. This seriously affects farmers' decision making in management and use of agricultural land, and in nutrient mining.

3. **Policies to Improve Agro-Inputs Supply Efficiency.** The timely and efficient supply of agro-inputs such as seeds and fertilizers can be improved through provision of credit and technical assistance

(TA) to farmers as well as the producers, importers, wholesalers, and dealers involved in the procurement and distribution of seeds, fertilizers, and other inputs. In this context, TA involves providing technical and managerial assistance, as well as training and the dissemination of relevant information to business entrepreneurs and farmers.

4. **Policies to Expand the Demand for Agricultural Products and Stabilize Prices.** The goal and expected outcome of this policy is to expand the demand for agricultural products that farmers can efficiently produce in a competitive environment and in a way that is consistent with price stability. Growth in demand for agricultural products that is consistent with stability in the prices that farmers receive for their products promotes the profitability of fertilizers and modern inputs and increases the productivity of agriculture and the incomes of farmer households. Expansion in the demand for agricultural products can be attained as a result of (i) policies and investments that increase the domestic demand for agricultural products and (ii) policies that increase the demand for exports of these products. Policy measures and investments include, but are not limited to, the following:
   a. Investments in marketing infrastructure for farmers, wholesalers, and retailers of agricultural products. This involves construction of properly located facilities for product trade among farmers, wholesalers, retailers, and consumers.
   b. Measures to facilitate credit and technical and managerial assistance to marketing intermediaries of agricultural products such as wholesalers and retailers, including those interested in investing in marketing infrastructure.
   c. Provision of credit and technical and managerial assistance to exporters of agricultural products, and to agribusinesses involved in the processing and then the marketing of processed products in the domestic and export markets.

   All of these policies involve direct investments by the public sector and measures to create a policy environment that stimulates investments and dynamic participation of the private sector. Growth in demand for agricultural products that can stimulate sustainable growth in agricultural production and productivity can be a powerful source of agricultural and economic development. This is particularly evident when demand growth is due mainly to expansion in demand for processed agricultural products. Then the growth in demand can result in rapid development of the agricultural sector and agribusinesses involved in product processing. Some countries in Latin America and Asia have experienced this kind of development as a result of growth in the export demand for processed agricultural products.

5. **Social Support Programs for Poverty Alleviation and Public Health.** These programs are needed to combat poverty and malnutrition among both rural and urban populations, and to alleviate the HIV/AIDS epidemic. Policies that are primarily directed to promote economic development should be implemented, along with social support programs. These programs should be designed to reduce malnutrition and hunger, provide health care to combat the HIV/AIDS epidemic, and offer basic education and information to fight these two problems.

Conclusions and Recommendations on Policy Development—To reverse and prevent soil nutrient mining, policies and investment strategies must be designed and implemented at the national level, focusing on well-defined target areas. Furthermore, it is evident that these measures must successfully promote the judicious use of mineral fertilizers in conjunction with sound soil conservation practices.

Given the complex nature of the multiple constraints affecting the use of fertilizers, a well-integrated strategy involving the simultaneous implementation of all or some of the policy measures described above should be adopted to achieve the goals of increased fertilizer use and soil fertility conservation. Key conclusions and recommendations on policy development to combat soil nutrient mining and depletion in some agricultural land areas of Africa can be summarized as follows:

1. Well-designed policy measures and investment strategies that target specific agricultural areas where soil nutrient mining is extensively occurring in a country can successfully increase the judicious use of fertilizers and the adoption of sound soil fertility management practices. These policies can reverse soil nutrient mining and provide important and substantial benefits to farmers, on-farm workers, marketing intermediaries, consumers, the land resource base, and the countries' economies.
2. In the target countries, the implementation of policy strategies to reverse this process through measures and investments that promote fertilizer use and soil conservation practices should be a national priority.
3. To develop national policy reform and investment strategy programs for target countries, strategies must be tailored to overcome the constraints and circumstances prevailing in well-defined target areas within a country. Then, ex-ante assessments of alternative pre-designed policy strategies can be conducted to select or design policy and investment strategies with the highest probabilities of success in terms of impact, benefits, and costs for the target country.
4. Results of ex-ante assessments can also be useful to derive estimates of the magnitude and boundaries of the total expenditures that a country could incur in costs of implementation of a policy strategy in order to have satisfactory levels of expected benefit:cost ratios on those expenditures.
5. Finally, it is important to note that national policy and investment strategies must include details about geographic coverage, the chronology of policy interventions and investments, and the specific modus operandi to be used in the implementation of policy measures, such as the provision of technical assistance and credit. Thus, the proper design of national policy and investment strategies to reverse soil nutrient mining in African countries can, in some instances, be involved and demanding.

This paper represents a significantly enhanced update of a 1999 publication produced by IFDC, an International Center for Soil Fertility and Agricultural Development, as part of its efforts to provide additional information and develop strategies and policies for improved crop production in Africa. The dissemination of this information is crucial for the design and implementation of policy interventions that can prevent the continuous mining of nutrients and associated damage to the environment and the resource base.

The information, methodologies, databases, and procedures described in this report should be viewed as components of an evolving process of continuous improvement and refinement. IFDC is interested and actively involved in developing and enhancing innovative approaches to improve the scope and quality of data, information, and technologies that are crucial for improving agricultural production and preserving the environment in developing countries. The monitoring of nutrient mining and the evaluation of fertilizer requirements for sustainable crop production in agricultural lands of the developing world is part of this effort.

Agricultural Production and Soil Nutrient Mining in Africa: Implications for Resource Conservation and Policy Development

I. Introduction

Population pressure on land resources is forcing farmers to use current agricultural land more intensively and to cultivate less fertile soils on marginal lands. In addition, agricultural production in Africa is hampered to a large extent by the predominance of fragile ecosystems, low natural soil fertility, and low use of external inputs, mainly mineral fertilizers and seeds. It is also widely reported that declining soil fertility, resulting from increasing soil nutrient mining, is a major cause of the decrease in food production per capita in Africa. The continuous assessment and monitoring of plant nutrients in soils of agricultural lands and a better understanding of the main causes of soil nutrient mining are essential to identify appropriate measures for reversing trends in nutrient depletion and the decline in soil fertility and productivity of the land.

In this paper, estimates of soil nutrient mining and assessments of nutrient requirements are calculated by taking into account agricultural land and production practices in Africa between 1980 and 2004. The methodology to derive estimates of nutrient mining includes the assessment of various paths and sources of nutrient inputs and outputs. It includes assessments of the nutrient uptake by crops, nutrients recycled in crop residues, and soil nutrient losses through leaching, erosion by wind and water, and other causes. The nutrient inputs are derived from organic and mineral fertilizer practices and the practice of fallow and crop rotation systems. Other sources of nutrient inputs include those derived from soil and water in irrigated and flooded areas and the nutrients derived from biological nitrogen fixation.

The main objectives of this paper are:

- Present updated information on indicators of nutrient mining and revise methods and procedures to assess the effect of agriculture production practices on soil nutrient mining and potential land degradation.
- Conduct assessments of the impacts of factors influencing nutrient mining and its effect on land productivity and degradation, crop production, and food security.
- Evaluate and discuss the implications of current levels of nutrient mining for the development of agricultural policy to reverse soil nutrient mining of agricultural land in Africa, particularly in sub-Saharan Africa.
- Assess and recommend policy measures and investment strategy options that can be adopted to reverse current and expected trends of soil nutrient mining in areas of agricultural land in sub-Saharan Africa as a means to promote agricultural development and resource conservation in countries of the region.

The report has been organized in parts and sections. The first part of this paper presents a summary description of the agricultural land and production systems and some observations on the impact of nutrient mining and land degradation in Africa. The second part deals with the methodology used to assess nutrient mining and the evaluation of different factors influencing nutrient mining. For these purposes, time-series and cross-sectional data sets are used to derive estimates and illustrate the nature, sources, and extent of nutrient mining and land degradation in countries and agro-ecological regions of Africa. Estimates of nutrient mining and requirements to replenish soil nutrients and restore and improve soil fertility are derived on the basis of agricultural production levels between 1980 and 2004 in countries and regions of Africa.

The third part of the paper, assessments of the impacts and interdependencies of nutrient mining with land productivity and degradation, crop production, food security, fallow periods, migration, economic development, and poverty are presented and discussed to derive implications for policy development and design.

In the last part of the paper, the implications of nutrient mining for policy design and development are discussed. The economics of nutrient mining in conjunction with socioeconomic and other circumstances are used as the basic rationale for the design of policy measures and investment strategies that can be adopted to reverse nutrient mining and promote food security, resource conservation, and economic development. Ex-ante assessments of selected general policy options are used to illustrate the use of an approach for the design of sound comprehensive national policy reform programs to reverse soil nutrient mining by promoting fertilizer use and improved crop production to achieve food security and agricultural development. Finally, recommendations for the proper design of effective policy options and investment strategies are provided.

II. Agricultural Land in Africa

1. Land Characteristics and Agricultural Production

African countries show great diversity in the endowment of agricultural resources. In Africa, the total area of land potentially suitable for the production of one or more cropping systems is estimated to be 874 million hectares (ha), about 30% of the continent's landmass. Out of this area, about 210 million ha is currently cultivated, but as a result of requirements for fallow and the constraints imposed by other factors, only about 150 million ha is currently harvested yearly.

The production of food and cash crops and the productivity of agricultural land are restricted mainly by the climate and the fertility of the soils. The duration and patterns of rainfall vary from a mono-modal regime of 12 months, to a bimodal regime of several months of duration, and to no rainfall at all. As a result, agricultural land areas are spread over a wide range of agro-ecological zones and regions (Figure 1) that significantly affect the growth of characteristic crop production systems, determine the length of the growing period (LGP), and ultimately influence the prevalence of certain farming systems and farm management practices.

An important agricultural zone is the dry area that includes land in the Semi-Arid and Arid regions with rainfall ranging from 200 to 700 mm per year. This area accounts for 54% of the total agricultural land and is very important across most of sub-Saharan Africa, with the exception of more humid areas in Central Africa, i.e., in Congo, Gabon, and the Central Africa Republic. Another important agricultural land area is in the Central Africa region and accounts for 59% of the humid zone in Africa where rainfall is greater than 1,500 mm per year.

Large savannahs with inclusions of highlands that are more suitable for livestock and agro-forestry production are found within the Semi-Arid, Humid, and Sub-Humid zones. These areas are mainly located in Eastern, Central, and Southern Africa, cover only 25% of the total land area, and support high population densities of inhabitants who use the land for the production of cereals and mixed crop-livestock production systems.

In summary, one-third of the total agricultural land in Africa is too dry to support intensive rainfed agriculture, and the potential and currently unused agricultural lands are located in the Sub-Humid wooded savannah and Humid forest areas of the Humid Central region. In these areas of the Humid Central region, the infrastructure is particularly poor; the incidence of human, livestock, and plant diseases is high; and rainfall is exceptionally variable. All the above factors restrict agricultural production systems, limit crop productivity, and increase crop losses and risk. An evaluation of the potential capability of the agricultural land area in Africa indicates that there is good rainfall in only 60 million ha or 35% of the harvested land,

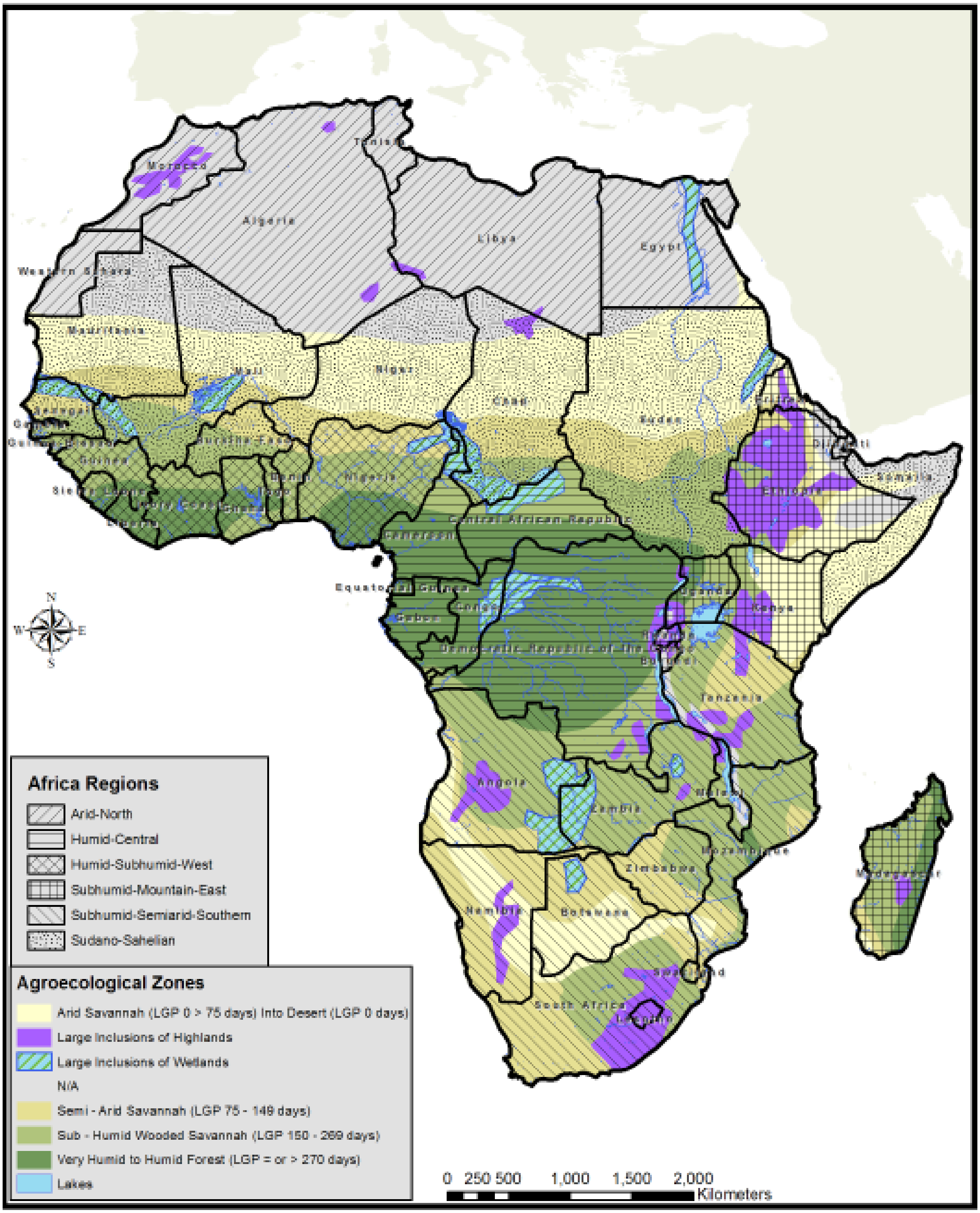


Figure 1. Major Agricultural Zones in Africa

while 15% has low rainfall, 25% is a high risk area due to unpredictable rainfall, 7% is naturally flooded, and about 18% is suitable for irrigation.

Under natural conditions, cultivated land areas in Africa are poorly endowed with basic nutrients and in general have low soil fertility. Most of the soils of agricultural lands have been formed over ancient crystalline rock of the Precambrian age, in association with small areas of sedimentary rocks and others of volcanic origin. These factors in combination with the climate and prevailing management practices have formed the main soil groups, which according to the FAO soil classification system (Deckers, 1993) broadly include Luvisols, Arenosols, and Vertisols in the Semi-Arid Savannah. Ferralsols, Luvisols, Arenosols, Acrisols, and Cambisols are predominant in the Sub-Humid wooded savannah and large inclusions in the highlands. In the Humid Forest, Ferralsols, Acrisols, and Arenosols are the most frequent and typical. Some of the agricultural lands are highly weathered, present gravel layers and iron pans, and have low nutrient retention and high erosion hazards. Younger soils of volcanic origin and sedimentary soils of moderate to fine texture, such as those found in the highlands, valley bottoms, and floodplains in East Africa tend to be more fertile. With respect to crop production, Ferralsols, Acrisols, Luvisols, and Arenosols which account for 90% of the arable land are widely used soils. These soils have low soil fertility and low moisture retention and have become heavily leached and eroded, triggering a process of vast soil degradation with high losses of organic matter and soil nutrients. All of these factors in conjunction with poor crop management practices and infrequent and insufficient use of modern inputs adversely affect crop production and the establishment of permanent and sustainable productive farming systems.

Given the agro-ecological factors and soil conditions described above, most crop production systems in Africa have poor yields. Compared with crop yields in Arid zones of Africa, crop yields tend to be higher in the Sub-Humid and Semi-Arid Savannahs and in the large inclusions of highlands than in the Central and Humid areas, where sufficient moisture is available but there are other limitations. With the exception of areas on high mountains and in the desert regions, Africa produces a wide range of crops, livestock, and farming systems (Box 1), but most of these systems are not sustainable in the long term (Okigbo, 1989). About three-fifths of African farmers are essentially subsistence farmers cultivating small plots of land to feed their families, with no use of inputs from commercial sources and as a result with only a minimal production surplus that can be sold in the market.

Agricultural production is low because yields (production per unit of land) of most of the important food crops in Africa, which include grains, tubers, and legumes, are low. The dramatic increases in agricultural production in Asia—known as the Green Revolution—were mostly through higher yields. But Africa’s far lower increases in production have mostly been through expansion of the cultivated land (Figures 2 and 3). The average cereal yield in sub-Saharan Africa, particularly in the Sudano-Sahelian region, is the lowest among the developing regions of the world. During 1998, the average yield of cereals in sub-Saharan Africa was 15% lower than the world average (World Bank, 2000). Low crop productivity, principally in these densely populated areas of Africa, has seriously eroded economic development in most countries and the competitiveness of their agriculture in the world market. Africa’s share of the total world agriculture trade has been falling in recent decades; for instance, it fell from 8% in 1965 to 3% in 1999/2000.

As shown in Tables 1 and 2, the stagnation and decline of agricultural productivity in food and cash crops is happening in most agricultural regions in the continent, and although the area of arable land is increasing to compensate for the decline in yields, this expansion is approaching the limits of cultivable land available. In the Cen-

Box 1. Extent of Major Climatic Zones and Agricultural Land Use in Africa

Climatic Zone or Region	Total Area Million Hectares (percent)	Annual Rainfall (mm)	Land Use, Farming Systems, and Main Agricultural Constraints
Desert	822.0 (29.1)	<100	Nomadic pastoralists and hunter/gatherers, camels, sheep, goats. Too dry and hot for agriculture.
Arid: North Africa and areas in Southern Africa	844.0 (17.1)	100–400	Nomadic pastoralists, sheep, goats, camels, some cattle. Main crops are rice, wheat, barley, and sorghum. Production-based irrigation. High animal population, overgrazing, deforestation causing soil degradation. Frequent drought.
Semi-Arid: Southern Africa Sudano-Sahelian	233.0 (8.1)	400–600	Nomadic pastoralists. Millet/sorghum, cowpea, groundnut, cotton, some maize. Low potential for rainfed agriculture and very variable annual rains. Production mainly based peri-urban systems. Pervasive soil nutrient mining.
Dry Sub-Humid: Sub-Humid West Sub-Humid South	314.0 (11.0)	600–1,200	Zone of arable crop production – maize, sorghum, groundnut, cassava, sweet potato, cowpea, rice, tobacco, cotton, tea, soybeans, cocoa. Some animals – cattle, sheep, and goats. Declining yields, severe land degradation, and soil nutrient mining. High degree of deforestation and use of marginal lands.
Moist Sub-Humid: Mountain East	584.0 (20.4)	1,200–1,500	Transition zone with cereals (maize) and root crops (cassava, yam), banana, pineapple, sugar cane. Wheat, coffee in East Africa highlands. Livestock. High erosion potential and soil fertility limitations.
Humid: Humid West Humid Central Wetlands	409.0 (14.3)	>1,500	Tree crop zone – oil palm, rubber, cocoa, and food crops, yams, cassava, banana, rice, pineapple, and forest resources. Severe disease infestations, which limited exploitation of crops and livestock. Low fertility of soils.

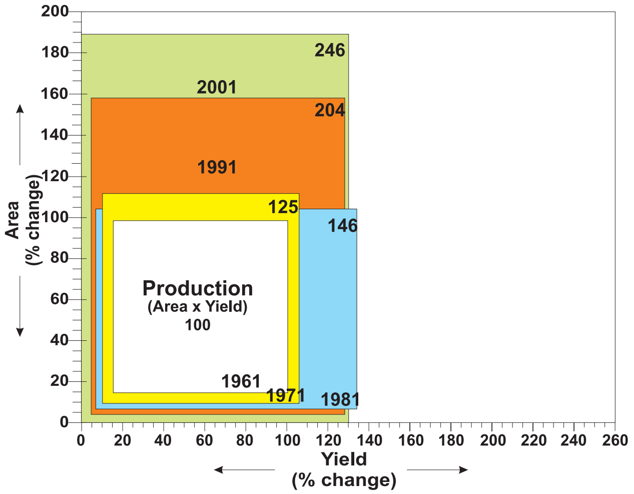


Figure 2. Changes in Cereal Production in Sub-Saharan Africa Due to Changes in Area and Yield (1961 = 100)

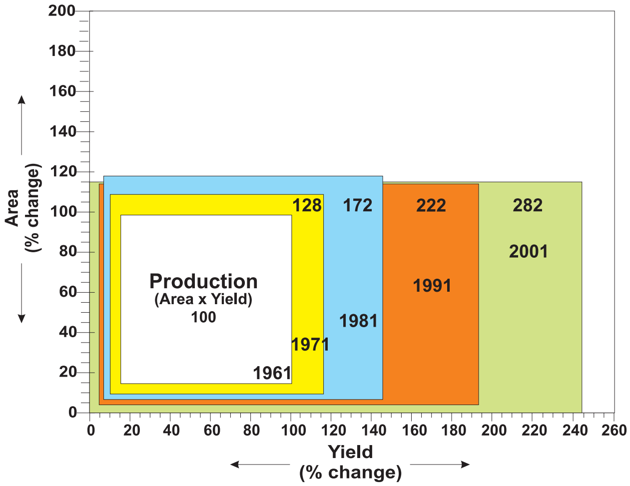


Figure 3. Change in Cereal Production in Asia Due to Changes in Area and Yield (1961 = 100)

tral region, yields of cereals and tubers have shown some increases, but productivity per hectare is very low. In Humid and Sub-Humid West Africa, yields of rainfed food crops are decreasing. Cereals are the dominant crops in North Africa, and productivity has been increasing due to improved management practices, including intensive use of mineral fertilizers and irrigation. As a result, irrigated rice and maize yields in Egypt are among the highest in the world.

Millet and sorghum are among the main food crops in the Sudano-Sahelian region, accounting for about 70% of the cultivable land planted with crops, and these two crops represent the main source of income and food supply for farmers in the region. The average yield of these crops in most countries of Africa is not greater than 1 t/ha. Cereals, particularly maize and sorghum, dominate the cropped area in the Sub-Humid and Mountain East region. Average cereal and tuber yields, although low, are among the highest in Africa, but levels of production are still too low to meet the increased demand due to population growth.

Patterns of production systems in the Sub-Humid and Semi-Arid Southern regions are similar to those in East Africa. However, because of the influence of climatic factors, coupled with low use of mineral fertilizer and intensity of land use, yields of staple foods such as maize, wheat, millet, sorghum, and pulses tend to be lower across the Semi-Arid Southern region, except in South Africa where fertilizer use and yields are among the highest in Africa.

Industrial crops such as those for beverages, fiber, and oil production continue to have high priority in Africa. Oil crops such as groundnuts and cotton are the most important cash crops grown for export in sub-Saharan countries (Table 2).

Improved technology and modern inputs such as improved seeds, fertilizers, and crop protection products (CPPs), and the support of extension ser-

Table 1. Production of Food Crops in Agricultural Areas of Africa

Region/Crop	Growth per Year 1995–2004		Area and Yield Period: 2002–04		
	Area	Yield	Area	Area	Yield
	(%)	(%)	(ha)	(%)	(t/ha)
Humid Central					
Cassava	-0.6	-0.2	2,394,600	38.6	7.78
Maize	0.6	1.2	1,886,000	30.4	1.09
Pulses	1.3	1.3	605,900	9.8	0.81
Sorghum	-0.7	2.6	593,000	9.5	1.09
Humid and Sub-Humid West					
Cassava	2.5	-0.6	5,433,700	12.4	9.51
Maize	-0.5	-0.8	7,404,000	17.0	1.13
Millet	1.6	-0.7	6,577,500	15.1	0.99
Pulses	3.2	-0.9	5,819,900	13.3	0.44
Rice	6.4	-2.7	6,513,000	14.9	1.14
Sorghum	1.4	0.1	7,927,000	18.2	1.13
Mediterranean and Arid North					
Maize	-0.4	3.0	1,078,000	9.1	5.51
Pulses	0.3	2.3	700,312	5.9	1.26
Rice	0.7	1.6	632,500	5.3	9.51
Wheat	5.6	0.6	9,282,000	78.1	1.80
Sub-Humid and Mountain East					
Cassava	1.5	3.5	1,035,609	7.2	9.65
Maize	1.0	0.1	4,206,095	29.2	1.60
Pulses	2.1	0.0	3,729,910	25.9	0.70
Rice	0.9	0.7	1,351,290	9.4	2.29
Sorghum	2.7	-0.9	2,006,000	13.9	1.10
Wheat	1.3	0.1	1,178,200	8.2	1.41
Sudano-Sahelian					
Maize	6.7	2.4	1,191,483	3.7	1.41
Millet	0.5	3.1	12,192,458	37.9	0.53
Pulses	1.0	5.0	4,639,587	14.4	0.33
Rice	2.5	1.1	698,389	2.2	1.92
Sorghum	2.4	2.5	13,144,363	40.8	0.67
Sub-Humid and Semi-Arid Southern					
Cassava	1.5	3.2	2,700,625	13.3	8.27
Maize	0.7	2.4	11,107,000	54.7	1.50
Millet	-1.0	0.8	1,055,021	5.2	0.54
Pulses	1.1	0.4	2,214,640	10.9	0.53
Sorghum	-0.8	1.0	1,619,342	8.0	0.96
Wheat	-3.7	4.4	1,033,550	5.1	2.29

Source: FAO, IFDC.

Table 2. Production of Cash Crops in Agricultural Areas of Africa

Region/Crop	Growth per Year 1995–2004		Area and Yield Period: 2002–04		
	Area	Yield	Area	Area	Yield
	(%)	(%)	(ha)	(%)	(t/ha)
Humid Central					
Coffee	-3.6	-0.6	360,000	15.4	0.32
Groundnuts	-1.7	3.0	841,000	36.1	0.88
Oil Palm	0.5	0.6	329,200	14.1	7.83
Humid and Sub-Humid West					
Groundnuts	4.5	0.8	3,900,500	35.0	0.96
Oil Palm	1.0	-0.2	3,944,200	35.4	3.22
Seed Cotton	4.3	-0.3	1,570,500	14.1	0.89
Mediterranean and Arid North					
Barley	3.5	6.6	3,918,000	84.4	1.16
Seed Cotton	-1.0	2.6	272,270	5.9	2.77
Sub-Humid and Mountain East					
Bananas	1.2	-0.2	571,395	14.9	4.92
Barley	-4.5	2.9	767,000	20.0	1.19
Coffee	0.2	-0.8	955,670	25.0	0.61
Sudano-Sahelian					
Groundnuts	2.6	-0.5	3,943,550	68.8	0.73
Seed Cotton	5.6	-0.4	1,610,461	28.1	1.06
Sub-Humid and Semi-Arid Southern					
Groundnuts	3.4	0.6	1,193,137	31.1	0.54
Seed Cotton	1.9	1.9	1,040,600	27.1	0.81
Sugar Cane	1.2	0.3	474,000	12.3	70.78

Source: FAO, IFDC.

vices are used to cultivate cash crops and industrial crops. Even with these inputs, the production and productivity of these crops can vary substantially from year to year due to the variability of climate-related factors and annual differences in the availability and use of water. Large-scale irrigation systems have been a key factor in maintaining and increasing productivity in those export-oriented countries such as Morocco and Egypt in North Africa; in some sub-Saharan countries such as Nigeria, Mali, and Senegal; and in part of the rice production system in the Sudan. In the other regions of Africa, irrigation is extremely rare. The production of export crops such as oil, cotton, coffee, and tea grew significantly during the 1980s in countries in the sub-Saharan region. However, cultivated areas and yields have been declining, drastically affecting the trade and markets of raw materials and processed products.

Slow growth in the development of agriculture in some regions is due not only to adverse climatic variation and infertile soils but also to management constraints, low use of inputs, adverse socioeconomic circumstances and debilitating diseases such as malaria and HIV/AIDS. Many

African countries today face the challenge of having to increase their agricultural production under conditions of overall resource scarcity. They also must increase productivity and growth while preventing land degradation and conserving the natural resource base, which has been damaged significantly as a consequence of depletion of essential plant nutrients from African soils.

2. An Overview of Soil Nutrient Mining and Land Degradation

Land degradation is referred to as the loss of productivity of the land and its capacity to produce reasonable quantities of goods or services as a result of natural and human-induced changes in physical, chemical, and biological processes (Oldeman et al., 1990). One of the human-induced changes is the depletion of soil fertility caused by a continuous process of soil nutrient mining occurring as a result of crop production without the proper replenishing of the nutrients taken from the soils.

In the last two decades, the degradation of agricultural land in Africa and its consequences to the environment and human life have increasingly become the focus of national and international attention. During the same period, the capability of agricultural land to sustain crop production has continued to deteriorate noticeably. The degradation of land in Africa has been attributed to socioeconomic and policy-related factors and to poor management of crops, soils, and other natural resources.

Available evidence leaves no doubt that land degradation caused by nutrient mining and other associated factors, such as deforestation, use of marginal lands, and poor agricultural practices, is undermining the very resources on which African farmers and their families depend for their welfare and survival. Declining soil fertility is a key factor that explains yield reductions, food shortages, migration, and desertification throughout Africa. The inadequate replenishment or redistribution of removed nutrients by crop production and the continuous loss of soil nutrients and organic matter are becoming critical factors in the continuous decline in soil fertility and have even increased current rates of land degradation. It has been estimated that between 1945 and 1990, nutrient mining in Africa caused the light degradation of 20.4 million ha of agricultural land, moderate degradation of 18.8 million ha, and severe degradation of 6.6 million ha (Oldeman et al., 1990; Oldeman, 1994, 1999). According to an evaluation performed by the Southern African Research Center (SARC), soil losses in South Africa alone were about 400 million t annually (SARDC, 1994).

2.1 Impact on Soil Fertility and Land Resources

Soil nutrient mining in Africa is associated with the unsustainable intensification of crop production on agricultural land. This depletion of nutrients is associated with the breakdown of many traditional soil-fertility maintenance strategies, such as land fallow, the recycling of residues and manure, or the use of crop rotation systems. Soil management practices have direct short- and long-term consequences on the fertility of the soils. Moreover, as a consequence of the lack of fertilization, soils in the West and Central regions of Africa have become strongly weathered and leached. The cation exchange capacity of these soils, which is in part affected by their low organic matter content, has decreased in some instances. Repeated cropping without replenishing essential elements such as nitrogen, phosphorus, potassium, and calcium can result in some soils becoming more acid. Macro-scale studies on nutrient balances performed by van der Pol (1992), Stoorvogel et al. (1993), and Henao and Baanante (1999), among several researchers, show that nutrient depletion is relatively severe in areas characterized by low soil fertility in the Sudano-Sahelian region, particularly in Mali, Nigeria, Ghana, Côte d'Ivoire, Niger, Chad, Sudan, and north of Central Africa Republic, and in the fertile highlands in East Africa where agriculture is intensive and less than 30% of the land is kept fallow.

In the tropical moist forest and savannahs that are characteristic of the Humid and Per-Humid regions and are predominant in Cameroon, Ghana, Nigeria, Gabon, Congo, Sudan, and part of Uganda, intensification of agriculture with very low use of fertilizer inputs and the clearing of forest lands are the major causes of nutrient mining and land degradation. Many soils in the more humid zones of Africa are low in plant nutrients. The nutrient recycling mechanisms that sustain soil fertility are being disrupted, land is being degraded, and soil fertility is declining to levels unsuitable to sustain marginal productivity (Bationo et al., 1994; Kang et al., 1990).

In the Sudano-Sahelian and Southern regions, intensive, mixed farming systems are predominant in the pasture and savannah areas that have low soil nutrient content. Nutrient depletion and deficiencies are becoming significant constraints in these areas. Breman (1994) and Breman and Niangado (1994) evaluated nutrient balances in pasture systems and their impact on the sustainability of livestock production systems in the Sahel. About 50% of the vast Sahelian grazing lands located on sandy soils with very low soil fertility has been affected by high rates of nutrient mining. The low nutrient levels of the soils and the limited availability of water are significantly restricting the agricultural potential of these lands. Agro-forestry-based systems in the Sudano-Sahelian region of West Africa are also limited by the very low nutrient reserves in the soils after years of cultivation (Breman and Kessler, 1995).

2.2 Evidence of Impact on Crop Productivity

The United Nations Environment Program (UNEP) estimated in 1991 that more than a quarter of the African agricultural land is at present in the process of becoming useless for cultivation due to degradation. Moreover, the productivity of the soil in some areas in Africa has declined by 50% as a result of land degradation factors (Dregne, 1990). For example, estimates of yield reduction in Africa due to nutrient mining through soil erosion have ranged from 2% to 40%, with a mean loss of 8.2% for the continent (Lal, 1995a). It has been estimated that if nutrient mining and land degradation were to continue unabated, yield reductions by 2020 could be in the range of 17%–30%, with an expected additional decline in production of about 10 million t of cereals, 15 million t for roots and tubers, and 1.0 million t of pulses. Other researchers have also observed that in Africa where many people are already malnourished, crop yields could be cut by half in 40 years if the degradation of cultivated lands continues at the current high rates (Scotney and Dijkhuis, 1989).

There are areas in the Humid and Sub-Humid regions (40 million ha) and in the Sudano-Sahelian region (30 million ha) where yields of basic food crops such as maize, millet, and sorghum are less than 1 t/ha per year and have not increased during a decade (FAO, 2004c). In these areas, smallholders have removed large quantities of nutrients without applying sufficient quantities of manure and fertilizers to replenish nutrients in the soil. This has caused depletion of soil fertility, which is becoming a significant biophysical cause of low per capita food production in the Sahelian and other regions in Africa (Pieri, 1989; Rabbinge, 1995; Breman et al., 2001; Sanchez, 2002). These regions are currently characterized by per capita cereal production that is estimated to have declined from 150 kg/person to 130 kg/person during the past 10 years.

In central and south Sudan, Ethiopia, Uganda, and western Kenya, in some rural highly populated areas with fertile soils, the continued cropping without the use of external inputs has decreased production and severely depleted the land (Hoekstra and Corbett, 1995). Long-term trials in western Kenya indicated that after 18 years of continuous cultivation of maize and common beans (*Phaseolus vulgaris* L.) in rotation and without the use of nutrient inputs, the soil lost about 1 t/ha of nitrogen and 100 kg of phosphorus from organic matter per hectare. Maize yields decreased from 3 to 1 t/ha during that period (Swift et al., 1994).

It has been estimated that yields of most food and cash crops in Africa should increase by at least 4% annually if there is to be a chance for some regions to grow economically and become food self-sufficient in the long term (Badiane and Delgado, 1995). There is, however, no single solution and probably no simple solution to the problem of preventing soil fertility loss as one of a number of measures to increase yields in Africa. Many possible measures for solutions have been proposed, but most of them should probably be based on the ways farmers cope with the soil fertility problem in specific areas.

Trends of increasing crop productivity (yield) have been found in many sites and regions of Africa where the production of food crops has increased and the fertility of the soils is maintained (Mazzucato and Niemeijer, 2001; Scoones, 2001). It is important to observe that, in those cases, strategies adopted by farmers include the use of their limited resources and low input agriculture. These strategies are based on the use of organic fertilizers, crop residues, and crop sequences (rotations) to reduce temporal variability, diversify risk, and reduce nutrient mining. Increases in crop productivity are found in some commercial and irrigated cropping systems in North Africa and Southern and Sahelian African countries. In these countries, industrial crops and livestock account for about 70% of export revenues. Fertilizers combined with integrated management approaches have been adopted to offset the loss of nutrients in production and maintain productivity in West African soils (Bationo et al., 1995; FAO, 2001c).

2.3 Impact on Rural and Urban Areas

The impact of nutrient mining on agricultural lands has been stated as one of the main causes of observed changes in land use and the increased exodus of rural population to urban areas in some agricultural areas of Africa. For example, extensive degradation of the agricultural land by soil nutrient mining has been documented in the highly populated areas of the dry regions in West and East Africa. In the Peanut Basin of Senegal, intensive cultivation with low use of inorganic and organic fertilizers and inadequate soil management practices have exhausted the soils (Charreau and Nicou, 1972; Pieri, 1985). Farmers have been migrating eastward and southward to reclaim new lands. Also, in the highly populated Mossi Plateau of Burkina Faso, millet areas have been degraded by continuous cropping (Broekhuyse, 1983), and many farmers have migrated to coastal countries. Since coastal opportunities are declining, Mossi farmers are increasingly adopting conservation practices (Sanders et al., 1994); others have permanently migrated to the Sub-Humid regions of coastal areas in Benin, Ghana, Nigeria, and Côte d'Ivoire. In northern Nigeria, around Kano, where population density is very high, soil fertility has been depleted due to poor crop management practices (Smith, 1994).

Increasing population, particularly urban population, has been associated with the intensification of agricultural production in the Sudano-Sahelian region. In major parts of the areas where cereals such as maize and sorghum are grown, agricultural land has become scarce and fallows have virtually disappeared (Manyong et al., 1996a, 1996b). Consequently, farmers reduced field fallows or migrated to other areas. Much of the West African Humid zone is being deforested as farmers seek fertile soil, having depleted essential plant nutrients from agricultural lands due to almost continuous cropping. Where longer fallows are still possible, few farmers use fertilizers, even when they are available, and they rely on the restorative function of the natural fallow to recover from the losses of soil nutrients. Agricultural intensification supported by substantial additions of external inputs (fertilizer, improved seed and integrated pest management) is not merely an option but has become a necessity created by the process of soil nutrient mining.

Specific areas identified by UNEP (1991) as warranting special consideration include the Fouta Djallon Mountains in West Africa (Guinea), the East African highlands (Kenya, Burundi, Ethiopia, Rwanda, Malawi, Tanzania, Zambia, and Zimbabwe) and the highlands of Southern Africa (South Africa, Botswana, Lesotho, and Swaziland). Population pressure and poor crop management practices coupled with the topography make the mountainous and hilly areas of some regions in East Africa prone to excessive water runoff, soil erosion, and soil nutrient depletion. Stocking (1986) estimated the economic cost of the nutrient loss (N, P, and K) by soil erosion in Zimbabwe. The annual losses of N and P alone amounted to US $1.5 billion/year. Because of severe shortages of energy and fodder, the continuous cropping on steep slopes and the low use of nutrients and organic matter, soils have been severely degraded in some of these areas, principally in Uganda, Rwanda, Burundi, and Lesotho. Although the recycling of essential plant nutrients and organic matter from crop residues is highly desirable in these regions, competing demands for firewood and fodder to feed animals prevent a significant recycle of these sources of nutrients to the soil. Thus, in the croplands of these regions, soil fertility is declining, erosion accelerating, and the degradation of land continues.

The low productivity and continued decline in yields that are primarily caused by nutrient mining have had a high impact on the nutrition and health of rural and urban populations. The number of undernourished people in Africa has nearly doubled from 100 million in the late 1960s to nearly 200 million in 1995. Moreover, projections indicate that most regions will be able to feed only 40% of their populations by 2025 (Nana-Sinkam, 1995). To avoid food shortages in some regions such as the Sudano-Sahelian region, countries have increased food imports, cereals in particular. About 15%–20% of the food supply in Africa is now imported.

III. Evaluating Soil Nutrient Mining in Cropland Areas

1. Establishing a Geo-Referenced Base Estimation System to Monitor Nutrient Mining

The widespread depletion of essential plant nutrients from soils (nutrient mining) is a process in important agricultural areas of Africa that needs to be evaluated, arrested and corrected by improved soil management. Nutrient mining is linked to several forms of land degradation and desertification occurring in the cultivated lands of the 54 countries of the continent. Methods and procedures to monitor nutrient mining have been developed and are being continuously upgraded, particularly for Africa’s crop production systems. The methods and results are evaluated in the context of current land use practices and other prevailing factors and circumstances, such as levels of crop production, inherent soil fertility conditions, and the resilience (or fragility) of the soils and the agricultural environments. The baseline data, although limited, are integrated into a monitoring system to evaluate agricultural land resources and estimate nutrient balances and requirements. The data collected to assess changes in soil productivity can be updated periodically to account for changes in the management of agricultural lands and crop production technologies and the observed variability in use of external inputs.

Most of the approaches used to monitor nutrient mining involve the use of (a) data of fertilizer use and crop management practices in combination with data on soil characteristics, cultivated areas, and commodity production and (b) empirical, simulated crop models and spatial analysis to derive estimates of indicators needed to monitor nutrient mining and characterize input use and production systems at the macro-level (country), meso-level (regional), and micro-level (farmer) scales. The estimation methods built upon approaches used by Pieri (1983,1985), Gigou et al.

(1985), Stoorvogel (1993), Smaling (1993), Smaling and Fresco (1993), van Duivenbooden (1990), van der Pol (1992), Henao and Baanante (1999), OECD (2001) and by recent approaches as suggested by FAO (2004a) and Sheldrick et al. (2002) and Sheldrick and Lingard (2004).

A very simple specification of a general model to monitor nutrient (N, P, and K) mining in soil ecosystems at national or regional scales is given by the following equation (Henao and Baanante, 1999):

$$Rn_t = \Sigma^t (AP_t + AR_{\Delta t} - RM_{\Delta t} - L_{\Delta t}) \qquad (1)$$

Where Rn_t is the quantity of nutrient coming from inorganic and organic sources assumed to remain available in the soil after a period of time t; AP_t is the inherent soil nutrient available at time t; $AR_{\Delta t}$ is the total of mineral forms and organic compounds added or returned to the soil during the time interval Δt. The $RM_{\Delta t}$ estimate is the plant nutrients removed in the crop-harvested product and residue managed during the time interval Δt, and $L_{\Delta t}$ is the inorganic and organic nutrients lost through different pathways during the time interval Δt.

Equation (1) simply states that if the amounts of available nutrients removed from the soil (nutrient outflows) by crop production are greater than the additions (nutrient inflows) either by fertilization, crop residues, and applications of manure or other management practice in a long-term period, then the reservoir (pool) of nutrients or stock of nutrients in the soil will decline and so will crop productivity. Precise estimation of different soil nutrient pools is not possible because of the complex dynamic and stochastic nature of many processes of nutrient transformations in the soil and cropping systems. Because of this limitation and the lack of reliable data to evaluate soil fertility in the various agro-ecological regions and crop management systems, it is difficult in many instances, especially at macro-level scales, to properly quantify causal relationships between results of nutrient mining assessments and changes in soil productivity.

The attribute data and the information collected which describe soil constraints, soil characteristics, and climate for regions and countries are all assembled into a management information system to support the monitoring decision system based on model (1). A summary of information assembled in a system to monitor at macro scale or regional level is presented in Figure 4. Data on crop production, residue management, pasture and livestock production systems allow the assessment of the total quantities of nutrients that are removed by crops. Those nutrients are exported from soils when crop outputs are transported to consumption centers. The influence of weather and soil constraints, and soil fertility and other characteristics inherent to agro-ecological zones are used to estimate soil nutrient losses due to erosion, leaching, and volatilization (gaseous losses), which are the main processes influencing permanent soil nutrient losses. Nutrient replenishment of the soil is estimated principally from the application of mineral fertilizers, and also from the use of crop residues and manures, and from biophysical processes of deposition, sedimentation, and fixation. Estimates of nutrient gains and losses in the soil are adjusted using assumed soil-nutrient transfer functions and through the estimation of empirical statistical models (Larson and Pierce, 1991; Bouma and Van Lanen, 1987; Smaling et al., 1993; Stoorvogel et al., 1993).

Spatial analysis conducted through a geographic information system (GIS) is used to produce georeferenced information, perform interpolation and analyses, and present regional assessments of nutrient mining in the form of maps and spatial outputs. The GIS system includes information on soils, climate, agro-ecological regions, and land classification systems defined according to major taxa for the regions (Buol, 1972; FAO, 1989; FAO, 1976; Landon, 1991) and also information on population, land use, and other social and economic factors. The GIS system can be used at

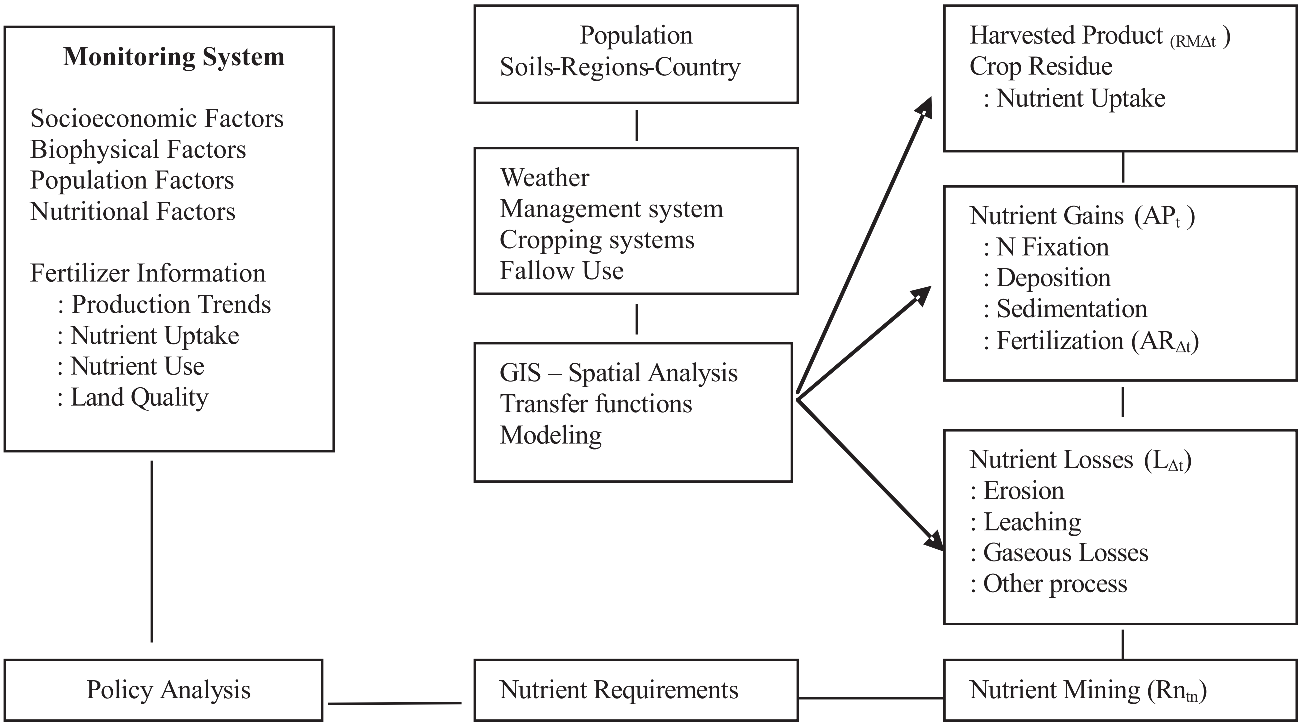


Figure 4. Monitoring Nutrient Mining System at Macro and Regional Level

macro-level scale to include coverage that identifies area constraints and land quality factors that can be used to improve soil and land management practices or to find areas suitable for agricultural intensification.

The integration of a model and assessment of estimates that underlie the nutrient mining monitoring approach have a number of significant data requirements and assumptions. These are described in more detail in Appendix I. For this study, the agricultural land evaluated accounts for about 95% of the total cultivated area in Africa. The process uses primarily data series of crop production and crop areas from 1980 to 2004 (FAO, 2004c; FAO yearbook series, 2004b; IFDC time series and research data) and of mineral fertilizer consumption by country and region for the same period (FAO and IFDC time-series data).

Estimated values of nutrient mining and results from simulated strategies are to be validated using field observations, literature data, and well-established knowledge of agronomic relationships. The assessment of soil nutrient mining associated with crop production could be better estimated by controlled, long-term experiments. However, the evaluation of nutrient flows through modeling strategies and time-series data provides reliable evidence of a continuous nutrient flow process that affects the productive capacity of agricultural lands. This is particularly useful in the African agricultural environment.

2. Site Factors and Nutrient Outflows and Inflows in Agricultural Lands of Africa

Factors contributing to soil nutrient mining are not unique to a specific region. The factors are components of a complex interdependent set of constraints that a country or region must overcome to improve crop production. Climate is the most critical and highly variable factor affecting nutrient flows and nutrient mining in Africa. It is globally influenced by high temperatures and wind circulation patterns that determine periods of high rains, drought or dry spells, and aridity in the region, particularly in sub-Saharan countries. Soil characteristics are other important factors crucial to the occurrence of nutrient mining in a number of ways. Physical properties of soils such as clay content and organic matter content are related to soil water holding capacity and cation exchange capacity. Low soil organic matter content characterizes the agricultural production systems and nutrient mining pathways of the typically shallow areas and basins in the Sudano-Sahelian region and the Sub-Humid West and East, and the Southern Arid regions, key agricultural production land areas in the continent.

The above factors, coupled with the intensive use of land with poor soil management, make the agricultural areas highly susceptible to wind and water erosion that causes high losses of nitrogen, phosphorus, and other essential plant nutrients. The loss of essential plant nutrients from soils in Sub-Humid regions of Africa is associated with leaching of nitrogen and potassium in coarse-textured soils and heavy rainfall. Gaseous losses of nutrients through denitrification, the ultimate process for the return of fixed nitrogen to the atmospheric pool, occur principally in waterlogged situations in the Humid and Sub-Humid regions. Volatilization of nitrogen in the form of ammonia occurs principally in peri-urban agriculture and in livestock areas due to the decomposition of residues and manures from crops and livestock. A summary assessment and indicators of the amount of outflows of nutrients occurring in key agricultural lands in Africa are presented in Table 3.

The high level of weathering of the soils which have low buffering capacity in the Sub-Humid West and the Sub-Humid and Mountainous East resulted in acidic conditions with a high tendency for phosphorus fixation and aluminum toxicity. Phosphorus availability and nitrogen fixation are low in acid soils. Salinity problems and losses of nitrogen and potassium by leaching and runoff continue to affect agricultural land under irrigation in North and Southern Africa, especially in areas under poor water management. A major factor of nutrient mining of soils is the loss of nutrients due to nutrient uptake by crops at rates that are many times greater than the rates at which those nutrients are being returned to the soil. Key processes that return nutrients to the soil are the dissolution of soil minerals, microbial decomposition of organic matter in the soil, biological nitrogen fixation, addition of mineral and organic fertilizers, and addition from other sources of plant nutrients in nature, such as flooding and deposition of sediment.

As observed in Table 3, nutrient loss is significantly affected by escalating rates of soil erosion by wind and water in most of the agricultural regions in Africa. Erosion has been pervasive in Africa and rates have not been reduced noticeably; instead, rates have increased during the past 10 years. This phenomenon has also been the cause of other environmental problems, including the loss of arable land and reduction of water supply. Rates of soil nutrient losses due to erosion are generally similar across all Africa; they range from 16.6 kg/ha of NPK per year in the Mediterranean and Arid North Africa to 23.5 kg/ha per year in the Sudano-Sahelian and Semi-Arid Southern Africa. Erosion by wind during Harmattan periods and by water due to heavy rains is characteristic in very populated rural areas and in farming systems of the Sub-Humid West, Sudano-Sahelian, and the Southern African regions. Soil erosion rates range from 45 to 90 t/ha per year in soils of these three regions. These are regions where there is intensive cultivation of food crop cereals and tubers such as maize, millet, sorghum, cassava, and yams and intensive use of pasture lands. These areas are also characterized by the reduction of land area under fallow and the increased cultivation of marginal lands. Very high rates of soil erosion have been observed in highly erodible landscapes, such as the Ethiopian highlands.

Table 3. Estimates of Nutrient Outflows in Agricultural Lands of Africa

Region/ Nutrient	Growth Rate[a] 1995–2004	Nutrient Losses and Outflows Period: 2002–04				
		Production	Residues	Leaching	Gaseous	Erosion
	(%)	(kg/ha)				
Humid Central						
N	0.5	11.3	3.4	4.7	9.3	18.8
P_2O_5	–0.7	4.2	1.9			1.4
K_2O	–0.1	10.1	3.7	4.4		2.9
Humid and Sub-Humid West						
N	–2.1	16.3	6.1	3.2	4.6	17.3
P_2O_5	–1.4	6.0	2.7			1.3
K_2O	–2.1	12.6	6.2	3.3		2.6
Mediterranean and Arid North						
N	0.3	31.5	7.6	2.7	4.3	13.5
P_2O_5	0.0	9.1	3.1			1.0
K_2O	1.0	13.3	3.3	3.0		2.1
Sub-Humid and Mountain East						
N	0.3	17.4	6.5	3.6	5.2	18.4
P_2O_5	0.7	6.9	3.2			1.4
K_2O	–1.0	13.5	6.2	2.7		2.8
Sudano-Sahelian						
N	0.1	13.5	3.7	4.2	7.3	16.9
P_2O_5	0.0	5.3	2.1			1.3
K_2O	0.1	10.0	3.8	4.8		2.5
Sub-Humid and Semi-Arid Southern						
N	1.0	24.4	6.6	5.3	7.6	19.0
P_2O_5	1.4	10.5	4.4			1.5
K_2O	0.8	17.5	6.6	3.8		3.0

a. Nutrient losses due to leaching, volatilization, and erosion.

The total losses or outflows of nitrogen, phosphorus and potassium due to the nutrient mining factors described above range from 30 kg/ha per year for the Mediterranean and Arid North Africa to 60 kg/ha per year for the Sudano-Sahelian region. Unless these processes are halted by using integrated nutrient management practices sustained by sound agricultural policies, efforts to increase crop production only through the development of improved crop varieties or better farming systems will be of little value in reversing the trends of declining agricultural production.

Agricultural production in Africa is conducted mainly by small farmers that are usually located on areas with more intensive cultivation of annual food crops such as sorghum, millet, cowpeas, maize, and rice with the use of low or no external inputs of nutrients such as mineral fertilizers and manure. Traditional agricultural systems, based on

Table 4. Estimates of Nutrient Inflows in Agricultural Lands of Africa

Region/ Nutrient	Growth Rate 1995–04	Nutrient Gains and Inflows					
		Period: 2002–04					
		Manure	Deposition	Fixation	Sediments	Fallow	Fertilizer
	(%)	(kg/ha)					
Humid Central							
N	–1.0	0.2	2.8	4.2	0.1	1.9	1.1
P_2O_5	–0.9	0.1	0.9		0.1	1.9	0.8
K_2O	–1.3	0.3	2.4		0.1	1.0	1.1
Humid and Sub-Humid West							
N	0.3	1.4	3.6	4.7	0.8	0.7	2.9
P_2O_5	0.5	0.7	1.3		0.3	0.7	1.5
K_2O	–0.1	2.8	2.8		0.8	0.4	1.1
Mediterranean and Arid North							
N	2.0	0.9	1.7	3.0	0.7	1.3	41.0
P_2O_5	–0.1	0.5	0.6		0.3	1.3	10.2
K_2O	1.1	0.8	1.3		0.4	0.7	5.0
Sub-Humid and Mountain East							
N	2.2	1.2	2.7	3.6	0.6	0.6	7.3
P_2O_5	2.2	0.6	1.0		0.3	0.6	3.1
K_2O	0.2	1.4	2.2		0.5	0.3	0.9
Sudano-Sahelian							
N	1.6	1.7	2.4	4.2	0.7	1.4	3.0
P_2O_5	–1.1	0.8	0.8		0.2	1.4	0.7
K_2O	0.9	3.1	1.8		0.4	0.7	0.5
Sub-Humid and Semi-Arid Southern							
N	2.1	1.6	3.1	4.9	0.7	1.7	23.8
P_2O_5	–0.7	0.6	1.0		0.1	1.7	8.8
K_2O	0.6	3.0	2.5		0.6	0.8	7.2

soil fertility recovery through the use of long fallows, the intensive application of crop residues and manure, and the use of crop rotations to fix nitrogen, are currently being practiced in only few small areas and are often confined to peri-urban systems. Although these systems are very useful for improving soil conditions and maintaining soil fertility and land productivity, the extent and scope of impact are very limited in providing significant improvements in crop production and agricultural development.

Trends and estimates of nutrient inflows presented in Table 4 show that the amounts of inflows of nitrogen, phosphorus and potassium coming from different sources are very low in Africa. Such amounts come from organic residues and manure, wet and dry deposition of nutrients, sedimentation in irrigated or flooded areas, biological fixation of nitrogen through rotations or multiple cropping systems, shifting cultivation-fallow systems, and mineral fertilizers.

The amount of nutrient deposited in the soil by fallow systems and assumed available for crop production ranged from 1.5 kg/ha per year of NPK in the Humid and Sub-Humid West to 4.8 kg/ha per year in the Humid Central Africa regions. Long fallow systems are no longer feasible in most of Africa, due to the pressure of higher demand for food and feed. Moreover, because agricultural systems based on crop rotations or recycling of residues are not fully implemented or not feasible in most areas, the amounts of nutrients actually returned to the soils in these systems are usually very small. The nitrogen provided by crop fixation was 4 kg/ha per year and the animal manure used is very low. The highest amounts of manure use occurring in the Sudano-Sahelian region and in Southern Africa are about 5.6 kg/ha per year. However, the fact that observed yields are low but stable in some areas in the Sudano-Sahelian and Sub-Humid East Africa may be explained by the practice of an effective recycling system of organic and animal waste applied as fertilizer. In some areas in the Sudano-Sahelian region (Burkina Faso, Mali, and Niger) and the Sub-Humid and Mountainous East Africa (Ethiopia, Uganda, and Kenya), nutrient excretion in animal waste exceeds nutrients in mineral fertilizers by a factor of 10.

Mineral fertilizer use is still very low in Africa. Fertilizers are used primarily in the production of wheat and barley in North Africa and Southern Africa. Fertilizer use is limited to a very few countries and to selected farming systems in a few agricultural areas in West Africa. The use of mineral fertilizer in sub-Saharan Africa is particularly very low (Tables 4 and 5), and this trend has not changed over the past 10 years. The average use of mineral fertilizers in most agricultural areas is still below 10 kg NPK/ha per year. Its consumption in Africa ranges from as low as 3.0 kg NPK/ha per year in Humid Central Africa to 56.2 kg NPK/ha per year in the Mediterranean and North Africa regions.

During 2002–2004, fertilizer use in Africa was only 21 kg of NPK per ha of harvested land per year and was even lower in sub-Saharan Africa at 8.8 kg per ha of arable land. It is evident that a major factor influencing nutrient mining and the fertility of soils under intensive use is the low use of mineral fertilizers. Measures to halt or reduce nutrient mining must be sought in the context of an adequate use of mineral fertilizers and organic sources of nutrients. The challenge in most agricultural areas therefore lies in the search for environmentally sound practices for fertilizer use that will reverse soil nutrient mining by restoring and maintaining soil fertility, prevent land degradation, and improve agricultural productivity and crop production on a sustainable basis.

3. Country and Region Assessment of Nutrient Mining

The depletion of essential plant nutrients or nutrient mining of soils necessary for the production of food, feed and fiber continues to have major, negative impacts on the economy and diet of both the rural and urban populations in Africa. During the 2002–2004 cropping seasons, about 90% of the countries in Africa had negative balances of nutrients greater than 30 kg NPK/ha per year whereas about 40% of countries had rates of nutrient mining equal or greater than 60 kg NPK/ha per year (Table 6). Moderate rates of nutrient mining (less than 30 kg of NPK/ha per year) are more prevalent in North Africa countries. Medium to high rates (greater than 30 kg of NPK/ha per year) occur across the sub-Saharan region where countries in the Humid Central and the Sub-Humid and Semi-Arid Mountainous East regions have the highest rates of nutrient mining.

Rates of soil nutrient mining are highly variable among regions and countries. The range of nutrient mining for the whole continent ranges from 9.0 kg NPK/ha per year for Egypt to 88 kg NPK/ha per year for Somalia in the East African region (Table 7). Losses of nitrogen (N) range from 4.1 kg/ha per year in South Africa to 52.3 kg/ha per year in Somalia in the Sudano-Sahel of East Africa. Losses of phosphorus as P_2O_5 range from none or minor losses in the Mediterranean and Arid North Africa countries to 9.2 kg/ha per year in Burundi and Somalia in East Africa. Losses in

Table 5. Mineral Fertilizer Use in Africa, 2002–04

Country/Region	Area	N	P_2O_5	K_2O	NPK	NPK
	('000 ha)	(kg/ha)				(t)
Humid Central						
Cameroon	3,565	3.7	2.4	3.7	9.8	34,898
Central Africa	810	0.3	0.3	0.3	0.8	607
Congo Dem. Rep.	5,882	0.6	0.8	0.4	1.8	10,471
Congo Rep.	226	0.9	0.1	0.1	1.0	235
Equatorial Guinea	105	0.8	0.6	0.1	1.4	150
Gabon	211	0.5	0.5	0.5	1.4	297
Humid and Sub-Humid West						
Benin	2,566	10.0	4.8	3.9	18.6	47,824
Côte d'Ivoire	5,933	8.9	5.1	4.4	18.4	108,982
Ghana	5,647	2.5	1.5	1.5	5.5	31,004
Guinea	2,143	0.5	0.7	0.4	1.5	3,193
Guinea Bissau	427	2.3	1.6	1.6	5.6	2,400
Liberia	456	1.2	0.5	0.8	2.4	1,105
Nigeria	47,387	4.0	1.2	1.8	7.0	331,234
Sierra Leone	586	2.5	1.0	1.5	5.0	2,911
Togo	1,541	4.7	3.2	3.2	11.1	17,057
Mediterranean and Arid North						
Algeria	3,165	20.5	7.9	9.2	37.6	118,838
Egypt	5,792	166.5	20.6	10.0	197.1	1,141,439
Libya	740	23.9	10.9	4.8	39.6	29,320
Morocco	6,906	36.1	14.5	7.2	57.8	398,986
Tunisia	2,678	30.9	15.3	1.9	48.1	128,760
Sub-Humid and Mountain East						
Burundi	1,167	0.7	0.6	0.8	2.2	2,544
Eritrea	470	5.6	2.2	0.0	7.8	3,676
Ethiopia	10,221	7.6	5.1	0.6	13.3	135,629
Kenya	3,954	14.4	12.9	0.8	28.1	111,221
Madagascar	2,781	0.8	1.4	1.1	3.3	9,120
Rwanda	1,678	3.1	3.0	3.0	9.1	15,301
Uganda	6,539	1.0	0.4	0.4	1.7	11,247
Sudano-Sahelian						
Burkina Faso	4,300	4.2	1.1	1.7	7.0	30,098
Chad	3,031	3.6	0.7	1.5	5.8	17,486
Djibouti	4	2.2	1.0	2.0	5.3	23
Gambia	254	2.4	0.4	0.4	3.1	797
Mali	4,327	5.6	3.2	2.9	11.7	50,450
Mauritania	198	10.6	0.0	0.0	10.6	2,094
Niger	11,837	1.3	0.1	0.3	1.7	19,887
Senegal	2,336	9.2	2.6	2.6	14.3	33,495
Somalia	3,426	0.2	0.1	0.1	0.4	1,370
Sudan	11,153	4.9	1.0	0.3	6.2	69,592
Sub-Humid and Semi-Arid Southern						
Angola	2,418	1.3	0.7	1.0	3.0	7,255
Botswana	230	17.8	1.3	0.9	20.0	4,601
Lesotho	214	22.9	15.9	14.0	52.8	11,299
Malawi	2,895	25.0	6.0	4.2	35.2	101,897
Mozambique	4,187	3.8	0.5	1.7	6.0	24,911
Namibia	292	0.3	0.7	0.0	1.0	298
South Africa	7,884	72.4	15.3	18.7	106.4	838,855
Swaziland	162	12.3	15.4	15.4	43.2	7,001
Tanzania	6,865	2.9	0.1	0.5	3.5	23,754
Zambia	1,032	32.3	10.5	12.8	55.6	57,350
Zimbabwe	2,727	22.0	11.0	7.3	40.3	109,995
Total Africa	**193,345**				**21.3**	**4,110,957**
Sub-Saharan Africa[a]	**166,179**				**8.8**	**1,454,759**

a. Excludes South Africa

NPK: ($N+P_2O_5+K_2O$)

Sources: FAO, IFDC.

Table 6. Countries Grouped by Average Levels of Losses of Nitrogen, Phosphorus, and Potassium (NPK) (kg/ha per year), 2002–04 Cropping Seasons

Moderate/Low Less than 30 kg/ha		Medium Between 30 and 60 kg/ha		High Greater than 60 kg/ha	
	(kg/ha)		(kg/ha)		(kg/ha)
Egypt	9	Libya	33	Tanzania	61
Mauritius	15	Swaziland	37	Mauritania	63
South Africa	23	Senegal	41	Congo Republic	64
Zambia	25	Tunisia	42	Guinea	64
Morocco	27	Burkina Faso	43	Lesotho	65
Algeria	28	Benin	44	Madagascar	65
		Cameroon	44	Liberia	66
		Sierra Leone	46	Uganda	66
		Botswana	47	Congo Democratic Rep.	68
		Sudan	47	Kenya	68
		Togo	47	Central Africa Rep.	69
		Côte d'Ivoire	48	Gabon	69
		Ethiopia	49	Angola	70
		Mali	49	Gambia	71
		Djibouti	50	Malawi	72
		Mozambique	51	Guinea Bissau	73
		Zimbabwe	53	Namibia	73
		Niger	56	Burundi	77
		Chad	57	Rwanda	77
		Nigeria	57	Equatorial Guinea	83
		Eritrea	58	Somalia	88
		Ghana	58		

NPK: ($N+P_2O_5+K_2O$)

potassium as K_2O range from 6.5 kg/ha per year in Algeria to 30.4 in Equatorial Guinea in Humid Central Africa.

The highest depletion rates of N (greater than 45 kg N/ha per year) were found in the Central Africa Republic, Namibia, Somalia, Rwanda, and Burundi in East Africa. The highest depletion rates in phosphorus (greater than 7 kg P_2O_5/ha per year) were found in Somalia, Burundi, Equatorial Guinea, Gambia, Malawi, and Ghana. The highest depletion of potassium (greater than 25 kg K_2O/ha per year) was found in Equatorial Guinea, Gabon, Somalia, Kenya, Malawi, and Guinea Bissau.

The geographical distribution and relative importance and extent of nutrient mining in agricultural land areas of Africa for two cropping seasons are presented in Figure 5. It is observed that nutrient mining continues to expand in most agricultural areas affecting particularly Humid and Sub-Humid regions in West and East Africa. The assessment for 2002–2004 shows that about 80% of the countries in those regions have rates of nutrient mining greater than 45 kg of NPK/ha per year. Consequently, the nutrient mining in those areas is having a greater effect on the production of key food and cash crops, compared with the drier regions of north or Southern Africa. North Africa, particularly Egypt, Morocco, and Algeria

Table 7. Nutrient Mining Estimates by Region and Country

Region/Country	Total Area	N	P_2O_5	K_2O	NPK
	(’000 ha)	(kg/ha)			
Humid Central					
Cameroon	7,622	–29.0	–2.7	–12.0	–44
Central Africa Rep.	809	–49.4	–3.2	–16.6	–69
Congo Dem. Rep.	7,787	–43.8	–4.7	–19.2	–68
Congo	437	–37.2	–4.9	–21.8	–64
Equatorial Guinea	105	–43.3	–8.8	–30.4	–83
Gabon	217	–36.7	–5.7	–26.9	–69
Humid and Sub-Humid West					
Benin	2,569	–24.7	–3.7	–15.5	–44
Côte d'Ivoire	7,152	–32.3	–2.5	–13.0	–48
Ghana	5,646	–31.9	–7.3	–19.1	–58
Guinea	2,145	–40.4	–6.2	–17.5	–64
Guinea Bissau	427	–42.3	–4.8	–25.7	–73
Liberia	456	–41.7	–5.6	–19.1	–66
Nigeria	47,387	–34.0	–5.9	–17.2	–57
Sierra Leone	737	–26.2	–4.5	–15.7	–46
Togo	1,650	–30.4	–3.2	–13.5	–47
Mediterranean and Arid North					
Algeria	4,651	–21.5	0.0	–6.5	–28
Egypt	9,293	4.5	0.3	–13.7	–9
Libya	740	–14.8	1.1	–19.0	–33
Morocco	7,630	–12.1	0.3	–15.4	–27
Tunisia	6,278	–24.5	–2.4	–15.0	–42
Sub-Humid and Mountain East					
Burundi	1,321	–45.0	–9.2	–22.9	–77
Eritrea	570	–33.5	–4.5	–20.2	–58
Ethiopia	10,219	–28.3	–4.4	–16.1	–49
Kenya	5,353	–35.2	–6.8	–26.4	–68
Madagascar	2,781	–39.0	–6.0	–20.3	–65
Mauritius	81	–40.0	5.5	19.6	–15
Rwanda	1,578	–48.8	–5.1	–23.2	–77
Uganda	6,640	–38.8	–7.0	–19.7	–66
Sudano-Sahelian					
Burkina Faso	4,674	–30.1	–2.1	–10.5	–43
Chad	3,533	–34.9	–5.6	–16.6	–57
Djibouti	9	–24.3	–6.0	–19.4	–50
Gambia	353	–39.8	–7.8	–23.6	–71
Mali	4,322	–29.9	–4.4	–14.8	–49
Mauritania	328	–40.9	–3.8	–18.2	–63
Niger	11,837	–35.1	–6.1	–14.4	–56
Senegal	2,836	–21.7	–1.9	–17.7	–41
Somalia	1,461	–52.3	–9.2	–26.5	–88
Sudan	11,154	–30.1	–4.2	–12.9	–47
Sub-Humid and Semi-Arid Southern					
Angola	2,036	–41.3	–5.2	–23.6	–70
Botswana	545	–30.5	–0.3	–15.9	–47
Lesotho	213	–38.8	–4.3	–22.2	–65
Malawi	2,894	–39.4	–7.6	–25.0	–72
Mozambique	4,587	–29.5	–5.4	–16.3	–51
Namibia	352	–50.1	–5.7	–17.6	–73
South Africa	7,884	–4.1	–2.1	–16.5	–23
Swaziland	261	–19.6	–4.7	–12.2	–37
Tanzania	8,264	–37.7	–6.3	–17.3	–61
Zambia	3,145	–17.5	0.1	–7.4	–25
Zimbabwe	4,046	–35.1	–2.7	–14.8	–53

NPK: $(N+P_2O_5+K_2O)$

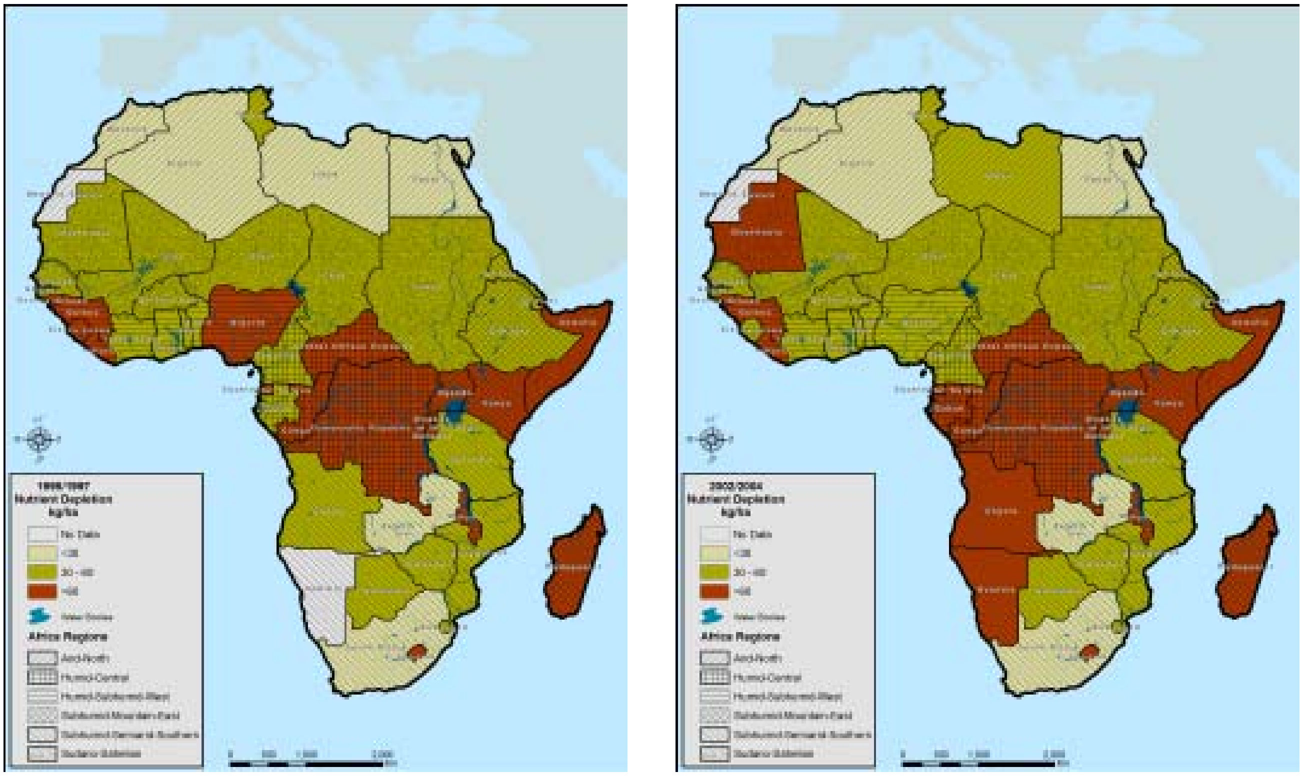


Figure 5. Nutrient Mining in Agricultural Lands of Africa (1995–97 and 2002–04)

and South Africa and Zambia in Southern Africa have nutrient mining rates less than 30 kg NPK/ha per year. North and Southern Africa are regions with countries characterized for using relatively high amounts of mineral fertilizer and for maintaining higher levels of productivity in crop production especially of cereals.

Assessments of total nutrient depletion in each of the major agricultural regions (Table 7) show nitrogen as the nutrient most depleted from soils. Average losses of nitrogen from soils ranged from 10 kg/ha per year in the Mediterranean and Arid North to about 40 kg/ha per year in the Humid Central Africa region. The total loss of nitrogen in Africa is about 5.5 million t per year. Losses of phosphorus ranged from little or no losses (less than 2 kg/ha per year) in the Mediterranean and Arid North to about 8 kg/ha per year in the Sub-Humid and Mountain East Africa regions. The total loss of phosphorus in Africa is about 800,000 t per year. Potassium losses from soils do not vary substantially across most agricultural lands; the losses ranged from as low as 13 kg/ha per year in North Africa to about 25 kg/ha per year in the Sudano-Sahelian. The total loss of potassium from soils in Africa is 3 million t per year. Total loss of nitrogen, phosphorus, and potassium in farmlands of Africa is about 9.3 million t per year.

High nutrient imbalances caused by nutrient mining continue to be prevalent in the Sudano-Sahelian region and are becoming a serious problem in the Humid and Sub-Humid areas in West and East Africa. A nutrient balance example in Figure 6 shows high net export (losses) of nutrients from soils and very low or no recovery by organic or inorganic fertilization principally in nitrogen and potassium across all agricultural regions in Africa.

The estimated total annual losses (net depletion) of nutrients (NPK) from soils per year amount to about 800,000 t for Humid Central Africa; 3

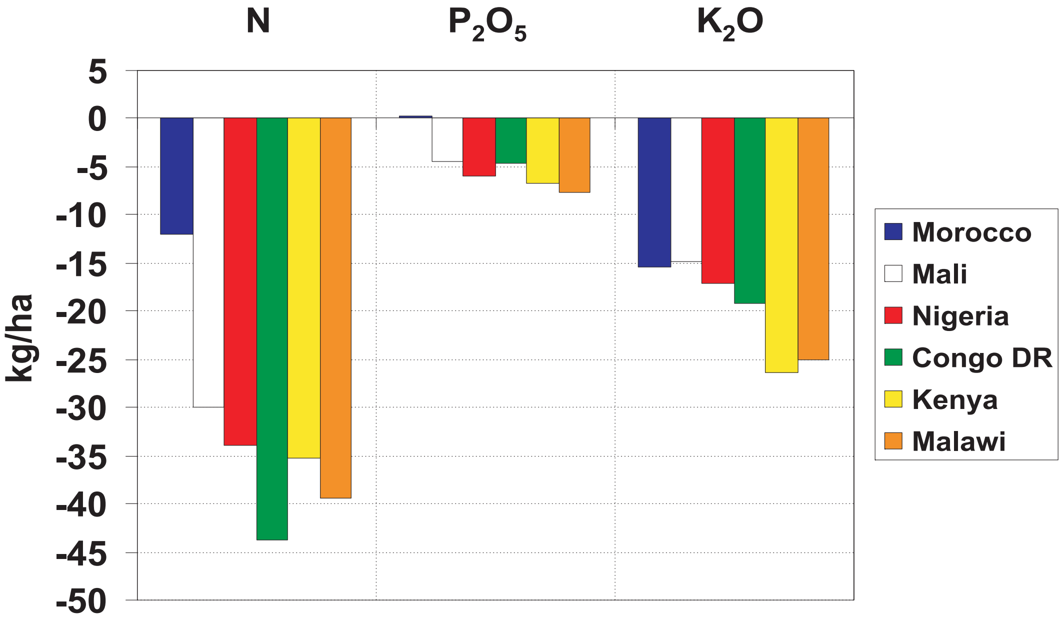


Figure 6. Nutrient Balance in Selected Countries of Africa

million t for Humid and Sub-Humid West Africa; 600,000 t for the Mediterranean and Arid North Africa; 1.5 million t for Sub-Humid and Mountain East Africa; 1.7 million t in the Sudano-Sahel; and 1.4 million t in Sub-Humid and Semi-Arid Southern Africa. The loss of nutrients from soils in the sub-Saharan region can be estimated at about 8 million t of NPK per year. The total loss of nutrients from soils in about 170 million ha of agricultural land (75% of the cultivated area) in Africa is 9 million t of NPK per year.

Most of the nutrient losses are permanent or not recovered since they usually represent nutrient flows taken from soils in the production of crops for human and livestock consumption or for export (trade). Other pathways of nutrient loss are streams and lakes, contributing to environmental damage or remaining in soils or areas not accessible to plants during the cropping season. Only a small amount of nutrients needed by crops is returned to the soils in the form of crop residues, nitrogen fixation, manure, and fertilizer applications. The complete nutrient mining process in Africa represents a very significant loss of the natural capital embodied in the land. Nutrient mining also is associated with externalities caused by impacts on the fertility of soils and the quality of water—crop productivity declines, livestock production is affected and the human population has less access to adequate quantities of nutritious food.

IV. Assessment of Impacts of Soil Nutrient Mining

1. Potential Impact on the Soil Fertility of Agricultural Land

Soil fertility is a necessary and valuable component of a sustainable crop production system. Soil fertility depends on the rates at which plant nutrients are made available by natural processes (e.g., mineralization of organic matter, biological nitrogen fixation, and dissolution of soil minerals containing essential plant nutrients) in the soils in a country and region. However, soil fertility can change noticeably due to soil management practices, such as fallowing, application of soil amendments such as lime, gypsum or organic matter, and especially through fertilization. Most of the agricultural lands in Africa (Figure 7 and Table 8) are classified as areas with soils in intensive use for agricultural production having moderate to low fertility (about 175 million ha), while areas in a few regions covering less than 15% of the agricultural land (about 25 million ha) are classified as areas with fertility graded as good for crop production.

Intensive crop production systems conducted during many cropping seasons over long periods of time have progressively drained the soil nutrient pool and caused a decline in soil fertility and the productivity of these systems. Estimates of nutrient mining for soils of varying soil fertility in agricultural regions of Africa during the 2002–2004 cropping seasons are presented in Table 8. Soils experiencing high nutrient mining are located mainly in the savannah areas and the forest-savannah boundaries of Sub-Humid and Semi-Arid West Africa (about 65 million ha) and also in the Sub-Humid and Semi-Arid East Africa countries (about 60 million ha), principally in Ethiopia, Tanzania, Rwanda, Burundi, and Mozambique. Estimates of nutrient mining in Humid and Sub-Humid areas in the West and Mountain areas show soils losing from 22 to 74 kg of NPK/ha per year. The most prevalent soils in those areas are Acrisols, Ferralsols, and Luvisols. They are mostly classified as soils with low fertility, which are intrinsically low in plant nutrients and respond favorably to fertilizers provided moisture is available for crop production.

The productivity of the Acrisols and Luvisols (45 million ha) in the Sub-Humid areas is constrained mainly by low nutrient levels, the presence of exchangeable aluminum, and elevated nitrogen losses through water erosion. The soils are common in Uganda, Rwanda, and Burundi and in the Sub-Humid savannah areas of West Africa in Senegal, Gambia, Guinea, Côte d'Ivoire, and Ghana. They produce good crops during the first few years, about the time it takes for the nutrient reserve from organic matter to decompose and be taken up by the crop or be leached from the soil. Additionally, intensive cropping on steep lands in the Sub-Humid and Mountain areas of East Africa has led to high erosion rates. Agro-forestry systems can be a sound and valuable alternative use of these soils.

About 25% of the agricultural lands in Africa are located on soils subject to extreme weathering with low nutrient reserves; they are sequioxide-rich minerals with weak retention of bases applied as fertilizers or amendments. Rates of nutrient mining in these soils, range from 48 to 70 kg NPK/ha per year. These soils are classified as Ferralsols, occupy an area of approximately 35 million ha, and predominate in high-subsistence farming, low-intensity grazing environments, and in intensive plantation agriculture such as sugarcane, banana, cotton, tea, and coffee. Nutrient depletion, principally nitrate losses through leaching and losses of potassium, is also common in the Humid and high rainfall areas. Soil mining ranges from 22 to 67 kg NPK/ha per year and occupies an area of about 16 million ha. Most of these soils are located in Humid Central Africa (Gabon, Equatorial Guinea, Congo, and Central Africa Republic), Semi-Arid Southern Africa (Angola, Namibia, Zimbabwe, Botswana, Zambia, Mozambique, and Malawi), and Sub-Humid and Mountain East Africa (Rwanda, Burundi, Kenya, Uganda).

Agricultural production is less developed and productivity is very low in Arenosols. These soils are located extensively in the Sudano-Sahelian and in Semi-Arid Southern Africa (Angola, Namibia, Zambia, Botswana, and part of South Africa), occupy about 15% of the agricultural land (35 million ha), and have nutrient depletion rates ranging from 30 to 48 kg NPK/ha per year. The use of these soils for agriculture is severely limited by

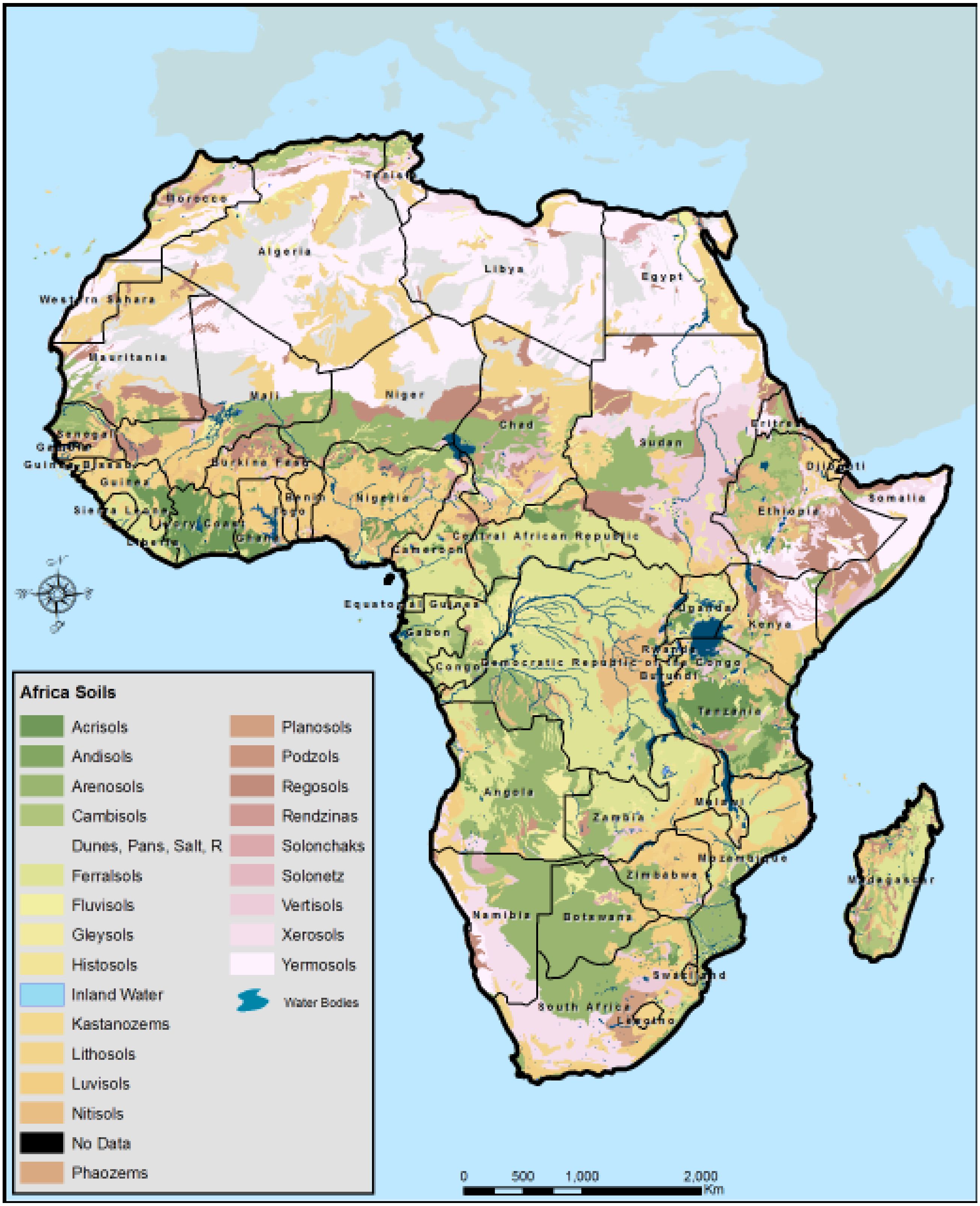


Figure 7. Major Soils of Africa

Table 8. Nutrient Mining Estimates in Soils of Africa

Region/Soil	Fertility Class Index[a]	Area	Nutrient Mining				Rain
			N	P_2O_5	K_2O	NPK	
		(%)	(kg/ha)				(mm)
Humid Central							
Ferralsols	2	7.5	37.8	3.8	16.3	57.9	1,365
Humid and Sub-Humid West							
Acrisols	1	12.3	36.7	3.9	16.1	56.8	1,400
Arenosols	1	2.1	20.5	3.3	7.4	31.3	600
Ferralsols	1	7.0	37.2	6.1	23.5	66.8	1,573
Fluvisols	1	0.3	17.7	10.8	18.8	47.3	1,438
Gleysols	2	1.1	8.4	6.7	7.3	22.4	1,400
Luvisols	2	8.4	32.5	7.5	15.8	55.8	1,175
Mediterranean and Arid North							
Cambisols	3	3.6	14.0	0.0	10.2	24.2	767
Fluvisols	2	2.5	25.0	4.2	18.3	47.5	573
Lithosols	1	3.8	9.3	2.4	12.1	0.5	450
Luvisols	2	2.4	16.6	0.2	14.9	31.2	600
Xerosols	1	0.9	32.2	4.3	14.0	50.5	375
Sub-Humid and Mountain East							
Acrisols	1	0.8	45.6	6.6	22.2	74.4	1,400
Cambisols	3	3.9	33.0	5.9	22.1	61.0	1,298
Ferralsols	1	4.5	40.6	7.2	22.9	70.7	1,390
Luvisols	1	1.2	31.8	3.7	15.2	50.7	700
Nitosols	2	1.3	31.4	4.5	15.3	51.2	1,450
Regosols	2	1.2	23.5	4.0	10.5	38.0	608
Sudano-Sahelian							
Arenosols	1	11.6	30.7	4.5	12.3	47.5	450
Cambisols	2	1.4	30.2	2.5	12.0	44.7	639
Ferralsols	1	0.3	34.8	7.3	12.0	54.1	1,125
Luvisols	1	2.2	30.9	4.0	19.2	54.0	1,060
Regosols	2	1.3	42.8	8.2	17.3	68.3	550
Vertisols	3	0.5	35.6	6.7	19.9	62.2	820
Yermosols	1	0.7	44.3	5.5	34.4	84.2	300
Sub-Humid and Semi-Arid Southern							
Acrisols	2	0.5	32.2	3.2	12.3	47.7	475
Arenosols	2	3.8	17.7	1.3	14.5	33.5	800
Cambisols	2	2.0	29.7	5.0	14.7	49.5	706
Ferralsols	1	4.6	34.9	5.3	18.7	58.9	1,071
Luvisols	2	3.5	20.6	4.1	16.8	41.5	781
Vertisols	1	0.7	44.6	8.1	21.1	73.8	1,060

a. Fertility Class: 1=Low; 2=Moderate; 3=Good.

NPK: $(N+P_2O_5+K_2O)$

the lack of water and low soil moisture retention. The soils in these areas degrade rapidly with intensive cropping. Mixed maize-based cropping systems with very low use of external inputs, usually in combination with cattle and sheep production are the typical farming systems in most of these areas. Cultivation of soils in the Semi-Arid areas is highly risky because of the highly variable amounts and timing of annual rainfall and the dependency upon irrigation systems and rivers for more dependable sources of water for crop production.

Soils such as the Fluvisols that occupy a small area (5% or 10 million ha) are located in Sudan and Congo and some areas in North Africa, principally in Morocco and Algeria. These soils have nutrient depletion rates of 0 to 30 kg NPK/ha per year. With good management practices such as appropriate irrigation and drainage, sound crop rotations, and proper fertilization practices, these soils can be highly productive. Phosphate fertilization problems due to the alkaline nature of some of these soils are important constraints to agricultural production and the conservation and productivity of agricultural land areas.

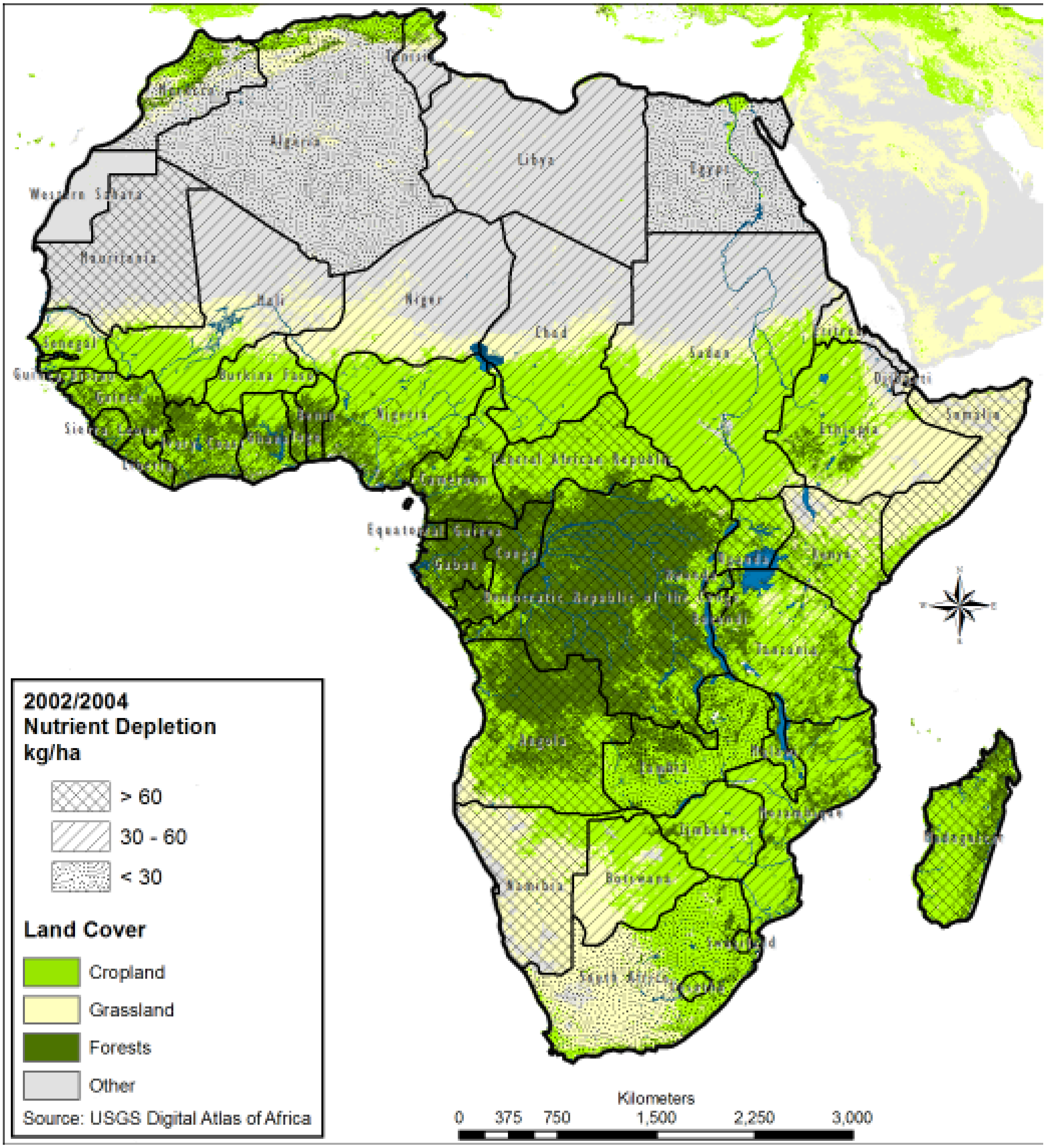
Agricultural areas with Cambisols and Vertisols occupy about 15% or 30 million ha of the agricultural land across North Africa, the Sudano-Sahel, and Southern Africa. Some of these soils have good soil fertility and are extensively and intensively used for the production of food crops and for range and seasonal grazing. Nitrogen is the most limiting nutrient. Nutrient depletion ranges from about 24 kg NPK/ha per year in irrigated and well-managed soils in North Africa to 74 kg NPK/ha per year in other areas such as in the Sudano-Sahel and the Semi-Arid Southern Africa.

Increases in agricultural productivity in Africa are possible if the environment is protected and if natural resources are conserved. In cases where soil nutrient mining is a key practice in the production of food crops, natural resources are depleted. Grasses, trees, hedgerows, and shrubs do more than provide food, energy, and animal fodder; they also help to conserve soil fertility for the cultivation of crops, prevent erosion, conserve water resources, counteract climate changes, and provide habitat for wildlife. Yet the process of environmental degradation is widespread in Africa, and it is fueled with the mining of nutrients from soils in forest areas and marginal lands where extensive agriculture with low inputs is becoming a common practice.

The evidence is abundantly clear that the very resources on which African farmers and their families depend for welfare and survival are being undermined by soil degradation caused by nutrient mining and associated factors such as deforestation, use of marginal lands, and poor management practices. About 50,000 ha of forest and 60,000 ha of Africa's grassland are lost to the extensive spread of agriculture yearly. There are about 40 million ha of forest and grassland areas that are in danger of being degraded because of the increased demand for agricultural land for crop production. The extensive practice of agriculture with low fertilizer use and the clearing of forest and grassland is one aspect of nutrient mining and land degradation in the tropical forest, savannahs, and wetlands. This extensive, rather than intensive, development of agriculture in Africa is characteristic of the Humid and Sub-Humid regions that predominate in the Sudano-Sahel—Cameroon, Ghana, Nigeria, Congo, Sudan, and part of Uganda and Tanzania (Figure 8). The nutrient recycling mechanisms that sustain soil fertility are insufficient to support increased production without fertilizers. More land is being degraded annually in Africa through the practice of extensive, low-input agriculture, the most notable characteristic of which is soil fertility declining to levels unsuitable to sustain economic production. The practice and productivity of intensive agriculture are severely limited without adequate availability and use of fertilizers.

2. Impact on Crop Production Systems

The complex interaction of climate, water availability, and soil fertility in managing crops, soils, and crop pests determines the productivity of crop



Source: USGS Digital Atlas of Africa

Figure 8. Nutrient Mining Associated with Land Cover in Africa

production and the long-term conservation of the resource base in most agro-ecological regions of Africa. Decisions in managing crops, soils, and pests also affect the success or failure of agricultural practices and farm production systems. The geographical distribution of diverse cropping systems is strongly associated with prevailing patterns of climate. For instance, in the Arid and Semi-Arid savannahs of Africa, mixed systems of millet (*Panicum spp*), sorghum (*Sorghum bicolor.* Moench), and some maize (*Zea mays* L.) are the most important crop production systems (Figure 9). In these areas, nutrient mining is high (40 to 85 kg of NPK/ha per year) affecting about 45 million ha of agricultural land; the use of mineral fertilizers is very low (less than 10 kg/ha per year of NPK) and the recycling of nutrients is limited or not practiced.

In other areas such as in Senegal, Burkina Faso, Mali, and Ghana in West Africa and Ethiopia, Kenya, and Tanzania, the increased use of mineral fertilizers has contributed to some recycling of nutrients and a better use of organic matter residues. The nutrients tend to accumulate very slowly in the soils, particularly in soils under the savannah vegetation. These nutrients, which have an important beneficial impact on soil fertility, are lost when the vegetation is cleared and land use is intensified. Small farm holders grow millet, maize, and sorghum mixed systems because the cropping period is very short and, in many instances, because the crop production season coincides with a period of drought. Initial, intensive crop production typically decreases within a few years as soil fertility will naturally decline with continuous crop production, if there adequate amounts of fertilizer are not applied.

The Guinea Savannah zone occupies most of the Sub-Humid wooded savannah (about 65 million ha) at the border of the Semi-Arid zone. Cereals and

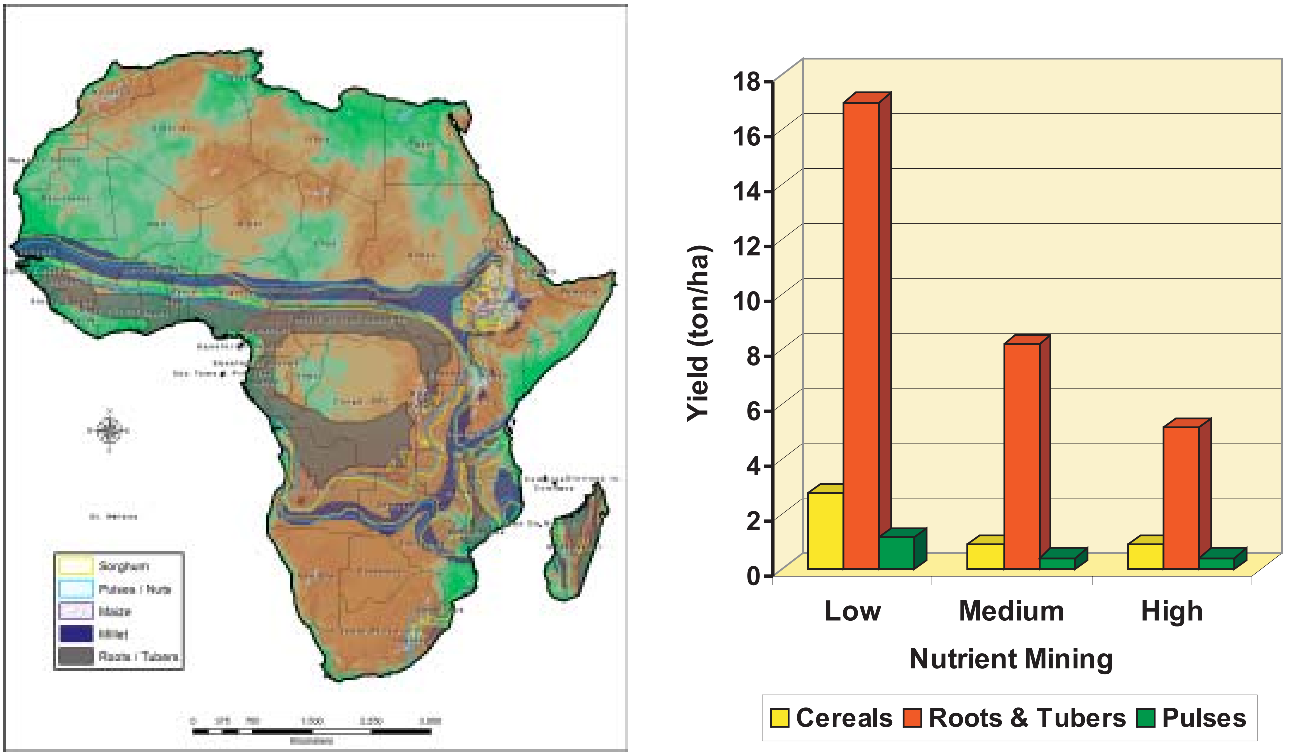


Figure 9. Cropping Systems and Nutrient Mining Systems in Africa

root crop mixed systems are predominant in a zone that enjoys greater rainfall than the Sahelian or Sudan Savannah, but the rainfall is often concentrated over a few months. When this occurs on deep soils that store more water, vigorous grasslands are supported often on more fertile and less nutrient-depleted soils. Soil nutrient mining in this area is quite prevalent and ranges from 35 to 74 kg of NPK/ha per year, limiting crop yields. The Guinea Savannah merges into the Derived Savannah, which is followed by the Drier Forest, and the moist and very Humid Forest, as the rainfall and number of wet months increase. As rainfall increases in these zones to more than 1,500 mm/year, the soils become increasingly more acid and are often depleted of nutrients. Root and tuber crop systems and mixed cereal and pulse systems are common in small farms. Nutrient mining occurs frequently in these systems because farmers use very little fertilizer and use the land quite intensely; nutrient mining in these systems ranged from 30 to 65 kg NPK/ha per year, resulting in declining yields.

Agricultural lands in the Semi-Arid zone of West Africa and in East and Southern Africa, from Somalia and Ethiopia to Southern Africa, occupy an area of about 50 million ha where rainfed sorghum, millet, and pulses are important sources of food. The productivity and conservation of the agricultural land in these areas are adversely affected by high rates of nutrient mining that vary between 30 and 90 kg NPK/ha per year. The consequences of soil management practices, and particularly, nutrient mining, on the cropping systems and land productivity in these regions are aggravated by the highly variable rainfall, both in timing and amount, erosion, and lack of water that prevails in the whole region.

Average cereal yields of 1 t/ha or less in sub-Saharan Africa are mainly affected by medium and high rates of nutrient mining (Figure 9). These yields were in 2000/2004 about 15% lower than the world average of 1.2 t/ha in 1965. Other important food crops such as tubers and pulses are also affected by nutrient mining practices and have low yields. It was observed that agricultural production and the productivity of basic food cropping systems have stagnated or declined for important crops such as cereals, root and tubers, and pulses; soil nutrient mining being a major factor contributing to such productivity decreases. Crop yields in most African soils, particularly in sub-Saharan Africa, are about the same or less than 20 years ago. Yields of cereals are the lowest among developing countries in the world (Figure 10). The low productivity of cereals in sub-Saharan Africa represents a serious threat to food security and the economic development of countries in this region.

Nutrient mining effects on crop productivity are compounded by climatic changes affecting agricultural lands, particularly in sub-Saharan Africa. The climatic variability influences the length of the growing period (LGP) and restricts the diversity of the cropping systems and the use of appropriate crop and livestock management practices. In areas with limited diversification of cropping systems, farmers grow crops mainly for their own consumption with little or no extra production reserved for seed and trade in local markets. Agriculture in these areas is characterized by its low productivity, particularly in the production of cereals where the observed LGP varies between 0 and 145 days. To survive during part of the season, farmers have to use diversified farming systems that include livestock production or crops intensively cultivated on marginal lands and wetlands with limited resources, or they rely on part-time, off-farm employment to earn money to purchase food and other goods and services.

Arid climates with growing periods of less than 75 days dominate most of the Sudano-Sahelian region where rates of nutrient depletion can reach up to 60 kg NPK/ha per year. Without irrigation, an appropriate, economic use for this land is extensive grazing. Other contrasting areas in west and central Africa are characterized by moist climates with LGP >270 days and where excess water, high variability in soils and management practices limit yields and decrease soil fertility. The climate in more humid areas allows diverse crop-

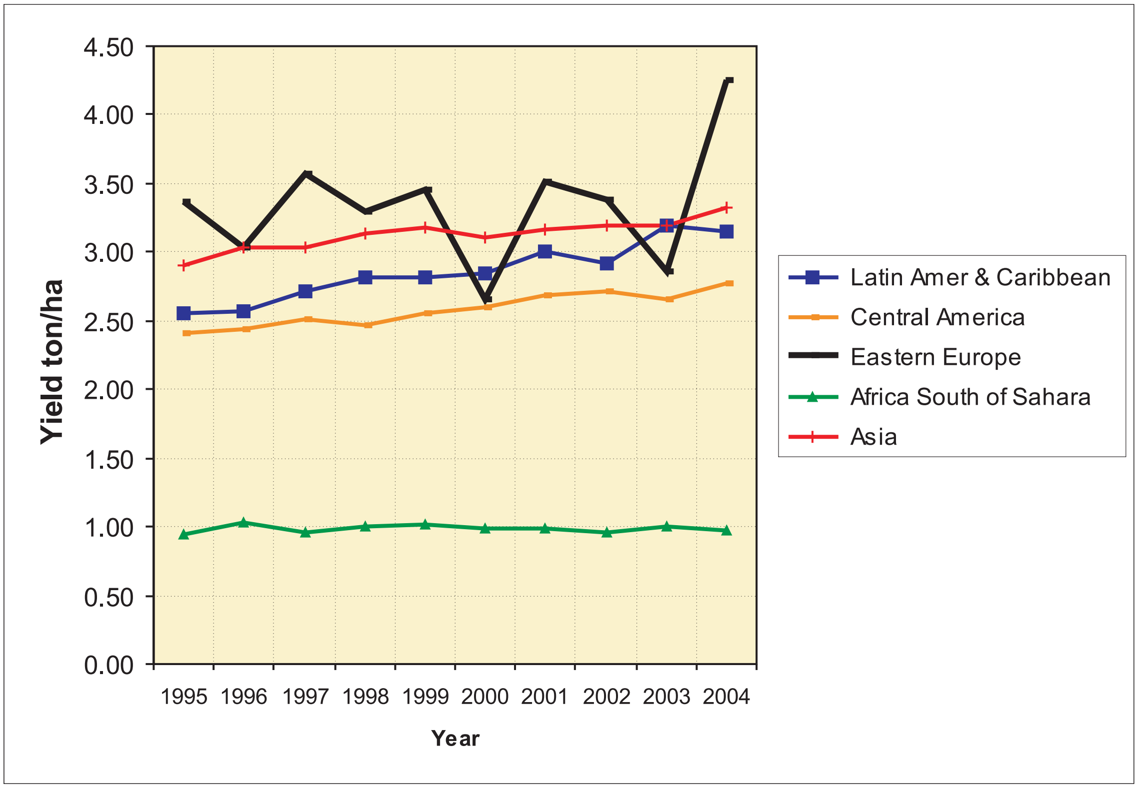


Figure 10. Yields of Cereals in Selected Developing Regions

ping systems. In these areas, soils have better fertility, but poor management practices and acidity are usually the main sources of the large variability in rates of nutrient depletion. Nutrient depletion rates in these regions varied during the 2002/2004 cropping seasons from 30 to more than 80 kg NPK/ha per year.

3. Intensification of Agriculture, Carrying Capacity of the Land, and Nutrient Mining

Continued population growth migrations caused mainly by low production and drought, and the limitations of land resources in Africa have accelerated the degradation of agricultural land. Estimates of the actual supporting capacity of the land were calculated using crop area and population data (FAO, 2004c) and data from the Center for International Earth Science Information Network (CIESIN, 2004) and by assuming a limited use of inputs (rainfed production without mechanization, mineral fertilizers or major conservation practices) and the calculated levels of nutrient mining across Africa. These estimated supporting capacities for human populations are presented in Figure 11 and show that the average estimates of supporting capacity in terms of population density ("carrying capacity") range from less than 0.1 to 5.0 persons/ha. This means that the current high rates of population density in many countries are already pressuring the land at levels that exceed its long-term population-carrying capacity.

The common causes of agricultural land degradation associated with high population pressure in sub-Saharan Africa are the inappropriate use of land and poor crop management practices, such as the continuous cultivation of crops without external inputs or the continuous cultivation and grazing on steep slopes without conservation measures. Other additional causes of agricultural land degradation associated with nutrient mining and high population densities, observed mainly in

Semi-Arid areas, are deforestation and overuse of marginal lands for grazing and crop production.

Figure 11 shows that most countries in which there is intensive nutrient mining (more than 30 kg/ha of NPK per year) have agricultural land where population pressure exceeds the potential capacity of the land for crop production. The variation of population density in agricultural land areas is the highest in the fragile soils (Ferralsols, Acrisols, and Arenosols) of the Semi-Arid areas in West and East Africa. In these areas population density varies from as low as 5 persons/ha in Semi-Arid areas of East Africa to as much as 150 persons/ha in some Semi-Arid areas of West Africa. High population densities also occur in Humid and Sub-Humid areas in the coastal areas in West Africa and in some fertile areas in East Africa in Ethiopia, Kenya, Uganda, Mozambique, Tanzania, Burundi, Rwanda, Namibia, and Angola. These areas also have high rates of nutrient mining.

Relative overpopulation occurs in areas where crop production potential is low because of climate, low soil fertility, and other edaphic constraints. Generally soils in over-populated areas are being overused. This is the case of some agricultural lands on soils which have developed on coastal sediments in Senegal, Gambia, Togo, Benin, Nigeria, Somalia, Kenya, and Mozambique. Nutrient depletion in these areas ranges from as low as 30 to as much as 120 kg NPK/ha per year. Most of the rural population in the Semi-Arid West and in Southern Africa is concentrated on coastal rivers and alluvial plains of dry savannahs. The carrying capacity of land along coastal rivers and alluvial plains of dry savannahs of Africa is very low (<1 person/ha) and the nutrient depletion can go up to 100 kg NPK/ha per year in agricultural areas of Mali, Burkina Faso, Nigeria, Ethiopia, Somalia, and Kenya. In the Sub-Humid wooded savannah and forest zones in Central Africa Republic, Equatorial Guinea, Gabon, and Congo, the population per unit of area is higher in specific areas, and these areas are scattered and experience high rates of nutrient mining. High concentrations of people are also observed on the more fertile soils of coastal areas in Madagascar.

Soil degradation and nutrient mining causing nutrient depletion have been particularly severe (30 to 60 kg NPK/ha per year) in the Sudano-Sahelian countries where the low carrying capacity of the land (<0.1 person/ha) has resulted in the cultivation of marginal lands. The land has also been additionally overexploited through deforestation and overgrazing.

Very low depletion of nutrients occurs in some agricultural land areas of Libya and Egypt. In these areas the capacity of the land to support humans is low, but there is high use of fertilizer nutrients. Humid areas with moderate nutrient depletion are located in Central Africa Republic, south of Sudan, Uganda, Congo, and Zambia. The capacity of these areas to support humans (0.1 to 1.0 persons/ha), lack of proper infrastructure, the climate, and human and animal diseases are serious constraints to the sustainable development of agriculture in these areas.

The association of nutrient mining and food production and nutritional indicators across Africa are presented in Table 9. African countries are importing food to meet demands of their population. According to FAO statistics (FAO, 2004c), Africa imported about 43 million t of cereals at a total cost of US $7.5 billion during 2003. From the total cereal imports, sub-Saharan countries (excluding South Africa) imported 19 million t at a total cost of US $3.8 billion. Assuming that the current agricultural land management practices will not change dramatically until 2020 and assuming that the population of Africa will continue to increase, it is projected that Africa will be importing about 60 million t of cereals, which could cost about US $14 billion. The sub-Saharan Africa (excluding South Africa) countries will be importing about 34 million t of cereal at a total cost of about US $8.4 billion by 2020. A part of the imports is used to satisfy demands for animal feed, but most is used to satisfy increasing demands of the human population for food. Low food production mainly in cereals and imports of other

Figure 11. Associating Nutrient Mining and Land Population Density in Africa

food products to meet increased demands has had a great impact in the countries' economies and made food security strategies very risky and difficult to implement.

As observed in Table 9, all African countries import food to satisfy domestic demands. Increasing food availability is one of the objectives in achieving food security. However, the production of food per hectare is still too low to satisfy minimal nutrition requirements in most African regions. This situation is aggravated in countries with high rates of nutrient mining. The productivity of crop production expressed in kilograms per hectare is particularly low in countries with high rates of nutrient mining such as the Sudano-Sahelian countries and the Humid and Sub-Humid West and Central areas and in East Africa. Countries such as Congo, Gabon, Liberia, Sierra Leone, Eritrea, Rwanda, and Botswana continue to import large quantities of cereals for food. North African countries have lower rates of nutrient mining and depletion and higher productivity, or production of food per hectare. North Africa is a major importer of coarse grains, mainly for animal feed.

The impact of nutrient mining on the capacity of soil to sustain population and production has additional long-term consequences besides the current loss of productivity and the exodus of farmers to other areas. According to nutritional indicators (FAO, 2004c), about 33% of people in sub-Saharan Africa are undernourished, compared with about 6% in North Africa and 15% in Asia. Most of the undernourished are in Eastern Africa, which is also a region with high rates of nutrient mining. In these areas more than half of the population shows rates of malnutrition between 10% and 50%. Africa's nutritional levels, measured in calories per person per day, show that levels in all countries are below a basic level of 2,500 kilocalories per person per day. Crop cereals provide more than 60% of these calories in the Semi-Arid and Sub-Humid areas, while animal products provide 5%–30%. Roots, tubers, and plantation crops provide most of the calories in Humid regions. Data presented in Table 9 show Egypt in North Africa with the highest amount of calories and protein consumption, while most countries have calorie consumption rates of less than 2,000 kilocalories and 40 grams of protein per person per day. A general assessment by FAO predicts that the nutritional levels of most people in sub-Saharan Africa, especially among adults who work the land and young people, will drop below minimum acceptable levels (1,600 kilocalories) if the decline of agricultural production continues in this region. Low yields in nutrient-mined areas seem to be an important factor contributing to the poverty and malnutrition that exist in some areas of sub-Saharan Africa.

Stagnant agricultural production, high erosion rates, deforestation and desertification have a reinforcing effect that traps African agriculture in a downward spiral. These symptoms appear throughout African farming regions and are symptoms of nutrient depletion and high population pressure. Agricultural land is being seriously degraded. Population growth in most of the agricultural regions of Africa continues to increase the demand for food and services and the migration of individuals who can no longer be supported by the degraded soil resources in the African countryside. This migration to other rural areas or to urban centers is becoming an increased source of concern. If current nutrient mining rates and degradation of land continue, it is very difficult to foresee how farmers in African countries will be able to have enough productive soil to grow adequate food and feed for the more populous urban centers and the rural areas of Africa during the next century.

4. Agricultural Practices to Reverse Nutrient Mining

For many African countries, the main challenge facing agriculture is how to increase the productivity of the large area of soils that are already being degraded. In this context, controlling erosion, developing and using irrigation where appropriate, producing and using improved seeds and mineral fertilizers, and using crop protection products

Table 9. Nutrient Mining, Imports and Productivity of Cereals, and Nutritional Indicators

Region/Country	Imports	Production	Food	Nutrition Index[a]		Soil Mining
	(t)	(kg/ha)	(kg/ha)	(Cal/Per/Day)	(Pro/Per/Day)	(kg NPK/ha)
Humid Central						
Cameroon	644,679	183	225	931	23.6	–44
Central African Rep.	42,440	237	250	449	11.8	–69
Congo Dem. Rep.	708,078	188	247	312	8	–68
Congo	245,588	19	622	611	16.6	–64
Gabon	74,377	146	672	938	22.5	–69
Humid and Sub-Humid West						
Benin	275,723	471	293	947	24.2	–44
Côte d'Ivoire	1,189,290	209	287	1,089	25.9	–48
Ghana	681,362	347	346	791	19.9	–58
Guinea	484,418	402	453	1,046	24.2	–64
Guinea Bissau	93,148	291	455	1,214	26.4	–73
Liberia	251,030	146	585	746	16.4	–66
Nigeria	3,980,306	454	389	1,253	32.8	–57
Sierra Leone	250,913	300	709	1,003	21.8	–46
Togo	201,726	481	416	1,158	30.6	–47
Mediterranean and Arid North						
Algeria	6,936,984	917	1,567	1,760	52.2	–28
Egypt	8,208,824	1,909	1,843	2,135	57.2	–9
Libya	1,733,711	288	1,544	1,588	41.7	–33
Morocco	3,437,257	1,044	999	1,896	56.2	–27
Tunisia	2,330,046	368	319	1,626	48.7	–42
Sub-Humid and Mountain East						
Burundi	73,049	200	175	294	7.5	–77
Eritrea	373,871	184	809	1,009	29.5	–58
Ethiopia	1,939,143	853	972	1,270	34.5	–49
Kenya	808,829	623	748	1,060	28.2	–68
Madagascar	370,389	790	756	1,174	26.4	–65
Mauritius	301,468	2	2,445	1,373	32.9	–15
Rwanda	47,516	183	171	281	7.5	–77
Uganda	336,197	358	253	533	12.2	–66
Sudano-Sahelian						
Burkina Faso	238,585	756	623	1,855	50.7	–43
Chad	75,136	390	328	1,092	30.4	–57
Djibouti	156,556	1	10,889	1,179	31	–50
Gambia	117,499	464	550	1,207	30.9	–71
Mali	162,739	573	559	1,611	39.2	–49
Mauritania	315,880	387	1,462	1,412	38.6	–63
Niger	269,521	277	224	1,549	33.5	–56
Senegal	1,304,954	485	601	1,435	34	–41
Sudan	908,175	571	400	1,145	32.6	–47
Sub-Humid and Semi-Arid Southern						
Angola	2,026,933	323	1,170	659	17.7	–70
Botswana	182,134	69	387	1,034	28	–47
Lesotho	88,854	843	2,074	2,066	56.6	–65
Malawi	147,261	730	614	1,277	33.5	–72
Mozambique	749,212	381	448	899	23	–51
Namibia	142,527	304	696	1,012	27.3	–73
South Africa	2,343,674	1,500	1,043	1,570	41.2	–23
Swaziland	115,038	351	657	1,082	28.5	–37
Tanzania	799,383	486	496	998	24.1	–61
Zambia	236,945	433	533	1,302	34.7	–25
Zimbabwe	636,726	311	391	975	26.1	–53

a. Cal/Per/Day: Calories per person per day – Prot/Per/Day: Protein per person per day.

NPK: (N+P_2O_5+K_2O)

Source: FAO, IFDC.

are essential components of yield-enhancing technologies that can be used to reduce the need for additional land to support the food and nutritional needs of the population.

Increased use of mineral fertilizer may be viewed as the centerpiece of the technologies that can be adopted to balance inputs and outputs of the soil's essential plant nutrients to improve soil productivity. However, the use of fertilizers must be combined with a broader spectrum of complementary technologies that assure the conservation of natural resources and an efficient and economically sustainable maintenance of soil fertility. Some of these technologies include:

- Cropping system management strategies. While it is difficult to generalize, given the diversity of cropping systems, four farming systems (World Bank, 2003; Dixon et al., 2001) are considered more prevalent in Africa from the point of view of the economic value of production, maintenance of soil productivity, and food requirements. Those systems are maize mixed; cereal/root and pulse crop mixed; irrigated, tree crop based, highland perennials; and large commercials. It is possible that by introducing improved and available management techniques on most of these crop-based systems, productivity (production per unit area, or yield) and production can be increased. For example, in Semi-Arid regions, some of these cropping systems could incorporate drought-tolerant varieties or species with higher water and fertilizer use efficiency and improved nutrient uptake (major and minor nutrient requirements). Other rural production systems to consider are those associated with livestock or mixed crop-livestock, which are prevalent in the Arid/Semi-Arid, Humid, Sub-Humid and Tropical Highlands of Eastern, Central, and Southern Africa. The use of cropping systems including both annual and perennial crops will allow farmers to produce food crops, while in the longer term, perennial crops can be established to diversify income sources and reduce farming risk in small-farm areas.
- Intercropping and crop rotation systems can be used to increase soil nutrient pools, and soil conservation practices can be employed to reduce the loss of organic matter and increase biomass production. The success of these systems depends on climatic variables such as temperature, solar radiation, and rainfall as well as on the choice of crops, the use of suitable varieties, the cropping sequence, and soil management practices. In suitable climates, crop rotation can improve soil productivity and can restore organic matter, especially where legumes supplemented with adequate nutrients and weed and pest control practices are included. Rotating an improved fertilizer-efficient maize variety with a nitrogen fixing crop can, under certain conditions, dramatically increase maize yields. This rotation can also be used as one of several means to provide integrated control of *Striga*, a parasitic weed prevalent in large areas of sub-Saharan Africa.
- Soil-management practices such as agro-forestry can be used to reduce erosion and improve soil structure, reduce runoff, and improve retention of soil moisture. Tillage practices that reduce erosion and enhance infiltration water and soil amendments that correct acidity in Acrisols and Ferralsols in Sub-Humid and Humid areas are examples of valuable soil-management techniques.
- Soil fertility can be improved by practices such as incorporation of crop residues, use of cover crops, addition of green and animal manure, and where possible, fallows. Cover crops can also serve as fodder-banks for livestock; the most promising are legume species, such as *Mucuna, Pueraria, and Centrosema,* which add nitrogen to the soil, reducing the amount of nitrogen required as mineral fertilizer. The above techniques can be applied through an integrated nutrient management approach that should be tailored to soil-management requirements and the agro-ecological areas and socioeconomic circumstances of the prevailing local farming systems.

- Associated with the use of essential plant nutrients and other inputs in cropping systems is the management of limited resources such as water, which is composed of two essential plant nutrients—hydrogen and oxygen. Although a limited component of the water management strategy in Africa, irrigation systems have played a major role in increasing productivity in some cropping systems. Due to irrigation, productivity increases have been significant and consistent over the past decades in farming systems in North Africa and Southern Africa. Africa has about 42.5 million ha of land which has the potential for agricultural production, and only 30% is irrigated. However, over 50% of the agricultural land currently under irrigation needs rehabilitation. Some methods of irrigation, such as using center-pivot irrigation, require very costly investments. However, a more cost-effective strategy for additional investments in water management, particularly in Semi-Arid and Sub-Humid areas, would be to focus on less costly water-harvesting techniques such as soil surface management practices (ditching, leveling, stone bunds on slopes, and earth bunds) and conservation (reduce) tillage. Small-scale irrigation systems are becoming a cost-effective alternative for enabling crop diversification in inland valleys and in high value crops in some areas in West and East Africa. Generally, farmers who use techniques to conserve moisture or increase soil organic matter are more likely to use mineral fertilizers and reduce nutrient mining.
- Combined with the practices above, the use of mineral and organic fertilizers is essential to eliminate nutrient mining, minimize land degradation and improve the productivity of soil resources. Mineral fertilizer use must be substantially increased, and better use of organic residues and manure is necessary to increase yields and to restore and then maintain soil fertility where crops are produced, particularly in sub-Saharan Africa. Integrated strategies of soil fertility management that include increasing use of mineral fertilizers and soil amendments are being adopted for production of food crops in Sub-Humid West Africa and the Sub-Humid East Africa.

5. An Assessment of Mineral Fertilizer Requirements

Fertilizer use in Africa is very low compared with other agricultural production areas in the world. For example, fertilizer consumption in Latin America currently amounts to about 70 kg of NPK/ha per year, South Asia consumption is greater than 100 kg NPK/ha per year; farmers in Southeast Asia apply an average of 70 to 80 kg NPK/ha per year. Farmers in developed countries which are characterized for their high productivity apply more than 200 kg NPK/ha per year. Farmers in Africa apply an average of 21.3 kg NPK/ha per year, and in sub-Saharan Africa (excluding South Africa) 8.8 kg NPK/ha per year, on average (Table 5). Mineral fertilizer requirements (recommendations) for Africa are needed to eliminate mining of the soils. Fertilizer recommendations should be devised according to productivity goals, taking into account the effects of other aspects of soil management, such as irrigation and application of soil amendments (Jansen et al., 1990; Vlaming et al., 2001).

An assessment of fertilizer requirements for nitrogen, phosphorus and potassium, which are three of the sixteen essential plant nutrients, based on some of the above factors and the current nutrient mining situation is presented in Table 10. Africa will require approximately 9 million t of NPK mineral fertilizers to drastically reduce nutrient mining and notably increase current average levels of production and productivity of crops. Of this total, North Africa will require about 1.6 million t (17%), South Africa about 683,000 t (8%), and sub-Saharan Africa will need about 6.8 million t (75%). Because each of the sixteen plant nutrients affects the uptake and utilization of the other fifteen, it should be recognized that while nitrogen, phosphorus, and potassium are essential for crop growth, other nutrients such as sulfur, manganese, zinc, and boron are also essential.

Average nitrogen requirements per year in North Africa range from 36 kg/ha in Libya to 126 kg/ha in Egypt. Phosphorus (P_2O_5) requirements range from 8 to 16 kg/ha, and potassium (K_2O) requirements range from 15 to 26 kg/ha per year. The total amount of NPK required annually in North Africa ranges from 58 kg NPK/ha in Algeria to 167 kg NPK/ha in Egypt.

Plant nutrient requirements in South Africa are, on average, met by amounts currently used in the country's fertilization practices and amount to about 111 kg/ha per year. However, it is important to recognize, when considering average NPK fertilizer application in South Africa, that there are crop production areas in the South that lack adequate amounts of fertilizer, while others have more than adequate fertilizer applied. There is a dramatic and widespread need for fertilization of crops in most sub-Saharan African countries. This is due to continuous crop production with very low rates of fertilizer application in the region. Total requirements of the three major, essential plant nutrients per hectare per year in sub-Saharan Africa range from 44 kg NPK/ha in Eritrea to 66 kg NPK/ha in Gabon in Humid Central Africa. The total amount of fertilizer (NPK) required in sub-Saharan Africa is about 6.7 million t (Table 10) in 166,000 ha of agricultural land. This is equivalent to about 40 kg/ha of NPK per year.

The total amount of nitrogen required in sub-Saharan Africa is estimated at 4.17 million t per year. Rates of nitrogen use required to significantly increase production, reverse nutrient mining, and increase productivity in sub-Saharan Africa range from 24 kg N/ha in Djibouti to more than 30 kg per ha in most countries in Humid Central Africa. Most countries in Africa have high requirements of nitrogen; those include Nigeria, Ghana, and Senegal in West Africa; the Sudano-Sahelian countries, Zambia, and Kenya in East Africa. Total phosphorus (P_2O_5) requirements are lower than the requirements for nitrogen and potassium. The total amount of phosphorus as P_2O_5 required in sub-Saharan Africa is estimated to be 800,439 t. Phosphorus requirements range from 4 kg P_2O_5/ha in Botswana and Equatorial Guinea to 11.0 kg P_2O_5/ha in Zimbabwe and Zambia and 13 kg P_2O_5/ha in Swaziland. Applications of potassium are not practiced in most countries in sub-Saharan Africa. However, high rates of nutrient mining principally in areas dedicated to the production of food crops are evident. It is estimated that to significantly impact crop production and essentially eliminate nutrient mining, at least 1.8 million t of potassium (K_2O) will be required. Potassium requirements range from 9 kg K_2O/ha in Botswana and Eritrea to more than 20 kg K_2O/ha in countries in Humid Central Africa.

Most of the nutrient mining and balance estimates in this study are negative and require integrated strategies in mineral fertilizer use and other coordinated action programs. The nutrient requirements estimated in this report are based upon the premise that nutrient mining is to be eliminated, namely that the amounts of essential plant nutrients added to the soil will equal the amounts of those nutrients which are removed by crops. The requirements estimated in this study to increase yields to be greater than those of the current low crop productivity should be taken as basic general recommendations to be considered in conjunction with other crop management practices and socioeconomic circumstances. These recommendations are intended to estimate needs for mineral fertilizers to balance the output of three essential plant nutrients (N, P, and K) from cropping systems with inputs of those three nutrients. High doses of fertilizer applied to local crop varieties with low yield potential, without proper water management, can increase nutrient losses due to erosion, leaching and volatilization. It is advisable to evaluate the availability of plant nutrients in the soil and recommend methods and rates of fertilizer application in conjunction with other practices of managing the crop and soil to minimize nutrient losses, maximize fertilizer use efficiency, and increase the likelihood of economically sound and environmentally sustainable crop production.

Table 10. Estimated Fertilizer Requirements According to Nutrient Mining in Soils of Africa

Region/Country	Area	N	P_2O_5	K_2O	NPK	N	P_2O_5	K_2O	NPK
	('000 ha)	(kg/ha)				(t)			
Humid Central									
Cameroon	3,697	31	5	12	47	90,505	14,197	35,492	140,193
Central Africa	803	36	6	12	54	23,132	3,855	7,968	34,955
Congo Dem Rep.	5,968	38	5	16	60	181,426	24,827	78,299	284,552
Congo Rep.	228	35	5	25	64	6,372	892	4,460	11,724
Equatorial Guinea	110	35	4	22	62	3,072	386	1,966	5,424
Gabon	210	37	6	23	66	6,143	959	4,006	11,108
Humid and Sub-Humid West									
Benin	2,665	31	5	16	51	65,452	10,233	33,046	108,731
Côte d'Ivoire	5,978	30	5	13	48	144,427	24,868	62,171	231,466
Ghana	5,806	30	7	16	53	140,283	33,909	71,999	246,191
Guinea	2,161	33	6	16	55	56,864	10,716	27,654	95,235
Guinea Bissau	422	32	5	15	52	10,728	1,754	5,060	17,543
Liberia	456	32	6	19	57	11,685	2,118	6,938	20,741
Nigeria	45,387	31	6	12	49	1,111,074	217,858	435,715	1,764,647
Sierra Leone	585	33	6	15	54	15,577	2,620	7,017	25,214
Togo	1,590	30	5	13	48	38,678	5,725	16,794	61,197
Mediterranean and Arid North									
Algeria	4,439	36	8	15	58	126,078	26,636	53,983	206,697
Egypt	5,841	126	16	26	167	588,752	72,893	120,087	781,732
Libya	740	36	10	15	60	21,137	5,921	8,585	35,643
Morocco	7,630	36	13	16	65	220,965	76,300	97,664	394,929
Tunisia	3,963	31	12	17	60	97,957	38,042	53,892	189,891
Sub-Humid and Mountain East									
Burundi	1,134	33	9	15	57	30,108	8,162	13,603	51,872
Eritrea	501	31	5	9	44	12,235	1,885	3,410	17,530
Ethiopia	10,173	29	5	16	49	231,936	38,249	130,210	400,395
Kenya	3,975	31	7	12	49	96,990	21,624	38,160	156,775
Madagascar	2,798	39	7	16	62	87,302	23,952	36,488	147,741
Mauritius	80	40	6	20	65	2,570	353	1,259	4,182
Rwanda	1,619	36	5	20	60	45,966	6,604	25,249	77,818
Uganda	6,629	35	7	17	59	185,626	38,186	87,509	311,321
Sudano-Sahelian									
Burkina Faso	4,763	30	9	14	53	114,697	32,390	54,110	201,197
Chad	3,127	35	6	15	55	86,568	14,261	36,529	137,357
Djibouti	4	24	6	16	46	83	20	54	157
Gambia	280	36	8	16	60	8,015	1,746	3,582	13,344
Mali	4,253	31	7	15	52	104,446	22,454	50,352	177,253
Mauritania	249	35	5	14	53	6,938	917	2,791	10,646
Niger	11,467	33	6	14	53	301,821	55,961	128,435	486,216
Senegal	2,332	29	6	15	50	53,539	11,939	27,982	93,460
Sudan	11,701	30	5	13	48	281,765	43,997	120,756	446,518
Sub-Humid and Semi-Arid Southern									
Angola	2,668	34	5	16	56	73,198	11,097	34,785	119,079
Botswana	235	25	4	9	38	4,729	788	1,595	7,112
Lesotho	292	38	7	10	55	8,878	1,519	2,360	12,756
Malawi	2,975	39	8	17	63	92,804	17,847	40,215	150,867
Mozambique	4,275	30	5	16	52	103,963	17,783	55,743	177,489
Namibia	286	35	6	10	51	8,040	1,420	2,291	11,751
South Africa	7,695	75	15	21	111	461,706	94,188	127,431	683,325
Swaziland	149	47	13	16	75	5,543	1,487	1,879	8,910
Tanzania	6,880	38	7	13	57	206,406	35,777	68,802	310,985
Zambia	1,340	35	11	13	59	37,506	11,466	13,716	62,689
Zimbabwe	2,686	35	11	11	57	75,207	23,637	23,207	122,050
Total						5,688,890	1,114,419	2,265,298	9,068,607
Sub-Saharan Africa						4,172,294	800,439	1,803,656	6,776,390

NPK: ($N+P_2O_5+K_2O$)

V. Nutrient Mining and Policy Development

In previous sections of this paper, information showing the extent and trends of soil nutrient mining in agricultural lands of Africa is presented. This information clearly shows that in important areas of many sub-Saharan countries, nutrients in the soils of agricultural lands are mined to produce crops. Nutrient mining is widespread and pervasive and occurs as a result of the overexploitation of agricultural lands in important areas of Africa. The process of nutrient mining causes a gradual depletion of essential plant nutrients in the soil and represents the consumption of a key component of the natural capital in the soil. The propensity for nutrient mining to occur and the severity of its consequences on land resources are substantially higher in agricultural land with fragile soils and inherently low soil fertility. These are often the circumstances prevailing in many agricultural areas of Africa. In those areas, soil nutrient mining is usually associated with agricultural production occurring on fragile soils of marginal land without the use of modern agricultural inputs and under drastic constraints of poverty in terms of physical capital (infrastructure) and human capital (health and education). Under these conditions, nutrient mining is conducive to a future of increased poverty, food insecurity, and the continuous degradation of land resources and damage to the environment. Reversing these trends is a necessary condition to attain the improvements in crop yields and food production that are required to overcome and reverse the worsening of the food security situation in Africa.

Proper understanding of the nature and causes of soil nutrient mining is crucial to design policies and investment strategies to efficiently reverse soil nutrient mining, restore soil fertility, and increase land productivity and food production. Such policies and investment strategies must be viewed as key contributors to the joint goals of increased agricultural production, food security, economic development, land conservation, and environmental protection. In this section, implications for the design of policies to reverse current trends in nutrient mining and promote agricultural development are derived on the basis of: (1) current knowledge and information about the nature, trends, and present status of soil nutrient mining in agricultural lands of key agro-ecological regions and countries of Africa; and (2) the rationale offered by the economics of soil nutrient mining in Africa.

General Considerations for Policy Development in Africa—The design and implementation of effective policies and investment strategies must take into consideration the problem of poor governance and corruption that is an important issue in many countries in Africa. Transparency International rates 10 countries in Africa among the 20 most corrupt countries in the world (Transparency International, 2005). Poor governance and corruption can seriously undermine and render ineffective the best-designed and sound economic policy. Another important factor that must be taken into consideration is the fact that Africa, especially sub-Saharan Africa, is suffering the drastic impact of the HIV/AIDS epidemic on the human resource base and its consequences for labor productivity and the need for health care support.

1. The Economics of Soil Nutrient Mining and Policy Design

It is well recognized that the cumulative effects of nutrient mining over a sequence of cropping cycles cause soil nutrient depletion, land degradation and continuous decline in crop yields. Then over a number of years, land degradation can render agricultural land unsuitable for the economic production of crops. In important agricultural areas of sub-Saharan Africa, fallow periods involving several cropping cycles (and years) are often used as a means to restore soil fertility and crop yields during a second sequence of cropping cycles. In this type of agriculture, the cost of leaving the land fallow for a number of years, measured in terms of lost benefits, is in part the opportunity cost of the soil nutrients mined during the previous cropping sequence. However, these patterns of land use for crop production are usually associated with patterns of temporary migration among agricultural areas. Then, the opportunity cost of the nutrients mined in terms of the land's lost benefits would be very small and insignificant for these farmers.

With population growth, fallow periods have been continuously shortened, accelerating the detrimental cumulative effects of nutrient mining on soil fertility, crop yields, and land conservation. Because fallow periods are not long enough to replenish soil nutrients and restore fertility, the following usually takes place: (1) crop yields are lower than in the previous sequence of cropping cycles just before the fallow; and (2) the number of feasible cropping cycles in the sequence will tend to decline. Then, as soil fertility declines and land degradation accelerates, impoverished farmers are forced to permanently migrate to other more fragile areas and to the cities. As a result of this process, countries and society as a whole end up absorbing the cost of land degradation and environmental damage, i.e., the permanent loss of natural capital. Thus, the cumulative effects of soil nutrient mining are directly linked to a legacy of increased poverty and environmental damage for the present and future generations.

It is clear that population growth and current implicit economic incentives for farmers to mine soil nutrients to produce crops are contributing to the degradation of agricultural land in some important areas of Africa. The overexploitation of land resources in these areas as a result of population pressures and poor management is increasing the damaging consequences of soil nutrient mining on crop yields, food security, and conservation of the resource base. Thus, policies that can effectively and efficiently prevent the current overexploitation of agricultural land are essential to achieve the broader goals of agricultural and economic development and the conservation of the resource base. A key objective of policy makers in most countries of Africa is, therefore, the development and implementation of comprehensive policy and investment strategies that can successfully achieve such goals in the shortest possible time.

Rationale for Policy Design—Soil nutrient mining by farmers in some agricultural areas of Africa is explained by factors and circumstances that affect the economics of nutrient mining and the decision making of farmers with respect to the use of land and crop production inputs and technology. The main objective and motivation of these farmers is typically to grow crops to meet their very basic needs and those of their families by using plant nutrients from the most inexpensive source available to them. These decisions are usually taken by farmers under severe constraints in all forms of capital—natural capital, man-made physical capital, and human capital. Under these prevailing conditions, farmers grow crops by mining plant nutrients from the pool of nutrients in the soils, i. e., by using the most inexpensive nutrients available to them.

The cost of plant nutrients mined from the soil and used by crops in a cropping cycle is determined by the size of the economic returns to land given up during the following cropping cycles as a direct result of the mining of these nutrients. Thus, the cost of the nutrient mined in a given cropping cycle is determined by the present value of the stream of economic returns to land given up as a result of the impact of nutrient mining on crop production during the following cropping cycles.

The continuous mining of nutrients from the soil over a sequence of cropping cycles has important cumulative adverse effects on land productivity. In Table 11 a rough approximation of the annual and cumulative effects of soil nutrient mining associated with producing a hectare of maize is used to illustrate the possible impact of nutrient mining on land productivity and crop production. These estimates show that the continuous mining of soil nutrients over a sequence of seven cropping cycles will have the following con-

Table 11. Annual and Cumulative Effects of Soil Nutrient Mining and the Cost of Nutrients Mined

Crop Period Time	Quantity of Nutrients ($N + P_2O_5 + K_2O$) Mined	Average Added Crop Output/ Nutrient Mined Response	Crop Yield Associated With Nutrient Mined	Decline in Productivity of Land Due to Soil Nutrient Mining	Cumulative Effects		Foregone Benefits Due to Nutrient Mined in First Crop Period	Present Value of Foregone Benefits Due to Nutrient Mined in First Crop Period
					Quantity of Nutrients ($N + P_2O_5 + K_2O$) Mined	Decline in Productivity of Land Due to Soil Nutrient Mining		
(Year)	(kg/ha)	(kg/kg)	(kg/ha)	(kg/ha)	(kg/ha)	(kg/ha)	($/ha)	($/ha)
(t)	Nt	Yt/Nt	Yt	(Yt-Yo)	N	¥	Py (Yt - Yo)	
0	*50*	5.00	250.00	0.00	50	0.00	0.00	0
1	*40*	4.50	180.00	70.00	90	70.00	14.00	12.73
2	*30*	4.05	121.50	128.50	120	198.50	25.70	21.24
3	*25*	3.65	91.13	158.88	145	287.38	31.78	23.87
4	*20*	3.28	65.61	184.39	165	343.27	36.88	25.19
5	*15*	2.95	44.29	205.71	180	390.10	41.14	25.55
6	*10*	2.66	26.57	223.43	190	429.14	44.69	25.22
		Cost of nutrients mined in first crop period in terms of foregone (given up) benefits ($/ha):						134
		Cost of nutrients mined in first crop period in terms of foregone (given up) benefits ($/kg of nutrient):						2.68

Assumptions:	
Added crop output/nutrient mined response (Yt/Nt):	*5.00*
Factor of annual change in Yt/Nt:	*0.90*
Price of crop output ($/kg):	*0.20*
Annual rate of discount to calculate present values:	*0.10*

sequences: (1) maize yields will decrease by 430 kg/ha; (2) about 190 kg/ha of nutrients will be mined from the soil; and (3) the cost of the 40 kg/ha of nutrients mined from the soil in the first crop period will be, in terms of lost benefits, $134/ha or about $2,680/t of nutrient ($N+P_2O_5+K_2O$) mined. This is a rough estimate of the per hectare social cost of nutrient mining that the countries and society are paying as a result of the decline in land productivity and the degradation of land resources caused mainly by soil nutrient mining and its associated consequences.

It is important to note that the social cost of nutrient mining will increase as a result of changes in the following variables and circumstances:

a. Increases in the prices of crop outputs.
b. Decreases in the rate of discount of future benefits—the social rate of discount in most countries of sub-Saharan Africa is probably less than the rate of 0.10 used in Table 11.
c. Rapid decrease in the rate at which nutrients are mined.
d. Rapid decline in the average response of crop output to nutrient mined, i.e., rapid decline in the overall status of soil fertility.

Key factors determining the pervasiveness of nutrient mining in crop production in many areas of sub-Saharan Africa are the prevailing land tenure arrangements and the lack of farmers' access to sources of plant nutrients, especially mineral fertilizers, and to other modern inputs such as seeds of crop varieties more responsive to fertilizer.

Differences between the cost of nutrient mining to individual farmers and to society as a whole do exist mainly as a result of land tenure arrangements that make the farmers unresponsive to the loss of future returns to land caused by the mining of soil nutrients. When the possession of agricultural land by farmers is well established through property rights or land tenure arrangements, and there is a functioning market for agricultural land, farmers internalize costs associated with the loss of the land's productive capacity, increasing significantly the cost to farmers of the soil nutrients mined. The opposite occurs when land tenure rights are not well established and there is not a functioning market for agricultural land. Then, costs associated with the loss of the land's productive capacity become an externality and, therefore, a social rather than a private cost.

The prevailing situation in many agricultural areas of Africa where nutrient mining is occurring is in general characterized by the lack of land property and tenure rights. In these areas the loss of land productivity and the degradation of land caused by nutrient mining are costs to society as a whole. Then, from the farmer's private point of view, the nutrients mined from the soil are perceived as the most inexpensive source of plant nutrients for their crops. For these farmers, soil nutrient mining is an economically sound practice in crop production. This is particularly evident for farmers who practice shifting cultivation and perceive that they are not significantly affected by the land productivity decline associated with nutrient mining. Rough estimates presented in Table 11 also show that if farmers would own the land, they would be better off by purchasing fertilizer at a price lower than \$2,680/t of nutrient (NPK) rather than by mining nutrients from the soil.

The economics of nutrient mining briefly discussed above and a good understanding of the agro-climatic factors and socioeconomic circumstances that affect farmers' decisions on soil nutrient mining provide the rationale for the development and design of policies and investment strategies to reverse trends in soil nutrient mining. The key goal of such policies and strategies is to prevent soil nutrient mining by making external sources of plant nutrients, such as organic and mineral fertilizers, more economically attractive to farmers than the mining of nutrients. This implies the implementation of policy measures and investments that increase the cost of the nutrients mined and decrease the cost of organic and mineral fertilizers supplied to farmers thus increasing their profitability.

2. Design and Implementation of Policy and Investment Strategies

Criteria for Policy Design—The design of policy and investment strategies that can successfully contribute to the prevention of soil nutrient mining in Africa agricultural land areas should take into consideration the following: (1) factors and circumstances that are sources of diversity (and uniqueness) among countries must be considered in designing policies and investment strategies for a given country; (2) successful policy strategies must be designed to simultaneously address and overcome a complex set of multiple constraints that are frequently interrelated; (3) policies and investment strategies designed to reverse soil nutrient mining must be complementary and consistent with the broad macroeconomic policies and goals of the country; and (4) policy and investment strategies can be critically affected by special circumstances such as social unrest, political instability, widespread corruption, and war that can significantly and adversely affect and deter the implementation and impact of any policy and investment strategy. Moreover, policies and investment strategies to reverse soil nutrient mining should be designed and implemented nationally, and sometimes locally, but always as a key part of a comprehensive policy approach to economic development.

Description of Key Components of Policy Strategies—Policy measures and investment strategies that are key components of a comprehensive policy approach to reverse soil nutrient mining, promote economic development, and reduce poverty are presented and briefly described in Table 12. In this table, policy measures and investment strategies are concisely specified and described in terms of their expected outcomes, measures of impact on capital endowments, their term of execution and impact, the main sectors of the economy involved in their implementation, and the expected changes in the incentives or disincentives for farmers to mine nutrients from the soil.

The policies and investment strategies described in Table 12 vary in terms of scope of impact and purpose but are highly complementary and reinforcing in reversing soil nutrient mining and achieving the overall goal of economic development. These policy measures and investment strategies are briefly discussed to provide a better perspective about the possible roles, impacts, and limitations that they can have in reversing soil nutrient mining to promote improved crop production and economic development in Africa.

Broad Scope Development Policies**—**The first three policy measures described in Table 12: (1) investments in roads and associated infrastructure, (2) investments in schools and education, and (3) measures to promote good governance and control corruption are very broad in their scope of impact and purpose. These policies benefit all sectors of the economy and are usually necessary but not sufficient to achieve sustainable long-term economic development. These policy measures and investment strategies are mainly implemented by the public sector and have long-term positive impacts on the countries' endowments of physical man-made capital (roads and infrastructure) and human capital (education and governance).

Expected outcomes of these broad scope development policies are the increased availability (and lower costs) of fertilizers and other agricultural inputs to farmers and infrastructure to significantly improve the access of farmers to information and markets for their products. The important impact of these policies on the ratios of fertilizer/crop-output prices for farmers will provide significant economic incentives for farmers to use fertilizers and other modern inputs and to reduce or discontinue the practice of growing crops at the expense of soil nutrient mining. Moreover, the improved access of farmers to technical and market information will promote the adoption of modern agricultural production technology and, in the long term, completely eradicate the practice of soil nutrient mining and depletion in crop production.

Policy measures to promote good governance and transparency through democratic principles, education, and the establishment of mechanisms of checks and balances to control and prevent corruption are critical to the successful implementation of all other policy measures and investment strategies. Poor governance, civil unrest, and widespread corruption in a country can seriously jeopardize the implementation of policy measures and can frequently turn into ineffective, policy measures and investment strategies that otherwise could be very effective and successful.

Land Tenure Policy**—**Policy measures or legislation to improve the long-term rights of the farmers to possess agricultural land can drastically affect the importance that farmers assign to the stream of benefits (economic returns to land) that they attain through the long-term usufruct of the land. This seriously affects the decision making of farmers with respect to the management and use of agricultural land. Land tenure arrangements and property rights have a direct impact on the manner in which farmers manage and use land resources and agricultural production technology to maximize long-term economic returns to their fixed factors of production, the profitability of agricultural production, and ultimately, the farmers' household income.

Table 12. Components of a Comprehensive Policy Approach to Reverse Nutrient Mining, Promote Economic Development, and Reduce Poverty

	Policy Measures and Investment Strategies	Expected Outcomes of Policy Measures	Impact on Capital Endowments Affecting Nutrient Mining			Implementation of Policy		Impact on Nutrient Mining Incentives
			Natural Capital	Physical Man-Made Capital	Human Capital	Term	Main Sector Involved	
1	Investments in roads and associated infrastructure	Increased availability and lower costs of agri-inputs. Higher prices received by farmers for agricultural products. Improved access to markets, information, education and health care.	*Indirect Positive and Negative*	***Direct Positive***	*Indirect Positive*	*Long-term*	*Mainly Public Sector*	Lower fertilizer/output price ratios will promote fertilizer use and reduce incentive for nutrient mining.
2	Investments in schools and education	Better access to information, knowledge, technology and health care.	*Indirect Positive*	*Indirect Positive*	***Direct Positive***	*Long-term*	*Public and private*	Improved access to information and knowledge will facilitate adoption of modern technology and reduce nutrient mining.
3	Measures to promote governance and control corruption.	Good governance and well-controlled incidence of corruption. Critical for the success of any other policy and investment strategy.	*Indirect Positive*	*Indirect Positive*	***Direct Positive***	*Mid and Long-term*	*Public and private*	Improved governance and less corruption will facilitate implementation and impact of all policies and reduce incentives for nutrient mining.
4	Legislation to establish property rights and/or land tenure arrangements that ensure the long-term use and usufruct of the agricultural land by farmers.	Land tenure laws clearly establishing that the long term stream of economic returns to agricultural land will directly affect the income of farmers and the value of land.	***Direct Positive***	*Indirect Positive*	*Indirect Positive*	*Mid and Long-term*	*Public Sector*	The adverse effect of nutrient mining on the future stream of economic returns to land will significantly reduce the income of farmers and the incentive for nutrient mining.
5	Credit and technical assistance (TA) to farmers and agribusinesses to promote the efficient supply of agri-inputs to farmers. Regulatory framework and institutional development.	Timely availability of fertilizers, seeds and other inputs at lowest possible cost to farmers. Increased profitability of fertilizers. Restoration of soil fertility and increased land productivity.	*Indirect Positive*	***Direct Positive***	***Direct Positive***	*Mid and Long-term*	*Public and private*	Improved access of farmers to fertilizers, improved seeds, and other inputs will promote the use of these inputs and substantially reduce the incentive for nutrient mining.

Table 12. Components of a Comprehensive Policy Approach to Reverse Nutrient Mining, Promote Economic Development, and Reduce Poverty (Continued)

			Impact on Capital Endowments Affecting Nutrient Mining			Implementation of Policy		
	Policy Measures and Investment Strategies	Expected Outcomes of Policy Measures	Natural Capital	Physical Man-Made Capital	Human Capital	Term	Main Sector Involved	Impact on Nutrient Mining Incentives
6	Measures to expand demand for farmers products in domestic and export markets. Through investments in network of market outlets and the provision of TA and credit to marketing intermediaries.	Increased access of farmers to market outlets for their products network of market outlets for farm products accessible to farmers. Information and credit to facilitate the marketing and export of agricultural products.	*Indirect Positive and Negative*	***Direct Positive***	*Direct Positive*	*Mid and Long-term*	*Public and private*	Increased demand and better prices for farm products will increase the profitability of fertilizers and reduce the incentive for nutrient mining.
7	Provision of credit and technical assistance (TA) to promote growth in the demand for processed agricultural products and the development of agribusinesses involved in the processing, marketing and export of these products.	Increased access of entrepreneurs to sources of credit and TA needed to facilitate the growth of the agribusiness sector involved in the processing, marketing and export of farm products.	*Indirect Positive*	*Indirect Positive*	***Direct Positive***	*Mid-term*	*Public and private*	The increased demand and better prices for farm products, as a result of growth in the agribusiness sector, will increase the profitability of fertilizers and reduce the incentive for nutrient mining.
8	Social support programs to control malnutrition, reduce poverty, and improve human capital and the availability of a healthier more skilled labor.	Increased availability of programs and centers to provide meals, food, and basic education to the poor in exchange for work in public projects when appropriate.	*Indirect Positive*	*Indirect Positive*	***Direct Positive***	*Mid and Long-term*	*Mainly Public Sector, Donors and Charities*	Increased availability of healthier and more skilled labor may reduce incentives for nutrient mining.
9	Health care support programs to control the spread of the HIV virus and AIDS among people and reduce its impact on the availability of labor and the welfare of the population in general.	Increased availability of programs and centers for the provision of basic health care to the poor and victims of the HIV virus and AIDS.	*Indirect Positive*	*Indirect Positive*	***Direct Positive***	*Long-term*	*Mainly Public Sector, Donors and Charities*	Increased availability of a healthier labor force may reduce incentives for nutrient mining.

This policy is usually designed and implemented by the public sector through legislation that (1) determines the rights of farmers with respect to the possession and ownership of agricultural land; and (2) establishes the basis for a functional market for agricultural land. Given that strong cultural preferences for traditional methods of land tenure may exist in a number of countries (or regions) in Africa, these policies may be difficult to design and implement in those situations. The implementation of this policy usually requires the establishment of supporting institutions. Despite these difficulties, efforts must be made to establish land tenure systems that ensure that farmers have access to the long-term stream of benefits associated with the prevention of soil nutrient mining through fertilizer use and soil conservation practices.

Policies to Improve Agri-Inputs Supply Efficiency—Improvements in the timely and efficient supply of agri-inputs such as seeds and fertilizers can be attained through the provision of credit and technical assistance (TA) to producers, importers, wholesalers, and dealers involved in the procurement and distribution of these inputs to farmers. In this context, TA involves the provision of technical and managerial assistance, as well as training, and the dissemination of relevant information to business entrepreneurs and farmers. The provision of this assistance in conjunction with the availability of credit to agribusinesses involved in the procurement, distribution, and retailing of agri-inputs shall improve the timely availability of seeds, fertilizers, and other inputs to farmers at the lowest possible costs.

These policies have a direct positive impact on human capital by improving the technical and managerial expertise of agribusiness entrepreneurs involved in the procurement, distribution, and retailing of agri-inputs and, indirectly, in the technical know-how and managerial capacity of farmers. The public and private sectors have a role in the implementation of these policy measures and investment strategies. These policies have a mid- and long-term impact on the profitability of fertilizer use by farmers and, therefore, in the reversal and discontinuity of soil nutrient mining in agricultural land. The increased availability and use of improved seed varieties more responsive to fertilizers and the expanded supply of fertilizers at lower costs to farmers will significantly increase the profitability and use of fertilizers and, essentially, eliminate any incentive for farmers to mine soil nutrients to grow crops.

Returns to investments in the implementation of these policies (TA, credit) and in the construction of roads and associated facilities in rural areas can be substantially increased if complementary policy measures are implemented in conjunction with these investments. There are strong synergies associated with the impact of simultaneously implementing these types of policy measures and investments. Economic returns to often substantial long-term investments in the construction of roads and infrastructure in rural areas are greatly increased by the implementation of policies and investments that (1) promote efficiency in the supply of agricultural inputs, (2) relax financial and knowledge constraints for the use of modern inputs, and (3) expand the demand for agricultural products that can be produced by farmers in the agricultural area benefiting from the construction of the road infrastructure.

Policies to Expand Demand for Agricultural Products and Have Stable Prices—Policy measures and investment strategies 6 and 7, described in Table 12, focus on the expansion of demand for agricultural products. The goal (and expected outcome) of these policies is to expand in a sustainable and stable way the demand for agricultural products that farmers can efficiently produce in a competitive environment. Growth in the demand for agricultural products that is consistent with stability in the prices that farmers receive for their products promotes the profitability of fertilizers and modern inputs and increases the productivity of agriculture and the incomes of farmers' households. Expansion in the demand for agricultural products can be attained as a result of (1) policies and investments that increase the domestic demand for agricultural products and (2) policies that increase the demand for exports of these products.

Policy measures and investments that are expected to result in the expansion of demand for agricultural products in a given country/agricultural area are described in Table 12 as policy measures and investment strategies 6 and 7 and include the following:

1. Investments in marketing infrastructure for farmers, wholesalers, and retailers of agricultural products. This involves the construction of properly located facilities for the trade of products by farmers, wholesalers, retailers, and consumers. These investments can be made by the public sector, the private sector, and the community. The resulting network of market outlets should facilitate expansion in the domestic demand for agricultural products, reduce marketing margins and, with proper competition, result in more revenues for farmers and better prices for consumers.
2. Measures to facilitate the provision of credit and technical and managerial assistance to marketing intermediaries of agricultural products, such as wholesalers and retailers, including those interested in investing in marketing infrastructure. These policies should be successful in overcoming the financial constraints and the limitations of marketing intermediaries in technical and managerial know-how.
3. Provision of credit and technical and managerial assistance to exporters of relevant agricultural products and to agribusinesses involved in the processing and then the marketing of processed products in the domestic and export markets. These policies should increase the domestic and export demand for processed and unprocessed agricultural products and the added value of a country's exports.

These policies involve direct investments by the public sector and measures to create a policy environment that stimulates the investments and dynamic participation of the private sector. Growth in the demand for agricultural products that can stimulate sustainable growth in agricultural production and productivity can be a powerful source of agricultural and economic development in a country. This is particularly evident when the growth in demand is due mainly to expansion in the demand for processed agricultural products. Then, the growth in demand can result in the rapid development of the agricultural sector and the agribusinesses involved in the processing of agricultural products. Some countries in Latin America and Asia have experienced this kind of development as a result of growth in the export demand for processed agricultural products.

Policy measures and investment strategies that promote the sustainable growth of demand for agricultural products have positive mid- and long-term impacts on economic development and the profitability and increased use of fertilizers. These policies can successfully reverse and prevent soil nutrient mining in agricultural target areas. They will have a direct positive impact on (1) human capital by improving the technical and managerial know-how of farmers and agribusiness entrepreneurs, including marketing intermediaries, food processors, and exporters; (2) physical man-made capital through the construction of facilities and infrastructure for the marketing and processing of agricultural products; and (3) natural capital by preventing soil nutrient mining, restoring soil fertility, and improving the conservation of land and water resources.

Social Support Programs for Poverty Alleviation and Public Health—These programs are needed to combat poverty and malnutrition among rural and urban populations in many African countries, and the spread and consequences of the HIV/AIDS epidemic. Thus, policies that are primarily directed to promote economic development should be implemented in conjunction with social support programs. These programs should be designed to reduce malnutrition and hunger, provide health care to combat the HIV/AIDS epidemic, and offer basic education and information on these two problems. Economic development policies should be implemented in combination with the creation and support of "social safety nets" to protect the human resource base and the economy from the destructive consequences of extreme poverty and the HIV/AIDS epidemic. Policy measures that can be important components of the "social safety nets" are briefly described in Table 12 as policy measures and investment strategies 8 and 9.

3. Strategies for Policy Implementation

From discussions presented above, it is easy to conclude that the more direct and effective way to reverse and prevent soil nutrient mining in important areas of agricultural lands of Africa is through policies that promote the judicious use of mineral fertilizers and sound soil conservation practices. Given the complex nature of the multiple constraints affecting the use of fertilizers, a well-integrated strategy involving the simultaneous implementation of all or some of the policy measures described above should be adopted to achieve the goals of increased fertilizer use and soil fertility conservation.

The actual specification of the policy measures that should be included in a comprehensive successful policy strategy and the approach that should be adopted for its implementation in a given country (target area) in sub-Saharan Africa will depend mainly on (1) the current goals and status of implementation of on-going macroeconomic policies designed for the country's economic development; (2) the nature and extent of soil nutrient mining in the agricultural lands of the country/area; (3) the relative importance of the agricultural and agribusiness sectors in the country's economy; and (4) the political situation and prevailing circumstances regarding governance, corruption, and social and political instability.

It is well known that in most circumstances in Africa where fertilizers are not used and soil nutrient mining occurs, the critical constraints to fertilizer use are the lack of availability and very high prices of fertilizers. Thus, the policy strategy should focus on measures and investments for overcoming these constraints to facilitate farmers' access to fertilizers and their use. In this context, the issue of lack of roads and transportation infrastructure should be addressed on a priority basis to determine the feasibility of investments in roads and transportation infrastructure. If such investments are feasible, the construction of the roads and other infrastructure could serve as the cornerstone of a comprehensive policy strategy to promote the availability and use of fertilizers and other inputs. Then, the policy strategy and approach for policy implementation should involve the explicit inclusion of other complementary policy measures described in Table 12 as part of a comprehensive strategy. This approach should effectively relax or overcome multiple constraints to ensure the rapid and sustainable adoption of fertilizers and the reversal and prevention of soil nutrient mining in the agricultural areas benefiting from the investment in the road and transportation infrastructure. This strategy, if feasible and properly implemented, may be viewed as the "best policy option" to achieve success in some agricultural areas of Africa in terms of agricultural and economic development and the conservation of land resources.

Implementation of "Best Policy Option"—An important broad-based, ambitious effort to promote fertilizer use and the adoption of crop yield-enhancing technology in agricultural lands of Africa could be carried out by implementing the "best policy option" in a number of countries where it is feasible. Such an effort should seek to establish *focal development areas* that could serve to learn more about the policy and demonstrate its effectiveness. Success of this effort and policy strategy in a number of *focal development areas* could have a substantial impact on the judicious use of fertilizers in countries of sub-Saharan Africa and, thereby, on agricultural development and the conservation of land resources. Moreover, well-demonstrated measures of success of the policy in *focal development area*s could have substantial positive spillover effects in other countries/areas where the policy strategy can be replicated.

Implementation of “Second Best Policy Options”—These policies are defined here as strategies that may involve, in the most comprehensive policy option scenario, all policy measures and investments described in Table 12 except investments in the construction of roads and associated infrastructure. Policy measures and strategies pertaining to this comprehensive second best policy option scenario should be adopted when the construction of roads and transportation infrastructure is not feasible and other policy measures can successfully facilitate the availability and enhanced profitability of fertilizers to farmers. These policy strategies focus mainly on measures to increase the profitability of fertilizers through credit, technical assistance, and a favorable policy environment to improve the efficiency of fertilizer supply and the creation of an expanded and stable demand for agricultural products. These policies are implemented by public and private sectors in the context of a free competitive market system.

Various components (policy measures) of the “second best policy options” defined above have been used in different ways in some countries of Africa, usually as isolated efforts to promote the adoption of fertilizers and improved technology (seeds) in some crops (i.e., maize), but with limited success. As part of these endeavors, implicit and explicit subsidies have sometimes been used as a means to provide incentives for farmers to learn about fertilizers and adopt them. Isolated actions and subsidies have been usually temporary and unsustainable and have often resulted in short-lived limited successes. Although these policy interventions (subsidies) have not been very successful in the past, it is important to note that such measures may be viewed as useful temporary actions that can be taken for the introduction of fertilizers in an area. This is especially effective if such efforts are followed by a comprehensive policy strategy that ensures the sustainable use of fertilizers without subsidies. However, it is also important to indicate that when subsidies are used as temporary measures, it is frequently very difficult for policymakers to remove them later.

A number of diverse policy strategies can be designed as “second best policy options” to properly address and overcome the critical constraints to fertilizer use that are present in different countries and agricultural areas. Thus, depending on the circumstances at country and local levels, different policy strategies can be designed by using various combinations of the policy measures and investments summarized in Table 12. These strategies may vary in terms of scope, from the implementation of very simple extension projects (to disseminate information and knowledge about the use of fertilizers) to the simultaneous implementation of measures to improve efficiency in the supply of fertilizers and other agri-inputs and in the marketing of agricultural products. Success of these strategies depends essentially on their effectiveness to overcome all the critical constraints to fertilizer use. Policy strategies must be sufficiently comprehensive to simultaneously address all critical constraints. Failure to do this is often the cause of the lack of success of some policy and investment strategies. For instance, policies focusing only on improving fertilizer supply efficiency may fail because prices of agricultural products could collapse as a result of increased production and the lack of demand, making fertilizer use unprofitable.

Although soil nutrient mining is significantly affected by agro-climatic, demographic, and socioeconomic factors and circumstances, which are often common among countries, policy strategies should be designed and implemented by the individual countries at the national level. In conducting this task it is important to (1) identify the constraints that are common to a number of countries and (2) recognize that much can be learned from the successes and failures experienced by each country.

4. Ex-Ante Assessment of Performance of Policy Strategies

Ex-ante assessments of pre-designed policy strategies can be conducted to determine their probable performance in terms of expected outcomes and potential impacts on factors and variables such as fertilizer use, soil nutrient mining, crop production, farm labor employment, and farmers' revenues. The anticipated performance of selected policy strategies can be assessed by:

(1) Describing the expected impacts of the policy strategy's outcomes in the selected target agricultural area or areas in a country.

(2) Estimating measures of expected impact such as: (a) the rates of adoption of fertilizer use by farmers; (b) the average rates of fertilizer use by farmers; (c) actual levels of increased crop yields and production as a result of the use of fertilizers and improved technology; (d) levels of control and prevention of soil nutrient mining, and the actual restoration and improvement of soil fertility; (e) increased employment of labor in agriculture and the agribusiness sector as a result of the policy strategy implemented; (f) changes in the levels of growth and the extent of processing of agricultural products (value added); (g) growth in exports of processed and unprocessed agricultural products; (h) levels of investments in marketing infrastructure for the supply of agri-inputs to farmers and the sale of their products; (i) increase in GDP as a result of policy strategy impacts; (j) measures of poverty alleviation, for instance, number of people below (or above) a certain level of income or consumption; and, (k) the development and effectiveness of institutions to support the continuous implementation of policy measures in the strategy, such as the successful implementation of land tenure arrangements and a regulatory framework for fertilizers and other agri-inputs.

The measures of impact estimated for a set of selected policy strategies will show differences in the magnitude of benefits associated with the selected policy strategies, and also the differences in their scope of coverage and their costs of implementation. Then, with sufficient information about country-specific target areas, and the scope and cost associated with the implementation of proposed policy strategies, benefit/cost analyses can be conducted to compare and evaluate ex-ante the expected performance of alternative policy strategies. This approach can be used to select for implementation in a given country, policy strategies that are expected to provide a superior level of economic performance and/or have a higher probability of success.

5. Conclusions and Recommendations on Policy Development

1. Well-designed policy measures and investment strategies that target specific agricultural areas where soil nutrient mining is extensively occurring in a country can successfully increase the judicious use of fertilizers and the adoption of sound soil fertility management practices to reverse soil nutrient mining. Such policy measures and investments will provide very important and substantial benefits to farmers, on-farm workers, marketing intermediaries, consumers, the land resource base, and the countries' economies.
2. In countries of Africa where soil nutrient mining of agricultural lands is widespread and pervasive (target countries), the implementation of policy strategies to reverse this process through measures and investments that promote fertilizer use and soil conservation practices should be a national priority.
3. In order to develop national policy reform and investment strategy programs for target countries, strategies must be tailored to overcome the constraints and circumstances prevailing in well-defined target areas within the country. Then, ex-ante assessments of alternative predesigned policy strategies can be conducted to select/design policy and investment strategies that are expected to have the highest probabilities of success in terms of impact, benefits, and cost for the target country.
4. Results of ex-ante assessments can also be useful to derive estimates of the order of magnitude and boundaries of the total expenditures that a country (government) could incur in the

costs of implementation and investments of a policy strategy in order to have satisfactory levels of expected benefit/cost ratios on those expenditures.

5. In the process of designing effective policy strategies, it is important to recognize the following:
    a. There is not a unique “silver bullet” type of policy and investment strategy that will swiftly result in the adoption of fertilizers and improved technology to reverse soil nutrient mining and rapidly increase productivity of crop production in Africa.
    b. A good understanding of the economics of nutrient mining and well-documented knowledge about the local and national circumstances that determine and promote the widespread use of this practice by farmers can greatly facilitate the design of effective policy and investment strategies.
    c. Ex-ante analyses of well-designed policy strategy alternatives can significantly improve the final selection/design of a successful policy and investment strategy for target areas in a country.
6. Finally, it is important to note that national policy and investment strategies must be specified in much more detail than the one used in this paper. The strategy should include details about geographic coverage, the chronology of policy interventions and investments, and the specific *modus operandi* to be used in the implementation of policy measures, such as the provision of technical assistance and credit. Thus, the proper design of national policy and investment strategies to reverse soil nutrient mining in countries of Africa can, in some instances, be a very involved and challenging task.

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Appendix I

Nutrient Mining Methodology

1. General Concepts

A general model to monitor nutrient mining (N, P, and K) in soil ecosystems at country or regional scales was specified as follows:

$$Rn_t = \Sigma^t (AP_t + AR_{\Delta t} - RM_{\Delta t} - L_{\Delta t}) \qquad (1)$$

Where Rn_t is the quantity of nutrient from inorganic and organic sources assumed to remain available in the soil after a period of time t, AP_t is the inherent soil nutrient available at time t and $AR_{\Delta t}$ is the total of mineral forms and organic compounds added or returned to the soil during the time interval Δt. The estimate $RM_{\Delta t}$ is the plant nutrient removed in the product and residue of the crop harvested during the time interval Δt and $L_{\Delta t}$ is the inorganic and organic nutrient lost through different pathways during the time interval Δt.

The methodology for monitoring nutrient mining deals with the estimation of nutrient inputs (inflows) and outputs (outflows) in the soil system. Nutrient inputs include mineral fertilization, organic residues, nitrogen fixation, the nutrient content recycled during fallow periods, and nutrient gains through physical processes such as sedimentation and deposition of soil particles. Nutrient outputs include nutrients lost from the soil through processes such as erosion, leaching, and volatilization. Crop nutrient uptake in the produce and straw is another important cause of nutrient outflow from the soil system because the produce is usually removed from farmers' fields for human and animal consumption and the straw is used for various purposes and not completely returned to the soil.

A soil nutrient mining monitoring system includes components of strategies based on the management of information, simulation modeling, and transfer functions used to quantify nutrient flows and their impact on crop production. Management information through database systems allows the consolidation of a series of data sets with primary and secondary information on soils and crops, consumption and use of inputs, and production. The nutrient mining monitoring system is evaluated at scales that range from small soil aggregates to regions, countries, and even the African continent. The process also includes the use of spatial analysis and geographic information system (GIS) to identify crop areas, analyze and classify production, evaluate nutrient fluxes, interpolate data, and display regional nutrient mining assessments.

2. Interfacing Information Systems in Nutrient Mining Evaluation

The process of interfacing information on nutrient mining depends on the type and quality of data sources. Quantitative data such as soil nutrient availability, climate (rainfall, temperature), crop areas and yields, nutrient inputs and outputs, livestock, and population densities are often provided as interpolated surfaces in raster (grid) format. Soil fertility classifications, land use, land cover, natural resource distribution, and crop and livestock distribution and density, population density, and administrative divisions are commonly recorded in the form of tables and maps (polygons) in vector format. The present study combines tables, raster data, and polygon formats to assess and project nutrient mining at regional and country scale.

Geographic information developed by FAO and the International Institute for Applied System Analysis (IIASA) was used to assess land use and match this information with crop nutrient requirements, production levels, and nutrient use in Africa (FAO, 1976; FAO/IIASA, 2000). Time-series information on agricultural land and crop areas, livestock quantities and density, and population indicators in Africa were taken from several statistical database sources (FAO, 2004c; IFDC, 2004), national agricultural centers, the ministry of agriculture offices, and other national offices in African countries. Information associated with fertilizer use, crop area, and fertilizer rates was taken mainly from FAO statistics (FAO, 2004c) and from data available on the fertilizer-use-per-crop reports of the International Fertilizer Industry Association (IFA), IFDC, and FAO (IFA/IFDC/FAO, 2000). The global agro-ecological zones (AEZs) and the United Nations Environment Program (UNEP) were used to verify information about crop areas, production, and the length of the growing season as a function of weather conditions (FAO/IIASA, 2000; UNEP, 2004). Soil data, land under agriculture and other uses, and land cover were used to determine agricultural constraints and classify land as cropland, mixed cropland, forestry areas, natural vegetation, and estimate transfer models. The main sources of this information were country collaborators and geo-referenced information from the US Geological Survey and the EROS center (USGS, 2000), the International Food Policy Research Institute (IFPRI), the World Resource Institute (WRI) (Wood et al., 2000), soil map of the world (FAO 1989; FAO/UNESCO, 1997), and soil profiles data at macro-level from the World Inventory of Soil Emission (WISE) potential database developed by the International Soil Reference and Information Centre (ISRIC) (Batjes, 2002).

Attribute information on nutrient requirements of crops and crop response to fertilizers were obtained from the nutrient balance database at IFDC (NUBAL), national agricultural centers, and from FAO (Yearbook, 2004b) and the crop environment response database ECOCROP (FAO, 1998a). The crop areas and associated fallow areas were assessed on the basis of reports on production and their suitability to soils and coverage as reported by maps on land use and land cover. Where available, this information was validated with satellite images and geo-referenced or remotely-sensed database information.

The spatial information on raster coverage (images, grid) or geographical-explicit grid cells and maps (polygons) were interfaced using spatial analysis techniques such as interpolations, contouring, map density, reclassification, and surface analysis. They were geo-referenced to attribute data (databases) by coding and classification of spatial locations (elevation points, longitude, latitude, villages, and cities). The GIS software, ArcGIS, developed by the Environmental System Research Institute (ESRI®) was used for the geographic assessment and spatial analysis. Finally, the estimations of nutrient mining at macro-level scales (country and region) combined geographic analysis with statistical and simulation packages and developed software (ESRI, 2002; McCoy and Johnston, 2001; Booth, 2000).

Nutrient mining estimations were validated, where possible, using data sets of soil characteristics, fertilizer use, nutrient uptake, and crop yield responses. These validations were conducted as sensitivity analyses of the nutrient mining estimations. Depending on the availability of data, specific validation and sensitivity analyses were performed by including factors such as soil nutrient, crop productivity, fertilizer use, climate, soil erosion, and management practices including fallow systems. Caution was taken to differentiate between the results of sensitivity analyses and the variability of estimators associated with the limitations of spatial scales and the geo-referenced information.

3. Assessment of Nutrient Outputs and Outflows

Nutrient uptakes in crop produce harvested (Nu)—The harvest and removal of crop produce and residues from fields are significant mechanisms for removing nutrient from soils. The quantity of nutrient uptake in kilogram per hectare of nitrogen (N), phosphorus as P_2O_5, and potassium as K_2O in the harvested product was estimated by multiplying total crop production in metric tons by a crop nutrient uptake index expressed in kilogram per metric ton. The values of crop nutrient uptake indexes were derived from the literature and from experimental results (Russell, 1973; Van Keulen, 1986; Sanchez, 1976; Swift et al., 1994;

Stoorvogel and Smaling, 1990; Fried and Broeshart, 1967; IFDC, 2004; FAO, 2004a). Indicative values of the average concentrations of nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) in the produce and straw of several types of crops at current given levels of production in Africa are presented in Table A1.

Nutrient uptake in crop residues (Nr)—Indexes of the content of N, P_2O_5, and K_2O in crop residues were obtained from bibliographic references and field studies (Lal, 1995b; Geiger et al., 1992; Larson et al., 1978; Bationo and Mokwunye, 1991; Bationo et al., 1994). The nutrient removed from the soil by crop residues was calculated by multiplying the residue nutrient content index by the crop production and the harvest index. The value was then adjusted by the percent of residue left on the soil after crop harvesting. The harvest index measures the proportion of the economically produced part of the biomass that is harvested. Estimates of average values of nutrient uptake in crop residues are presented in Table A1. The estimates of the amount of residue left on the soil after harvesting and grazing were obtained from various references and country reports.

Nutrient loss from soils by leaching or runoff (Nl)—Leaching or runoff is an important mechanism of nitrogen (N) and potassium (K_2O) losses for shallow-rooted crops in the sandy soils of Semi-Arid zones and areas of the Sudano-Sahel and Southern Africa. Nitrogen and potassium losses can be high and are associated mainly with the chemical and physical characteristics of soils, rainfall intensity, soil moisture content, and soil organic matter. Leaching or runoff periodically removes most of the nitrate N from the profiles of permeable soils in cropping systems of the Humid and Sub-Humid areas of sub-Saharan Africa (Dudal and Byrnes, 1993). Soil phosphorus (P_2O_5) leaching is considered to be negligible in the tropical soils of Africa.

Most of the literature on nutrient leaching is confined to information on N and K point observations, which are variable and difficult to extrapolate (Charreau, 1972; Charreau and Nicou, 1972; Pieri, 1985; Gigou et al., 1985). Other authors (Addiscot and Wagenet, 1985; Burns, 1975; Bouma and Van Lanen, 1987), using experimental data, have developed empirical transfer functions and used them for prediction purposes; those models are based on experimental results from a wide range of soils and climate. Data from research results and empirical models such as the ones developed by the Nutrient Monitoring for Tropical Farming Systems (NUTMON) approach (De Willigen, 2000) were used to estimate nutrient leaching of N and K_2O at country and regional levels. The models (FAO, 2004a) were specified as follows:

$$NL = (0.0463 + 0.0037\ (R/(Cl * L)))\ x\ (F + OM * OM_n - N_u); \qquad (2)$$

$$KL = -6.87 + 0.0117*R + 0.173*F - 0.265*CEC \qquad (3)$$

NL and KL are the amounts of leaching of N or K respectively at a specific site, expressed in kg N or K per hectare; R is the rainfall in mm/year; Cl is the percentage of clay in the soil; and L is the approximate rooting depth in meters, derived from FAO (FAO, 1998a). F is the estimated mineral and organic fertilizer applied in kilograms per hectare; OM is the organic matter decomposition rate in percentage per year; OM_n is the approximate amount of N in the soil organic matter expressed as kilograms N per hectare; N_u is the amount of N uptake by the crop in kilograms N per hectare; and CEC is the cation exchange capacity of the soils in cmol per kilogram.

Nutrient gaseous losses (Ng)—Nitrogen is lost to the atmosphere by volatilization of ammonia (NH_3) from soils and by denitrification, which is the reduction of nitrate to nitrous oxide and nitrogen gas or N_2O and NOx components. Losses of N through ammonia volatilization can occur in areas with high use of mineral fertilizer and organic sources and depend mostly on soil management, soil acidity conditions, and climatic factors such as temperature and rainfall (Hargrove, 1988). Small losses by volatilization of ammonia may occur in some alkaline soils in North Africa. The

Table A1. Nutrient Content of Harvested Products and Crop Residues

Class	Crop	Harvested Product			Crop Residues		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O
		kg/ton			kg/ton		
Beverages	Coffee	32.0	6.5	15.0	6.3	4.2	10.7
	Hops	17.8	4.5	10.1	62.0	25.0	66.0
	Tea	37.0	4.5	14.0	0.9	0.5	1.2
	Tobacco Leaves	42.6	10.4	49.3	0.5	1.2	1.6
Cereals	Barley	16.4	4.2	5.8	10.0	3.1	15.6
	Maize	15.5	4.5	5.7	10.0	2.7	20.5
	Millets	19.2	7.5	8.5	14.5	6.5	21.8
	Oats	16.7	6.3	6.6	20.0	5.0	16.4
	Rice-Paddy	12.5	4.8	5.1	9.0	3.6	23.0
	Rye	16.3	8.3	6.1	17.5	2.5	20.5
	Sorghum	17.0	6.0	6.7	10.2	7.0	20.5
	Wheat	18.3	6.9	7.5	6.2	2.8	16.0
Fibers	Hemp Fiber	12.5	4.5	10.6	4.8	1.5	4.5
	Hemp Seed	6.6	3.1	8.3	6.5	4.1	11.2
	Jute	5.5	2.3	4.8	1.2	0.5	1.8
	Seed Cotton	22.7	11.5	10.0	16.0	6.7	23.0
	Sisal	6.2	2.4	8.6	1.8	0.7	1.1
Fruits	Avocados	1.2	0.4	1.8	0.6	0.3	0.8
	Bananas	1.5	0.6	2.8	1.2	0.6	1.5
	Citrus	1.8	0.5	1.5	0.8	0.3	1.4
	Figs	2.2	0.3	1.9	1.2	0.2	1.2
	Grapefruit & Pomelo	1.1	0.5	2.6	0.7	0.3	1.2
	Grapes	1.2	0.8	3.1	0.8	0.5	1.5
	Lemons	1.6	0.4	2.2	1.2	0.3	1.5
	Mangoes	1.2	0.5	1.5	0.8	0.5	1.2
	Oranges	2.0	0.5	2.6	1.3	0.5	2.1
	Papayas	0.8	0.5	0.8	0.5	0.3	0.6
	Pineapples	1.1	0.3	1.5	0.5	0.2	0.8
	Plantains	1.5	0.9	4.1	1.8	0.6	1.8
	Strawberries	2.4	0.5	1.7	1.4	0.5	1.9
	Tang. Mand. Clementines	1.6	0.7	2.6	1.4	0.5	2.0
Nuts	Cashew Nuts	12.6	5.1	7.2	6.4	1.7	5.0
	Chestnuts	9.2	2.1	6.3	5.0	0.8	4.8
	Pistachios	8.6	3.5	9.7	6.6	1.7	7.9
	Walnuts	15.8	4.1	6.7	6.5	1.7	7.2
Oil Crops	Groundnuts	28.0	8.0	7.0	15.0	3.6	16.5
	Linseed	26.5	5.2	7.5	11.8	5.3	10.5
	Olives	18.0	7.5	8.1	5.2	1.2	2.5
	Rapeseed	33.5	12.5	28.4	18.3	9.2	13.5
	Safflower Seed	32.6	9.8	22.6	24.2	5.6	15.2
	Sesame Seed	28.6	14.5	9.6	15.2	9.6	8.2
	Soybeans	52.1	15.2	24.0	13.0	5.5	11.8
	Sunflower seed	24.0	5.3	7.6	20.0	3.6	18.6

Table A1. Nutrient Content of Harvested Products and Crop Residues (Continued)

Class	Crop	Harvested Product			Crop Residues		
		N	P_2O_5	K_2O	N	P_2O_5	K_2O
		kg/ton			kg/ton		
Pasture and Fodder	Alfalfa (Lucerne)	40.0	9.1	37.0	0.0	0.0	0.0
	Grass/Clover	30.0	10.0	30.0	0.0	0.0	0.0
	Green Maize	9.5	1.8	10.6	0.0	0.0	0.0
	Rye Grass (Forage)	18.5	7.0	14.6	0.0	0.0	0.0
Pulses	Chick Peas	25.3	9.4	13.5	10.4	2.3	15.7
	Cowpeas	20.0	7.5	12.0	10.0	2.0	11.5
	Dry Beans	32.5	12.4	15.1	10.0	4.1	16.9
	Dry Broad Beans	30.8	9.4	15.1	10.0	3.1	17.3
	Dry Peas	25.3	9.6	15.1	10.3	3.1	16.9
	Lentils	30.8	9.4	13.5	10.4	2.3	15.7
Roots and Tubers	Cassava	1.3	0.8	2.8	0.8	0.3	2.2
	Potatoes	4.5	0.8	5.8	1.5	0.5	3.8
	Sweet Potatoes	2.5	0.8	4.2	1.8	0.5	2.8
	Taro	3.2	1.6	4.0	4.1	1.0	4.2
	Yams	3.6	1.1	4.3	1.9	1.1	4.0
	Yautia (cocoyam)	3.6	1.1	4.3	1.9	1.1	4.0
Sugar	Sugar Beets	4.2	1.1	6.5	1.5	0.5	1.6
	Sugarcane	3.4	0.8	4.1	0.3	0.4	0.6
Tree Crops	Cocoa Beans	36.5	6.5	15.2	16.6	4.2	23.6
	Coconuts	35.3	3.1	6.0	16.8	1.5	6.5
	Natural Rubber	5.3	1.0	3.0	1.2	1.5	0.5
	Oil Palm Fruit	4.1	1.5	5.5	4.1	1.4	4.6
Vegetables	Asparagus	16.5	7.0	12.0	5.5	4.5	6.5
	Cabbages	3.8	1.1	2.8	1.6	0.5	1.5
	Cantaloupes	1.9	0.6	4.5	1.0	0.3	1.2
	Carrots	3.0	1.2	3.8	1.2	0.8	2.2
	Cauliflowers	4.5	1.6	2.3	2.5	0.7	2.5
	Cucumbers	1.9	1.1	3.8	1.2	1.0	0.8
	Dry Onions	1.8	0.8	2.1	0.9	0.3	0.8
	Eggplants	1.8	0.5	2.8	1.2	0.8	1.1
	Garlic	5.2	1.4	4.3	1.6	0.9	1.2
	Green Beans	30.6	7.5	16.2	13.2	6.1	13.8
	Green Peas	15.9	4.3	10.7	6.1	2.1	6.8
	Green Peppers	5.2	0.8	3.0	1.5	0.8	2.8
	Lettuce	4.1	1.2	6.2	2.5	0.5	1.5
	Lupins	14.2	5.5	8.3	7.4	2.6	5.2
	Okra	4.0	1.6	4.5	2.3	1.3	3.8
	Onions/Shallots	3.4	1.3	5.0	1.2	0.7	2.3
	Pepper	5.2	0.8	3.0	1.5	0.8	2.8
	Pigeon Peas	25.0	7.5	14.0	15.0	4.0	11.5
	Pimento	4.3	1.2	3.5	1.8	0.9	3.2
	Pumpkins	2.1	0.7	2.7	1.2	0.6	1.1
	Spinach	3.2	0.5	4.7	2.1	0.6	2.7
	Tomatoes	3.2	0.9	6.5	1.4	0.5	1.2
	Watermelons	3.7	1.4	6.0	1.1	0.8	1.1

Source: IFDC.

likelihood of such losses increases in the sandy soils of West and Central Africa. Losses through denitrification are common in wet areas and are influenced principally by climate (rainfall), soil type (moisture and clay content), soil structure, organic matter content affecting N mineralization, and crop and fertilizer management (Smaling, 1993; Black, 1957; IFA/FAO, 2001). Since a dynamic model to predict nutrient losses through both loss mechanisms is very difficult to apply in this type of study, an empirical approach was used to relate nitrogen losses by volatilization and denitrification as a function of soil, climate, and fertilizer use. Experimental results and data from the literature were used to develop empirical models that include rainfall, soil characteristics, and fertilization practices. The soil factors were obtained from modal profiles of agricultural lands in Africa. The prediction model was specified as follows:

$$Ng = \alpha + (\beta_1 + \beta_2 R)F_n + \beta_3(Fm) + \beta_4(O_c) + \beta_5(S_{pH}) + \varepsilon \quad (4)$$

The amount of nitrogen loss (Ng) is expressed in kg/ha. The parameter estimates $\alpha, \beta 1, \beta 2, \beta 3, \beta 4$, and $\beta 5$ provide indexes to measure the effects of nitrogen fertilization (Fn) in kg/ha, the interaction between rainfall (R) in mm/1000 and nitrogen fertilization, the use of manure and crop residues (Fm) in kg/ha, and relevant soil factors of the soil (site) top layer such as percentage of organic carbon (O_c) and pH (S_{pH}). The value (ε) is the random variability among sites. Soil characteristics were included as proxy of soil fertility influencing the dynamics of nitrogen in soils. Empirical models were estimated for each region to account for variations in climate (moisture and temperature) and soil management. Different models were tested including reduced models and some specific transfer functions. Spatial analysis was used for extrapolation across geographic areas. Estimates of the parameters of model (4) for nitrogen gaseous losses are presented in Table A2.

Soil erosion (Ne)—Whether by wind or water, soil erosion is the cause of about 50%-60% of the degradation of soils and loss of nutrients in Africa. Many factors influence nutrient losses due to soil erosion: climate, topography, nutrient content of the soil profile, plant and litter cover, and physicochemical properties of the subsoil horizon. Variable rainfall in the form of high-energy storms is important in West and Southern Africa, whereas steep slopes are major factors of erosion in East Africa. Continuous overuse of fragile soils with low fertility and land clearing are widespread in the Western Semi-Arid regions and in Southern Africa. All these factors contribute to make erosion the main cause of soil fertility decline in Africa and other tropical areas (UNEP, 1997). In addition to biophysical factors, soil erosion in Africa is also attributed to factors such as high population densities, inappropriate and extensive land use, uncontrolled grazing with high stocking rate, and poor use of crop residues and pasture management practices (Salako et al., 1991).

There is abundant information in the literature on the amount of soil eroded from different areas and soil types in Africa (Lal, 1984; Lal, 1988; Lal, 1995; Charreau and Nicou, 1972; Mensah-Bonsu and Obeng, 1979; Stocking, 1986; Elwell and Stocking, 1982; Elwell, 1978). The present study based the calculations of soil erosion and nutrient losses by water in three basic models: the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978); the Revised Universal Soil Loss Equation (RUSLE), (Kenneth et al., 1991), and the Soil Loss Estimation for Southern Africa (SLEMSA) (Elwell, 1978). The erosion models represent a composite of the effects of crops and crop sequences, tillage practices, and the interaction between these factors and the occurrence of rainfall through the year. The models to estimate soil erosion in ton/ha/year include a rainfall erosivity index (R) that can be defined as the erosive force of rainfall and the soil erodibility factor (K) representing the difference in the propensity for soils to erode. Topographic factors such as slope gradient and length (SL) were considered in charts computed and adapted to regions reflecting soil losses for various lengths and gradients of slopes. Land cover and crop management factors (C) were used as the ratio of soil loss from land cropped

Table A2. Parameter Estimates of Model to Predict Nitrogen Gaseous Losses

Estimates[a]	HCA	HSWA	MANA	SHMEA	SSA	SSASA
Region	10.1	7.4	10.9	8.5	11.4	11.7
F (Fertilizer)	2.7 (1.2)	0.5 (0.3)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)	0.1 (0.1)
F*R	2.1 (1.1)	0.4 (0.2)	0.1 (0.1)	0.1 (0.1)	0.2 (0.1)	0.1 (0.1)
M (Manure)	0.2 (1.5)	0.1 (0.5)	0.5 (0.6)	0.7 (0.7)	0.4 (0.7)	2.3 (1.0)
OC (Org Carbon)	1.6 (1.5)	0.8 (0.7)	3.4 (1.6)	0.3 (0.8)	0.5 (0.8)	0.1 (0.8)
pH	0.2 (0.5)	0.1 (0.3)	0.1 (0.5)	0.2 (0.3)	0.3 (0.3)	0.1 (0.3)
Mean (kg/ha)	10.1	7.4	10.9	8.5	11.4	11.7
RMS (kg/ha)	7.1	6.1	10.7	7.1	8.1	7.8
R2 (%)	76.0	64.0	65.0	70.0	74.0	76.0
N	22	44	26	39	48	52

a. Numbers in parenthesis are standard errors of estimated coefficients.

HCA: Humid Central Africa
HSWA: Humid and Sub-Humid West Africa.
MANA: Mediterranean and Arid North Africa.
SHMEA: Sub-Humid and Mountain East Africa.
SSA: Sudano-Sahelian Africa.
SSASA: Sub-Humid and Semi-Arid Southern Africa.

under specific conditions to soil loss from tilled and continuous fallow land. Selected values of soil erosion parameters for African regions calculated using the erosion models are summarized in Table A3.

The SLEMSA model was used for estimations of soil erosion in Southern Africa. This has been regarded as a useful model in differentiating areas of high and low erosion potential (Igwe et al., 1999). The model was used to predict mean annual soil loss in tons per hectare per year as a function of rainfall kinetic energy (E), percent of effective vegetal cover (I), soil erodibility index (F), percent of slope steepness (S), and slope length (L). These variables are generally combined (Bobe, 2004) into three factors namely, a factor that describes soil loss from bare plot (K) in tons per hectare per year, a canopy cover factor (C), and a topographic factor (X).

Erosion by wind is noticeable in the dry areas of Africa (North and sub-Saharan) due to the intensity of sand and dust storms during Harmattan periods. Empirical equations have been derived to estimate soil erosion caused by wind; most of these equations require data on wind velocity, precipitation, and soil moisture (Lal, 1985; Lal, 1994). The functional relationships between factors influencing wind erosion have been included in a wind erosion model (Chepil and Woodruff, 1963; Skidmore and Williams, 1991; Hagen, 1991). The model specifies soil loss (E) in tons per hectare per year as a function of soil erodibility index I (t/

Table A3. Selected Values of Soil Erosion Parameters

Country/Region	Erosivity (R)	Erodibilty (K)
	(t/acre/year)	
Algeria	100–500	0.10–0.2
Angola	300–800	0.20–0.5
Botswana	300–600	0.20–0.3
Burkina Faso	200–600	0.20–0.3
Congo DR	400–1,000	0.30–0.6
Côte d'Ivoire	300–1,000	0.20–0.4
Egypt	60–300	0.05–0.2
Ethiopia	200–800	0.20–0.3
Ghana	300–800	0.20–0.3
Kenya	400–1,000	0.10–0.3
Lesotho	100–400	0.10–0.3
Madagascar	400–1,200	0.30–0.3
Mali	300–800	0.20–0.3
Morocco	50–300	0.10–0.2
Nigeria	400–1,000	0.10–0.4
Rwanda	500–1,200	0.30–0.5
Senegal	400–800	0.05–0.2
South Africa	200–800	0.10–0.4
Sudan	400–1,000	0.30–0.4
Tanzania	300–650	0.20–0.4
Togo	400–800	0.10–0.3
Tunisia	60–300	0.10–0.2
Uganda	300–1,000	0.20–0.4
Zimbabwe	300–800	0.20–0.4

Crop Cover and Management Factor C[a]

Bare Soil	1.00
Forest or dense shrub	0.001
Savanna or prairie grass	0.01
Overgrazed savanna or prairie grass	0.10
Meadow grass	0.01–0.025
Millet and Sorghum	0.3–0.9
Maize, sorghum or millet with low productivity, no or minimum tillage	0.02–0.1
Maize, sorghum or millet: high productivity, chisel plowing	0.3–0.45
Cotton	0.5–0.7
Cassava	0.3–0.4
Groundnuts	0.4–0.8
Cowpea	0.2–0.4
Soybeans	0.2–0.5
Maize	0.4–0.7
Rice Paddy	0.3–0.5
Sugarcane	0.13–0.4
Papaya	0.21
Potatoes	0.1–0.4
Yams	0.4–0.5
Palm trees	0.1–0.3
Coffee	0.1–0.4

Selected Data for LS Factor

Slope Length (ft-m)	Slope (%)	LS Factor
100 ft (31 m)	10	1.3800
	5	0.5362
	1	0.1290
	0	0.0693
200 ft (61 m)	10	1.9517
	5	0.7582
	1	0.1588
	0	0.0796
400 ft (122 m)	10	2.7602
	5	1.0723
	1	0.1955
	0	0.0915
800 ft (244 m)	10	3.9035
	5	1.5165
	1	0.2407
	0	0.1051
1,600 ft (488 m)	10	5.5203
	5	2.1446
	1	0.2964
	0	0.1207
3,200 ft (975 m)	10	7.8069
	5	3.033
	1	0.3649
	0	0.1386

Supplemental (Conservation) Practices P[b]

Contour farming	0.5–0.6
Straw mulch	0.1–0.2
Grass fallow	0.1–0.4
Contour plowing	0.4–0.8

a. Ratio: Soil loss of crop to soil loss of fallow crop.

b. Ratio: Soil loss of practice to soil loss of fallow crop under slope conditions.

ha) that represents the annual soil loss for a level, bare, and dry field. It also includes a soil-ridge roughness factor K, that is a measure for the effect of surface roughness perpendicular to the main wind direction generally produced by soil management; a climatic factor C that estimates the mean annual wind velocity and the soil moisture of the surface layer; the field length along a prevailing wind erosion direction L; and an index of vegetative cover V (kg/ha) lying on the soil. Although few data were available to use the wind model, assessments were made in selected sites and interpolated to areas using empirical models and spatial analysis techniques.

The following geographical information was combined with erosion models and empirical regression equations to estimate and interpolate through spatial analysis the nutrient loss caused by wind and water erosion in agricultural regions of Africa:

- Land-use map (FAO, 1976).
- Land cover map (USGS et al., 2000).
- Digital Elevation Model (DEM), HIDRO1K. Data set for Africa 1-50 km resolution. Consists of a raster grid of regularly spaced elevation values derived from topographic maps (USGS, 1998).
- Rainfall maps and database. Global agro-ecological zones (FAO/IIASA, 2000).
- Soil erodibility (K) factor and soil depth, derived from soil map of the world (FAO/UNESCO, 1997).
- Soil nutrient availability, derived from soil map of the world (FAO/UNESCO, 1997).
- Rainfall data.
- Area of crops and land-use data.

The most important caveat on estimations of soil loss due to erosion in Africa stems from the lack of published data on soil erosion and the uncertainty in the assignment of land cover data (C factor) principally in the Sudano-Sahelian and Sub-Humid East Africa countries. In many cases it was not possible to verify estimates of soil loss except by reference to a few field measurements carried out in several countries. Estimations were also compared using results from simulations obtained with the Erosion Productivity-Impact Calculator (EPIC) model (Williams et al., 1990; Skidmore and Williams, 1991). In general, most soil loss estimates obtained in this study fall within the range of tolerance limits used for characteristic areas in the regions (Table A3).

The enrichment value or the nutrient content of the eroded soil particles was estimated by using empirical models (Bishop and Allen, 1989), the EPIC simulation model (Williams et al., 1990) and reference tables used to convert soil erosion losses to nutrient (NPK) losses (Sobulo and Osiname, 1986; Stocking, 1986; Stoorvogel and Smaling, 1990; Vuillaume, 1982; Walling, 1984; Williams et al., 1982). Estimates of soil nutrient losses due to erosion were adjusted by the amount of mineral and organic fertilizer use. This was done at country and regional levels by using empirical regression models combined with spatial analysis routines.

4. Assessment of Nutrient Inputs and Inflows

Use of mineral fertilizers (Mf)—Nutrient consumption in tons (N, P_2O_5, and K_2O) and crop areas were recorded from an FAO database (FAO, 2004c) a NUBAL IFDC database (IFDC, 2004), fertilizer-use-per-crop reports (IFA/IFDC/FAO, 2000), agricultural research institutions, and offices of the ministries of agriculture in Africa. The data were extrapolated using information on crop areas, land use and land cover data to estimate nutrient use in kg/ha (FAO, 2004c; USGS, 2000). The data was geo-referenced by village, country, and region. Fertilizer response functions, fertilizer recommendation routines (Janssen et al., 1990; Vlaming et al., 2001; Swift et al., 1994), and GIS routines were used to calculate fertilizer rates and validate consumption at higher levels of aggregation (regional basis, soil classes, land-use class, agro-ecological zones, and country).

Use of organic fertilizers (Of)—Because of the low use of mineral fertilizers and the relatively high number of livestock in Africa (Breman and

Niangado, 1994), the use of animal manure is an important component of soil fertility management in some regions. Presently, the average rates of application of manure by farmers range from 175 to about 700 kg/ha in countries in Africa (Bationo et al., 1995). Livestock management practices vary from intensive grazing in open areas to on-the-spot feeding of livestock on crop residues. The latter is the common practice in many rural areas in Africa.

The data required to calculate organic nutrient inputs mainly in the form of animal manure include the livestock numbers and density (kg/km^2). The density was converted to Tropical Livestock Units (TLU) for selected production systems (camels, cattle, poultry, goats, and sheep) to assess the amount of manure produced and its nutrient content (FAO, 2001a, 2004c). Additional information about organic fertilizers, where available, includes the amount of nutrients (NPK) in household wastes and industrial refuse. Basic information on nutrient content in organic residues used as organic fertilizer and manure conversion factors are presented in Table A4. (Fairbridge and Finkl, 1979; Gershuny and Smillie, 1986; FAO, 2001a). Information on livestock density is presented in Table A5 (FAO, 2004c).

Estimations of the amount of nutrient returned to soil in the form of solid manure, at region and country levels, were adjusted from indicators on the basis of the amount of excreta (residue) left on the field that is grazed, and the fraction of the residue that remains in the field. The nutrient content of manure (percent of NPK) and the approximate nutrient amount left in soils in kilograms per hectare were assessed using index tables and related information collected from the literature (Fernandez-Rivera et al., 1995). The value of this fraction was based on the literature review (Stoorvogel and Smaling, 1990; Williams et al., 1995). Livestock density maps were created and combined (interpolated) with crop areas (grids) to assess site and regional rates of nutrient (NPK) in manure in kilograms per hectare.

Table A4. Average Content of Nutrients in Some Natural Organic Materials

Materials	N	P_2O_5	K_2O
	(percent by weight)		
Activated Sewage Sludge	5.6	2.5	0.3
Alfalfa	3.0	1.0	2.0
Bone (raw)	3.5	19.8	0.0
Cocoa Shell	2.5	1.0	2.5
Coffee Grounds (dry)	2.0	0.4	0.7
Compost	1.5	1.0	1.5
Cotton Gin Trash	0.7	0.2	1.2
Cottonseed (dry)	6.0	2.5	1.7
Fish	10.0	4.0	0.0
Digested Sewage Sludge	2.0	0.5	0.3
Tobacco Stems	1.5	0.2	0.7
Grape Pomace	3.0	0.0	0.0
Soybean	6.7	1.6	2.3
Wood Ashes	0.0	1.5	5.5
Manure (fresh)			
Horse	0.3	0.2	0.5
Sheep	0.6	0.3	0.8
Poultry (30% water)	3.0	2.5	1.5
Poultry (15% water)	6.0	4.0	3.0
Manure (dry):			
Goat	2.7	1.8	2.8
Dairy	0.7	0.3	6.0
Horse	0.7	0.3	0.5
Steer	2.0	0.5	1.9
Hog	1.0	0.7	0.8
Sheep	2.0	1.0	2.5

Excretion of Animal
(kg fresh matter per kg body weight)

	Day	Year
Cattle	0.0162	5.85
Poultry	0.0208	7.56
Sheep/goat	0.0198	7.22
Pig	0.0175	6.63

Tropical Livestock Units (TLU) – Basic Indicators

Stocking rate (TLU/km^2/year)	5.2–11.8
Amount of manure deposited (kg/ha/year)–Urban-Village land	89–124
Amount of manure deposited (kg/ha/year)–Cultivated land	410–660

Table A5. Livestock Density in Agricultural Areas in Africa

Country/Region	Area	Camels	Cattle	Poultry	Goats	Sheep
	('000 ha)	(Head/km^2)				
Humid Central						
Cameroon	3,622		15.5	85.6	12.1	10.5
Central Africa	803		41.7	59.4	38.4	3.2
Congo Dem. Rep.	5,968		1.3	32.9	6.7	1.5
Congo Rep.	228		4.4	98.0	12.9	4.3
Equatorial Guinea	110		0.5	29.2	0.8	3.4
Gabon	210		1.7	147.3	4.3	9.3
Humid and Sub-Humid West						
Benin	2,675		6.3	37.4	4.9	2.5
Côte d' Ivoire	5,999		2.4	55.0	2.0	2.5
Ghana	5,935		2.3	44.5	6.0	5.1
Guinea	2,161		14.5	62.5	5.6	4.7
Guinea Bissau	422		12.3	35.6	7.8	6.9
Liberia	456		0.8	105.2	4.8	4.6
Nigeria	49,274		3.1	27.9	5.5	4.6
Sierra Leone	584		6.9	128.5	3.8	6.4
Togo	1,570		1.8	54.1	9.4	11.5
Mediterranean and Arid North						
Algeria	4,654	0.5	3.3	268.7	6.9	40.2
Egypt	5,841	0.2	7.2	166.0	6.5	8.5
Libya	740	0.6	1.8	337.8	17.1	60.8
Morocco	7,628		3.5	179.6	6.8	21.9
Tunisia	3,712	0.6	2.0	178.9	3.7	17.8
Sub-Humid and Mountain East						
Burundi	1,168		2.8	36.8	6.4	2.0
Eritrea	512	1.5	37.6	26.7	33.2	41.0
Ethiopia	10,172	0.5	38.3	37.4	9.5	14.7
Kenya	3,975	2.1	31.5	75.2	30.1	25.0
Madagascar	2,798		28.7	92.9	4.5	3.0
Rwanda	1,652		6.0	10.9	5.7	2.3
Uganda	6,629		9.9	34.7	11.8	2.4
Sudano-Sahelian						
Burkina Faso	4,673		15.6	52.2	21.5	14.3
Chad	3,140	2.3	20.0	15.9	17.8	8.0
Gambia	271		12.1	22.2	9.7	5.4
Mali	4,263	1.1	17.2	68.0	26.9	18.7
Mauritania	249	52.2	64.2	168.5	224.7	353.1
Niger	11,967	0.4	1.9	20.9	5.8	3.8
Senegal	2,262	0.0	13.3	199.0	17.5	20.4
Sudan	13,681	2.4	28.0	27.0	30.7	35.1
Sudano and Semi-Arid Southern						
Angola	2,688		15.4	25.3	7.6	1.3
Botswana	240		70.9	166.9	93.9	16.7
Lesotho	292		18.5	61.6	22.3	29.1
Malawi	2,983		2.5	51.0	5.7	0.4
Mozambique	4,275		3.1	65.5	0.9	0.3
Namibia	286		87.6	122.2	73.3	101.3
South Africa	7,812		17.3	184.9	8.1	33.1
Swaziland	149		35.0	215.2	18.4	2.4
Tanzania	6,746		26.2	44.5	18.6	5.2
Zambia	1,340		19.4	224.0	9.5	1.1
Zimbabwe	2,743		19.7	80.3	10.8	2.2

Source: FAO statistics (FAO, 2004c).

Nutrient inputs due to soil deposition (Nd)— This is the amount of nutrients returned to a soil by dry or wet deposition processes. Dry deposition is mainly associated with the amount (kg/ha) of dust deposited in an area as a result of wind stream patterns. To assess the amount of nutrient in the dust was necessary to consider the amount of nutrient used, the soil fertility in the area of influence, and the concentration of nutrients (NPK) in the dust. Dry deposition due principally to Harmattan dust was evaluated for selected areas using transfer functions and tables of indexes from previous studies (Stoorvogel and Smaling, 1990; Smaling and Fresco, 1993; Stoorvogel et al., 1997b).

The amount of nutrients (NPK) deposited by water (wet deposition) in kilograms per hectare was assumed to be a function of the annual rainfall, and the amount of nutrient (NPK) content in rainwater derived from the literature (Stoorvogel, 1997b; Pieri, 1985). The amount of rainfall was estimated from an IIASA rainfall map. The amount of nutrient deposited from wind storms and rainwater was projected using geo-reference data and interpolations with empirical functions and geographic maps of land use and land cover, soil fertility data, topographic maps, and impact zones.

Nutrient inputs due to soil sedimentation (Ns)—This mechanism is particularly important in irrigated areas, on naturally flooded soils, and inland valleys. Another important source is the nutrients in sediments as a result of erosion. Methods used to account for those sources of nutrients included geographic analysis with land use and irrigation maps (AQUASTAT) (FAO, 2001d), the use of erosion models (RUSLE, EPIC) and interpolations using raster data (50 km grid cell) and topographic indexes. The Unit Stream-based Erosion Deposition (USPED) model to assess sedimentation (Merrit et al., 2003; Mitasova et al., 1996) was used to predict where erosion and associated deposition were likely to occur in selected drainage basins.

It was difficult to obtain reliable information on the nutrient content of water and sediments. Due to the limited information found on nutrient content, the nutrient input in irrigation water in 300 mm/ha/year was assumed; according to Stoorvogel and Smaling (1990), the nutrient content is about 3.3 mg of N/liter, 0.43 mg of P/liter, and 1.4 mg of K/liter. Index values for sediments in eroded areas were adjusted using empirical models that include nutrients in eroded areas, soil fertility, and amounts of fertilizer for the particular area. The total nutrient from sedimentation was expressed in kg/ha/year.

Nitrogen inputs due to N fixation (Nf)— Based on information from the literature, three basic situations were identified depending on the nature of N uptake by crops:

1. Of the total nitrogen uptake by leguminous crops (soybean, groundnuts, and pulses), about 60% (and 15% in sugar cane) is supplied through symbiotic N fixation (Giller, 2001).
2. Of the total nitrogen demanded by wetland rice, up to a maximum of 20 kg/ha/year is supplied through chemoautotrophic N fixation (Giller, 2001; Danso, 1992).
3. All crops benefit from N that is fixed non-symbiotically or by N-fixing trees that are left growing in the fields. Contributions of non-symbiotic fixation to nitrogen requirements of crops are negligible in the Arid and Semi-Arid regions. Nitrogen fixation by growing trees has been estimated to range from 2 to 10 kg N/ha; about 25% is assumed to return to the soil (Danso, 1992).

The amount of nitrogen fixed was adjusted because of the influence of rainfall and soil fertility. Empirical functions were derived including rainfall and soil fertility indicators that facilitated interpolations and aggregation to geographic areas.

Nutrient inputs due to fallow practices (Nt)— Nutrient content derived from fallow practices was assessed by taking into account the area under crops or harvested and the area under fallow and under grass. Maps of land use and land cover were used and combined with grid cells for interpolation purposes. The amount of nutrient added to the soil due to fallow was computed by assessing the amount of nutrient returned to the soil by grasses, manure, and other organic residues plus the amounts returned by crop residue from the site and surrounding areas plus additions coming from eroded soil and water deposition.

5. Assessment of Nutrient Balance and Nutrient Requirements

According to model (1) above, an indicator of nutrient mining is the balance of nutrient inflows and outflows. With proper information, a soil nutrient balance (Nb) in kilograms per hectare per year for each country and crop can be aggregated and calculated at regional scale as:

$$Nb = \Sigma\,(Mf, Of, Nf) + \Sigma\,(Nd, Ns) - ((\Sigma\,(Nu, Nr) + \Sigma\,(Nl, Ng, Ne)) \qquad (5)$$

Given the level of nutrient mining, the nutrient requirement (Nur_i) of a crop (i) for a specific target yield, soil, and region was calculated by taking into account the amounts of nutrient inflows and outflows and the soil fertility. Fertilizer requirements for meeting a given pre-established level of production target were calculated by:

- Assessing how much of each nutrient (element) the crop must take up to produce the pre-established "target yield." This is the minimum quantity of nutrient uptake requirement (Nur). The nutrient uptake requirements of crops in each country are calculated by multiplying the amounts of production of crop outputs and straw (residue) by their respective minimum element concentrations (Table A1). Thus, the calculated nutrient uptake requirements are viewed as minimum nutrient uptake indexes for specific crop yield. The indexes were developed from fertilizer response trials done across Africa. Generally, a crop could take up more nutrient than it requires, but this would not result in more production or yield. It could improve the quality of the product (Driessen and Konijn, 1992).
- Assessing how much nutrient is furnished by the soil itself. This includes the nutrient mining assessment and the evaluation of soil fertility (soil NPK availability) usually collected in soil analyses and survey samples. The assessment of nutrient mining and nutrient uptake requirements was conducted at macro scale for each country in the agricultural regions of Africa.
- Assessing the efficiency of the fertilizer or the fraction of the fertilizer that is used by the crops in the crop production systems. In calculating nutrient requirements and assessing yields, it is assumed that there are not serious growth limitations other than soil fertility.

Because of significant variability within countries, estimates of crop yield response were calculated for selected areas within countries. For those areas, more elaborated sensitivity analyses were conducted using empirical and simulated response models (Wolf et al., 1989; Jansen et al., 1990). The country assessment of crop yields was done based on land-use maps and interpolations based on geo-referenced information and spatial analysis routines.

The target yield for crops was pre-established on the basis of current and potential crop yields expected at given conditions of management practices (seed variety, fertilizer, and water availability), the projected reductions in nutrient mining, and projections for Africa on population growth rate, crop imports, and food security targets.

Appendix II

Acronyms, Abbreviations, and Glossary

AEZs	Agro-Ecological Zones
CEC	Cation Exchange Capacity (of soils)
CIESIN	Center for International Earth Science Information Network
CPPs	Crop protection products
DEM	Digital Elevation Model
ECOCROP	Database interface that identifies suitable plants for a specified environment
EPIC	Erosion Productivity-Impact Calculator
EROS	Earth Resources Observation and Science
ESRI	Environmental System Research Institute
FAO	Food and Agriculture Organization of the United Nations
GDP	Gross domestic product
GIS	Geographic Information Systems
ha	Hectare
IFA	International Fertilizer Industry Association
IFDC	An International Center for Soil Fertility and Agricultural Development
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied System Analysis
ISRIC	International Soil Reference and Information Centre
K	Potassium
K_2O	Potassium oxide (expressed as K)
kg	Kilogram
LGP	Length of the Growing Season
N	Nitrogen
NUBAL	Nutrient Balance Database
NUTMON	Nutrient Monitoring for Tropical Farming Systems
OECD	Organization for Economic Co-operation and Development
OM	Organic Matter in soils
P	Phosphorus
P_2O_5	Phosphorus pentoxide (expressed as P)
RUSLE	Revised Universal Soil Loss Equation
SARC	Southern African Research Center
SARDC	Southern African Research and Documentation Center
SLEMSA	Soil Loss Estimation for Southern Africa
t	Metric ton
TLU	Tropical Livestock Units
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USAID	United States Agency for International Development
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
USPED	Unit Stream Power-Based Erosion Deposition
WB	World Bank
WISE	World Inventory of Soil Emission Potentials
WRI	World Resource Institute
Yield	Crop production per unit of land

Glossary

Available soil nutrient: Plant nutrients in chemical forms in the soils that are accessible to plant growth.

Agricultural land: Land currently under farming that includes annual and perennial crops and livestock.

Agricultural system: Organization and structure of agriculture production as determined by the influence of local agroclimatic and socioeconomic circumstances on crops and crop production cycles and sequences, and crop and soil management practices such as the use of crop varieties, fertilizers, crop protection practices, and nutrient recycling and soil conservation practices.

Crop productivity: It is used in this report interchangeably with crop yield and land productivity as a measure of crop production per unit of fixed factors of production during a year or season.

Fallow: Land left unsown, usually for the whole season, or land usually under permanent crop, meadows or pastures that is not being used for that purpose for at least one year.

Farming system: Agricultural activities developed in a defined piece of land cultivated by a household and his family. It includes farm enterprise patterns that characterize an agricultural area.

Fertilizer: Organic and inorganic material added to a soil to supply one or more plant nutrients essential to plant growth.

Nutrient balance: The difference between the sums of nutrient inputs and outputs on agricultural lands.

Nutrient depletion: Is the process of making soil nutrients unavailable to plant growth and crop production.

Nutrient mining: Is equivalent to nutrient depletion and includes the assessment of processes leading to nutrient depletion.

Soil fertility: Is a term regularly used to describe the soil's ability to support crops through its own nutrient reserves and physical characteristics.

Soil productivity: Is used to describe a soil's ability to support crops when cultivated correctly, including supplements of organic and mineral nutrients to compensate for removal and losses and to maintain soil reserves.

Units in the Report

Nitrogen is given as the elemental N.

Phosphate and potassium are given as oxides: P_2O_5 (Phosphorus Pentoxide) and K_2O (Potassium Oxide). For simplicity the sum of N, P_2O_5, and K_2O is expressed as (NPK).

Area: generally expressed in hectare: 10,000 m^2 = 2.47 acres

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