AN AGRO-ECOLOGICAL FRAMEWORK FOR INTEGRATED NUTRIENT MANAGEMENT,

with special reference to Kenya

4095

Promotor : dr. ir. J. Bouma
hoogleraar in de bodeminventarisatie en landevaluatie, speciaal gericht op de (sub)tropen
Co-promotor: dr. ir. B.H. Janssen
universitair hoofddocent aan de Vakgroep Bodemkunde en Plantevoeding

ERIC SMALING

AN AGRO-ECOLOGICAL FRAMEWORK FOR INTEGRATED NUTRIENT MANAGEMENT, with special reference to Kenya

Proefschrift
ter verkrijging van de graad van doctor
in de landbouw- en milieuwetenschappen
op gezag van de rector magnificus,
dr. H.C. van der Plas,
in het openbaar te verdedigen
op woensdag 27 januari 1993
des namiddags te vier uur in de Aula
van de Landbouwuniversiteit te Wageningen.

'Dans le vaste débat concernant l'imminence d'une catastrophe écologique en Afrique au sud du Sahara, il convient de baser son jugement sur le maximum d'indicateurs agronomiques quantifiables, pour tenter modestement de mieux apprécier les évolutions du patrimoine foncier de cette vaste zone'

Christian Pieri, 1989. Fertilité des terres de savanes.

This thesis is dedicated to *Gé Smaling*,
my staunchest supporter.

TABLE OF CONTENTS

STELLINGEN

behorende bij het proefschrift:

An agro-ecological framework for integrated nutrient management, with special reference to Kenya.

Eric Smaling
Wageningen, 27 januari 1993

1. Als gevolg van de bevolkingsaanwas en de daarmee gepaard gaande toenemende druk op het landbouwareaal, is de bodemvruchtbaarheid in Afrika bezuiden de Sahara de afgelopen decennia sterk afgenomen. Zonder grootscheepse toepassing van meststoffen zullen vooral landen in semi-aride gebieden binnenkort structureel op noodhulp aangewezen zijn.

   - *Van Keulen, H. and Breman, H., 1990. Agricultural development in the West African Sahelian region: a cure against land hunger? Agric. Ecosystems Environ. 32: 177-197.*
   - *Van der Pol, F., 1992. Soil mining. An unseen contributor to farm income in southern Mali. Bulletin 325, Royal Tropical Institute (KIT), Amsterdam, 48 pp.*
   - *Dit proefschrift*

2. Duurzame landbouw in de Oostafrikaanse hooglanden is zelfs bij de huidige bevolkingsdichtheid technisch mogelijk, maar vergt een intensief proces van institutionalisering en vertaling naar de (boeren)praktijk van het begrip 'duurzaamheid' bij nationale en lokale overheden.

   - *Dit proefschrift*

3. De betrouwbaarheid van de berekening van de nutriëntenbalans in Afrikaanse landbouwsystemen wordt o.a. beperkt door het gebrek aan veldgegevens over nutriëntenverlies als gevolg van watererosie. Dit is mede een gevolg van de overmaat aan miniplot-metingen, waarbij het accent sterk ligt op het meten van totaal bodemverlies, en geen rekening gehouden wordt met sedimentatie van geërodeerd bodemmateriaal binnen hetzelfde stroomgebied.

   - *Dit proefschrift*

4. Simpele dosis-effectstudies noch gecompliceerde mechanistische simulatiemodellen hebben hun nut bewezen bij het lenigen van landbouw- en voedselproblemen in Afrika. Er is dringend behoefte aan ontwikkeling en validatie van theoretisch onderbouwde 'pedotransfer functions' met relatief geringe invoervereisten, die zich tussen deze extremen in bevinden.

   - *Janssen, B.H., Guiking, F.C.T., Van der Eijk, D., Smaling, E.M.A., Wolf, J., and Van Reuler, H., 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46: 299-318.*
   - *Dit proefschrift*

10. Het met elkaar in verband brengen van geologische tijdschalen en ecologische duurzaamheid versterkt het gevoel dat we snel het tienduizendjarig jubileum van het Holoceen moeten vieren aangezien een volgende (smeltende?) ijstijd zich sneller lijkt aan te dienen dan tot nog toe te doen gebruikelijk.

    - *Fresco, L.O. and Kroonenberg, S.B., 1992. Time and spatial scales in ecological sustainability. Land Use Policy 9: 155-168.*

11. Het percentage vrouwen in bestuurlijke functies vormt geen afspiegeling van de aangetoonde sociale en communicatieve superioriteit ten opzichte van mannen.

    - *Fasteau, M.F., 1974. The male machine. Bruna, Utrecht.*
    - *Tannen, D., 1990. You just don't understand. Prometheus, Amsterdam.*

12. Liever een huis met geesten dan honderd jaar eenzaamheid.

5. Bodem- en klimaatskaarten op regionale schaal zijn onmisbaar bij het aanbrengen van geografische nuancering in de 'blanket' bemestingsadviezen in Afrika. De hogere bemestingsefficiëntie die daarmee kan worden bereikt is voordelig zowel voor de boer als de nationale economie en het milieu.

   - *Dit proefschrift*

6. De bewering dat de kans op stikstofuitputting in de Oxisols en Ultisols van de Amazone-regio zeer gering is, wordt onderbouwd door een te optimistische voorstelling van de stikstofbalans, waarbij bovendien de suggestie wordt gewekt dat stikstof die vrijkomt uit afstervende wortelmassa als invoer moet worden aangemerkt.

   - *Sanchez, P.A. and Salinas, J.G., 1981. Low-input technology for managing Oxisols and Ultisols in tropical America. Advances in Agronomy 34: 279-406.*

7. Met de ontwikkeling van de kwantitatieve fysische landevaluatie zal een einde komen aan het vinden van zelf verstopte eieren waarin deze discipline tot voor kort dreigde te verzanden.

   - *Van Diepen, C.A., 1983. Evaluating land evaluation. ISM Annual Report, pp. 13-29.*
   - *Bouma, J., 1989. Using soil survey data for quantitative land evaluation. Advances in Soil Science 9: 225-239.*
   - *Van Diepen, C.A., Van Keulen, H., Wolf, J., and Berkhout, J.A.A., 1991. Land evaluation: from intuition to quantification. Advances in Soil Science 15: 139-204.*

8. De stille diplomatie die de Nederlandse overheid zo graag betracht bij misstanden in het buitenland, en die haar beslag krijgt in het via de ambassadeur 'uiting geven aan onze bezorgdheid', stemt meer tot droefenis dan de eenzijdige beëindiging van de bilaterale ontwikkelingsrelatie door Indonesië.

9. 'Institution building' in ontwikkelingslanden kan slechts slagen wanneer (i) het donorland de moed opbrengt een langdurige committering aan te gaan en (ii) het ontwikkelingsland zorgt dat het instituut een duidelijke en logische plaats inneemt in de overheidsstructuur en het eigen personeel een salaris tegemoet kan zien dat boven de absolute ontmoedigingsgrens ligt.

ABSTRACT

Smaling, E.M.A., 1993. An agro-ecological framework for integrated nutrient management, with special reference to Kenya. Doctoral thesis, Agricultural University, Wageningen, The Netherlands, (X) + 250 pp.

This thesis provides a framework for integrated nutrient management in agricultural land use systems, with particular reference to its impact on productivity, fertilizer use efficiency, and sustainability in well-delimited tracts of land (agro-ecological units), characterized by a specific set of soil and climatic properties. Most of the research was conducted in Kenya, but methodology and results can be applied to any tropical region.

Quantitative assessments are made of the nitrogen, phosphorus and potassium balance in the root zone of the arable land in sub-Saharan Africa. Land use systems are characterized by nutrient inputs (mineral fertilizer, manure, atmospheric deposition, biological nitrogen fixation, sedimentation) and nutrient outputs (removal of harvested crop parts and residues, leaching, denitrification, erosion), and the balance between the two. It is shown that outputs exceed inputs all over the continent. As scale-inherent simplifications were inevitable, a more detailed study is presented for the Kisii District in Kenya, with similar results. The alarming figures call for agronomic and policy interventions in the soil nutrient balance. A scale-neutral decision-support model of this nature is described, in which scenarios for improved nutrient management are worked out.

Mineral fertilizers are, with the present abolishment of subsidies in many African countries, increasingly expensive, and it is evident that they must be used efficiently. With this in mind, a network of 70 researcher-managed, but farm-based factorial fertilizer trials was established in rainfed agricultural Kenya. The trial sites were chosen such that they represent wider ranges of similar environments. As such, the results form a basis for fertilizer recommendations that are not just crop-specific, but also specific for agro-ecological units. The site selection procedure is demonstrated, based on a profound scrutiny of soil and climate maps in Kenya, and followed by results of four years study on the response of maize to fertilizers and manure in three agro-ecological units.

The above approach leads to recommendations which apply to a district scale, but do not account for spatial variability between and within individual farmers' fields. Field-level heterogeneity, however, affected some trials as it was beyond the researcher's control. Two examples are dealt with in detail, i.e. (i) bypass flow and associated nitrogen leaching in a cracking clay soil, and (ii) the spotty emergence of the parasitic weed *Striga hermonthica.*

As the establishment and maintenance of a trial network is costly and time-consuming, computer models are increasingly used as an alternative. The QUantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model describes relations between (i) soil chemical parameters, (ii) potential supply of N, P and K from soils and fertilizers, (iii) actual uptake of N, P and K by maize, and (iv) maize grain yield. Characteristic features of the model are the inclusion of all macronutrients, acknowledging interactions between them, and the low input requirements enabling agronomists in tropical environments to test the model. The four steps of QUEFTS are calibrated with input data from fertilizer trials in different agro-ecological units. A complete run of the modified version shows a high correlation between measured and calculated yield, but although new relations are found, the basic structure and theoretical concepts of the original QUEFTS still stand.

Additional index words: agro-ecology, chemical soil fertility, nutrient balance, sustainable agriculture, fertilizer use efficiency, bypass flow, nitrogen leaching, *Striga hermonthica*, modelling, maize, sub-Saharan Africa.

PREFACE

This thesis was written in the context of my assignment as a (tropical) soil scientist at the Winand Staring Centre for Integrated Land, Soil and Water Research, Wageningen, The Netherlands, an institute in the Agricultural Research Department (DLO) of the Ministry of Agriculture, Nature Management and Fisheries.

Most of the work described in this thesis is based on a 2.5 year posting at the Fertilizer Use Recommendation Project (FURP), Nairobi, Kenya. The aim of the FURP, financed by the Governments of Kenya and Germany, and by the European Communities, was to establish fertilizer recommendations for rainfed, annual crops, based on the agro-ecological diversity of the country's arable land. The FURP is an integral part of the National Agricultural Research Laboratories (NARL) in Nairobi, one of the research centres in the Kenya Agricultural Research Institute (KARI), a parastatal body in the Ministry of Research, Science and Technology.

Another considerable part of the thesis came into being as a result of an initiative by the United Nations Food and Agriculture Organization (FAO), and in particular its Land and Water Division (AGL). At the request of FAO, and based on its extensive data base on crop production and fertilizer use, the issue of nutrient depletion in sub-Saharan African soils was approached in a quantitative sense, and scenarios were developed for more sustainable forms of agriculture in a district in Kenya.

A great number of individuals played a supporting role during the research period. My promotor, Johan Bouma, and my co-promotor, Bert Janssen, have been a continuous source of inspiration and encouragement. My director, Gerard Oosterbaan is acknowledged for his interest and support, and my head of department, Wim Andriesse, for the highly appreciated, thorough way of commenting on all the papers, for enabling me to finish the job, and for his friendship. Many other colleagues at the Winand Staring Centre have been supportive, notably staff from the departments of scientific editing (Bram ten Cate, Liesbeth Ruyten), word processing (Riet Meijnen, Cis van Eijck), and cartography (Martin Jansen, Dasja ten Cate).

I am very thankful to my many Kenyan friends and colleagues, who were involved in the research: Cyrus Ndiritu, Director KARI, for granting me the opportunity to conduct the research; Frederick Muchena, Director NARL, for his encouragement and friendship, and the provision of laboratory facilities; Steven Nandwa, FURP Coordinator, for the great friendship and shared interests; Stanley Wokabi, Head Kenya Soil Survey (KSS), for all his support after I left the FURP in 1987, but came back to next-door KSS as a liaison officer in 1988; and the KSS staff in the field, in particular Charles Gachene, John Kibe, Ben Gunn Mwangi and Stanley Wataka, for everything we shared, from hard round-the-clock labour to leisurely nights in the bars of Homa Bay, Kisumu, Nakuru or Nyahururu. I also owe a lot to Herbert Stroebel, former FURP Coordinator for his encouragement and maintenance of a highly spirited atmosphere in the project, and my FURP colleague Reimund Roetter from Trier University, with whom I worked together in Kenya, and the friendship and common research interests that remained afterwards.

Highly motivating and pleasant has been the cooperation with Jetse Stoorvogel and Louise Fresco on the quantification of nutrient balances, and the steps ahead we managed to make in quantifying sustainability. At FAO, Robert Brinkman is greatly acknowledged for his ideas and enthusiasm, and his comments on various texts related to the subject.

Special words of thanks go to Roel van de Weg, Director of the International Agricultural Centre, and former Deputy Director of the Winand Staring Centre. Without his energy and confidence, I would not have been part of the FURP, and FAO would not have found the way to the Winand Staring Centre; to Reintje van Haeringen, who underwent my wailing more than once, and got me back on the track, when I casted doubts on the success of the whole undertaking; to her sister Annemarie van Haeringen, for her artistic explanation of integrated nutrient management on the cover; and to my parents, Gé Smaling and Femy Nink, for their boundless interest in my studies, my work, and my well-being at large.

PART I INTRODUCTION

1. General introduction
2. Literature review

Chapter 1

General Introduction

1 GENERAL INTRODUCTION

1.1 Constraints to agricultural production in Africa

It was 1981 when Sanchez and Salinas, reviewing agricultural production technology on low-fertility soils in Latin America, stated that 'the outcome of the race between world food production and population will largely be determined in the tropics, where most of the world's undernourished people live'. In 1992, the race is in an advanced stage, and we must admit that as far as sub-Saharan Africa is concerned, food production, though growing, lies several laps behind. In other words, *per capita* food production has been declining throughout the 1980's, in spite of FAO's optimistic forecasts that between 1985 and 2000, agricultural production and population would both grow at annual rates of approximately 3.3% (Alexandratos, 1988).

There are several reasons why food production has remained below expectations in sub-Saharan Africa. First, there have been quite a number of sudden, catastrophic events such as droughts (Ethiopia, the Sahelian countries, and recently southern Africa and Madagascar), flash floods (Sudan) and locust invasions (Sahelian countries).

Second, the 'Green Revolution', boosting agricultural production in Asia and, to a lesser extent Latin America, seems to have bypassed sub-Saharan Africa, where traditional farming methods were largely maintained, in spite of the growing pressure on agricultural land. As a result, shifting cultivation was gradually replaced by permanent cropping, leaving land devoid of any vegetal cover during part of the year. The subsequent exposure to battering downpour has triggered physical soil degradation in many places.

Third, many African countries are involved in prolonged civil wars, mostly as an indirect result of past colonialism, when white rule pegged off occupied territory by artificial 'pencil-and-ruler' borders, bluntly disregarding the intrinsic geographic patterns of different ethnic communities. The present turmoil in those countries has severely reduced crop and livestock production and has largely wiped out agricultural infrastructure, with Mozambique and, of late, Somalia, probably as the most pathetic examples.

Finally, there is a rather hidden reason for agricultural production in sub-Saharan Africa to be lagging behind so much. This is the gradual process of soil nutrient depletion in many of the subcontinent's agricultural land use systems. This phenomenon receives much less public attention than erratic rainfall, crop failures and civil wars, which are directly associated with famine and starvation. Nonetheless, several studies have shown that it is often the supply of nutrients that dictates the productivity of land, even in the Sahel. Increasing evidence is gained that dwindling soil fertility is a major constraint to crop production on the subcontinent. In most land use systems, the amount of nutrients leaving the soil in crops, but also by leaching and erosion, is grossly exceeding the amount of nutrients imported by natural processes such as atmospheric deposition and biological nitrogen fixation, or artificially, by organic manure and mineral fertilizers.

Increased food production in Africa is the concern of many parties at different hierarchical levels, including governments, (inter)national monetary, research and donor organizations, provincial and district rural development projects, and the African farming community itself. Although all are concerned about the same subject matter, there is an apparent divergence between the perspectives of land use at the different levels. Mascarenhas et al. (1986) mention some of the commonly recognized problems at the donor level, such as poor mutual coordination of efforts, overlapping projects and missions, and overburdening the management capacity of recipient countries. A study by the International Institute for Environment and Development revealed that in the early 1980s, Malawi was dealing with 50 separate donors for 188 projects, Kenya had to liaise with 60 donors on 600 projects, while in Zambia no fewer than 69 donors were involved in 614 projects. A huge share of the time of senior government personnel is taken up with dealing with all the donors, preparing accounts and reports, and ferrying round visiting missions (Harrison, 1987). Also, donor priorities shift as governments are replaced. In The Netherlands, for example, each new Minister of Development Cooperation formulates new priorities, often reflecting convictions of his or her political party. Next, individual line-ministries in the recipient countries have their own, sometimes conflicting strategies, and are often overruled by Finance ministries, which are lacking expertise in issues of natural resource management and agricultural production.

An African Minister of Planning recently said in an interview that 'as long as economic growth outstrips population increase, we will have no problems' (EC

Courier 130, 1991), and continued to emphasize that small-holders could still realize considerable production increases, if only they would become more efficient. Although the article did not elaborate on the incentives the Minister had in mind, a common one in many countries has been the subsidy on mineral fertilizers. Table 1.1 shows that Kenya and Zimbabwe consume approximately equal amounts of fertilizer but, whereas Zimbabwe has a considerable domestic production, Kenya has to import all its fertilizer. Yet, it has been supplied to farmers at subsidized prices for a long time. With supra-nationally imposed structural adjustment policies, however, these subsidies were largely abolished in 1992, and the subsequent increases in fertilizer prices will discourage farmers. Because of such developments, there is an increasing need to use external inputs such as mineral fertilizers very efficiently. In other words: the input 'mineral fertilizer' should as much as possible be converted into useful output (harvested product), as opposed to non-useful outputs such as loss of nutrients by erosion, leaching and denitrification.

Table 1.1 Consumption and import of mineral fertilizer (July 1986-June 1987) in some African countries (adapted from FAO, 1988)

	N		P		K	
	consumption (t)	import (%)	consumption (t)	import (%)	consumption (t)	import (%)
Africa	2 010 032	38	484 796	33	370 593	96
Egypt	655 450	8	52 870	0	25 083	124
Kenya	62 718	100	19 733	100	11 428	100
Senegal	7 500	65	3 261	0	5 000	33
S-Africa	361 706	9	146 424	0	99 383	107
Zimbabwe	81 885	15	18 598	0	27 671	93

With soil and climate maps at regional scale (1 : 50 000 - 1 : 100 000) at hand, fertilizer studies can be transformed from mere point observations into recommendations that are meaningful for areas with similar soils and climate. Type and amount of fertilizer to be applied is then no longer governed by the requirements of a crop only, but rather by the prevailing soil and agro-climatic conditions in the area considered. For the message of 'fertilizer application according to agro-ecological diversity' to be carried to farmers, insight is needed in the functioning of the overall national and regional agricultural infrastructure, with special emphasis on extension services. In addition, research is needed on farmers' indigenous knowledge on low-external-input agricultural options, and the rationality behind their decision-making with respect to input use.

The issue of fertilizer use efficiency does not only apply to sub-Saharan African agriculture. In Western European countries, mineral fertilizers are cheap, providing an incentive to farmers to aim at high production. Moreover, they often have a lot of animal manure to get rid of, and are less concerned whether their soils can handle all these nutrients. In both continents we fear leaching of nutrients, but the motives are entirely different. In Africa, we do not want to lose nutrients from the topsoil as it lowers productivity, whereas in Western Europe we do not want these nutrients to reach the increasingly polluted groundwater. Similarly, research on phosphorus retention by soil colloids in tropical soils focuses on the problem that the nutrient is rendered unavailable to plants, whereas in for example The Netherlands, the focus is on how much phosphorus a soil can possibly fix before the element is leached to the groundwater.

1.2 Maintenance of productivity over time: sustainability

The statement of the Minister quoted in the previous section is a typical though understandable example of short-term thinking, whereas the long-term maintenance of the required production levels seems to be of less concern. In today's sub-Saharan African agriculture, very few (if at all) land use policies are operational that simultaneously address both productivity and sustainability. Productivity can be defined as the output of valued product per unit of resource input, and sustainability as the capacity of a system to maintain output at a level approximately equal to its historical average (Lynam and Herdt, 1989). For agriculture to be both productive and sustainable, (i) renewable resources must be maintained, (ii) non-renewable resources must be used with foresight, (iii) the intrinsic value of the natural environment must be recognized, (iv) farm families must be able to make a decent living, and (v) increasing and changing demands for agricultural products must be satisfied at affordable prices. The combination of these commandments harbours conflicting productivity and sustainability demands that have to be satisfied at the same time, forming a continuing source of political debate (De Wit, 1990).

Sustainability is a popular subject in a plethora of literature, and scores of natural resource and agricultural scientists, donor representatives, rhetoric politicians and the likes tell the world how much sustainability of agricultural land use systems in Africa is at stake. Fresco and Kroonenberg (1992) observe that nearly without exception, the concept of sustainability is applied to land use systems of divergent spatial scales, from individual fields or farms to regions, countries or even the world as a whole, but refers to a relatively limited time scale (decades or less). Nonetheless, it was in 1841 when Von Liebig already stated "Als Prinzip des Ackerbaues muss angesehen werden, dass der Boden in vollem Masse wieder erhalten muss, was ihm genommen wird". Similarly, Van Diest (1986) described nutrient transfers in the pre-fertilizer era such as the creation of the 'plaggen' soils in The Netherlands, where man concentrated the fertility of soils in large areas onto small areas, and nutrient transport in river sediment, sustaining past civilizations along, for example, the Nile, Euphrate and Yellow River for centuries.

In the past decade, European farmers have been too diligent with respect to Von Liebig's commandment, as the amount of nutrients entering soils grossly outnumbers the amount withdrawn. Extreme cases are the livestock producing farms in The Netherlands, with huge nutrient inputs in mineral fertilizer and feedstuffs. Cooke (1986), in a review of the present-day intercontinental nutrient translocations, shows that each year, The Netherlands imports 38 000 tons of N, 12 000 tons of P, and 106 000 tons of K from Thailand, in the form of cassava. The implications at the farm level are shown in a study by CLM (1989) in Table 1.2. The quantity of feedstuffs bought by a Dutch livestock producer is no longer determined by the nutrient requirement of his soil, but by the caloric requirements of his animals, in other words: the relationship between number of animals raised and hectares farmed no longer exists (Van Diest, 1986).

Next to nutrient exports across international boundaries, of which the Thailand example is as appalling as it is appealing, processes such as erosion and denitrification, and the very low use of fertilizers and manure further contribute to net negative nutrient balances in many tropical nations. The lower part of Table 1.2 shows that the mountaineous, densely populated Central African state Rwanda experiences such problems and has a considerable annual nutrient deficit. To equilibrate this 'unbalanced ledger', the soil nutrient pool is exploited every cropping season to obtain somehow constant yield levels. Such countries have to cope with both a gradually deteriorating resource base as well as a growing population; hence, the Honourable Minister is surely going to have a problem!

Table 1.2 Nutrient balance for an average dairy farm in The Netherlands (CLM, 1989), and for the arable land in Rwanda in 1982-1984 (Stoorvogel and Smaling, 1990)

		Amount (kg ha^{-1} yr^{1})		
		N	P	K
THE NETHERLANDS				
<u>Inputs</u>				
IN 1	Mineral fertilizers	440	19	25
IN 2	Imported Fodder	200	36	138
IN 3	Atmospheric deposition	50	1	4
IN 2, 4, 5	Others	8	2	3
Total		698	58	170
<u>Outputs</u>				
OUT 1	Milk	69	12	20
OUT 1	Beef	13	4	1
Total		82	16	21
<u>Nutrient balance</u>		616	42	149

Conclusion: IN - OUT >>> 0; nutrient storage in soils, leaching and associated pollution of aquifers, denitrification, ammonia volatilization.

Table 1.2 (continued)

		Amount (kg ha^{-1} yr^{1})		
		N	P	K
RWANDA				
<u>Inputs</u>				
IN 1	Mineral fertilizers	0.4	0.1	01
IN 2	Organic manure	1.6	0.4	27
IN 3	Atmospheric deposition	5.0	0.8	33
IN 4	Biological N fixation	8.8		
IN 5	Sedimentation	1.8	0.3	11
Total		17.6	1.6	72
<u>Outputs</u>				
OUT 1	Harvested product	22.0	4.1	234
OUT 2	Residue removal	5.3	1.5	97
OUT 3	Leaching	3.8	0.0	26
OUT 4	Gaseous losses	11.5		
OUT 5	Water erosion	28.8	4.5	180
Total		71.4	10.1	537
<u>Nutrient balance</u>		-53.8	-8.5	-465

Conclusion: IN - OUT << 0: depletion of the soil nutrient pool.

What is the long-term outlook for agriculture in sub-Saharan Africa? Is it so bleak, that we should be prepared for just another form of colonialism, i.e. a developed world, in future structurally feeding a large part of the population in Africa, by virtue of its excess soil nutrients and surplus production? This is a frightening prospect which, only a few decades ago, would definitely have ranked under 'science fiction'. One could put forward that African farmers in densely populated areas ought to abstain from permanent cropping, increasing their fallow rates which should include nitrogen fixing cover crops and trees, and partly be given western food aid in return. It may be a way of getting the supra-national nutrient balance right, and although it may be socially unacceptable, it is environmentally very sound! The other extreme case, i.e. continuation of soil nutrient removal by crops and land degradation processes, is however environmentally very unsound and largely irreversible! In this context, it is worthwhile to mention the bewildering results of a recent study by the Netherlands Scientific Council for Government Policy (WRR, 1992). It shows that the combination of EC countries can, by virtue of the ever-increasing productivity, realize today's agricultural production on a mere 20-50% of the land presently under agricultural use, under different boundary conditions of employment, nature management, and environmental protection.

Without being overly optimistic, one of the objectives of this thesis is to show that there is still a large playground in between the two extreme situations, including agricultural options that are socially acceptable, economically viable, as well as environmentally sound. This playground is rather cryptically known as 'integrated nutrient management', and will be translated here as the judicious manipulation of all input and output processes that govern the nutrient balance in agricultural land use systems. The five input processes are application of mineral fertilizer (*IN 1*) and organic manure (*IN 2*), atmospheric deposition (*IN 3*), biological nitrogen fixation (*IN 4*), and sedimentation from natural flooding and irrigation water (*IN 5*). The five output processes are removal of harvested product (*OUT 1*) and crop residues (*OUT 2*) from the arable field, leaching (*OUT 3*), gaseous losses (*OUT 4*), and water erosion (*OUT 5*).

African farmers apply mineral fertilizers (increasing *IN 1*) solely from a productivity perspective, i.e. to increase the yields of crops that are grown during a particular season. Erosion control measures (reducing *OUT 5*), incorporation of N-fixing trees in cropping systems (increasing *IN 4*, and reducing *OUT 3* and *OUT 5*), and more intensive use of organic manures and town and (agro-)industrial refuse (increasing *IN 2*) however, serve both productivity and sustainability, as their effects are relatively lasting. The resulting agricultural systems may truly deserve the name agro-ecosystems. Unlike mature natural ecosystems, where nearly all biomass produced is reinvested to maintain chemical, physical and biotic stability of the system, the reinvestment in agro-ecosystems is more limited, as man extracts part of its produce. In well-managed agro-ecosystems, the strained nutrient balance as shown for Rwanda in Table 1.2 can be alleviated and, in case of radical measures, redressed.

Research on sustainable land use systems requires long-term commitment, as long-term viability of systems is an inherent component of any quantitative research effort on sustainability. The earlier mentioned rapid changes in donor priorities, however, make planning and funding of long-term field studies difficult. Or, as Army and Kemper (1991) phrase it for the US: "in quick and overlapping succession we see groundwater quality, sustainable agriculture, food safety, global warming and greenhouse gases as priorities of sufficient public concern to merit new funding".

1.3 This thesis

In this thesis, a framework is provided for integrated management of nutrients in tropical land use systems, and its impact on productivity, fertilizer use efficiency, and sustainability in well-delimited tracts of land, characterized by a specific set of soil and climatic properties (agro-ecological units). Recent publications also touching on parts of this subject encompass work by Bunting (1987), Conway (1987), Lynam and Herdt (1989), Edwards et al. (1990), Okigbo (1990), Vlek (1990), Fresco and Kroonenberg (1992), and Reijntjes et al. (1992).

A pivotal role in this thesis is played by the balance between input and output of macronutrients in the root zone of sub-Saharan African land use systems. The difference in soil fertility between two subsequent years is determined by the difference between the annual values of these input and output processes. As almost all processes can be influenced by man, their integrated (integrate = combine parts into a whole) management determines whether agricultural production will be high and at what level of input use, and whether production in the particular land use system can remain high over long periods of time.

Subjects covered in this thesis, and published in several journal articles comprise (i) the calculation, monitoring and possible manipulation of the macronutrient balance in agricultural land use systems (*IN 1-5* versus *OUT 1-5*), (ii) the measurement and modelling of the effects of native soil fertility and the input of mineral fertilizers and manure on the yield of maize (*IN 1-2* and *OUT 1-2*), with special emphasis on increased efficiency of mineral fertilizers (*IN 1* largely converted to *OUT 1* and not to *OUT 2-5*), and (iii) the acknowledgement of differences in scale (field - farm - district - country - continent), and the implications as to both spatial variability of land as well as agronomic decision-making.

Special emphasis is given to Kenya, where most of the research was conducted. The subject matter, however, applies to any (sub)-tropical region.

Part I comprises the present introduction, and an extensive literature review on the different components of the thesis subject (Chapter 2).

Part II describes the results of a quantitative assessment of the nitrogen, phosphorus and potassium balance in the root zone of sub-Saharan African land use systems. This was done for 38 countries and for 35 crops (Chapter 3). Land use systems were defined, characterized by the nutrient inputs and outputs, and the balance between the two. It is shown that the sum of all inputs minus outputs was negative in almost all countries includ~~ed in~~ing the ~~study~~ country. As the supra-national scale inevitably encompassed numerous assumptions, estimates, simplifications and aggregations, a similar but more detailed exercise was done for the Kisii District in Kenya (Chapter 4). Also here, input minus output of N, K and, to a lesser extent, P, was negative. The alarming figures call for systematic monitoring of the soil nutrient balance, and interventions to ameliorate it. A decision-support model of this nature was defined, to be used at local, regional as well as (supra)national level. At the regional scale (Kisii, Kenya), scenarios were defined for improved nutrient management, reflecting on-going activities in the district as well as possible activities to further redress the nutrient balance (Chapter 5).

Part III then focuses on improvement of the efficiency of mineral fertilizers (*IN 1*) and manure (*IN 2*), based on knowledge of climate and soils at the regional (district) level. Mineral fertilizers are scarce and, with abolishment of subsidies, increasingly expensive. Hence, there is an increasing need to apply them timely and modestly, selecting the proper type of fertilizer, and complying with recommendations that are both crop and soil-specific. As a result, fertilizer use efficiency can be maximized, increasing *OUT 1*/*IN 1* at the expense of *OUT 2-5*. With this in mind, a network of 70 researcher-managed, but farm-based fertilizer trials was established in rainfed agricultural Kenya. In this thesis, eleven trials, all planted to maize, are in the limelight (Table 1.3).

The factorial trials were laid out in a randomized complete block design (two replications). A 4^2 experiment included four levels of nitrogen: 0, 25, 50 and 75 kg ha^{-1} (single topdressing of calcium ammoniumnitrate), and four levels of phosphorus: 0, 11, 22 and 33 kg ha^{-1} (at planting as triple superphosphate). In a second

2^4 experiment, maize received 0 and 50 kg N, 0 and 22 kg P, and 0 and 5000 kg ha^{-1} farmyard manure. The fourth factor was potassium or sulphur or lime, depending on inherent soil fertility and pH. The sites were established only after a profound scrutiny of soil and climate maps, such that they represent wider ranges of similar environments. As such, the trial results form the basis for fertilizer recommendations that are specific for well-delimited agro-ecological units. Only then will they be meaningful to the farming community. The methodology of site selection, using site a as an example, is demonstrated in Chapter 6, followed by results of four years study on the response of maize to fertilizers at sites a, e, and f (Chapter 7).

Table 1.3 Trial sites in the Fertilizer Use Recommendation Project, dealt with in this thesis

Site	Location (District)	Chapter						
		4	5	6	7	8	9	10
a	Kiamokama (Kisii)	x	x	x	x			x
b	Oyugis (South Nyanza)						x	x
c	Rongo (South Nyanza)							x
d	Rodi Kopany (South Nyanza)					x		x
e	Homa Bay (South Nyanza)				x			x
f	Shimba Hills (Kwale)				x			x
g	Chonyi (Kilifi)							x
h	Tezo (Kilifi)							x
i	Kavutiri (Embu)							x
j	Embu-KARI (Embu)							x
k	Gachoka (Embu)							x

Translating the results obtained from the field trials to agro-ecological units at a regional level does not take spatial variability within and between individual farmers' fields into account. This field-level heterogeneity is dealt with in Part IV. An indication of heterogeneity in factorial trials is obtained from the coefficient of variation (c.v.). Average c.v. of maize trials in the period 1987-1990 was approximately 30% for sites b, c and d, whereas the other sites all had an average c.v. below 20%. The high c.v. at site d was a result of its soil being a cracking clay (Vertisol) on flat land. The swell-shrink nature of this soil causes pore size and continuity to change through the seasons. In the course of the wet season, periodic and spotty waterlogging was observed and adversely affected crop development. At the onset of the rainy season, however, shrinkage has caused air-filled macropores to be wide open. They then act as preferential pathways, causing 'bypass flow', i.e. the vertical movement of free water along macropores in an unsaturated soil matrix. To characterize spatial variability, bypass flow and associated nitrogen leaching were studied at trial site d, and on adjacent rangeland plots (Chapter 8).

At site b, the presence of the parasitic weed *Striga hermonthica* caused a high c.v. The weed emerges in a spotty, seemingly uncorrelated pattern and it does most harm to the host plant prior to its own emergence. Chapter 9 describes how trial results could still be usefully interpreted when Striga infestation was included in a regression model. Ways to combat the weed were also studied, including use of a 'trap crop' (sunflower) and fertilizer application.

The establishment of a trial network is costly and time-consuming and requires considerable organizational capacity, staff training and supervision. A presently much-valued alternative is the use of computer models. Part V describes a model that predicts maize yield from inherent soil fertility and fertilizer application, provided that moisture supply is adequate. This model, known as the QUantitative Evaluation of the Fertility of Tropical Soils (QUEFTS), describes relations between (i) soil chemical parameters, (ii) potential supply of N, P and K from soils and fertilizer, (iii) actual uptake of N, P and K by maize, and (iv) maize grain yield (Janssen et al., 1990). Characteristic features of QUEFTS are the inclusion of all three macronutrients and acknowledging interactions between them, and the relatively low input requirements.

QUEFTS was run with input data from fertilizer trials in different agro-ecological units, but correlation between measured and calculated yield proved to be moderate. Reasons were that (i) the original data set used to develop QUEFTS comprised few high pH-soils, while of the present data set, three soils had a pH of more than 7, (ii) some of the soils at the trial sites did not meet the stipulated boundary conditions of free drainage and P-Olsen, and (iii) N and P fertilizer applications were modest and K was not applied at all in the present experimental set-up. Hence, it was decided to employ the data set for a calibration of QUEFTS, so as to extend its applicability. Chapter 10 summarizes the input data for this model, collected at sites a, c, e, f, g and h. All four individual steps were calibrated, and the complete new version gave a high correlation between measured and calculated yield. Although new relations were established, the basic structure and theoretical concepts of QUEFTS were maintained. Trial results from sites b, d, i, j and k were used to validate the modified version of QUEFTS. Agronomists in the tropics should be encouraged to collect the relatively few data that are needed to run the two versions. QUEFTS should become a management tool to improve decision-making at both farm and regional level as to what type and amount of fertilizer is required in which agro-ecological units to realize targeted yields.

In conclusion, let us go back to Sanchez and Salinas' race between the two competitors. We are in the early nineties and 'population growth' is on its way to hammer 'food production'. The African Minister of Planning is found hustling the latter, rather than trying to stop the former. This thesis tries to show that even when the Minister succeeds and the two competitors follow each other at close range, there will be no winner at the finish. The only real solution is to slow the leader down, make him stop and turn back to his opponent, and eventually call the whole event off. Not a single spectator will boo them. This can only be achieved with successful family planning programmes, which is however not the subject of this thesis at all. Yet, it is absolutely essential that birth control gains world-wide momentum (Ehrlich and Ehrlich, 1990). Meanwhile, ways and means of sustainable agricultural production must be developed, and that is what this thesis wants to contribute to. By the time population growth finally levels off, agricultural production systems in the tropics may still be viable enough to support a by then stable population. Hopefully this will not be merely the result of climatic hardship, starvation and diseases, but rather of improved national policies, and the spin-off of activities related to the forthcoming UN-chaired international conference on Population and Development.

References

Alexandratos, N. (Editor), 1988. World agriculture towards 2000. Food and Agriculture Organization, Rome. Belhaven Press, London, 338 pp.

Army, T.J. and Kemper, W.D., 1991. Support for long-term agricultural research. Agron. J. 83: 62-65.

Bunting, A.H., 1987. Agricultural environments, characterization, classification and mapping. CAB International, Wallingford, 335 pp.

CLM, 1989. Centre for Agriculture and Environment. Melkveehouderij en milieu in balans. CLM, Utrecht, 50 pp. (in Dutch).

Conway, G.R., 1987. The properties of agro-ecosystems. Agric. Systems 24: 95-117.

Cooke, G.W., 1986. The international transfer of plant nutrients. Proc. 13th Congress of the International Potash Institute. Worblaufen/Berne, pp. 267-287.

De Wit, C.T., 1990. Understanding and managing changes in agriculture. In: Jones, J.G.W. and Street, P.R. (Editors). Systems theory applied to agriculture and the food chain. Elsevier, New York, pp. 235-249.

Edwards, C.A., Lal, R., Madden, P., Miller, R.H. and House, G. (Editors), 1990. Sustainable agricultural systems. Soil and Water Conservation Society, Ankeny, Iowa, 696 pp.

Ehrlich, P.R. and Ehrlich, A.H., 1990. The population explosion. Touchstone Book, Simon & Schuster, 320 pp.

FAO, 1988. Fertilizer Yearbook 1987. Food and Agriculture Organization, Rome, 123 pp.

Fresco, L.O. and Kroonenberg, S.B., 1992. Time and spatial scales in ecological sustainability. Land use policy 9: 155-168.

Harrison, P., 1987. The greening of Africa. Breaking through in the battle for land and food. International Institute for Environment and Development, London, 380 pp.

Janssen, B.H., Guiking, F.C.T., Eyk, D. van der, Smaling, E.M.A., Wolf, J., Reuler, H. van, 1990. A system for Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS). Geoderma 46: 299-318.

Lynam, J.K. and Herdt, R.W., 1989. Sense and sustainability: sustainability as an objective in international agricultural research. Agric. Economics 3: 381-398.

Mascarenhas, A., Odero-Ogwel, L.A., Masakhalia, Y.F.O. and Biswas, A.K., 1986. Land use policies and farming systems. Kenya, Tanzania, Zambia and Mozambique. Land Use Policy 3: 247-259.

Okigbo, B.N., 1990. Sustainable agricultural systems in tropical Africa. In: Edwards, C.A., Lal, R., Madden, P., Miller, R.H., and House, G. (Editors), Sustainable agricultural systems. Soil and Water Conservation Society, Ankeny, Iowa, pp. 323-352.

Reijntjes, C., Haverkort, B. and Waters-Bayer, A., 1992. Farming for the future. An introduction to Low-External-Input and Sustainable Agriculture. ILEIA, Leusden, 250 pp.

Sanchez, P.A. and Salinas, J.G., 1981. Low-input technology for managing Oxisols and Ultisols in tropical America. Advances in Agronomy 34: 279-406.

Stoorvogel, J.J. and Smaling, E.M.A., 1990. Assessment of soil nutrient depletion in sub-Saharan Africa, 1983-2000. Report 28, Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), Wageningen, 137 pp.

Van Diest, A., 1986. The social and environmental implications of large-scale translocations of plant nutrients. Proc. 13th Congress of the International Potash Institute, Worblaufen/Berne, pp. 289-299.

Vlek, P.L.G., 1990. The role of fertilizers in sustaining agriculture in sub-Saharan Africa. Fert. Res. 26: 327-339.

Von Liebig, J., 1841. The organic chemistry and its application on agriculture and physiology Braunschweig, 506 pp. (in German).

WRR, 1992. Grond voor keuzen - vier perspectieven voor de landelijke gebieden in de Europese Gemeenschap. Rapport 42, Wetenschappelijke Raad voor het Regeringsbeleid (Scientific Council for Government Policies). SDU, Den Haag, 149 pp. (in Dutch).

Chapter 2

Literature review

2 LITERATURE REVIEW

This chapter summarizes some of the literature related to the thesis subject. Much recent literature has been used, as it mostly includes or refers to research data obtained before, which were looked up if deemed necessary. Several volumes of 'Advances in Agronomy' and 'Advances in Soil Science' were scrutinized in order to see to what extent elements of this thesis have been covered in their state-of-the-art articles. The order of sections in this chapter coincides with the order of the topics discussed in Parts II-V. When reviewing the literature, reference is made to the work presented in this thesis.

The word 'nutrient' in this thesis is largely confined to the three macronutrients nitrogen (N), phosphorus (P) and potassium (K). For general reference, three comprehensive pieces of work are mentioned here, describing the role of each nutrient in soils, fertilizers and crop production: *Nitrogen in crop production* (Hauck, 1984), *The role of phosphorus in agriculture* (Khasawneh et al., 1980), and *Potassium in agriculture* (Munson, 1985), all published by the American Societies of Agronomy, Crop Science and Soil Science.

2.1 Quantification and management of the soil nutrient balance

2.1.1 General

A good series of conference papers on quantification and management of nutrients in tropical land use systems has been issued in the past seven years under the editorship of Kang and Van der Heide (1985), Mokwunye and Vlek (1986), and Van der Heide (1989). Much has been published on the fertility status and nutrient balance of soils in West Africa, in particular in the francophone journal 'l'Agronomie tropicale', by French research institutes concerned with agricultural development in the region (ORSTOM, CIRAD), and by the African branch of the International Fertilizer Development Center (IFDC). Large parts of this work have been excellently summarized and aggregated by Pieri (1989). Of very recent date are calculations of the NPK balance under agricultural land use by Malinese and Dutch agricultural research institutes (Van Duivenbooden and Gosseye, 1990; Van der Pol, 1992). The approach used in this thesis differs from the previous work in that (i) a supranational scale is addressed first (Chapter 3), (ii) at the regional scale, the geographical referencing of land use systems is given due attention (Chapter 4), and (iii) scenarios are described to influence the nutrient balance, and are partly based on on-going developments in a well-surveyed region (Chapter 5). It should be borne in mind that next to nitrogen, phosphorus and potassium, deficiencies and imbalances of other nutrients also occur in many tropical soils. Sanchez and Salinas (1981), for example, list the numerous problems encountered in this respect on the 'fertility deserts' of the Amazon basin. In the area covered by Oxisols and Ultisols, a stunning 71% of the soils has sulphur, 62% zinc, and 30% copper deficiency; hence, paying attention to N, P and K only is a simplification, applying to both the nutrient balance model developed in Chapters 3 and 4 (NUTBAL), as well as the nutrient uptake and yield prediction model calibrated in Chapter 10 (QUEFTS), which postulates that no other factors than N, P and K limit crop growth. In this respect, however, all other models are 'over'simpifications, as they almost always address the fate of one single nutrient.

2.1.2 Nutrient inputs and outputs

The nutrient balance model (NUTBAL), elaborated in Chapters 3 and 4, recognizes five input and five output processes. Relevant literature on these processes is discussed in this section.

Mineral fertilizers (IN 1)

Hundreds of books, journal articles and conference papers are devoted to the properties and yield-increasing effects of mineral fertilizers (e.g. Cooke, 1982; Finck, 1982; Tisdale et al., 1985; Böckman et al., 1990). Also, and often at the request of donor agencies wanting to assess the effectiveness of input support, the national fertilizer infrastructure and economics of fertilizer use at different scales have been subject of study. These are largely governed by the degree of domestic fertilizer production, by national and regional handling, bagging, distribution and pricing, and by the effectiveness of extension services at regional and farm level. Worth mentioning is IFDC's work in this respect, including both technical as well as infrastructural and economic considerations in evaluating the fertilizer sector on a national scale in Togo (André, 1990) and Burkina Faso (André et al., 1991). Next, the FAO Fertilizer Yearbooks provide a wealth of information on amounts produced and consumed, and exported and imported. Figure 2.1 shows that Africa's average fertilizer consumption is way below world average. It also shows that fertilizer consumption in Kenya has been well above the continental average, which is quite remarkable for a country that imports 100% of its fertilizers. For the development of the nutrient balance model (Chapters 3 and 4), the FAO database provided country totals of fertilizer use. In case no detailed data were available on their regional distribution, the amounts of fertilizer were partitioned over the different agro-climatic zones in the country.

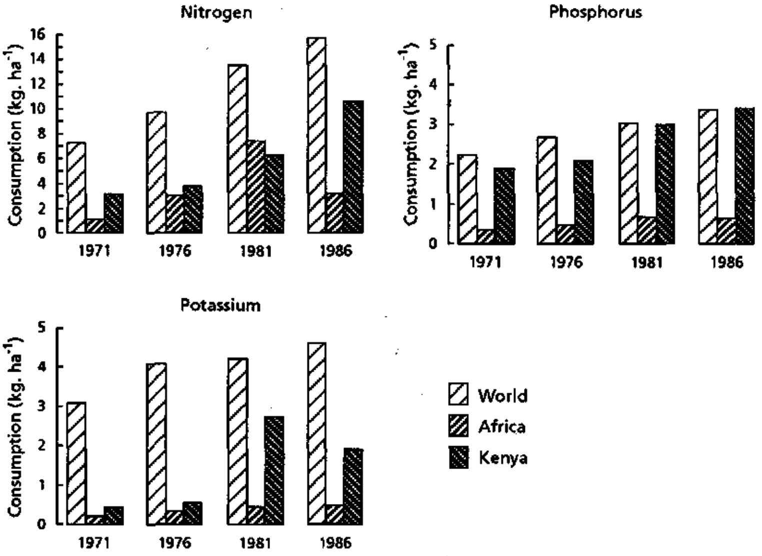


Fig. 2.1 Nitrogen, phosphorus and potassium consumption (in kg ha^{-1} agricultural land) in the world, in Africa and in Kenya (1971-1986)

Organic manure (IN 2)

In traditional livestock production systems in Africa, natural pasture, browse and crop residues are the major feed sources. Their relative importance varies among ecological zones, farming systems, and livestock species. Much work on livestock systems in Africa was done by the International Livestock Centre in Africa (ILCA), and, largely in Nigeria, by the International Institute of Tropical Agriculture (ILCA, 1987; Kang et al., 1990).

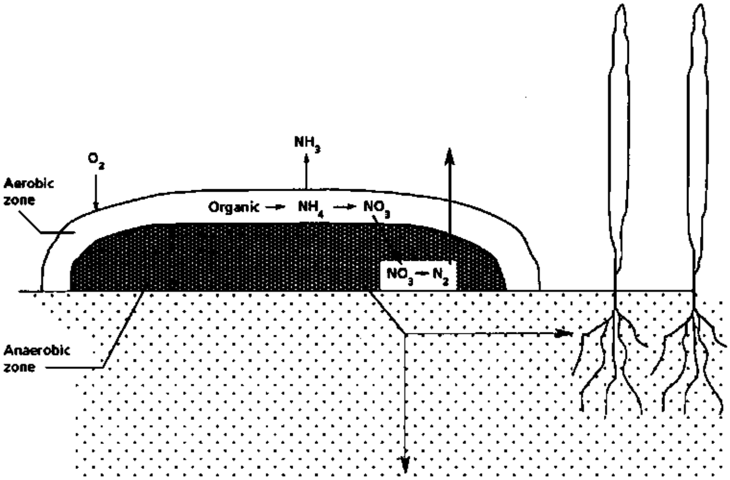


Fig. 2.2 Pathways of nitrogen in feces deposited in a pasture (King, 1990)

In pasture production systems, an estimated 80% of the N, P and K consumed by cattle is returned to the soil via excreta. This percentage is a rough estimate and depends considerably on factors such as stocking rate and grazing management (Sanchez and Salinas, 1981). King (1990) describes the pathways of nitrogen in feces deposited in pasture (Fig. 2.2). Next to leaching and denitrification, ammonia volatilization is an important loss mechanism, as much of the nitrogen in feces and urine is in the ammonia form. Because most of the excreta remains on the soil surface, the potential for ammonia volatilization is high. Another complexity in calculating *IN 2* is that nutrient concentrations in manure vary greatly as fodder sources vary. In general, the nutritive value of natural grasses declines rapidly as the plant matures, but that of browse is more constant. Whereas Pieri (1986) gives a percentage of 0.7% N and 0.6% K in farmyard manure in Madagascar, Pichot et al. (1981) found up to 2.3% N and 5.4% K in Burkina Faso.

Average values of literature data, summarized by Stoorvogel and Smaling (1990), were used in Chapters 3 and 4 to quantify this component of the nutrient balance.

Atmospheric deposition (IN 3)

Nutrient inputs through atmospheric deposition are, at present, undesiredly high in parts of the industrialized world. Jenkinson (1991) showed data for the Rothamsted field station in the UK, situated in the vicinity of London and other industrial towns. Soils in the renowned 'Wilderness' accumulated nitrogen at rates of 23-65 kg N ha^{-1} yr^{-1} by atmospheric deposition. The scarce documented measurements of atmospheric deposition in Africa are summarized by Pieri (1985), Poels (1987) and Stoorvogel and Smaling (1990), and have the following approximate ranges: 3-15 kg N, 0.2-2 kg P, and 2-15 kg K ha^{-1} yr^{-1}.

Biological N fixation (IN 4)

N-fixing plants offer an economically attractive and ecologically sound means of reducing external inputs and improving the quality and quantity of internal resources (Bohlool et al., 1992). Recent reviews on nitrogen input by biological fixation in tropical land use systems were written by Ofori and Stern (1987), Giller and Wilson (1991), and Peoples and Craswell (1992). They are all comprehensive and contain a lot of quantitative information, meanwhile avoiding the stereotype, unsubstantiated ramblings on the assumed benefits of agricultural systems that include leguminous species.

Ssali and Keya (1986), using labeled N, found *Phaseolus* bean in Kenya to fix 74-91 kg N ha^{-1}, coinciding with 43-52% of total uptake. Cowpea in Nigeria fixed 80 kg N ha^{-1}, which was 55-60% of total uptake, both when sole-cropped and intercropped (Eaglesham et al., 1981). Soybean, groundnut and *Vigna* bean all fix over 100 kg N ha^{-1} in various parts of the tropics, when grown solely (Giller and Wilson, 1991). All data were obtained from experiments where pests and diseases were controlled, and adequate P was supplied to the crops. On the residual effect of legumes to follow-up non-leguminous crops, results are divergent, ranging from no effect at all (cowpea in Nigeria) to 50 kg N ha^{-1} from pigeon pea, soybean and groundnut (Giller and Wilson, 1991).

Sedimentation (IN 5)

Nutrient input in naturally flooded and irrigated lands can be considerable. To some extent, there is a link between *IN 5* and *OUT 5*, as erosion in the upper reaches of a river catchment will benefit floodplains further down the river. Examples are the inland delta of the Niger river in Mali, carrying sediment from the Guinea Highlands, the floodplains of the Limpopo and Incomati in Mozambique, importing soil fertility from Zimbabwe and South Africa or, at a local scale, irrigation schemes in Kenya's Kano plains, where water is enriched with sediments from the fertile Kericho and Nandi hills. Literature on the nutrient content of irrigation waters is, however, very scarce (Stoorvogel and Smaling, 1990).

Removal of harvested product (OUT 1)

The production of crops and subsequent removal from the arable land of the useful parts for human or animal consumption or further industrial processing is a key component of the nutrient balance. A 'good crop' means that a lot of nutrients were withdrawn from the soil. Satisfaction about a good crop is the reflection of high productivity of the particular tract of land. *OUT 1* is a measure of this productivity. At the same time, high values for *OUT 1* imply that the soil nutrient balance has a strongly negative value to cope with. Table 2.1 shows that *OUT 1* in Kenya has increased with time, as production of most crops increased between 1979 and 1988 (FAO, 1989a).

Table 2.1 Annual production (10^3t) of major crops in Kenya

Crop	1979-1981	1986-1988
Maize	1714	2611
Sweet potato	351	360
Cassava	588	527
Pulses	185	483
Sugarcane	4211	4487
Coffee	89	117
Tea	93	154
Coffee (Africa)	1173	1244
Tea (Africa)	198	265

Next to total production and cropped hectarages, obtained from the FAO database, crop nutrient content is needed to calculate nutrient output. The literature provides many data on nutrients withdrawn by different crops, but ranges are sometimes very broad for different varieties of the same crop (Baligar and Bennett, 1986). Comprehensive listings are, for example, those by Nijhof (1987) and Stoorvogel and Smaling (1990). In Chapter 3, average values were taken from these reviews, as the supranational nature of the work made differentiation per country or agro-ecological region difficult. In Chapter 4, real uptake data could be used, as measured during land evaluation projects in the Kisii District in Kenya.

Removal of crop residues (OUT 2)

Crop residues serve different purposes, depending on the prevailing farming systems in any one area. Prasad and Power (1991) recently reviewed the management of crop residues in different farming systems. Stoorvogel and Smaling (1990) provide a list of researchers who have measured nutrient contents in residues of different crops. Average values from this review were used for the supra-national nutrient balance model of Chapter 3, and measured data in the regional model of Chapter 4. The amount of residues removed from the arable field and their destination was also taken from literature data for Chapter 3, and from field observations and resource persons for Chapter 4.

Leaching (OUT 3)

Measurements of leaching in Africa are scarce and apparently confined to West-Africa (Pieri, 1985; Stoorvogel and Smaling, 1990). Therefore, leaching was estimated in Chapter 3 and 4 by means of transfer functions, using recognized determinants such as rainfall, texture, soil N and K content, and fertilizer input. An excellent review and classification of leaching models by Addiscott and Wagenet (1985) revealed that comprehensive simulation models on solute leaching in soils have very high data demands, and only a few have been sufficiently validated for a reliable prediction of leaching under field conditions. A successfully applied mechanistic leaching model of the recent past is LEACHN, the nitrogen version of the Leaching Estimation and CHemistry Model. This is a one-dimensional model of water infiltration and redistribution and nitrogen transport within the saturated zone (Hutson and Wagenet, 1991). The model has also been discussed in a recent review on the required sizes of data sets to feed soil interpretive models (Wagenet et al., 1991).

Suitable for use in the nitrogen balance calculations of Chapter 4 was a functional, capacity-type model, like the one by Burns (1975), who calculated leaching of surface-applied nitrogen as a function of the quantity of water draining through the soil and the percentage volumetric field capacity. Data are needed on rainfall and evaporation, soil porosity, initial water content, and water content at field capacity. Literature reviews on leaching losses of phosphorus (not accounted for in Chapters 3 and 4) and potassium were written by Barrow (1980) and Malavolta (1985).

Denitrification (OUT 4)

The complexity of the processes involved, and the paucity of direct measurements that vary widely with environmental conditions, especially temperature and water content, has so far limited accurate assessments of the magnitude of denitrification under field conditions (Leffelaar, 1977; Vlek et al., 1981). As a result, N balance studies have ascribed unaccounted fractions to denitrification losses.

Denitrification can play an important role in N losses under 'upland' conditions, as anaerobiosis occurs when respiratory activity is locally concentrated (within structural elements, around plant roots), and the diffusion of oxygen is impaired by water layers around these spots. Field measurements have shown large variability associated with NO, N_2O, and N_2. Smith et al. (1990) mention annual cropland losses for the two major gases N_2 and N_2O to be in the range of 5 to 25 and 0.1 to 3 kg N ha^{-1} respectively. Mengel (1985) mentions a number of studies in which 10-60% of fertilizer N was lost by denitrification under moist field conditions.

In Chapters 3 and 4, denitrification was treated the same way as leaching. Recognized determinants of the process such as rainfall, texture and the nitrogen content of soils and fertilizers were used to build transfer functions. The parameter coefficients applied in these chapters followed from multiple regression analysis.

Water erosion (OUT 5)

Measurements of runoff and associated soil loss in Africa have been numerous. During the past two decades, major work on water erosion was published by Roose and Lal for West Africa, and by Hudson, Elwell and Stocking in Southern and

East Africa. Data provided by these researchers were used to calculate erosion at the supranational level (Chapter 3). Next to the multi-temporal measurements of runoff and sediment load, erosion models have been developed, with the USLE (Wischmeier and Smith, 1978), SLEMSA (Elwell, 1981), and EPIC (Williams et al., 1983) as the most commonly known. Less attention has been paid to two other values needed to calculate nutrient loss in eroded material, i.e. (i) the actual nutrient loss in eroding sediment (Pagel et al., 1982), and (ii) the enrichment factor, which is usually between 1.5 and 2.5 for organic matter, the clay fraction, and the concentration of different plant nutrients (Lal, 1984; Stocking, 1984).

In Kenya, soil conservation is now a well-established discipline. A considerable number of research data was available to calibrate the USLE for estimation of erosion in the Kisii District (Chapter 4). Recent research findings in East Africa (Thomas et al., 1989) and an annotated bibliography on soil and water conservation (Karanja and Tefera, 1990) largely facilitated the search in the grey circuit, and increased the size of the data set on which transfer functions were based.

2.1.3 Integrated nutrient management systems

In this section, some options for integrated nutrient management as suggested in Chapter 5 are supported by published results. Included are: agroforestry systems, erosion control, nitrogen fixation, crop residue management and zero-grazing. In Chapter 5, they all feature as components of agro-ecosystems that alleviate a strained nutrient balance.

2.1.3.1 Agroforestry and related systems

General

Agroforestry is a collective name for land use systems in which woody perennials are grown in association with herbaceous plants and/or livestock in a spatial arrangement, a rotation or both, and in which there are both ecological and economic interactions between the tree and non-tree components of the system. Table 2.2 lists some of the commonly recognized agroforestry systems (Young, 1989). Interest has grown in the development and use of more productive land use technologies involving agroforestry systems (Steppler and Nair, 1987). Two such technologies are alley cropping for food production and alley farming for both food and animal production (Kang et al., 1990). Integration of trees, especially N fixing trees, into agroforestry and silvo-pastoral systems can make a considerable contribution to sustainable agriculture by (i) restoring and maintaining soil fertility (*IN 4*), (ii) combating leaching (*OUT 3*) and erosion (*OUT 5*), and (iii) providing timber and fuelwood.

Table 2.2 Agroforestry practices (Young, 1989)

MAINLY AGROSYLVICULTURAL (trees with crops)
- Rotational:
  - Shifting cultivation
  - Improved tree fallow
  - Taungya
- Spatial mixed:
  - Trees on cropland
  - Plantation crop combinations
  - Multistorey tree gardens
- Spatial zoned:
  - Hedgerow intercropping (barrier hedges, alley cropping) (also agrosylvopastoral)
  - Boundary planting
  - Trees on erosion-control structures
  - Windbreaks and shelterbelts (also sylvopastoral)
  - Biomass trasfer

MAINLY OR PARTLY SYLVOPASTORAL (trees with pastures and livestock)
- Spatial mixed:
  - Trees on rangeland or pastures
  - Plantation crops with pastures
- Spatial zoned:
  - Live fences
  - Fodder banks

TREE COMPONENT PREDOMINANT
- Woodlots with multipurpose management
- Reclamation forestry leading to multiple use

OTHER COMPONENTS PRESENT
- Entomoforestry (trees with insects)
- Aquaforestry (trees with fisheries)

Apart from the numerous non-governmental projects on agroforestry, some of which are critically reviewed by Kerkhof (1990), three members of the Consultative Group of International Agricultural Research (CGIAR) work on agroforestry and alley farming systems and are all based in Africa: IITA (Nigeria), ICRAF (Kenya), and ILCA (Ethiopia).

Most of the research data on agroforestry that are presently available stem from the humid zone with annual precipitation of more than 1200 mm, and from soils that are nonacidic. *Leucaena leucocephala* and *Gliricidia sepium* are the two woody species that have so far been studied in depth. Screening work is needed for other species, and particularly for other agro-ecological zones. Similarly, there is a need for selection of suitable species for the humid zone dominated by acidic soils. In areas with an annual rainfall of less than 800 mm, tree-grass combinations / are mentioned as having the greatest potential for improved management systems. Grass-legume pastures are more persistent than grass-only fields, provided that they are not overgrazed, which of course is a condition that is hard to meet when natural pasture is a common property (Kang et al., 1990).

Biological N fixation and crop yields

Leucaena is reported to fix 75-200 kg N ha^{-1} and produces up to 40 t ha^{-1} of fresh green manure, depending on interrow spacing and number of cuttings (Sanginga et al., 1989; Juo and Kang, 1989; Kang et al., 1990). Annual nitrogen yield in five prunings of *Gliricidia* and *Leucaena* hedgerows in Nigeria was 170-250 kg ha^{-1}, as opposed to 40-85 kg ha^{-1} in the non-leguminous species *Acioa barterii* and *Alchornea cordifolia* (Kang et al., 1990). The same authors mention sustainable yields of maize on a sandy soil to application of *Leucaena* prunings (Table 2.3). The effective N contribution from *Leucaena* and *Gliricidia* hedgerows to alley farmed maize was estimated at about 40 kg N ha^{-1}. Next to positive effects on yield, mulching also increased maize stover production, with the associated possibility to reduce the amounts removed from the land (*OUT 2*). Rather confusing is a review by Lal (1991), who has Table 2.4 accompanied by the text that "addition of 80 kg N ha^{-1} of fertilizer resulted in more yield increase than addition of *Leucaena* prunings. Furthermore, prunings had no effect on maize yield in the fourth year". What the table actually shows is that *Leucaena* prunings cause considerable maize yield increases, which are even higher when additional N is

Table 2.3 Grain yield (t.ha^{-1}) of main season maize in maize-cowpea rotation grown on a Psammentic Ustorthent in alley farming with Leucaena[a] *from 1979 to 1986 (Kang et al., 1990)*

Treatment[b]	Yield (t.ha^{-1})						
	1979	1980	1981[c]	1982	1983	1984	1986
0N.-R	-	1.04	0.48	0.61	0.26	0.69	0.66
0N.+R	2.15	1.91	1.21	2.10	1.91	1.99	2.10
80N.+R	3.40	3.26	1.89	2.91	3.24	3.67	3.00
LSD (0.5)	0.36	0.31	0.29	0.44	0.41	0.50	0.18

[a] Plots fallowed in 1985.

[b] Rate: 80 kg N ha^{-1}; -R: *leucaena* prunings removed; +R: *leucaena* prunings retained. All plots received basal dressing of P, K, Mg and Zn.

[c] Maize crop affected by drought.

Table 2.4 Main season grain yield of maize alley cropped with Leucaena leucocephala as affected by application of Leucaena prunings and nitrogen fertilizer (Lal, 1991)

N rate (kg ha^{-1})	*Leucaena* Prunings	Yield (t.ha^{-1})				
		1979	1980	1981	1982	1983
0	Removed	-	1.0	0.5	0.6	0.3
0	Retained	2.1	1.9	1.2	2.1	0.9
80	Retained	3.5	3.3	1.9	2.9	3.2
	LSD (0.5)	0.4	0.3	0.3	0.4	0.8

supplied in chemical fertilizer. There is no treatment included where fertilizer is applied solely, rendering Lal's statement null and void. Another peculiarity is that Table 2.4 in fact presents the same information as Table 2.3, and although it was published later, the trial results for the years 1984 and 1986 were left out by Lal. Remains the question whose secretary made the typing error that changed *Leucaena*-supported maize yield in 1983 from 1.9 (Table 2.3) to 0.9 t ha^{-1} (Table 2.4). Another objection against Lal's review article is that it claims to discuss sustainability, but in fact pays a considerable amount of attention to short term productivity. The author also persists in comparing the effects of alley cropping with zero-tillage, without elaborating on the rationality behind such a comparison.

Reduction of erosion and deterioration of organic matter content

Erosion (*OUT 5*) is strongly reduced under agroforestry, but Lal (1991) shows that zero-tillage is even more effective in reducing erosion (Table 2.5). Moreover, in the plow-till system, organic carbon content decreased from 1.7 to 0.4% in the upper 5 cm (1982-1986), whereas in *Leucaena* and *Gliricidia*-based systems, the decreases were from approximately 2.5 to 0.7%. At the no-till plots, however, the reduction was lowest: from 2.5 to 1.1%, which, surprisingly, goes uncommented in the text. The author then continues to mention that "... woody perennials and tree species characteristically produce large amounts of above-ground biomass. Because of their perennial nature, there is a continuous addition of organic matter and biomass to the soil. Tree crops influence the microclimatic factors such as soil and air temperatures, net radiation reaching the ground surface, evaporative demand, etc. Expectedly, soil and air temperatures are lower during the day in the vicinity of perennial hedges than farther away from them. Under these conditions, soil organic matter content is being continuously increased, activity of soil fauna increased and soil structure improved". The apparent inconsistency between

Table 2.5 Alley-cropping effects on runoff and soil erosion under maize-cowpea rotation measured in 1984 (Lal, 1991)

Treatment	Runoff		Soil erosion ($t.ha^{-1}.yr^{-1}$)
	(mm)	(% of rainfall)	
Plow-till	232	17.1	14.9
No-till	6	0.4	0.03
Leucaena, 4 m	10	0.7	0.2
Leucaena, 2 m	13	1.0	0.1
Gliricidia, 4 m	20	1.5	1.7
Gliricidia, 4 m	38	2.8	3.3

this statement and the above data leaves the reader puzzled.

Economics and social acceptability

Kang et al. (1990) reviewed a number of economic studies on alley farming systems in Sierra Leone, Nigeria and Kenya, all of which concluded that the extra labor required for agroforestry practices is offset by yield increases and reduced requirements of fertilizer and herbicides. In India, however, fertilizer is cheap and fallow periods are few, thus requiring little labour for land clearing. It makes fertilizer use more attractive than sacrificing land to trees in an alley system.

An indirect but potentially important economic benefit from alley farming is the provision of staking material. Climbing crops such as yam (*Dioscorea rotundata*) have been shown to benefit from live staking. Budelman (1991) recently studied the potentials and problems of *Gliricidia sepium*, *Leucaena leucocephala* and *Flemingia macrophylla* as live support systems.

The social acceptability of agroforestry is governed by (i) land tenure rules, as rights over trees are often distinct from rights over land, (ii) cost-sharing devices between the government and rural farmers, (iii) the availability of an active extension service, and (iv) the potential for some direct economic output from the trees in the system (Kang et al., 1990). Very interesting are the results of a survey of 21 agroforestry projects in 11 different sub-Saharan African countries (Kerkhof, 1990). The author concluded that (i) many agroforestry projects began with preconceived ideas about what the local problems were and how they should be tackled, (ii) nitrogen fixing species have often been less popular than projects initially assumed, (iii) the market for construction wood provides the strongest motivation to grow trees, (iv) firewood shortages rarely provide an adequate incentive to plant trees, but when trees are grown, firewood is seen as a useful by-product, and (v) alley cropping has shown impressive results in research trials, but among the projects visited, farmers preferred more dispersed forms of intercropping.

2.1.3.2 Systems based on multiple cropping, green manures, and crop residue management

Intercropping is often mentioned as having many advantages over monocultures. Some of them are definitely true, but the N input by biological fixation from most tropical intercropping systems is low. Ofori and Stern (1987) reviewed numerous experiments in which sole cropping and intercropping were compared. The leguminous crops (mainly *Phaseolus* beans, cowpea, soybean, groundnut), grown in association with maize and sorghum, had yields of 1000-2500 kg ha^{-1} when sole cropped, but this decreased by 50%, and for soybean up to 80%, when grown in association. Cereal crop yields declined to a much lesser extent. In Kenya, sequential maize (long rains) and beans (short rains) systems outyielded intercropping systems (Nadar and Faught, 1984). In a highly productive Mollisol in the US, continuous maize produced less grain (5.5 t ha^{-1}) than in rotation with a legume (7.6 t ha^{-1}). Also, maize following a legume in rotation produced maximum grain yield at a fertilizer application 90 kg N ha^{-1}, while continuous maize required at least 180 kg N ha^{-1} for maximum yield (Peterson and Varvel, 1989).

In contrast to the role of grain legumes, a green manure legume is one which is grown wholly for use as an organic manure for a subsequent crop and this obviously maximizes the amount of N from the legume, available for another crop. Quoted examples are *Crotolaria*, *Mucuna* and *Sesbania* species, in which over 100 kg N ha^{-1} was accumulated in the above-ground plant parts (Giller and Wilson, 1991). Green manure cover crops are advocated in Chapter 5 as a means to redress the nutrient balance in the Kisii District, Kenya. It is, however, unusual for green manures to be adopted solely for their beneficial effects on soil fertility but where other benefits are also found, such as suppression of weeds, reduction of the incidence of pests or control of erosion, farmers may be persuaded to use them. Juo and Kang (1989) mention *Mucuna utilis* and *Pueraria phaseoloides* (kudzu) as green manures in rotation that can maintain maize yields at 2-3 t ha^{-1} over at least 10 years without fertilizer application (Nigeria). *Mucuna* grew faster and produced better ground cover than *Pueraria*, which, however, had the best nodulation in acid soils. Sanchez and Salinas (1981) attributed the same effect to *Pueraria* in Peru. However, the trade-off of labor did not hold in Peru, where farmers seem more interested in obtaining credit to purchase fertilizers and machinery rather than carry and incorporate *Pueraria* with a hand hoe.

The importance of crop residue mulch (*OUT* 2) in soil conservation (*OUT* 5) is widely recognized. Soil erosion in Ivory Coast ranged from 15 to 253 t ha^{-1} on bare soil at slopes of 4-20%. Corresponding values for mulched land were 0.1-7 kg ha^{-1}, and for incorporated residues 0.03-9.7 t ha^{-1}. When residues were burnt, 0.2-16.7 t ha^{-1} soil loss were recorded (Roose and Asseltine, 1978; cited in Lal, 1984). In the US, present government price support programs require that producers on erodible soils develop and follow a conservation program designed to significantly reduce erosion. The maintenance of crop residues on the soil surface is a key practice in these conservation production plans (Prasad and Power, 1991).

The impact of residues on soil fertility depends, amongst others, on the way they are managed (burning, mulching, incorporation), and on their C/N and C/P ratios. Although contributing to the sustainability of land use systems, incorporation of crop residues can seriously though temporarily depress soil productivity. Nguu (1987), who mixes up productivity and sustainability, found on a Plinthudult in Cameroon that burning of crop residues (4 t ha^{-1}) and weeds outyielded treatments in which crop residues were used as a mulch (2.7 vs. 2.3 t ha^{-1}); burning practices on degraded land, however, often result in invasion by spear grass (*Imperata cylindrica*), which is difficult to control (Kang et al., 1990). Incorporating crop residues with a high C/N and C/P ratio such as maize or rice stover causes initial immobilization of N and P. Smith et al. (1990) mention 1.2% N as a threshold value for residues below which N immobilization takes place. Green manure and legumes usually contain adequate N to promote mineralization shortly after soil incorporation. Kang et al. (1981) showed that *Leucaena leucocephala*, when incorporated, increases maize yield more than when applied as a mulch. Juo and Kang (1989) recorded a beneficial effect of crop residues (5-6 t ha^{-1} from two crops per year) on crop yield in long-term continuous cropping, but in the long run, yields still went down.

2.1.3.3 The need for long-term experimentation

In the United Kingdom, the famous Rothamsted long-term experiments showed that grain yields can be sustained (and even increased) for almost 150 years in monocultures of wheat and barley with annual applications of organic and inorganic fertilizer. One of the most useful features of the Rothamsted trials is that they enable us to follow the effects of soil and crop management on soil organic matter level over long spans of time. It was for example found that long-continued use of inorganic fertilizer containing N, P, K and Mg (*IN 1*) has increased soil organic matter levels but the increase was much less than that brought about by farmyard manure (*IN* 2) (Jenkinson, 1991). In the United States, the oldest continuous, long-term, agronomic research plots reflect the needs and resources available to the agricultural community of the late 19th century. Soil amendments were limited to animal and unprocessed mineral ores in limited quantities. Crop rotations and N-restoring legumes appeared to offer growers the best opportunity to improve and sustain production (Mitchell et al., 1991).

To monitor and evaluate sustainable crop and animal production in the tropics, long-term experimentation is required. In sub-Saharan Africa, only few long-term data sets are available. Chapters 3 and 4 of this thesis elaborate on relatively long-term maize trials in Kenya (Qureshi, 1987), Northeastern Tanzania (Haule et al., 1989), and Southwestern Nigeria (Juo and Kang, 1989). Pieri (1989) and Vlek (1990) summarize long-term experimentation on sorghum, millet and groundnuts. Although not from Africa, yet very useful are the long-term experiments by the Tropical Soils Programme of North Carolina State University on acid Amazonian soils in Peru and Brazil (e.g., Sanchez, 1987). Presentation of results of long-term experimentation should be done with care, as annual outliers can have a strong impact on any statistical analysis. A sound way of presentation is Figure 2.3, showing the development of sorghum yields in Burkina Faso by means of sliding averages over 15 years (Vlek, 1990). Figure 2.4 shows data points of annual maize yields for 6 consecutive years (Lal, 1991). The data are not very consistent, which can be the unfortunate fate of every researcher, but it is statistical overkill to draw a regression line here and state that each year, yield declines by 340 kg ha^{-1}.

Smith et al. (1990) air their ambitious though interesting views on long-term, integrated monitoring of the nutrient balance in different land use systems, following the different pathways of nutrients in a watershed. Field watershed studies have tended to consider only one specific avenue of input or output, such as leaching or erosion. The authors recommend that representative watersheds be instrumented in agricultural areas where NPK fertilizer usage is concentrated. Instrumentation should involve devices for studying mechanisms and processes related to losses by surface runoff, deep percolation as well as to the atmosphere. What may not be very easy is to trace a donor who will support such a programme, particularly because it can easily turn into a largely academic exercise.

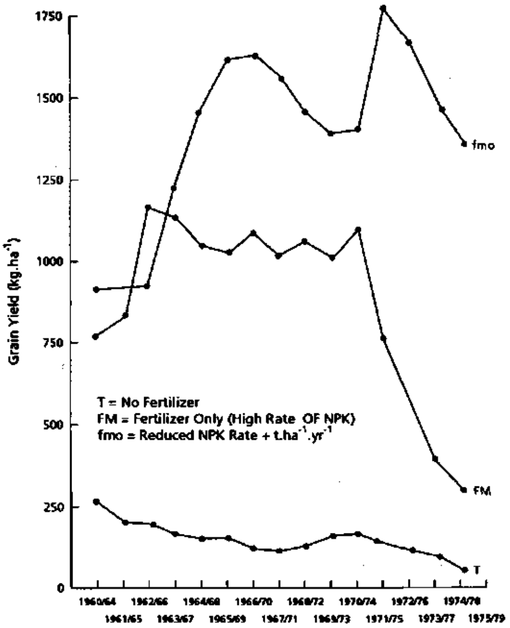


Fig. 2.3 Five-year sliding average yields of monoculture sorghum in Saria, Burkina Faso (Vlek, 1990)

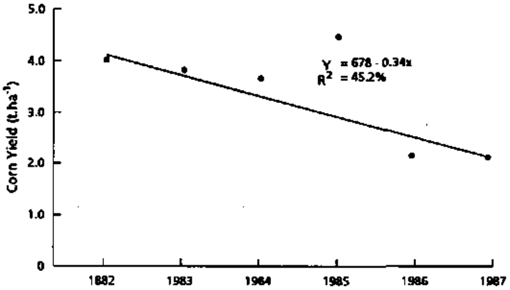


Fig. 2.4 Decline in yield of corn with continuous cultivation on a Nigerian Alfisol (Lal, 1991)

2.1.3.4 High or low external input use?

Based on (i) the fact that tropical farmers have become increasingly dependent on off-farm supplies, which require cash and may not always be available on time, (ii) the harmful effects on the environment of heavy use of N fertilizer in the temperate regions, and (iii) the increased scarcity and price of fossil fuels, which are used in the production of N fertilizer, Bohlool et al. (1992) urge the scientific community to search for all possible avenues to improve biological N fixation (*IN 4*) and its use by farmers, preferably in combination with rotating cereal crops with legumes, recycling manure and other organic wastes (*IN 2*), and using chemical fertilizers moderately and efficiently (*IN 1*).

Van Keulen and Breman (1990) discussed overexploitation of agricultural land in the West African Sahel. They conclude that increased productivity of the land, both in animal husbandry and in arable farming will require at least imports of phosphorus fertilizer (*IN 1*) from outside the system, because recycling of crop residues (*OUT 2*), manure and household waste (*IN 2*), regeneration of degraded rangeland, anti-erosion measures (*OUT 5*), etc., may at best prevent further deterioration of the land resource, but are insufficient to stop nutrient depletion. Independently, Van der Pol (1992) studied nutrient balances in southern Mali, and reported losses of 25 kg N and 20 kg K ha^{-1} yr^{-1}. Gaseous losses (*OUT 4*) and erosion (*OUT 5*) together were responsible for 40% of total losses. Even on doubling *IN 1* and *IN 2*, and reducing *OUT 2* and *OUT 5* by 50%, the values for the N and K balance were still negative.

Of particular interest may be the combination of rock phosphate and leguminous species. A legume, withdrawing N largely as N_2 and not as NO_3^-, tends to acidify its rhizosphere, leading to a more rapid dissolving of rock phosphates (Aguilar and Van Diest, 1981). Sanchez and Salinas (1981) even state that on the Amazonian Ultisols and Oxisols, the chemistry of soil acidity replaces the superphosphate factory at considerable energy savings, provided that Al-tolerant plant species are grown. Rock phosphates are generally cheap and are mined in many African countries (Vlek, 1990). A special issue of the scientific journal 'Fertilizer Research' (Volume 30, 2-3, 1991) was recently devoted to this subject.

Reijntjes et al. (1992) favour low external input use in tropical land use systems, and substantiate their opinion with successful examples, such as composting

Survey, 1991) created the possibility to run fertilizer trials on an agro-ecological basis. The site selection procedure, presented in detail in Chapter 6 of this thesis, encompasses (i) collection and interpretation of data on previous trials and existing maps and associated data sets on climate and soils, (ii) reclassification of soil and climate map units on the basis of a number of diagnostic soil and climatic properties that are relevant to crop production, and subsequent compilation of district maps, (iii) overlaying the two maps, and delimiting agro-ecological units, characterized by a specific set of biophysical conditions, and (iv) determining where to site experiments such that they adequately represent most agro-ecological units. After a profound scrutiny of all information on land resources, a total of 70 experimental sites was established (FURP, 1987).

This procedure of site selection lives up to the statement that 'a plant does not respond to a treatment *per se*, but to the soil's response to that treatment' (Sumner and Farina, 1986). Chapter 7 shows how true this is. Three sites in very different agro-ecological units, but all in maize-growing environments were monitored for several years, and crops indeed responded very differently to N, P and farmyard manure. Simple value/cost analysis provides an indication of the much farmers can gain if they apply type and amount of fertilizer according to the agro-ecological setting of their farmland.

During the late sixties and early seventies, research in East Africa on crop response to fertilizers already had some kind of an agro-ecological basis, as for example shown by Anderson (1969) and Foster (1973) for maize, and Anderson (1974) for beans. In general, the local scientific journal 'East African Agricultural and Forestry Journal' contains a wealth of information on research in those days, which is too often and quite unjustly overlooked.

2.3 Field-scale heterogeneity

2.3.1 General

Adjacent plots, planted simultaneously to the same variety and treated as alike as possible, will differ in as many characters as one would care to measure (Gomez and Gomez, 1984). This observation has not withheld agronomists from attempting to carry out experiments on soils which they consider most representative of the region involved. Plots for different treatments are established on blocks of land assumed to be homogeneous as regards type of soil, slope, etc. Graded areas are avoided, and so are plots in the vicinity of shading trees, poles, structures, termite mounds and plots that had recently been used for experimentation.

Still, there is quite some less-manageable soil heterogeneity. Abrupt boundaries between soils are rare, and as soon as soils are positioned in a toposequential pattern, pedological changes take place over the whole length of the slope to form a gradient. Most of the land is then covered by intergrade soils reflecting various stages of development, and not by orthotypes (Valentin, 1988). In other words, soil variability is the product of soil-forming factors operating and interacting over a continuum of spatial and temporal scales. As chapter 6 and 7 address fertilizer trials and subsequent recommendations on a district (regional) scale, it is worthwhile to dwell on soil variability at field scale, so as to see how hard it is to aggregate data obtained at field scale to a regional scale.

The likelihood of successful transfer of technology from known to unknown sites is strongly influenced by the spatial and temporal variability of soil and other environmental parameters. Classical statistics assume that variability around the mean is random and contains no reference to the geographical distribution of differences within the sampling units (Trangmar et al., 1985). Research in the past two decades has shown that this random aspect of soil variability contains a component that is spatially dependent, giving geostatistics its well-deserved place in the midst of the geosciences (Burrough, 1986; Oliver and Webster, 1991; Stein, 1991; Bregt, 1992). Properties that are affected by soil management are commonly more variable than the morphological, physical and chemical properties used to define taxonomic units. Properties such as topsoil structure and chemical fertility are clearly within the first group.

Unfortunately, little attention was given to spatial patterns of soil variability in the Kenyan fertilizer trial network described in this thesis. This is reflected in (i) the emphasis on representativeness of the site at a district level, (ii) deciding to accept or reject the site on the basis of composite sampling of four 0.2 ha blocks, instead of sampling on a more intensive grid basis, (iii) the absence of pre-fertilization uniformity trials in the very first season, and (iv) the limited number of only two replications of most treatments. By virtue of the two different experiments, i.e. a 4^2 experiment including N and P, and a 2^4 experiment including N, P, farmyard manure and K or S or lime, treatments N_0P_0, $N_{50}P_0$, N_0P_{22}, and

$N_{50}P_{22}$ had four replications at most sites, drawn from two adjacent experiments. As a result, there was little sense in studying spatial variability along classical lines, particularly not after the different plots had received different amounts of fertilizer. Instead, attention was paid to a number of sources of heterogeneity beyond the researcher's control, i.e. (i) bypass flow and concurrent nitrogen leaching on a cracking clay (site d in Table 1.3), and (ii) incidence of *Striga hermonthica*, a noxious parasitic weed attacking the roots of cereal crops (site b). Earlier attempts to capture spatial variability, making use of crop yield differences are reported by Gomez and Gomez (1984) on moving-average techniques, and by Janssen (1970), who quantitatively described the relation between yield differences between replicates and (spatially variable) effective soil depth.

2.3.2 Bypass flow and concurrent nitrogen leaching

Soils with continuous macropores are common in Kenya's agricultural land. Most outspoken examples are Vertisols and Planosols (FAO, 1989b). Bouma (1983) described continuous macropores as pores that are significantly larger than elementary packing pores in a soil material (0.1 mm and larger). Continuity is, however, more important than size as such and this aspect should be emphasized when considering dynamic processes such as the movement of water in soil. Flow patterns in unsaturated soils with continuous, air-filled macropores are quite complex because macropores act either as preferential pathways (bypass flow, i.e. the vertical movement of free water along macropores in an unsaturated soil matrix), or as barriers to flow (horizontal cracks not allowing upward flow).

Soil water regimes in clay soils are difficult to characterize because swelling and shrinkage processes induce constantly changing pore size distributions and pore-continuity patterns. Measurement and monitoring techniques that work well in sandy or loamy soils may produce erroneous results in clay soils. The swell-shrink nature of clay soils requires the distinction of dynamic wetting and drying cycles, that are not only a function of environmental boundary conditions of the flow system (e.g. climate, watertable level), but also of the changing basic hydraulic properties of the soil (White, 1985; Bouma and Loveday, 1988; Bronswijk, 1991).

The work on bypass flow and concurrent nitrogen leaching, presented in Chapter 8, was based on similar studies conducted on different soils in The Netherlands (Bouma et al., 1981; Dekker and Bouma, 1984; Van Stiphout et al., 1987) and Greece (Kosmas et al., 1991). In a Vertisol in the Kenyan fertilizer trial network, bypass flow was measured at the onset of the growing season, when soils are still relatively dry. Rainwater then partly infiltrates along the vertically continuous cracks and macropores and may end up beyond the root zone, not contributing to the development of an emerging crop. In addition, the bypassing water may have a high N concentration, due to a build-up of inorganic N during the preceding dry months, and a flush of N mineralization in the topsoil upon rewetting (Birch, 1958; Sanchez, 1976). Fertilizer N applied at planting in cracking clay soils may be leached in a similar way, resulting in a low N recovery by the crop (Wild, 1972). The study in Kenya revealed that fertilizer N applied to rangeland was leached much more rapidly than N applied to cultivated cropland, which is much in line with Tyler and Thomas (1977), who found N leaching under no-till (in Kenya: grassed rangeland) to be much greater than under conventional till (in Kenya: tilled cropland).

2.3.3 Incidence of the parasitic weed *Striga hermonthica*

In many African countries, maize, sorghum and millet are badly affected by the incidence of the parasitic weed *Striga hermonthica*. Between the roots of *Striga* and those of its host a connection is formed, through which *Striga* drains absorbed water and nutrients from the host xylem. This leads to stunted growth of the host plant and symptoms resembling drought damage. Crop loss data due to *Striga* vary from 10% yield reduction to total crop failure. The weed is hard to eradicate, as mature seeds of *Striga* may remain dormant in the soil between 6 months and 20 years. A textbook on sorghum contains an excellent chapter on *Striga* (Doggett, 1988). Research on *Striga* in Africa is largely conducted by IITA and ICRISAT, and by different national research centres. Country reports on the struggle against *Striga*, and a series of research papers were recently brought together in a FAO Plant Production and Protection paper (FAO, 1989c) and by IITA (Kim, 1991).

Incidence of *Striga* is relevant to this thesis, as it was a conspicuous factor of influence in a number of fertilizer trials. Its spotty emergence and the virtual impossibility to eradicate it prior to planting the maize crop called for frequency counts of the weed and its subsequent incorporation into a regression model, describing maize yield as a function of N and P application and *Striga* count (Chapter 9). In this way, trial results still provided useful information, in spite of the extraneous factor.

2.4 Macronutrients in soils and plant tissue as related to crop yields

Part V of this thesis is centred around a calibration of the model QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils). It describes relations between (i) soil chemical and agro-climatic properties, (ii) potential supply of the macronutrients N, P and K from soils and fertilizers, (iii) actual uptake of N, P and K by a maize crop, and (iv) maize grain yield. The subsections of section 2.4 systematically describe relevant literature on the four components of QUEFTS, and section 2.5 describes which models have been developed to predict nutrient uptake and crop yield from the availability of nutrients in soils and fertilizers, culminating in the justification to further develop QUEFTS.

2.4.1 Soil test values as a measure of nutrient supply

In many soil laboratories in the tropics, values of individual chemical properties are interpreted independently: a high organic carbon content represents a good soil, a low pH a bad one, etc. Foster (1973) for example, mentions 6% organic matter as a level above which crops are unlikely to respond to N fertilizer in Uganda, and 20 ppm extractable P as a level above which response to phosphate fertilizer is unlikely. Gbadegesin and Areola (1987) compared 20 soil properties with maize yields on 50 sites in Nigeria, and explained 78% of yield variation in terms of soil organic matter. Although not related to crop yields, a very pragmatic system for use in regional, semi-quantitative land evaluations that often follow soil surveys, is the Fertility Capability Classification (Sanchez et al., 1982). It interprets combinations of soil properties that are often determined in tropical laboratories, and soil morphological features determined from soil profiles.

The amount of a nutrient extracted in a soil test is of little use until it has been calibrated to crop response in field experiments. The problem of calibration particularly applies to phosphorus, as the amount in soil solution is just a fraction of the amount taken up by a crop during its growth cycle. Adequate calibration requires numerous experiments on the soils to be tested and the crops to be grown. Cope and Evans (1985) reviewed the commonly used P extractants (Mehlich, Bray I and II, Olsen), and concluded that each of them is suitable for certain soils only, depending on pH and cation exchange capacity. Murugappan et al. (1989) and Oertli (1990) found that Olsen's procedure for available P estimation was inadequate to explain the relationship between soil-available P, P uptake and crop response. Sanchez and Salinas (1981) show how little P-Bray II increased on applied phosphorus rates of 0 to 40 kg P ha^{-1}, causing difficulties in establishing fertilizer P recommendations based on soil tests only.

In mineral soils in which K is present in average amounts, soil solution K makes up about 1 to 3% of the exchangeable K, which in turn represents only a small fraction of the total K content, which ranges between 0.04 and 3% in mineral soils (Sparks, 1987). Potassium in soil solution tends to equilibrate with K in the adsorbed fraction. The equilibrium is controlled to a large extent by the degree of K selectivity of the adsorption sites in the exchangeable fraction, which is low for organic matter and kaolinitic clay minerals. Soils with the same exchangeable K values may differ considerably in K concentrations in soil solution, because more selectively bound K is equilibrated with a relatively low K concentration and vice versa (Uribe and Cox, 1988). In sandy soils, small applications of K increase the K concentration in the soil solution appreciably and may thus result in substantial yield increases. In more clayey soils, however, K fertilizer applications may scarcely influence K concentration in the soil solution, so yield responses are often not obtained (Mengel and Kirkby, 1980).

2.4.2 Potential supply and actual uptake of macronutrients

A measure for nutrient availability should be indicative for the potential uptake by a crop. A complexity here is, however, that uptake of one nutrient partly depends on the availability of other nutrients. Table 2.6, for example, shows that the uptake of N appears to be strongly affected by the application of P fertilizer, especially in soils with a low P-Olsen value (Janssen et al., 1990). Evidently, at a low P-status, only a fraction of the potentially available N is taken up by the crop. Van Keulen and Van Heemst (1982) described how P application increased N uptake by a rice crop. Reasons were increased mineralization and root proliferation, and presumably a minimum P/N ratio that can not be surpassed in the tissue without upsetting metabolic processes. Kamprath (1987) described how N fertilizer stimulated P absorption by plants on soils with low N availability. Factors involved were (i) a decrease in the rhizoshere pH and increased solubility of soil phosphates, (ii) increased root growth, and (iii) increased physiological capacity of the root to absorb P. Sumner and Farina (1986), in a review article, listed several other documented examples of observed interactions between N and P in nutrient uptake and yield of maize. In this context, it is remarkable how many researchers attempt to link crop yields to the supply and uptake of single nutrients, ignoring the clearly proven interactions.

Table 2.6 Nitrogen uptake by maize as affected by phosphorus application on Kenyan soils with different organic carbon and P-Olsen values (Janssen et al., 1990)

Soil	Org. C g kg^{-1}	P-Olsen[2] mg kg^{-1}	N uptake (kg ha^{-1})		
			no P applied	fertilizer P applied	ratio -P/+P
RG[1]	23	1.6	24	94	0.26
MK	11	2.6	30	80	0.38
IB[1]	35	2.4	87	153	0.57
SH	17	3.5	34	52	0.65
CS	5	4.4	27	41	0.66
MS	9	4.6	36	54	0.67
LS	22	4.5	42	42	1.00
MZ	5	5.1	34	30	1.13

[1] These soils received 80 kg ha^{-1} fertilizer N.

[2] The P-Olsen values refer to soils that did not receive fertilizer phosphorus.

2.4.3 Relation between actual uptake and grain yield

Uptake of nutrients is largely governed by root morphology, mass flow and diffusion rates, which are a reflection of gradients of water potential and nutrient concentrations. Distinctions can be made between nutrients with respect to their mobility in the soil. Phosphate has the lowest diffusion coefficient (10^{-8} cm^2s^{-1}). Potassium has a diffusion coefficient in soil of 10^{-7} - 10^{-6} cm^2s^{-1} and nitrate of $5*10^{-6}$ cm^2s^{-1} (Fisher and Dunham, 1984). Root development is higher in soils with low bulk densities, which are porous, and less prone to spells of poor aeration in the growing period. Most plant species have only limited ability to extend roots into wet soils. Bouma (1984) mentions critical air contents of the root zone of 10% for sandy and 5% for clayey soils. There is abundant evidence of increased root proliferation in soil zones enriched by fertilizer (e.g., De Willigen and Van Noordwijk, 1987; Zhang and Barber, 1992).

Figure 2.5 provides a comprehensive look into nutrient supply and uptake, and their effect on crop yield. In the region of limited N availability, a proportional relation exists between uptake and yield, i.e. each unit of N taken up is converted to grain with equal efficiency (quadrant a in Fig. 2.5). N in the tissue is diluted to a minimum level, below which a further increase in dry weight is inhibited. With higher uptake the linearity disappears, reflecting increased contents of N in the harvested material. Finally the curve reaches a plateau where increased uptake of N does not lead to higher grain yields. At some stage, maximum accumulation of the nutrient in the crop is reached. Jokela and Randall (1989) found nitrogen use efficiencies of 50-75 kg grain per kg N on Phaeozems and Luvisols. Goodroad and Jellum (1988) found significant differences in N use efficiency (45-62 kg grain per kg N) among different maize hybrids.

Phosphorus mobility is very low in all but very sandy soils. P supply in soil solution is very low too, and has to be replenished several times a day in order to adequately supply growing plants. The chemical reactions to which P is subject are complex and depend on moisture content, temperature, pH, and the predominant form of P-containing oxides and minerals. In a range around pH 6.0-6.5, most phosphate compounds have a high solubility (Bolt and Bruggenwert, 1976). A pronounced pH effect can also be expected in soils that have a large proportion of organic P. The availability of P in such soils largely depends on the decomposition rate of organic matter and hence on microbial activity. The proportion actually taken up from the potentially available store depends on root growth characteristics, which may vary as a result of conditions other than the P status of the soil.

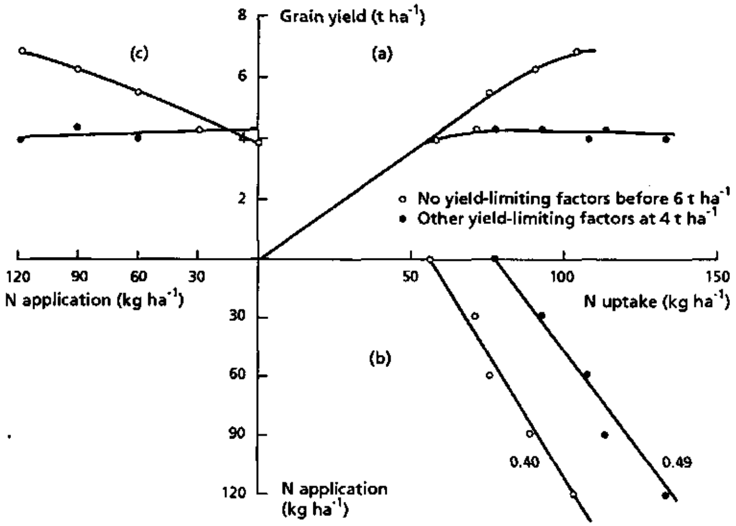


Fig. 2.5 The relation between nutrient uptake and grain yield (a: nutrient use efficiency), the relation between nutrient application and nutrient uptake (b: fertilizer recovery), and the relation between nutrient application and grain yield (c: fertilizer use efficiency). Numbers in relation (b) denote recovery fraction of applied fertilizer (adapted from Van Keulen and Wolf, 1986)

Potassium is mainly taken up during the vegetative period of plant growth. Drought during the early growth stages can seriously retard K uptake and vegetative development. A comprehensive review on the relation between K nutrition and maize yield has been written by Welch and Flanery (1985). Kuhlmann (1990) showed that subsoils can be important for the K nutrition of crops, as long as they have something to offer. In 34 German loess soils with similar K contents, uptake from the subsoil increased from 21 to 65% of total K uptake, as K contents in the topsoils decreased from 80 to 40 mg K kg^{-1}. Mengel and Kirkby (1980) quote several researchers who failed to record any immediate K fertilizer response, but after a number of cropping cycles, K application raised yields considerably, in particular when crop residues were removed from the field after harvesting. Maize proved not particularly responsive to K, unlike tea, banana, tobacco and potatoes. High availability of other growth factors such as water supply, N and P, generally leads to increased crop response to K. Anderson (1973), studying potassium responses of various crops in East Africa, found that sandy as well as acid soils were most responsive to K. On calcareous soils, induced K deficiencies were found. He warned against rapid depletion of the K reserves of many soils, particularly as continuous cropping and the introduction of high-yielding varieties at higher plant populations are becoming more common. The author's anticipation in 1973 that the demand for potassium fertilizers was likely to increase markedly 'in the next few years', has not really come out, as was shown in Figure 1.1.

2.4.4 Fertilizer recovery

The slope of the application-uptake curve in the lower half of Figure 2.5 (quadrant b) represents fertilizer recovery in the (above-ground) plant material. As this determines how much of the often expensive input is really utilized, it is a parameter of prime importance for the decision on economically feasible fertilizer application rates. The fraction recovered by the crop is a function of soil, weather and crop properties. The relation between the amount of N fertilizer applied and N uptake is often a straight line over a considerable range of applications. For phosphorus, the situation is more complex, as the reactions between P in soil solution and the solid phase are not of simple first-order kinetics. Potassium takes an intermediate position. Continuous additions change the K equilibrium between adsorption complex and soil solution, affecting the amount available for uptake.

Nitrogen

The relation between amount of N fertilizer applied and uptake is almost always a straight line over a large range of applications. Uptake and losses from the soil are apparently proportional to the concentration of the element in the soil solution. The line is characterized by two parameters: the intercept with the horizontal axis, and the slope with respect to the vertical axis, the first representing inherent soil fertility, the second the efficiency of fertilizer uptake (Van Keulen and Van Heemst, 1982). The generally higher recovery when N is topdressed is explained in part by the presence of an active root system that immediately absorbs the nutrient, leaving less opportunity for leaching and gaseous losses. The later availability of the N in major quantity also has been found to accent grain formation relative to vegetative development, thereby enhancing the grain to forage ratio (FAO, 1988; Jokela and Randall, 1989). Improved recovery with delayed N application is consistent with the concept of providing N at the time of maximum uptake, which occurs in a 2- to 3-weeks period just prior to silking. Excessive delays or unusually dry conditions sometimes reduce yields from late applications.

N recovery can be measured according to the 'difference' method, where the equivalent amount of N at natural abundance released in exchange for fertilizer N immobilized in the organic N fraction is treated as fertilizer nitrogen, since no distinction is made between ^{14}N and ^{15}N. FAO (1988), however, advocates the 'isotope-dilution method', where the N at natural abundance mineralized during biological interchange is not considered fertilizer N, and therefore the assumed effective amount of fertilizer N available to the crop is less than in the difference method. The difference method tends to overestimate recovery because of (i) increased root proliferation and (ii) a priming effect on N mineralization caused by fertilizer application. An important methodological disadvantage about isotope-dilution techniques, however, is that mineralization-immobilization turnover is not accounted for and leads to underestimation of recovery (Harmsen and Moraghan, 1987). The different results obtained when using either method were clearly demonstrated by Walters and Malzer (1990), who found recovery of leached fertilizer-derived N from successive applications in two years of 15 kg N ha^{-1} by the isotope-dilution method versus 47 kg N ha^{-1} by the difference method. Varvel and Peterson (1990) found that N recovery in a maize monoculture on a Mollisol, determined by isotopic methods was 52 and 43% at fertilizer rates of 90 and 180 kg N ha^{-1} respectively, being lower than in a rotation of maize and soybeans. Fertilizer N recovery estimated by the difference method, however, was much greater in the maize monoculture than in the rotation. Before accurate N recovery estimates by maize can be made in complex soil and crop management systems, procedures must be developed to explicitly follow N fertilizer pathways (immobilization, denitrification, ammonia volatilization, leaching).

Phosphorus

The relation between application rate and uptake is much more complex for phosphate fertilizers than for nitrogen. The processes of adsorption, precipitation and immobilization remove phosphate ions from the solution, so that the P concentration in the soil solution is not proportional to the amount applied to the soil (Van Keulen and Van Heemst, 1982).

Morel and Fardeau (1990) found that without isotopic tracers, evaluation of P fertilizer efficiency is based on the assumption that the quantity of P taken up from available soil P does not depend on the quantity of P applied as fresh fertilizer. All results obtained with isotopic tracers, however, show that an input of fresh fertilizer increases P uptake from soil P from P-poor soils, but decreases P uptake from P-rich soils.

In long-term experimentation, P recovery may be overestimated considerably as a result of a gradual build-up of residual fertilizer P, applied during previous seasons. A model was recently developed, calculating P accumulation and residual P recovery under such circumstances (Wolf et al., 1987). It was found that each year, 20% of labile residual fertilizer phosphorus is transferred to stable residual phosphorus (Janssen et al., 1987). The P recovery in year t (R_t) can then be calculated, at least for about 4 to 5 years (Janssen and Wolf, 1988), as a function of recovery during the first year of application (R_1), as shown in Equation (1):

$$R_t = (0.8 - R_1)^{t-1} * R_1 \tag{1}$$

2.5 Modelling relations between nutrient supply, nutrient uptake and crop yields

The conventional method of basing fertilizer recommendations on responses obtained in series of fertilizer experiments meets the sheer impossibility of carrying out and evaluating sufficient experiments on all crops and all soils. In such cases, use can be made of computer models that translate measurable climatic, soil and plant parameters into output, i.e. crop produce.

Two types of models are distinguished here, i.e. (i) empirical (statistical) models, in which a relation has been observed between a land quality value and the original attribute values, without referring to the processes connecting those variables, and (ii) mechanistic process models, describing a particular process in terms of known physical laws. Under control of state parameters and within given boundary conditions a model transforms input data to produce results. Models need calibration (what are the correct values of the control parameters in order to get the correct results at known data points), validation (do the models produce the correct results at independent, unsampled locations), and sensitivity analysis (how responsive is the model to changes in certain variables and parameters) (Burrough, 1989).

A common problem in the use of models is that (i) process-based models often require data that is hard to gather under ordinary (tropical) field and laboratory conditions, and (ii) empirical models are so site-specific that they can not be used in places away from their original environment.

2.5.1 Empirical response prediction models

There are no established rules for the choice of a particular response model; this can only be gauged by its 'goodness of fit' to a given set of experimental data. Cochrane (1988), for example, found an exponential model to best fit his dataset. Input requirements were: yield at zero fertilizer application, maximum yield, and fertilizer application to reach maximum yield. Waugh et al. (1975) used a linear-plateau model to fit their data, and Cerrato and Blackmer (1990) employed a quadratic-plus-plateau model best describing the yield responses observed in their study. Mombiela et al. (1981) included the initial soil nutrient level in their model in a form that is additive to the fertilizer rates. Their objective was to develop fertilizer recommendations based on a statistical estimate of the amount of plant-available nutrient in the soil, and its relationship to soil test values. One of their conclusions was, however, that results are specific to their soil-crop combinations and should not be extrapolated.

2.5.2 Mechanistic uptake models

Of very recent date is a publication in the 'Agronomy' series, edited by Hanks and Ritchie (1991), in which most soil-plant models developed by US researchers are reviewed. Of special interest are Chapters 13 and 14 in which the dynamics of N and P in the soil-plant system is described. Advanced mechanistic modelling on crop nutrient uptake and yields is also an important subject of study in The Netherlands (e.g. Penning de Vries and Van Laar, 1982; Van Keulen and Wolf, 1986). Moreover, numerous books and articles carry the name of S.A. Barber, as one of the major scientists in the field of nutrient uptake processes. Much research was done on the study of P and K uptake by plant roots under laboratory conditions. To run the models, input data were needed such as initial root length, rate of growth, mean root radius, half distance between root axes, kinetics of P absorption by the root, initial P and K concentration in the soil solution, the buffer power of solid phase P for P in solution, effective diffusion coefficient of P and K in the soil, and K buffering capacity (Caassen and Barber, 1976; Kovar and Barber, 1988; Chen and Barber, 1990).

A model developed at the Centre for World Food Studies (WOFOST) was designed for calculating the agricultural production potential for selected combinations of crop, soil and climate (Van Keulen and Wolf, 1986; Van Diepen et al., 1989). The calculated theoretical yields allow one to evaluate the relative importance of the principal constraints to crop production, such as light, temperature, water and the macro-nutrients N, P and K. This information is used to assess reasonable combinations of inputs needed for attaining certain target yields. The modelling procedure takes no account of geographical scale as it is applied basically as a point analysis. Its application to areas relies on the selection of representative points, followed by spatial aggregation or interpolation.

2.5.3 Mixtures

The response prediction models in subsection 2.5.1 hardly take spatial patterns of biophysical conditions into consideration. The regression equations arrived at when using such models are only meaningful for the particular soil for which they were developed, and the curve fitting which accompanies this work is rather arbitrary. The complex mechanistic models on nutrient uptake processes and crop yield have, however, not proved to be helpful either in resource management in tropical countries. So far they have been meaningful only from an academic point of view, helpful as they are in increasing our understanding of processes. The input requirements can, however, only be obtained in well-equipped specialist laboratories. Although the distinction between empirical and mechanistic models is useful, many crop models in fact contain a mixture of empiricism and mechanism. An example is a model by Wolf et al. (1989), requiring mineral and organic N fertilization, supply of N via rainfall, flood and irrigation water, and via biological fixation, the initial sizes of the labile and stable pool, and the time constants of conversion of both pools. For each of the external sources and for the N mineralized in the labile pool, partitioning between uptake by the crop, incorporation in the labile pool, and losses due to denitrification, leaching etc. is required. Environmental conditions are described in discrete, semi-quantitative classes of high (deep groundwater, limited leaching, high water and nutrient retention), moderate and low risk of N losses.

The model QUEFTS can also be classified as a mixture, comprising both empirical and theoretical components. It essentially differs from all previous models in that the yield-determining effects of, and the interplay between all three macronutrients are included. QUEFTS was developed during land evaluation projects of the Wageningen Agricultural University (1975-1982), where fertilizer trials were conducted in the high potential, but P-poor Kisii District and in the low to medium-potential, mainly N-poor Kilifi District, Kenya (Janssen et al., 1990). QUEFTS calculates the potential yield of an unfertilized maize crop from the native soil fertility as assessed from data usually collected in soil surveys. Next, it can determine crop response to fertilizers, and the optimal combination of fertilizers from both a nutritional and an economic standpoint. The theoretical background of QUEFTS is further described in Chapter 10, which also includes a calibration of all steps of QUEFTS, and a sensitivity analysis and validation of the modified version of this model.

References

Addiscott, T.M. and Wagenet, R.J., 1985. Concepts of solute leaching in soils: a review of modeling approaches. J. Soil Sci. 36: 411-424.

Aguilar, A.S. and Van Diest, A., 1981. Rock-phosphate mobilization induced by the alkaline uptake pattern of legumes utilizing symbiotically fixed nitrogen. Plant and Soil 61: 27-42.

Anderson, G.D., 1969. Responses of maize to application of compound fertilizers on farmer's fields in ten districts of Tanzania. East Afr. Agric. For. J. 34: 382-397.

Anderson, G.D., 1973. Potassium responses of various crops in East Africa. Proceedings of the 10th Colloquium of the International Potash Institute, Abidjan, pp. 413-437.

Anderson, G.D., 1974. Bean responses to fertilizers on Mt. Kilimanjaro in relation to soil and climatic conditions. East Afr. Agric. For. J. 39: 272-288.

André, M., 1990. Approvisionnement, commercialisation et demande des engrais en Republique du Togo. International Fertilizer Development Center, Lomé, 165 pp.

André, M., Gerner, H. and Dahoui, K., 1991. Approvisionnement, commercialisation et demande des engrais au Burkina Faso. International Fertilizer Development Center, Lomé, 149 pp.

Baligar, V.C. and Bennett, O.L., 1986. Outlook on fertilizer use efficiency in the tropics. Fert. Res. 10: 83-96.

Barrow, N.J., 1980. Evaluation and utilization of residual phosphorus in soils. In: Khasawneh, F.E., Sample, E.C. and Kamprath, E.J. (Editors), The role of phosphorus in agriculture. ASA/CSSA/SSSA, Madison, Wisconsin, pp. 333-359.

Birch, H.F., 1958. The effect of soil drying on humus decomposition and nitrogen availability. Plant and Soil 10: 9-31.

Böckman, O.C., Kaarstad, O., Lie, O.H. and Richards, I., 1990. Agriculture and fertilizers. Agricultural Group, Norsk Hydro, Oslo, 245 pp.

Bohlool, B.B., Ladha, J.K., Garrity, D.P. and George, T., 1992. Biological nitrogen fixation for sustainable agriculture: a perspective. Plant and Soil 141: 1-11.

Bolt, G.H. and Bruggenwert, M.G.M. (Editors), 1976. 4th Impression: 1988. Soil chemistry. A. Basic Elements. Developments in Soil Science 5A, Elsevier Scientific Publishing Company, Amsterdam, 281 pp.

Bouma J., 1983. Use of soil survey data to select measurement techniques for hydraulic conductivity. Agric. Water Manage. 6: 177-190.

Bouma, J., 1984. Estimating moisture-related land qualities for land evaluation. In: Land use planning techniques and policies. Proc. Symp. Atlanta, Georgia, 1981. SSSA, Madison, Wisconsin, pp. 61-76.

Bouma, J., Dekker, L.W. and Muilwijk, C.J., 1981. A field method for measuring short-circuiting in clay soils. J. Hydrol. 52: 347-354.

FURP, 1987. Fertilizer Use Recommendation Project. Final Report. Description of first priority trial sites. National Agricultural Research Laboratories, Nairobi, 31 volumes.

Gbadegesin, S. and Areola, O., 1987. Soil factors affecting maize yields in the south-western Nigerian savanna and their relation to land suitability assessment. Soil Survey and Land Evaluation 7: 167-175.

Giller, K.E. and Wilson, K.J., 1991. Nitrogen fixation in tropical cropping systems. CAB International, Wallingford, 313 pp.

Gomez, K.A. and Gomez, A.A., 1984. Statistical procedures for agricultural research. International Rice Research Institute. John Wiley & Sons, New York, 680 pp.

Goodroad, L.L. and Jellum, M.D., 1988. Effect of N fertilizer rate and soil pH on N efficiency in corn. Plant and Soil 106: 85-89.

Hanks, J. and Ritchie, J.T. (Editors), 1991. Modeling plant and soil systems. Agronomy, Vol. 31. ASA/CSSA/SSSA, Madison, Wisconsin, 545 pp.

Harmsen, K. and Moraghan, J.T., 1987. A comparison of the isotope recovery and difference methods for determining nitrogen fertilizer efficiency. Plant and Soil 105: 55-67.

Hauck, R.D., 1984. Nitrogen in crop production. ASA/CSSA/SSSA, Madison, Wisconsin, 804 pp.

Haule, K.L., Kimambo, E.I. and Floor, J., 1989. Effect of continuous cultivation and fertilizer applications on yield of maize and soil characteristics of a Ferralsol-Luvisol catena on gneiss in NE Tanzania. National Soil Service, Tanga, 10 pp.

Hutson, J.L. and Wagenet, R.J., 1991. Simulating nitrogen dynamics in soils using a deterministic model. Soil Use and Manage. 7: 74-78.

ILCA, 1987. Final Report to the Federal Livestock Department, Federal Military Govt. of Nigeria. FLD Grant Sept. 1986-Sept. 1987. International Livestock Centre for Africa Humid Zone Programme, Ibadan.

Jaetzold, R. and Schmidt, H., 1982. Farm management handbook of Kenya. Natural conditions and farm management information. Ministry of Agriculture, Nairobi, 3 volumes.

Janssen, B.H., 1970. Soil fertility in the Great Konya Basin, Turkey. Agric. Res. Rep. 750, Centre for Agricultural Publishing and Documentation, Wageningen, 115 pp.

Janssen, B.H. and Wolf, J., 1988. A simple equation for calculating the residual effect of phosphorus fertilizers. Fert. Res. 15: 79-87.

Janssen, B.H., Lathwell, D.J. and Wolf, J., 1987. Modeling long-term crop response to fertilizer phosphorus. II. Comparison with field results. Agron. J. 79: 452-458.

Janssen, B.H., Guiking, F.C.T., Van der Eyk, D., Smaling, E.M.A., Wolf, J. and Van Reuler, H., 1990. A system for Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS). Geoderma 46: 299-318.

Jenkinson, D.S., 1991. The Rothamsted long-term experiments: are they still of use? Agron. J. 83: 2-10.

Jokela, W.E. and Randall, G.W., 1989. Corn yield and residual soil nitrate as affected by time and rate of nitrogen application. Agron. J. 81: 720-726.

Juo, A.S.R. and Kang, B.T., 1989. Nutrient effects of modification of shifting cultivation in West Africa. In: Proctor, J. (Editor), Mineral nutrients in tropical forest and savanna ecosystems. Blackwell Scientific Publishers, Oxford, pp. 289-300.

Kamprath, E.J., 1987. Enhanced phosphorus status of maize resulting from nitrogen fertilization of high phosphorus soils. Soil Sci. Soc. Am. J. 51: 1522-1526.

Kang, B.T. and Van der Heide, J. (Editors), 1985. Proc. Symp. Nitrogen Management in the Farming Systems in the Humid and Subhumid tropics. IITA, Ibadan, 362 pp.

Kang, B.T., Sipkens, L., Wilson, G.F. and Nangju, D., 1981. Leucena (Leucena leucocephala (Lam.) de Wit) prunings as nitrogen source for maize (Zea mays L.). Fert. Res. 2: 279-287.

Kang, B.T., Reynolds, L. and Atta-Krah, A.N., 1990. Alley farming. Advances in Agronomy 43: 315-359.

Karanja, G. and Tefera, F., 1990. Soil and water conservation in Kenya. Bibliography with annotations, University of Nairobi, Dep. Agric. Engineering and SAREC, Nairobi, 254 pp.

Kenya Soil Survey, 1991. List of Publications. National Agricultural Research Laboratories, Kenya Agricultural Research Institute, Nairobi, 49 pp.

Kerkhof, P., 1990. Agroforestry in Africa. A survey of project experience. The Panos Institute, London, 216 pp.

Khasawneh, F.E., Sample, E.C. and Kamprath, E.J., 1990. The role of phosphorus in agriculture. ASA/CSSA/SSSA, Madison, Wisconsin, 910 pp.

Kim, S.K. (Editor), 1991. Combating Striga in Africa. Proc. Internat. Workshop by IITA, ICRISAT and IDRC, 22-24 August 1988. IITA, Ibadan, 151 pp.

King, L.D., 1990. Soil nutrient management in the United States. In: Edwards, C.A., Lal, R., Madden, P., Miller, R.H. and House, G. (Editors), Sustainable agricultural systems. Soil and Water Conservation Society. Ankeny, Iowa, pp. 89-106.

Kosmas, C., Moustakas, N., Kallianou, C. and Yassoglou, N., 1991. Cracking patterns, bypass flow and nitrate leaching in Greek irrigated soils. Geoderma 49: 139-152.

Kovar, J.L. and Barber, S.A., 1988. Phosphorus supply characteristics of 33 soils as influenced by seven rates of phosphorus addition. Soil Sci. Soc. Am. J. 52: 160-165.

Kuhlmann, H., 1990. Importance of the subsoil for the K nutrition of crops. Plant and Soil 127: 129-136.

Lal, R., 1984. Soil erosion from tropical arable lands and its control. Advances in Agronomy 37: 183-248.

Lal, R., 1991. Myths and scientific realities of agroforestry as a strategy for sustainable management for soils in the tropics. Advances in Soil Science 15: 91-136.

Leffelaar, P.A., 1977. Dynamics of partial anaerobiosis denitrification, and water in soil: experiments and simulation. PhD. thesis, Agricultural University Wageningen, 117 pp.

Malavolta, E., 1985. Potassium status of tropical and subtropical region soils. In: Munson, R.D. (Editor), Potassium in agriculture. ASA/CSSA/SSSA, Madison, Wisconsin, pp. 163-200.

Mengel, K., 1985. Dynamics and availability of major nutrients in soils. Advances in Soil Science 2: 65-131.

Mengel, K. and Kirkby, E.A., 1980. Potassium in crop production. Advances in Agronomy 33: 59-110.

Mitchell, C.C., Westerman, R.L., Brown, J.R. and Peck, T.R., 1991. Overview of long-term agronomic research. Agron. J. 83: 24-29.

Mokwunye, A.U. and Vlek, P.L.G. (Editors), 1986. Management of nitrogen and phosphorus fertilizers in sub-Saharan Africa. Martinus Nijhoff, Dordrecht, 362 pp.

Mombiela, F., Nicholaides, J.J. and Nelson, L.A., 1981. A method to determine the appropriate mathematical form for incorporating soil test levels in fertilizer response models for recommendation purposes. Agron. J. 73: 937-941.

Morel, C. and Fardeau, J.C., 1990. Uptake of phosphate from soils and fertilizers as affected by soil P availability and solubility of phosphorus fertilizers. Plant and Soil 121: 217-224.

Munson, R.D., 1985. Potassium in agriculture. ASA/CSSA/SSSA, Madison, Wisconsin, 1223 pp.

Murugappan, V., Kothandaraman, G.V., Palaniappan, S.P. and Manickam, T.S., 1989. Fertilizer requirements for specified yield targets. II. Field verification of mathematical models for the estimation of soil and fertilizer nutrient efficiencies. Fert. Res. 18: 127-140.

Nadar, H.M. and Faught, W.A., 1984. Effect of legumes on yield of associated and subsequent maize in intercropping and rotation systems. East African Agric. For. J. 44: 127-136.

Nguu, N.V., 1987. Effect of nitrogen, phosphorus and soil and crop residues management practices on maize (Zea mays L.) yield in ultisol of eastren Cameroon. Fert. Res. 14: 135-142.

Nijhof, K., 1987. The concentrations of macro-elements in economic products and residues of (sub)tropical field crops. Centre for World Food Studies (SOW), Staff working paper SOW-87-08. Wageningen, 52 pp.

Oertli, J.J., 1990. Limitations to the diagnostic information obtained from soil analyses. Fert. Res. 26: 189-196.

Ofori, F. and Stern, W.R., 1987. Cereal-legume intercropping system. Advances in Agronomy 41: 41-90.

Oliver, M.A. and Webster, R., 1991. How geostatistics can help you. Soil Use and Manage. 7: 206-217.

Pagel, H., Enzmann, J. and Mutscher, H., 1982. Pflanzennährstoffe in tropischen Böden. VEB Deutscher Landwirtschaftsverlag, Berlin, 272 pp.

Penning de Vries, F.W.T. and Van Laar, H.H., 1982. Simulation of plant growth and crop production. Centre for Agricultural Publishing and Documentation, Wageningen, 320 pp.

Peoples, M.B. and Craswell, E.T., 1992. Biological nitrogen fixation: investments, expectations and actual contributions to agriculture. Plant and Soil 141: 13-39.

Peterson, T.A. and Varvel, G.E., 1989. Crop yield as affected by rotation and nitrogen rate. III. Corn. Agron. J. 81: 735-738.

Pichot, J., Sedogo, M.P., Poulain, J.F. and Arrivets, J., 1981. Evolution de la fertilité d'un sol ferrugineux tropical sous l'influence de fumures minerales et organiques. l'Agron. Trop. 36: 122-133.

Pieri, C., 1985. Bilans minéraux des systemes de cultures pluviales en zones arides et semiarides. l'Agron. Trop. 40: 1-20.

Pieri, C., 1986. Fertilisation des cultures vivrières et fertilité des sols en agriculture paysanne subsaharienne. l'Agron. Trop. 41: 1-20.

Pieri, C., 1989. Fertilité des terres de savanes. Bilan de trente ans de recherche et de développement agricole au sud du Sahara. Ministère de la Coopération et CIRAD-IRAT, Montpellier, 444 pp.

Poels, R.L.H., 1987. Soils, water and nutrients in a forest ecosystem in Suriname. PhD. thesis, Agricultural University Wageningen, 253 pp.

Prasad, R. and Power, J.F., 1991. Crop residue management. Advances in Soil Science 15: 205-249.

Qureshi, J.N., 1987. The cumulative effects of N-P fertilizers, manure and crop residues on maize grain yields, leaf nutrient contents and some soil chemical properties at Kabete. National Maize Agronomy Workshop, Nairobi, February 17-19, 1987, 12 pp.

Reijntjes, C., Haverkort, B. and Waters-Bayer, A., 1992. Farming for the future. An introduction to Low-External-Input and Sustainable Agriculture. ILEIA, Leusden, 250 pp.

Sanchez, P.A., 1976. Properties and management of soils in the tropics. John Wiley & Sons, New York, 618 pp.

Sanchez, P.A., 1987. Management of acid soils in the humid tropics of Latin America. In: International Board for Soil Research and Management. Management of acid tropical soils for sustainable agriculture, Proc. IBSRAM inaugural workshop. Bangkok, pp. 63-107.

Sanchez, P.A. and Salinas, J.G., 1981. Low-input technology for managing Oxisols and Ultisols in tropical America. Advances in Agronomy 34: 279-406.

Sanchez, P.A., Couto, W. and Buol, S.W., 1982. The fertility capability soil classification system: interpretation, applicability and modification. Geoderma 27: 283-309.

Sanginga, N., Mulongoy, K. and Ayanaba, A., 1989. Nitrogen fixation of field-inoculated Leucaena leucocephala (Lam.) de Wit estimated by the 15N and the difference methods. Plant and Soil 117: 269-274.

Smith, S.J., Schepers, J.S. and Porter, L.K., 1990. Assessing and managing agricultural nitrogen losses to the environment. Advances in Soil Science 14: 1-43.

Sombroek, W.G., Braun, H.M.H. and Van der Pouw, B.J.A., 1982. Exploratory Soil Map and Agro-climatic Zones Map of Kenya, scale 1:1 000 000. Report E1, Kenya Soil Survey, Nairobi, 56 pp.

Sparks, D.L., 1987. Potassium dynamics in soils. Advances in Soil Science 6: 1-63.

Ssali, H. and Keya, S.O., 1986. The effects of phosphorus and nitrogen fertilizer level on nodulation, growth and dinitrogen fixation of three bean cultivars. Trop. Agric. 63: 105-109.

Stein, A., 1991. Spatial interpolation. PhD. thesis, Agricultural University Wageningen, 236 pp.

Steppler, H.A. and Nair, P.K.R., 1987. Agroforestry: a decade of development. ICRAF, Nairobi, 335 pp.

Stocking, M., 1984. Erosion and soil productivity: a review. Consultants' Working Paper No.1. FAO, Rome, 102 pp.

Stoorvogel, J.J. and Smaling, E.M.A., 1990. Assessment of soil nutrient depletion in sub-Saharan Africa, 1983-2000. Report 28, Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), 137 pp.

Sumner, M.E. and Farina, M.P.W., 1986. Phosphorus interactions with other nutrients and lime in field cropping systems. Advances in Soil Science 5: 201-236.

Thomas, D.B., Biamah, E.K., Kilewe, A.M., Lundgren, L. and Mochoge, B.O., 1989. Soil and water conservation in Kenya. Proceedings of the third national workshop. University of Nairobi, Dep. Agric. Engineering and SIDA, Nairobi, 579 pp.

Tisdale, S.L., Nelson, W.L. and Beaton, J.D., 1985. Soil fertility and fertilizers (4th ed). Macmillan Publishing Company, New York, 754 pp.

Trangmar, B.B., Yost, R.S. and Uehara, G., 1985. Application of geostatistics to spatial studies of soil properties. Advances in Agronomy 38: 45-94.

Tyler, D.D. and Thomas, G.W., 1977. Lysimeter measurements of nitrate and chloride losses from soil under conventional and no-tillage corn. J. Environ. Qual. 6: 63-66

Uribe, E. and Cox, F.R., 1988. Soil properties affecting the availability of potassium in highly weathered soils. Soil Sci. Soc. Am. J. 52: 148-152.

Valentin, C.V., 1988. Soil variability and experimental sites. IBSRAM Technical Note no. 1, Bangkok, pp. 99-114.

Van der Heide, J. (Editor), 1989. Nutrient Management for Food Crop Production in Tropical Farming Systems. Institute for Soil Fertility Research (IB-DLO), Haren, 394 pp.

Van der Pol, F., 1992. Soil mining. An unseen contributor to farm income in southern Mali. Bulletin 325, Royal Tropical Institute (KIT), Amsterdam, 48 pp.

Van Diepen, C.A., Wolf, J., Keulen, H. van and Rappoldt, C., 1989. WOFOST: a simulation model of crop production. Soil Use and Manage. 5: 16-24.

Van Duivenbooden, N. and Gosseye, P.A., 1990. Competition pour des ressources limitées, le cas de la cinquième région du Mali. Rapport 2: Productions végétales, animales et halieutiques. Centre des Recherche Agrobiologiques (CABO-DLO), Wageningen, et ESPR, Mopti, Mali, 265 pp. + annexes.

Van Keulen, H. and Van Heemst, H.D.J., 1982. Crop response to the supply of macronutrients. Agric. Res. Rep. 916. Centre for Agricultural Publishing and Documentation, Wageningen, 46 pp.

Van Keulen, H. and Wolf, J., 1986. Modelling of agricultural production: weather, soils and crops. Centre for Agricultural Publishing and Documentation, Wageningen, 479 pp.

Van Keulen, H. and Breman, H., 1990. Agricultural development in the West African Sahelian region: a cure against land hunger? Agric. Ecosystems Environ. 32: 177-197.

Van Stiphout, T.P.J., Van Lanen, H.A.J., Boersma, O.H. and Bouma, J., 1987. The effect of bypass flow and internal catchment of rain on the water regime in a clay loam grassland soil. J. Hydrology 95: 1-11.

Varvel and Peterson, 1990. Nitrogen Fertilizer Recovery by Corn in Monoculture and Rotation Systems. Agron. J. 82: 935-938.

Vlek, P.L.G., 1990. The role of fertilizers in sustaining agriculture in sub-Saharan Africa. Fert. Res. 26: 327-339.

Vlek, P.L.G., Fillary, I.R.P. and Burford, J.R., 1981. Accession, transformation, and loss of nitrogen in soils of arid regions. Plant and Soil 58: 133-174.

Wagenet, R.J., Bouma, J. and Grossman, R.B., 1991. Minimum data sets for use of soil survey information in soil interpretive models. In: Mausbach, M.J. and Wilding, L.P. (Editors), Spatial variabilities of soils and landforms. SSSA Special Publication Number 28, Madison, Wisconsin, pp. 161-182.

Walters, D.T. and Malzer, G.L., 1990. Nitrogen management and nitrification inhibitor effects on nitrogen-15 urea. II. Nitrogen leaching and balance. Soil Sci. Soc. Am. J. 54: 122-130.

Waugh, D.L., Cate Jr., R.B., Nelson, L.A. and Manzano, A., 1975. New concepts in biological and economical interpretation of fertilizer response. In: Bornemisza, E. and Alvarado, A. (Editors), Soil management in tropical America. North Carolina State University, Raleigh, pp. 484-501.

Welch, L.F. and Flannery, R.L., 1985. Potassium nutrition of corn. In: Munson, R.D. (Editor), Potassium in agriculture. ASA/CSSA/SSSA, Madison, Wisconsin, pp. 647-664.

White, R.E., 1985. The influence of macropores on the transport of dissolved and suspended matter through soil. Advances in Soil Science 3: 95-121.

Wild, A., 1972. Nitrate leaching under bare fallow at a site in northern Nigeria. J. Soil Sci. 23: 315-324.

Williams, J.R., Dyke, P.T. and Jones, C.A., 1983. EPIC - A model for assessing the effects of erosion on soil productivity. In: Laurenroth, W.K. (Editor), Proc. Third Int. Conf. on State-of-the-Art in Ecological Modelling, Fort Collins, 24-28 May 1982. Elsevier, New York, pp. 553-572.

Wischmeier, W.H. and Smith, D.D., 1978. Predicting rainfall erosion losses: a guide to conservation planning. USDA Agric. Handbook 537. US Gov. Print. Office, Washington DC, 58 pp.

Wolf, J., De Wit, C.T., Janssen, B.H. and Lathwell, D.J., 1987. Modeling long-term crop response to fertilizer phosphorus. I. The model. Agron. J. 79: 445-451.

Wolf, J., De Wit, C.T. and Van Keulen, H., 1989. Modeling long-term crop response to fertilizer and soil nitrogen. I. Model description and application. Plant and Soil 120: 11-22.

Young, A., 1989. Agroforestry for soil conservation. CAB International, Wallingford, 276 pp.

Zhang, J. and Barber, S.A., 1992. Maize root distribution between phosphorus-fertilized and unfertilized soil. Soil Sci. Soc. Am. J. 56: 819-822.

PART II THE SOIL NUTRIENT BALANCE

3. Calculating soil nutrient balances in Africa at different scales.
   I. Supra-national scale

4. Calculating soil nutrient balances in Africa at different scales.
   II. District scale

5. A decision-support model for monitoring nutrient balances under agricultural land use (NUTMON)

Chapter 3

Calculating soil nutrient balances in Africa at different scales.
I. Supra-national scale

Accepted for publication in Fertilizer Research

3 Calculating soil nutrient balances in Africa at different scales.

I. Supra-national scale

J.J. Stoorvogel[1], E.M.A. Smaling[1] and B.H. Janssen[2]

[1] *DLO The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen (The Netherlands)*

[2] *Department of Soil Science and Plant Nutrition, Agricultural University of Wageningen, P.O. Box 8005, 6700 AH Wageningen (The Netherlands)*

ABSTRACT

Nutrient balances were calculated for the arable soils of 38 sub-Saharan African countries. FAO production figures and forecasts for 35 crops for the period 1982-1984 and for 2000 were used to define land use systems, further characterized by fertility input through fertilizers, manure, rain and dust, biological N-fixation, and sedimentation, and fertility output through harvest of crops and removal of residues, leaching, denitrification, and erosion. The summarized output of the study is the sum of inputs minus the sum of outputs of nitrogen, phosphorus and potassium in the root zone. The alarming annual average nutrient loss for sub-Saharan Africa was 22 kg N, 2.5 kg P, and 15 kg K in 1982-84, and will be 26 kg N, 3 kg P, and 19 kg K in 2000. As the soil nutrient pool has to offset the negative balances each year, there is gross nutrient mining in sub-Saharan Africa. The need for integrated systems of nutrient management is emphasized, manipulating all inputs and outputs in a judicious way. Future scenarios of 'continued mining' and 'conservation of soil fertility' are discussed.

INTRODUCTION

The chemical fertility of any given virgin soil is determined by soil-forming factors such as (palaeo-)climate, parent material and vegetation. Changes take place very slowly and for soil under natural vegetation, there is a virtual steady state. As soon as land is altered by clearing natural forest or savanna vegetation, this steady state can no longer be maintained. Soil fertility declines at a rate dependent on cropping intensity and land management. Affected land will experience dwindling soil organic matter levels, leaching of nutrients, and erosion (Roose, 1986; Lal, 1989).

The role of soil nutrient loss has not been linked very often to recent food shortages because, unlike droughts and locust invasions which materialize abruptly, soil fertility decline is a gradual process. Nonetheless, several studies have shown that it is often the supply of plant nutrients that dictates the productivity of land, even in the Sahel (Penning de Vries and Djiteye, 1982; Centre for World Food Studies, 1985).

The Food and Agriculture Organization of the United Nations (FAO) estimated that in sub-Saharan Africa, the annual per capita growth rate for agricultural production between 1970 and 1985 was -1.3% (Alexandratos, 1988). FAO further anticipates that this growth will be +0.1% per year between 1985 and 2000, assuming that food production keeps pace with an annual population growth of 3.3%. The production increase should partly be realized by applying more mineral fertilizers. Farmers in the region used 1 000 000 t in 1983, and are expected to use 2 800 000 t in 2000 (Alexandratos, 1988). These figures, however, do not indicate whether that will be sufficient to keep the soil nutrient pool at a constant level. As a consequence, FAO called for comprehensive nutrient balance studies to gain a better insight into the present state and the short-term development of soil fertility.

This paper describes a method for calculating nutrient balances for the arable land of 38 sub-Saharan African countries, planted to 35 different crops (Stoorvogel and Smaling, 1990). FAO production figures for the period 1982-1984 and forecasts for 2000 were used to define land use systems, characterized by fertility inputs (mineral fertilizers, manure, wet and dry deposition, biological N-fixation, and sedimentation), and fertility outputs (harvest of crops and removal of residues, leaching, denitrification, and erosion). The final result is a set of figures per country on the balances of the macronutrients nitrogen, phosphorus and potassium in the root zone in 1982-84 and 2000. Although deficiencies in secondary nutrients and micronutrients may also limit crop production, they have not been included in this study.

MATERIALS AND METHODS

Land/Water Classes and Land Use Systems

In sub-Saharan Africa, arable land was 201 000 000 ha in 1983, 54% of which was actually harvested. In 2000, arable land is estimated to total 234 000 000 ha, with a cropping intensity of 60% (Alexandratos, 1988). To quantify nutrient balances, this area was classified into units of similar production potential. Three land/water classes (LWCs) were distinguished, viz. Rainfed, Naturally Flooded and Irrigated Land, for which the FAO data base provided yields and cultivated areas for 35 arable crops. Rainfed Land is further subdivided into Low Rainfall (LRA), Uncertain Rainfall (URA), Good Rainfall (GRA) and Problem Areas (PA), on basis of the length of the growing period. Subsequently, the soil map of Africa (FAO, 1977) was overlaid, and the soil orders were rated to label LWCs as having high, moderate or low inherent fertility (FAO, 1978). On the basis of this classification, a further agro-economic stratification was made to arrive at land use systems (LUSs), characterized by cropping pattern, levels of fertilizer and manure application, management of crop residues and erosion control.

Modelling the nutrient balance

- Inputs

Input from mineral fertilizers (*IN 1*) was given per country and per crop in the FAO data base and had to be calculated for each LWC. Where no data on actual fertilizer distribution were available, weighting factors were used to assess the partitioning of total fertilizer use. Farmers in areas with favourable rainfall (GRA, PA) were assumed to be more inclined to use fertilizers than those in semi-arid areas (URA and LRA). Groundnuts in Senegal, for example, received 3500 t N yr^{-1} in mineral fertilizer in 1983. This crop was grown in LRA (286 000 ha), URA (856 000 ha), GRA (51 000 ha) and PA (60 000 ha). At weighting factors of 0.2

(LRA), 0.3 (URA), and 1.0 (GRA and PA), *IN 1* for groundnuts in URA is thus 2.4 kg N ha^{-1}.

Animal manure (*IN 2*) enters the system after collection from stalled livestock and application prior to planting or, more often, through droppings of livestock feeding on crop residues after harvest. Data are then needed on the fraction of crop residues grazed (determined by land use system), the time animals spend in the field (fixed at 12 hours per day), and the fraction of nutrients retained in the animals (fixed at 10%).

Wet and dry deposition from the atmosphere (*IN 3*) can be an important source of plant nutrients. In West Africa, measurements of deposition of dust from the annual dry season 'harmattan' storms provided point data (Cooke, 1982; Pieri, 1985; Poels, 1987); elsewhere, data on deposition were scarce, but could be calculated thanks to a linear correlation between *IN 3* and the square root of average annual rainfall.

Biological nitrogen fixation (*IN 4*) is mainly important in leguminous crops and wetland rice. It was assumed that 60% of the total nitrogen requirement of these crops is supplied through biological fixation. In addition, small contributions (2-5 kg N ha^{-1}) from non-symbiotic N-fixation were accounted for in all LWCs.

Input from sedimentation (*IN 5*) was fixed for Irrigated Land (10 kg N, 1.5 kg P and 4 kg K ha^{-1} yr^{-1}). For Naturally Flooded Land, *IN 5* was assumed to even equilibrate the entire nutrient balance.

- Outputs

Export of nutrients in the harvested product (*OUT 1*) was derived from the yields in the FAO data base. For each LUS, these figures were multiplied by the nutrient contents in the harvested parts. This was complicated by plant species showing substantial variation in nutrient uptake efficiency, which moreover depends on climate and soil properties and farmer's crop management (Kassam, 1976; Sanchez, 1976; Cooke, 1982; Pieri, 1985; Goodroad and Jellum, 1987).

Export of nutrients in crop residues (*OUT 2*) varies depending on residue management by the farmer, which differs greatly between and within the countries studied. The totals removed in a LUS were derived from the literature, and multiplied by the nutrient content of the crop residues. Where residues are grazed, part of the nutrients will return to the soil in manure (*IN 2*).

Only a limited number of systematic studies has been carried out on leaching of nitrogen and potassium (*OUT 3*) in the tropics (Grimme and Juo, 1985). Through multiple regression, leaching losses have been correlated with rainfall, inherent soil fertility, and application of fertilizer and manure.

Gaseous losses (*OUT 4*) only refer to nitrogen and may comprise denitrification and volatilization. As most soils in sub-Saharan Africa are acidic, thus preventing volatilization, only denitrification is considered. There are few reliable data on denitrification in tropical soils. Through multiple regression it has been linked to inherent soil fertility, and to fertilizer and manure applications.

Data on total soil loss by erosion are amply available for many countries, derived from run-off plot research or from discharge and sediment load measurements in catchment areas (Stocking, 1984; Roose, 1986; Elwell, 1990). Inherent soil fertility was used to translate these data into nitrogen, phosphorus and potassium losses (*OUT 5*), which were then multiplied by an 'enrichment' factor. As fine particles are dislodged first in the process of erosion, eroded soil is richer in nutrients than soil *in situ* (Stocking, 1984; Gachene, 1987).

- Fallow and multiple cropping

In the FAO data base, the total area of arable land in an LWC generally exceeds the area actually harvested. The difference is considered to be fallow land, which is treated as a separate LUS with a modest net nutrient import. The benefits from fallowing are the result of a shift in nutrient status from stable forms present in the soil to the plant-available labile pool, through weathering, mineralization, and uptake by fallow biomass, which is later slashed and burned. For some LWCs the FAO data base shows a cropping intensity exceeding 100%, indicating multiple cropping systems.

NUTRIENT BALANCES

Senegal

Nutrient balances were calculated per crop for 1982-84 and 2000. Crop totals were first aggregated to LUS totals and subsequently to LWC totals. An illustration of the calculation procedure is given for the N balance for groundnuts in Senegal, LWC Uncertain Rainfall Area (Table 3.1). Aggregated inputs and outputs of N, P and K for this LWC for 1982-84 and 2000, as well as the nutrient balances per ha are given in Table 3.2. The last column shows that the calculated annual N loss is 14 kg ha^{-1} for 1982-84 and 20 kg ha^{-1} for 2000.

Table 3.1 The nitrogen balance for groundnuts in Land/Water Class URA in Senegal (1982-84).

* Groundnuts received 3500 t N in mineral fertilizer, which is distributed over:

	weighting factor	area (ha)
LRA	0.2	286 000
URA	0.3	856 000
GRA	1.0	51 000
PA	1.0	60 000

Hence, *IN 1* = **2.4 kg ha^{-1}**.

- Animals feed on crop residues (*OUT 2* = 11 kg ha^{-1}), of which 90% leaves the animals as manure and urine. The animals spend 12 hours per day on the field. Hence,
  IN 2 = 0.9 * 12/24 * 11.0 = **5.0 kg ha^{-1}**.
- For deposition of N at 900 mm rainfall, the regression equation *IN 3* = 0.14 * (rainfall)$^{1/2}$ yields **4.2 kg ha^{-1}**.
- Sixty percent of the total N uptake plus 4 kg N, fixed non-symbiotically in URA, gives *IN 4* = 0.6 * (OUT 1 + 100/80 * OUT 2) + 4 = **27.4 kg ha^{-1}**.
- Sedimentation is not relevant in URA. Hence, *IN 5* = **0 kg ha^{-1}**.
- ① Yield of groundnuts in URA is 700 kg ha^{-1}. At an N uptake of 37.2 g kg^{-1} harvested product, *OUT 1* = 37.2 * 700 * 0.001 = **26.0 kg ha^{-1}**.
- ② N uptake in crop residues is 19.6 g kg^{-1} harvested product. Since 80% is removed, *OUT 2* = 19.6 * 700 * 0.001 * 0.8 = **11.0 kg ha^{-1}**.
- Leaching follows from the regression equation *OUT 3* = 2.3 + (0.0021 + 0.0007 * F) * R + 0.3 * (*IN 1* + *IN 2*) - 0.1 * UN
  in which R = rainfall (annual average, mm), F = soil fertility class (1 low; 2 moderate; 3 high), and UN = total nitrogen uptake (kg ha^{-1}). URA has a moderate fertility. Hence, *OUT 3* = 2.3 + (0.0021 + 0.0007 * 2) * 900 + 0.3 * 7.4 - 0.1 * 39.0 = **3.8 kg ha^{-1}**.
- Denitrification is derived from the regression equation: *OUT 4* = X + 2.5 * F + 0.3 * (*IN 1* + *IN 2*) - 0.1 * UN, in which X is a LWC-specific fixed value (URA: 5 kg ha^{-1}). Hence,
  OUT 4 = 5 + 2.5 * 2 + 0.3 * 7.4 - 0.1 * 39.0 = **8.3 kg ha^{-1}**.
- The N content of soil in fertility class 2 is set at 0.1%. Given the enrichment factor of 2.0 at an annual soil loss of 10 t ha^{-1}, *OUT 5* = 0.001 * 2 * 10,000 = **20.0 kg ha^{-1}**.

- Σ *IN* - Σ *OUT* = (2.4 + 5.0 + 4.2 + 27.4 + 0.0) - (26.0 + 11.0 + 3.8 + 8.3 + 20.0) = **-30.1 kg ha^{-1}** for an area of 856 000 ha. Since, according to FAO data, 55% of the arable land has remained *fallow*, there is 1 045 000 ha that has received a fixed input of **+2 kg ha^{-1}**.
  The net nitrogen loss for the area is thus (0.45 * -30.1) + (0.55 * 2) = **-12.4 kg ha^{-1}**, i.e. slightly below the average for URA (14 kg ha^{-1}, Table 3.2).

Table 3.2 Nutrient balances of the Land/Water Class URA in Senegal; arable land was 3 189 000 ha in 1982-84 and is estimated at 3 444 000 ha in 2000

Nutrient	Year	Input	Output	Nutrient balance	
		($t\ yr^{-1}$)	($t\ yr^{-1}$)	($t\ yr^{-1}$)	($kg\ ha^{-1}\ yr^{-1}$)
N	1982-84	45 000	90 100	-45 100	-14
	2000	75 600	144 100	-68 500	-20
P	1982-84	5 800	12 900	- 7 100	-2
	2000	10 700	22 000	-11 300	-3
K	1982-84	16 300	53 200	-36 900	-12
	2000	29 400	89 900	-60 500	-18

Per country

Nutrient balances for LWCs were also aggregated per country (Table 3.3). High rates of nutrient depletion (N more than 40 and K more than 25 kg $ha^{-1}\ yr^{-1}$) were

Table 3.3 Average nutrient balances of N, P, and K ($kg\ ha^{-1}\ yr^{-1}$) of the arable land for some sub-Saharan African countries

Country	N		P		K	
	1982-84	2000	1982-84	2000	1982-84	2000
Benin	-14	-16	-1	-2	-9	-11
Botswana	0	-2	1	0	0	-2
Cameroon	-20	-21	-2	-2	-12	-13
Ethiopia	-41	-47	-6	-7	-26	-32
Ghana	-30	-35	-3	-4	-17	-20
Kenya	-42	-46	-3	-1	-29	-36
Malawi	-68	-67	-10	-10	-44	-48
Mali	-8	-11	-1	-2	-7	-10
Nigeria	-34	-37	-4	-4	-24	-31
Rwanda	-54	-60	-9	-11	-47	-61
Senegal	-12	-16	-2	-2	-10	-14
Tanzania	-27	-32	-4	-5	-18	-21
Zimbabwe	-31	-27	-2	2	-22	-26

calculated for the densely populated and erosion-prone countries in East and Southern Africa, in particular Ethiopia, Kenya, Malawi and Rwanda. Low or zero depletion rates (N less than 10 and K less than 8 kg ha^{-1} yr^{-1}) were calculated for countries in strongly semi-arid environments, such as Botswana and Mali. For most countries, the calculated balances for 2000 were even more negative than for 1982-84, notably with respect to potassium and nitrogen.
This was influenced by the optimistic FAO estimates for crop production in 2000 (high OUT 1), but also by the relatively large percentages of fallow arable land in 1982-84, and the increased use of this land in 2000.

Sub-Saharan Africa
Further aggregation provided average nutrient balances for sub-Saharan Africa as a whole. Loss of nitrogen averages 22 kg ha^{-1} yr^{-1} in 1982-84 and 26 kg ha^{-1} yr^{-1} in 2000 (Figure 3.1a). Export of nutrients in crops (*OUT 1*) was high in 1982-84, and increases strongly in 2000 as a result of the anticipated higher production. Losses due to erosion (*OUT 5*) and denitrification (*OUT 4*) were also conspicuous. On the input side, mineral fertilizers (*IN 1*) constitute the major contribution, but by no means do they offset the outputs. The calculated negative balance has to be compensated for by soil N that is mineralized from decomposing organic matter.

The calculated average loss of phosphorus is 2.5 kg ha^{-1} yr^{-1} in 1982-84 and 3 kg ha^{-1} yr^{-1} in 2000 (Figure 3.1b). Removal of nutrients in crops (*OUT 1*) and erosion (*OUT 5*) have the strongest negative impact on the balance. Inputs were few in 1982-84, but mineral fertilizers (*IN 1*) are expected to make a considerable contribution by 2000. In many (acid) tropical soils, applied P is susceptible to strong retention by amorphous Fe and Al (hydr)oxides, rendering it less available to plants. As this phosphorus is retained in the root zone, it was not treated as an output. The calculated negative balance has to be compensated for by soil P that is mineralized from decomposing organic matter and from weathering P-containing soil minerals (apatite, variscite, strengite).

Calculated potassium loss (Figure 3.1c) averaged 15 kg ha^{-1} yr^{-1} in 1982-84 and 19 kg ha^{-1} yr^{-1} in 2000, mainly as a result of export in crop residues, leaching and erosion (*OUT 2,3,5*). The potassium content in crop residues far exceeds that in harvested products. If residues are left in the field, K losses can be reduced considerably. *IN 1* is low because fertilizers containing potassium are applied sparsely by African farmers, as the element is, in general, less yield-limiting than N and

P. The calculated negative balance has to be compensated for by K from weathering feldspars, micas and high-activity clay minerals.

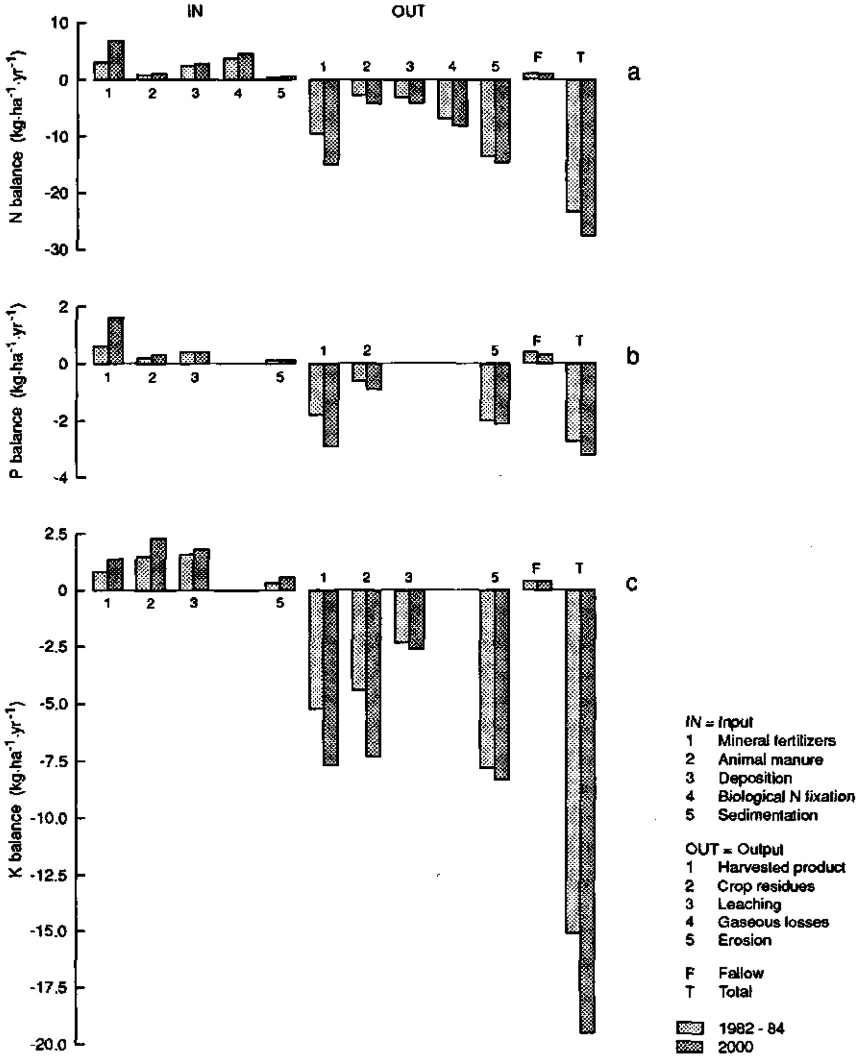


Fig. 3.1 Average nutrient balances for sub-Saharan Africa (1982-84 and 2000).
a: nitrogen; b: phosphorus; c: potassium

EVALUATION AND VALIDATION

The main shortcomings of the calculation procedure were that (i) LUSs defined for 1982-84 were used again for 2000; (ii) the discrete subdivision of inherent soil fertility into classes 1 (low), 2 (moderate), and 3 (high) was rigid, and for each LWC, the same classes were used for 1982-84 and 2000; (iii) values of some input and output determinants varied largely in literature, for example crop nutrient contents, erosion rates, and enrichment factors.

Table 3.4 Unfertilized maize yields (kg ha^{-1}), organic carbon (g kg^{-1}), pH(H_2O), and exchangeable potassium (mg kg^{-1}) in three Tanzanian soils

Period	Rhodic Ferralsol				Intergrade soils				Chromic Luvisol			
	maize yield	org. C	pH	exch. K	maize yield	org. C	pH	exch. K	maize yield	org. C	pH	exch. K
1981-1984	724	23	5.9	168	2253	25	5.7	416	4174	36	6.4	308
1985-1988	677	16	5.3	140	1245	15	5.2	264	2625	22	6.0	184
change (%)	-6	-30	-10	-17	-45	-40	-9	-37	-37	-39	-7	-40

Validation of the model was difficult because of the lack of independent data sets meeting all the input requirements. The few medium-term fertilizer trials in sub-Saharan Africa, however, showed trends which follow the calculated results. Table 3.4 shows that in Tanzania, unfertilized maize gave yields of up to 4 t ha^{-1} during the first four years of cultivation (Haule et al., 1989). Over the next four years average yields were up to 40% lower. A similar deterioration was observed for organic matter content, exchangeable potassium and pH. Also in Kenya, unfertilized maize yields declined in years 5 to 8 as compared with years 1 to 4 (Qureshi, 1987). Table 3.5 shows that maize that received either a crop residue mulch or animal manure or mineral fertilizer decreased, but less dramatically than in the Tanzanian situation. On receiving a combination of all three inputs, however, yields increased by 12%. In Southern Nigeria (rainfall 1250 mm yr^{-1}) yields of continuous maize receiving mineral NPK fertilizer, decreased from 7 t ha^{-1} to approximately 3.5 t ha^{-1} in a period of 10 years following clearing of secondary forest (Juo and Kang, 1989). Returning maize stover kept yields at high levels, with 8 t ha^{-1} in year 2 and still a substantial 6 t ha^{-1} in year 8. This brief review supports the outcome of the present study for Tanzania, Nigeria and Kenya, wh~~o~~ch experience increasingly severe nutrient depletion (Table 3.3).

Table 3.5 Maize yields (kg ha^{-1}) on a Kenyan Nitisol with application of crop residues, manure (5 t ha^{-1}), mineral fertilizer (60 kg N ha^{-1} and 25 kg P ha^{-1}), and both manure and NP fertilizer, and the soil fertility (organic carbon in g kg^{-1}, P-Mehlich in mg kg^{-1}, and exchangeable potassium in mg kg^{-1})

Period	Maize yields					Soil properties control plots		
	control	+crop residues	+manure	+NP	+NP +manure	org.C	P-Mehlich	exch.K
1976-1980	3214	3205	4024	4074	4568	19	14	560
1981-1985	1953	2410	3368	3863	5108	15	12	400
change (%)	-39	-25	-16	-5	+12	-21	-14	-29

CONCLUSIONS

1 Sum of inputs minus sum of outputs of nutrients is strongly negative in erosion-prone and relatively fertile East and Southern Africa, and slightly negative in semi-arid countries, with less intensive land use, gentle slopes and poor soils, that have little to lose anyway.

2 Given the FAO production data and projections, net export of nutrients (notably N and K) in 2000 will be higher than in 1982-84.

3 Both at the present and projected yield levels, more nutrients are withdrawn from the soil than added. The deficit is made up by the mineral and organic nutrient reserves in the soil, and if not replenished adequately, these pools gradually shrink. As a consequence, crop production declines and one can thus doubt whether the FAO projections for 2000 are realistic, as soils are becoming poorer all over the continent. Increased production is apparently expected from expansion of cultivated area and improved cultivars. (?)

4 To stop nutrient depletion and get the balance right, it does not suffice to just increase the use of mineral fertilizers. There is a need for integrated soil fertility management, where all inputs and outputs are manipulated in a judicious way.

FUTURE SCENARIOS

We will now discuss the implications of the conclusions, assuming two future scenarios, i.e. (i) continued mining of soil nutrients, with no changes in land use and cropping practices, and (ii) conservation of soil fertility, increasing inputs and reducing outputs simultaneously.

Continued soil nutrient mining

The unfavourable scenario is one of continued mining, with no improvement in land management between 1982-84 and 2000. The process of nutrient depletion continues (Conclusion 1), becoming more severe every year (Conclusion 2). Negative nutrient balances go at the expense of the nutrient store in the soil (Conclusion 3). Let us assume that a soil with 2000 kg N ha^{-1} has an annual depletion of 40 kg N ha^{-1}, i.e. 2%. After 20 years, this soil will remain with only $0.98^{20} * 2000 = 1335$ kg N ha^{-1}. As this soil has less and less nutrients to offer to crops, it is obvious that this has to go at the expense of crop yields, i.e. *OUT 1 and 2*.

Conservation of soil fertility

The favourable scenario assumes improved land management between 1982-84 and 2000 (Conclusion 4). This may be achieved by:

- applying modest amounts of mineral fertilizer, complying with specific recommendations for combinations of crop and agro-ecological zone (*IN 1* up). This will improve both the nutrient use efficiency and the fertilizer recovery by crops and alleviate the need for countries to import and for farmers to buy large amounts of nitrogen fertilizers (Baligar and Bennett, 1986; Vlek, 1990). Repeated application of high doses of acidifying fertilizers should be avoided (Schwab et al., 1990). In this respect, calcium ammonium nitrate is less harmfull than urea, which is still to be preferred to ammonium sulphate, whereas for phosphorus, superphosphates are less harmful than the popular compound diammonium phosphate.

- efficient use of animal manure and household waste, both releasing nutrients, and providing additional benefits such as increased water storage and nutrient retention (*IN 2* up).
- introducing more nitrogen-fixing species in cropping systems (*IN 4* up). Green manures (for example Pueraria spp.), grain legumes (when single-cropped), and woody species can supply 40-100 kg N ha^{-1} to a subsequent crop (Greenland, 1985; Dommergues and Ganry, 1986; Young, 1989; Giller and Wilson, 1991). Where sorghum yields of 3.4 t ha^{-1} were recorded in pure stands, 5.0 t ha^{-1} was harvested in rotation with soybean. For maize, these values were 5.5 and 7.6 t ha^{-1} respectively (Peterson and Varvel, 1989a; 1989b).
- letting livestock graze crop residues in the field, leaving residues as mulch or ploughing them in (*OUT 2* down). For monocultures, there is a pest risk, because larvae stay dormant in the residues and attack the following crop.
- properly-timed or split application of mineral fertilizers, and appropriate tillage and soil conservation measures (*OUT 3,4,5* down); terracing can stop erosion, but strip cropping, mulching, alley cropping, and multi-storey cropping are simpler and often effective techniques, fitting in existing farming systems; zero-grazing is promising in densely populated areas where land is scarce; contour-planted roughage is fed to stabled livestock. Grass, such as napier, grows vigorously and serves as a ground cover.

With a combination of the above-mentioned measures, losses may be reduced considerably, and crop yields and thus *OUT 1* may stay in line with FAO projections for 2000. More labour may be required for sustainable nutrient management, and farming systems research should elucidate what changes are desirable and feasible. Examples of sustainable systems have been reported for Latin America (Sanchez, 1976), tropical Africa (Okigbo, 1990), Cameroon (Nguu, 1987), and Rwanda (Egger, 1990), where the government has declared war on soil erosion. It offers hope that nutrient depletion in 2000 is below the values calculated in this study.

ACKNOWLEDGEMENTS

The FAO Land and Water Division (AGL) initiated the study on quantitative data on nutrient balances in sub-Saharan Africa. This initiative and the subsequent full support is gratefully acknowledged. Major support in The Netherlands was received from Wageningen Agricultural University, the Institute for Soil Fertility Research (IB-DLO), the Centre for Agro-biological Research (CABO-DLO), the Royal Tropical Institute (KIT) and the Institute for Research on Horse, Sheep and Cattle Husbandry (PR).

References

Alexandratos, N., 1988. World Agriculture: Toward 2000. A FAO Study. Belhaven Press, London.

Baligar, V.C. and Bennett, O.L., 1986. Outlook on fertilizer use efficiency in the tropics. Fert. Res. 10: 83-96.

Centre for World Food Studies, 1985. Potential food production increases from fertilizer aid: a case study of Burkina Faso, Ghana, and Kenya. Volume I. Centre for World Food Studies (SOW), Wageningen.

Cooke, G.W., 1982. Fertilizing for maximum yield. English Language Book Society, London.

Dommergues, Y.R. and Ganry, F., 1986. Biological nitrogen fixation and soil fertility maintenance. In: Mokwunye, A.U. and Vlek, P.L.G. (Editors), Management of nitrogen and phosphorus fertilizers in sub-Saharan Africa. Martinus Nijhoff, Dordrecht, pp. 95-115.

Egger, K., 1990. Ecofarming: a synthesis of old and new. ILEIA Newsletter 6: 3-5.

Elwell, H.A., 1990. The development, calibration and field testing of a soil loss and a runoff model derived from a small-scale physical simulation of the erosion environment on arable land in Zimbabwe. J. Soil Sci. 41: 239-253.

FAO, 1977. FAO/Unesco soil map of the world, 1: 5 000 000. Vol. VI: Africa. Unesco, Paris.

FAO, 1978. Report on the Agro-ecological Zones Project. Vol. I: Methodology and results for Africa. World Soil Resources Report 48. FAO, Rome.

Gachene, C.K.K., 1987. Nutrient losses in eroded soil material from some Kenyan soils. In: Thomas, D.B., Biamah, E.K., Kilewe, A.M., Lundgren, L. and Mochoge, B.O. (Editors), Soil and Water Conservation in Kenya. Proc. Third National Workshop. University of Nairobi/Swedish International Development Agency, pp. 34-37.

Giller, K.E. and Wilson, K.J., 1991. Nitrogen fixation in tropical cropping systems. CAB International, Wallingford.

Goodroad, L.L. and Jellum, M.D., 1987. Effect of N fertilizer rate and soil pH on N efficiency in corn. Plant Soil 106: 85-89.

Greenland, D.J., 1985. Nitrogen and food production in the tropics: contributions from fertilizer nitrogen and biological nitrogen fixation. In: Kang, B.T. and Van der Heide, J. (Editors), Proc. Symp. Nitrogen Management in Farming Systems in Humid and Subhumid Tropics. IITA, Ibadan, pp. 9-38.

Grimme, H. and Juo, A.S.R., 1985. Inorganic nitrogen losses through leaching and denitrification in soils of the humid tropics. In: Kang, B.T. and Van der Heide, J. (Editors), Proc. Symp. Nitrogen Management in Farming Systems in Humid and Subhumid Tropics. IITA, Ibadan pp. 57-72.

Haule, K.L., Kimambo, E.I. and Floor, J., 1989. Effect of continuous cultivation and fertilizer applications on yield of maize and soil characteristics of a Ferralsol-Luvisol catena on gneiss in NE Tanzania. National Soil Service, Tanga.

Juo, A.S.R. and Kang, B.T., 1989. Nutrient effects of modification of shifting cultivation in West Africa. In: Proctor J. (Editor), Mineral nutrients in tropical forest and savanna ecosystems. Blackwell Scientific Publishers, pp. 289-300.

Kassam, A.H., 1976 Crops of the West-African semi-arid tropics. ICRISAT, Hyderabad.

Lal, R., 1989. Soil management options in the tropics as alternatives to slash and burn. Soil Technol. 2: 253-270.

Nguu, N.V., 1987. Effect of nitrogen, phosphorus and soil and crop residues management practices on maize (*Zea mays* L.) yield in ultisol of eastern Cameroon. Fert. Res. 14: 135-142.

Okigbo, B.N., 1990. Sustainable agricultural systems in tropical Africa. In: Edwards, C.A., Lal, R., Madden, P., Miller, R.H. and House, G. (Editors), Sustainable Agricultural Systems. Soil and Water Conservation Society, Ankeny, pp. 323-352.

Penning de Vries, F.W.T. and Djiteye, M.A., 1982. La productivité des pâturages sahéliens. Centre for Agricultural Publishing and Documentation, Wageningen.

Peterson, T.A. and Varvel, G.E., 1989a. Crop yield as affected by rotation and nitrogen rate. II. Grain sorghum. Agron. J. 81: 731-734.

Peterson, T.A. and Varvel, G.E., 1989b . Crop yield as affected by rotation and nitrogen rate. III. Corn. Agron. J. 81: 735-738.

Pieri, C., 1985. Bilans minéraux des systemes de cultures pluviales en zones arides et semi-arides. Agron. Trop. 40: 1-20.

Poels, R.L.H., 1987. Soils, water and nutrients in a forest ecosystem in Suriname. Agricultural University, Wageningen.

Qureshi, J.N., 1987. The cumulative effects of N-P fertilizers, manure and crop residues on maize grain yields, leaf nutrient contents and some soil chemical properties at Kabete. National Maize Agronomy Workshop. CIMMYT, Nairobi.

Roose, E.J., 1986. Runoff and erosion before and after clearing depending on the type of crop in Western Africa. In: Lal, R., Sanchez, P.A. and Cummings, R.W. (Editors), Land clearing and development in the tropics. Balkema. Rotterdam.

Sanchez, P.A., 1976. Properties and management of soils in the tropics. John Wiley & Sons, New York.

Schwab, A.P., Owensby, C.E. and Kulyingyong, S., 1990. Changes in soil chemical properties due to 40 years of fertilization. Soil Sci. 149: 35-43.

Stocking, M., 1984. Erosion and soil productivity: a review. Consultants' Working Paper No.1. FAO, Rome.

Stoorvogel, J.J. and Smaling, E.M.A., 1990. Assessment of soil nutrient depletion in Sub-Saharan Africa, 1983-2000. Report 28. The Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), Wageningen.

Vlek, P.L.G., 1990. The role of fertilizers in sustaining agriculture in sub-Saharan Africa. Fert. Res. 26: 327-339.

Young, A., 1989. Agroforestry for Soil Conservation. CAB International, Wallingford.

Chapter 4

Calculating soil nutrient balances in Africa at different scales.
II. District scale

Accepted for publication in Fertilizer Research

4 Calculating soil nutrient balances in Africa at different scales.

II. District scale

E.M.A. Smaling, J.J. Stoorvogel and P.N. Windmeijer

DLO The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen (The Netherlands)

ABSTRACT

In a recent study on the NPK balance of land use systems in sub-Saharan Africa, it was found that scale-inherent simplifications were inevitable (Stoorvogel et al., 1992). This article reports on a similar exercise in a well-inventorized smaller area (Kisii District, Southwestern Kenya). Land use types and land/water classes (combinations of rainfall zones and soil units) were combined into geographically well-defined land use systems with NPK inputs by mineral fertilizers, manure, wet and dry deposition, and biological N fixation, and outputs by aboveground crop parts, leaching, denitrification, and erosion. Primary data were available on applied mineral fertilizers and manure, crop yields, nutrient contents, residue removal and erosion. Deposition, leaching and denitrification were estimated using rainfall, clay, N and K content, and fertilizer input. Erosion was estimated along the lines of the Universal Soil Loss Equation.

The aggregated nutrient balance for the Kisii District was -112 kg N, -3 kg P, and -70 kg K ha^{-1} yr^{-1}. For all nutrients, removal of harvested product was the strongest negative contributor, followed by erosion. In terms of land use, nutrient depletion was highest under pyrethrum and lowest under tea. Sensitivity analysis revealed that changing mineralization rate and soil N content had an important impact on the N balance. Varying slope gradient and length, soil erodibility, land cover and the enrichment factor for eroded material affected all nutrients.

Examples are given of possible ways to improve the NPK balance in the Kisii District by manipulating inputs and outputs. The methodology can prove valuable in any area where the farming community is receptive to integrated nutrient management systems.

INTRODUCTION

In natural ecosystems, loss of nutrients (outputs) is generally compensated by nutrient gains (inputs). Even in traditional bush-fallow systems with some nutrient input by manure and household waste, the soil fertility level can be stable (Jones, 1971). However, as soon as land is transferred to agricultural use on a more permanent basis, soil fertility tends to decline at a rate that is largely governed by the type of land use systems introduced and their management. Nutrient depletion in African soils has been described and analyzed in various studies (Pichot et al., 1977; Velly and Longueval, 1977; Wetselaar and Ganry, 1982; Pieri, 1985, 1989; Van der Pol, 1992).

Recently a comprehensive study was published of the nutrient balance in the arable land of 38 sub-Saharan African countries (Stoorvogel and Smaling, 1990). The NPK balance in the rootable soil layer was calculated as the sum of inputs (mineral fertilizers, manure, wet and dry deposition, biological N fixation and sedimentation) minus the sum of outputs (aboveground crop parts, leaching, denitrification and erosion). Because of the small scale, calculations were constrained by a number of factors:

(i) data on land use systems and their geographical position were unevenly distributed among and within countries;

(ii) instead of explicit input/output determinants such as texture, soil N and soil P content, and water holding capacity, a discrete soil fertility classification was used (low = 1, moderate = 2, high = 3), based on the Soil Map of Africa, at a scale of 1 : 5 000 000 (FAO, 1974);

(iii) the range in reported crop yields and nutrient contents was very wide;

(iv) quantitative information on deposition, leaching and denitrification was very scarce and unevenly distributed over the region;

(v) quantitative information on erosion was rather scarce; at the same time, the impact of erosion on the nutrient balance and hence on model output was considerable.

Because of these scale-inherent limitations, the study was repeated for the Kisii District, Southwestern Kenya. As a result of past inventories, part of the assumptions and estimates used in the regional study could be replaced by primary data. Hence input and output of nutrients for the Kisii District for 1990, could be calculated with greater reliability for well-defined agro-ecological entities.

BASIC DATA ON THE KISII DISTRICT

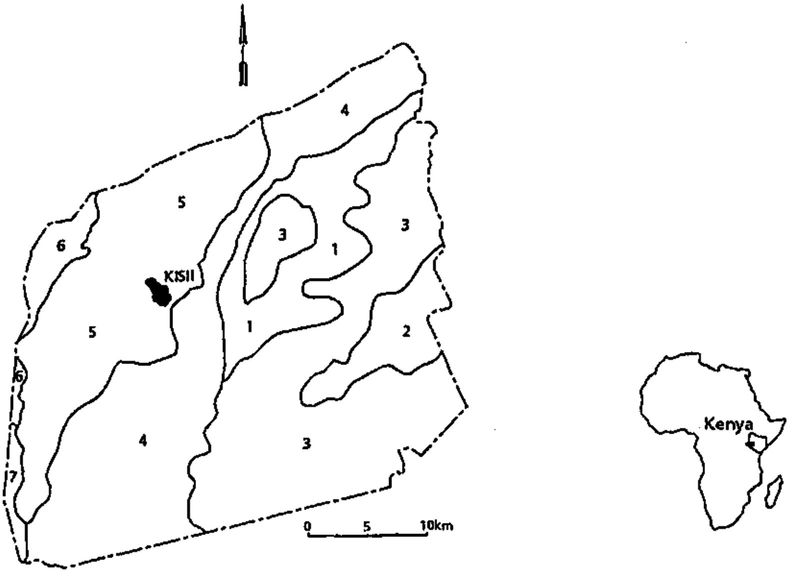


Fig. 4.1 Land use types in the Kisii District. Descriptions in Tables 4.1 and 4.2

The Kisii District is located around latitude 0^{0} 45'S and longitude 34^{0} 50'E, with a total land surface of 220 000 ha at altitudes between 1500 and 2200 m, and approximately 1 500 000 inhabitants in 1990 (Jaetzold and Schmidt, 1982). The district has a high agricultural potential, but at the present population density may well be on the verge of overexploitation.

Primary data were available on climate, landforms, soils and land use, use of mineral fertilizers and farmyard manure, crop yields and residues and their nutrient content (Jaetzold and Schmidt, 1982; Wielemaker and Boxem, 1982; Andriesse and Van der Pouw, 1985). Research data on erosion in Kenya were also at hand (Wenner, 1981; Avnimelech and McHenry, 1984; Ulsaker and Onstad, 1984; Gachene, 1987; Kilewe et al., 1989; Tong'i and Mochoge, 1991). Ten percent of the area was assumed to be under urban centres, villages, farm houses and roads.

Table 4.1 Distribution of land use types in the Kisii District

TZ	LUT		Distribution (%)													
		Area	Fallow	Grazing		Semi/perennial crops					Season	Annual cropping systems				
		(ha)	Fa-1	Ge	Pa	Te	Py	Co	Ba	Su		Ma	Be	Ma+Be	Tu	Fa-2
1	1	23100	5		17	33	8				1	11		16		
											2		10			17
	2	10700	5		17	21	20				1	11		16		
											2		10			17
	3	67200	5		17	10	24				1	12		22		
											2		10			24
2	4	56500	5		17	14	3	14		3	1	4	2	28		
											2	1	6	10		17
	5	48000	5		17			24	7		1	4	2	28	3	
											2	1	6	10		20
	6	13100	5	25	9			6			1	6	3	32	4	
											2	1	7	10		27
	7	2200	5	25	9					10	1	4	2	29	6	
										2	1	6	9		25	

TZ = temperature zone; 1 = 16.2-18°C, 2 = 18.0-20.5°C; LUT = land use type (see Fig. 4.1)
Season 1 = February-July, season 2 = August-December
Fa-1 = fallow (year-round), Fa-2 = fallow (seasonal), Ge = extensive grazing, Pa = continuous pasture, Te = tea, Py = pyrethrum, Co = coffee, Ba = banana, Su = sugarcane, Ma = maize, Be = beans, Tu = sweet potatoes

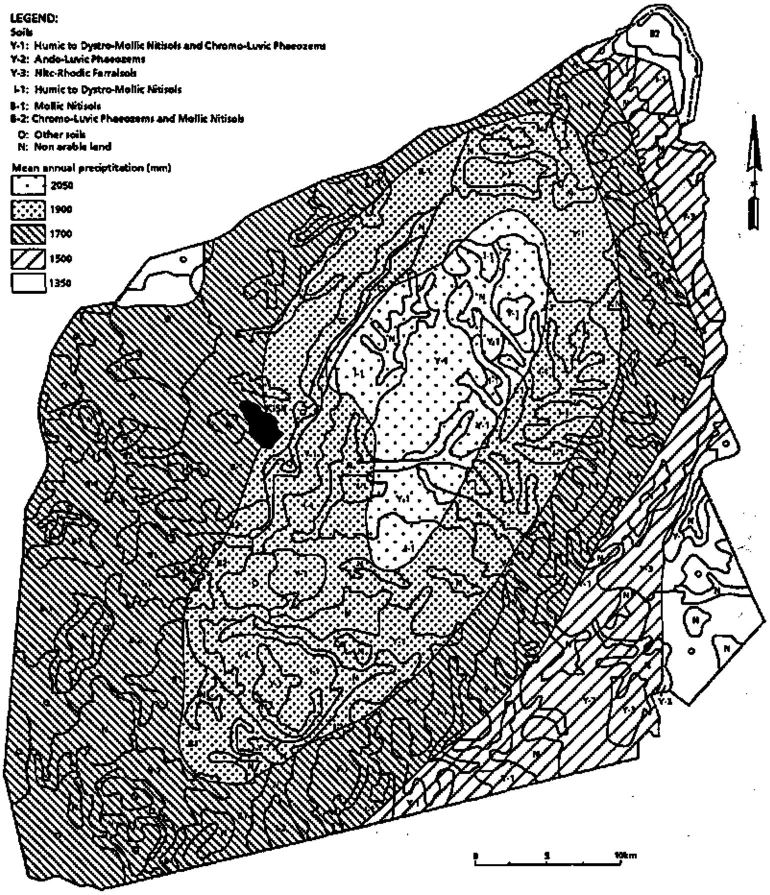


Fig. 4.2 Land/water classes in the Kisii District

For the purpose of this study, the agricultural land in the district was partitioned in two temperature zones, at annual mean temperatures of 16.2-18.0 °C (TZ 1) and 18.0-20.5 °C (TZ 2), respectively (Table 4.1). In these zones, seven land use types (LUT) have been distinguished, as indicated in Figure 4.1.

Table 4.2 Properties of land use types necessary to calculate inputs (IN) and outputs (OUT); explanation of abbreviations in Table 4.1)

LUT component	TZ	*IN 1*			*IN 2*	*OUT 1*				*OUT 2*				*OUT 5*
		Nutrients in mineral fertilizer (kg ha^{-1} yr^{-1})			Manure dry wgt. (kg ha^{-1} yr^{1})	Harvested product (kg ha^{-1} yr^{-1})	Nutrients in harvested product (kg t^{-1} harv.prod.)			Nutrients in crop residues (kg t^{-1} harv.prod.)			Residue removal (%)	Land cover factor
		N	P	K			N	P	K	N	P	K		
Fa-1	1	0	0	0	0	0	not relevant			not relevant			0	0.05
	2	0	0	0	0	0								
Ge	1	0	0	0	*	2000 leaves	10.0	1.5	10.0	0.0	0.0	0.0	0	0.05
	2	0	0	0	*	2000								
Pa	1	0	0	0	*	10000 grasses	15.0	2.3	15.0	0.0	0.0	0.0	0	0.01
	2	0	0	0	*	10000								
Te	1	43	8	5	0	5000 green	13.9	1.0	7.0	0.1	0.0	0.0	0	0.05
	2	26	1	4	0	2500 leaves								
Py	1	0	0	0	0	600 dried	40.0	5.0	40.0	13.3	2.2	13.3	10	0.4
	2	0	1	0	0	300 flowers								
Co	1	not cultivated					5.9	0.4	5.6	0.8	0.6	3.1	20	0.2
	2	8	0	0	820	3000 cherries								
Ba	1	not cultivated					1.2	0.2	1.8	1.5	0.2	4.8	25	0.2
	2	0	0	0	310	5000								
Su	1	not cultivated					6.1	0.9	14.7	3.1	1.2	4.2	100**	0.2
	2	0	0	0	0	3500 sugar								
Ma-1	1	3	16	0	10	3000 seed	9.3	3.4	3.6	4.3	1.4	12.3	75	0.5
	2	0	7	0	80	3000								
Be-1	1	6	0	1	0	1200 beans	16.5	2.7	8.1	8.5	0.8	9.5	75	0.4
	2	0	3	0	60	1200								

LUT component	TZ	*IN 1* Nutrients in mineral fertilizer (kg ha^{-1} yr^{-1})			*IN 2* Manure dry wgt. (kg ha^{-1} yr^{1})	*OUT 1* Harvested product (kg ha^{-1} yr^{-1})	Nutrients in harvested product (kg t^{-1} harv.prod.)			*OUT 2* Nutrients in crop residues (kg t^{-1} harv.prod.)			Residue removal (%)	*OUT 5* Land cover factor
		N	P	K			N	P	K	N	P	K		
Ma-1[***]	1	0	11	0	10	2500	9.3	3.4	3.6	4.3	1.4	12.3	75	0.3
	2	4	4	0	190	2500								
Be-1[***]	1	0	14	0	10	500	16.5	2.7	8.1	8.5	0.8	9.5	75	0.3
	2	0	3	0	80	500								
Tu-1	1	0	1	0	0	5000	4.6	0.3	2.9	1.9	0.5	3.1	50	0.3
	2	0	1	0	0	5000								
Ma-2	1	not cultivated					9.3	3.4	3.6	4.3	1.4	12.3	75	0.5
	2	0	10	0	0	2500								
Be-2	1	3	1	1	0	1500	16.5	2.7	8.1	8.5	0.8	9.5	75	0.4
	2	0	0	0	0	1500								
Ma-2[***]	1	not cultivated					9.3	3.4	3.6	4.3	1.4	12.3	75	0.3
	2	5	7	0	40	2000								
Be-2[***]	1	not cultivated					16.5	2.7	8.1	8.5	0.8	9.5	75	0.3
	2	0	3	0	0	750								
Fa-2	1	0	0	0	0	0	not relevant			not relevant			0	0.3
	2	0	0	0	0	0								

* 45% of nutrients in Ge and 72% of nutrients in Pa (*OUT 1* + 2) will be returned to the field as manure (*IN* 2)

** 100% N removal (burning), but no P and K removal

*** Maize (Ma) and beans (Be) as part of the maize/beans intercropping system

They include extensive grazing in bushland, intensive grazing on improved pastures, tea, pyrethrum, coffee, banana, sugarcane, maize and beans, either as sole crops or intercropped, tuber crops, i.e. mainly sweet potatoes, and fallow. The composition of the various land use types in each temperature zone is listed in Table 4.1, whereas relevant characteristics for the calculation of the nutrient balance are given in Table 4.2. A high yield and capital input level was assumed for tea and pyrethrum when grown in TZ 1, but a low level of both was assumed for TZ 2. A medium yield and capital input level was assumed for all other crops, apart from beans grown in intercropping systems, for which low levels were assumed (Wielemaker and Boxem, 1982).

Five rainfall zones have been distinguished, at mean annual precipitation values of 2050, 1900, 1700, 1500 and 1350 mm, and 20 soil units, mainly developed on volcanic rocks of acid (Y), intermediate (I) and basic (B) origin, often enriched with fresh pyroclastics (Figure 4.2). Excluded were isolated hills and scarps with a rootable topsoil too shallow for agricultural use, and swamps and bottomlands, prone to periodic flooding, salinity or sodicity. The input factor 'sedimentation' is thus not considered in this study. Table 4.3 shows the relevant properties of the six soil units that comprise three-quarters of the agricultural land of the district. Fifty different combinations of soil unit and annual rainfall, designated 'land/water class' (LWC), have been identified. Combining prevailing land use types (LUT) with the LWC, results in a total of 107 relevant land use systems (LUS).

Table 4.3 Soil properties of the major soil units necessary to calculate inputs and outputs

Soil unit	N_{tot}[1] (g kg^{-1})	P_{tot}[2] (g kg^{-1})	K_{exch}[3] (mmol kg^{-1})	Clay content (%)	Slope gradient (%)	Soil erodibility, K (-)
Y-1	4.0	1.50	18	43	12	0.07
Y-2	2.4	1.35	16	31	12	0.08
Y-3	1.6	0.50	9	47	10	0.08
I-1	3.5	0.95	19	62	10	0.06
B-1	3.0	0.95	18	66	10	0.07
B-2	3.7	0.85	13	40	10	0.07

Y (acid), I (intermediate), and B (basic) parent material

[1] semi micro-Kjeldahl; [2] digestion with Fleischmann's acid; [3] double acid (HCl-H_2SO_4)

CALCULATING INPUTS

Mineral fertilizers (IN 1)

Kenya is one of the major users of mineral fertilizers on the African continent. During the past decade, fertilizer use increased such that available data for 1980 for the Kisii District had to be multiplied by 2.5 for N, by 2.0 for P and by 3.0 for K to obtain approximations for 1990 (Jaetzold and Schmidt, 1982; FAO, 1988). The NPK input for each LUT is given in Table 4.2. Tea received most of the N fertilizers, whereas P was mainly applied to maize (and beans).

Animal manure (IN 2)

Most animal manure was applied to coffee and banana, and was mainly supplied from paddocks and stables. In LUTs that include extensive grazing or improved pasture, however, it was returned directly to the soil by grazing livestock. For that situation, 45 (Ge) and 72% (Pa) of the removed nutrients will be returned in manure if assuming that the animals spend 50 (Ge) and 80% (Pa) of the day in the field, and 10% of the nutrients is retained in the animal body. Part of the nutrients is excreted in urine, and when in contact with warm soil, nitrogen may be lost rapidly by volatilization. This has not been taken into consideration for reasons of model simplicity. Table 4.2 shows the use of manure in the different LUT components. The nutrient contents in the manure were set at 1.3 (nitrogen), 0.5 (phosphorus) and 1.6 (potassium) as percentages of dry weight (Jones, 1971; Cooke, 1982; Van der Noll and Janssen, 1983). Owing to increased arable cropping in a district with intensive agriculture, the scope for expansion of grazing grounds was very limited. Therefore, it was assumed that 1980 data on the production and application of manure were also valid for 1990.

Wet and dry deposition (IN 3)

Local data on wet and dry deposition were not available; hence, regression equations derived from the study on sub-Saharan Africa were used linking nutrient input (kg ha^{-1} yr^{-1}) to the square root of average rainfall (P, in mm yr^{-1}) (Stoorvogel and Smaling, 1990). The regression coefficients were 0.14, 0.023 and 0.092 for N, P and K, respectively.

Biological N fixation (IN 4)

French beans (*Phaseolus vulgaris*), the only leguminous species in the LUTs contribute to the N balance by symbiotic fixation. Because of low P availability in most soils of the Kisii District, it was assumed that 50% of the N requirement is derived from biological fixation, although values up to 75% are found in literature (Wetselaar and Ganry, 1982; Tisdale et al., 1985; Munyinda et al., 1988). In addition, a small rainfall-dependent contribution A (kg ha^{-1} yr^{-1}) from non-symbiotic N-fixers was accounted for in each LUT, as derived from the continental study:

$$A = 2 + (P - 1350) * 0.005 \qquad (1)$$

CALCULATING OUTPUTS

Export in harvested product (OUT 1) and crop residues (OUT 2)

Removing harvested product from the land entails loss of NPK, the quantity being determined by the yield and nutrient content of the product (Table 4.2). Differences in nutrient use efficiency (kg grain per kg nutrient taken up) related to soil type, crop cultivar and husbandry level, occur but insufficient information was available to take that into account in the present study. For LUTs that include grazing (Ge, Pa), part of the 'harvested' product is returned to the system directly in animal manure.

Export in crop residues was calculated in a similar way, taking into account the fraction of residues removed from the arable field (Table 4.2). For sugarcane (Su), all the N in crop residues was assumed to be lost because of burning.

Leaching (OUT 3)

There are no studies on leaching in or around the Kisii District. Therefore, we attempted to estimate leaching by means of transfer functions, using generally accepted determinants such as rainfall, texture, soil N and K content, and fertilizer input. Although comprehensive simulation models exist on solute leaching in soils, their data demands are too high for this study. Moreover, most have not been sufficiently validated for reliable prediction of leaching under field conditions

(Addiscott and Wagenet, 1985; Grimme and Juo, 1985; De Willigen, 1991). A simple, non-mechanistic model as developed by Burns would have been promising for the present exercise. He calculated leaching of surface-applied nitrogen (LN_{fert}) as a function of the quantity of water draining through the soil and the volumetric water content at field capacity. Data are required on rainfall and evaporation, soil porosity, initial water content, and water content at field capacity. Even these data have not been consistently collected in the Kisii District. Moreover, LN_{fert} and leaching of soil-derived nitrogen (LN_{soil}) tend to have different values in soils with continuous macropores. Lack of equilibrium between soil solution and drainage water does not allow calculation of leaching of newly mineralized soil-N inside aggregates from the fraction of water percolating (Wild, 1972). Literature data on LN_{fert} refer to a Hapludoll (18% clay) with 18 and 30% N leaching at application rates of 90 and 180 kg N ha^{-1} yr^{-1} respectively (Walters and Malzer, 1990), a Paleudult (16% clay) with 28% (split application) to 53% N leaching (single application) ((Arora et al., 1982), and a Nigerian acid sand with 1900 mm rainfall per year, where LN_{fert} was 34% at an application rate of 40 kg N ha^{-1} yr^{-1} (Omoti et al., 1983). These data formed the basis for Table 4.4, which gives estimates of leaching as a function of rainfall and soil texture.

Table 4.4 Nitrogen and potassium leaching as percentage of soil and fertilizer N and K for different average annual rainfall (1350, 1500, 1700, 1900 and 2050 mm yr^{-1}) and clay content

Clay content (%)	Leaching (%)									
	1350		1500		1700		1900		2050	
	N	K	N	K	N	K	N	K	N	K
<35	25.0	0.80	29.0	0.85	32.5	0.90	36.0	0.95	40.0	1.00
35-55	20.0	0.65	22.5	0.70	25.0	0.75	27.5	0.80	30.0	0.85
>55	15.0	0.50	16.5	0.55	17.5	0.60	18.5	0.65	20.0	0.70

In this study, total mineral soil N (N_{min}; kg ha^{-1}) was calculated from total soil N, assuming a fixed annual nitrogen mineralization rate M, set at 2.5% for TZ 1 and 3.0% for TZ 2. Total N content in the 0-20 cm soil layer is thus:

$$N_{min} = 20 * N_{tot} * M \qquad (2)$$

LN_{soil} was then calculated from Table 4.4 and ranged between 15% and 40% of N_{min}, depending on clay content (%) and average rainfall (mm yr^{-1}). In soil unit B-1, for example, N_{min} is 20 * 3.0 * 3 = 180 kg ha^{-1} yr^{-1}. At a clay content of 66% and under 1500 mm of rainfall, LN_{soil} is 16.5% * 180 = 30 kg ha^{-1} yr^{-1}. For lack of alternatives and to be in line with literature data, LN_{fert} was also derived from Table 4.4, and ranged between 15 and 40% of total fertilizer input (*IN 1* + *IN 2*).

Leaching of K on an acid sandy soil in southern Nigeria amounted to 16 kg ha^{-1} yr^{-1} of soil-derived potassium (LK_{soil}) and 10 kg ha^{-1} yr^{-1} surface-applied potassium (LK_{fert}) at an application rate of 60 kg K ha^{-1} yr^{-1} (Omoti et al., 1983). In fine-textured soils, however, K leaching generally does not exceed 2 kg ha^{-1} yr^{-1} (Tisdale et al., 1985). In soils with a high cation exchange capacity, as those in Kisii, a high percentage of soil and fertilizer K is adsorbed. High organic carbon contents, however, tend to enhance K leaching as the adsorptive force of organic matter for monovalent cations is low (Uribe and Cox, 1988). In our study, K leaching was expressed as a function of rainfall, clay content and exchangeable K (Tables 4.3 and 4.4). In soil unit B-1, K_{exch} is 1404 kg ha^{-1} yr^{-1}, and LK_{soil} is 0.55% of 1404 = 8 kg ha. LK_{fert} was also derived from Table 4.4, i.e. 0.5-1.0% of *IN 1* + *IN 2*.

Leaching of phosphorus was assumed to be negligible as most soils contain fresh volcanic constituents and, as a consequence, tend to strongly retain phosphorus.

Denitrification (OUT 4)

Extensive literature is available on denitrification in temperate regions of the world (Von Rheinbaben, 1990; Grant, 1991), but there have been few systematic studies on tropical soils (Grimme and Juo, 1985). Denitrification is known to occur under upland conditions when oxygen diffusion is impaired by water layers around structural elements and plant roots. However, N losses observed under waterlogged conditions are generally much higher than at field capacity or lower moisture levels (Ekpete and Cornfield, 1964; Pilot and Patrick, 1972; Dubey and Fox, 1974). Studies on Puerto Rican soils showed that denitrification losses were correlated with moisture level, organic carbon content and texture (Dubey and Fox, 1974). After two weeks of incubation, following an N application of 400 mg kg^{-1} soil, an Oxisol with 6 g kg^{-1} organic carbon and 22% clay and an Ultisol with 18 g kg^{-1} organic carbon and 30% clay showed no denitrification at field capacity, and 8% and 22% respectively at waterlogging. An Oxisol with 23 g kg^{-1} organic carbon and 70% clay, however, showed 7% denitrification at field capacity and 31% at waterlogging.

In this study, these results have been used to quantify denitrification as a function of clay content (%), average rainfall (P, mm yr^{-1}), and mineral soil N and fertilizer N. Denitrified soil N (DN_{soil}; percentage of N_{min}) and fertilizer N (DN_{fert}; percentage of *IN 1* + *IN 2*) are then calculated as follows:

$$DN = -9.4 + 0.13 * \text{clay content} + 0.01 * P \tag{3}$$

For soil unit B1, at 66% clay and 1500 mm precipitation, the percentage denitrification is thus 14.2%.

Erosion (OUT 5)

Erosion was calculated along the lines of the Universal Soil Loss Equation (USLE), which estimates annual soil loss per ha as a function rainfall erosivity (R), soil erodibility (K), slope gradient (S) and slope length (L), land cover (C) and land management (P) ((Wischmeier and Smith, 1978).

The R factor is not easily derived from commonly collected meteorological data. On the basis of literature data, however, this factor was set at 0.25 for the entire district (Wenner, 1981; Ulsaker and Onstad, 1984).

The K factor is listed in Table 4.3 for the major soils of the district, as derived from soil texture, organic matter content and permeability (Wischmeier et al., 1971; Mitchell and Brubenzer, 1980), bearing in mind that many of the deep volcanic soils in the district show very stable micro-aggregation (Ahn, 1977). In previous studies in Kenya, it has been shown that on a deep volcanic Nitisol, runoff and erosion was 5-8 times less than on a Luvisol with an unstable surface structure, leading to K-values of 0.06 and 0.2 respectively ((Barber et al., 1979).

The factors S and L were derived from as follows:

$$S = (0.43 + 0.30 * s + 0.043 * s^2) / 6.613 \tag{4a}$$

$$L = (d/22.13)^{0.5} \tag{4b}$$

in which s is the slope gradient (%) and d the slope length (m). The slope gradient is given in Table 4.3 for the major soil units. Slopes may be as long as 500 m, but since fences, hedges and homesteads act as barriers, the slope length was set at 100 m for the entire district. Equation (4b) then yields the value 2.1.

The degree of cover strongly varies temporally and spatially and was difficult to quantify in general terms for the district. Where on deep, red soils with a 10% slope in Southwestern Kenya very high erosion losses (140 tons ha^{-1}) were observed under young tea, mature tea on the same soils offered almost complete protection (Othieno, 1975). For the present study, an average C factor was estimated for each LUT component (Table 4.2).

Finally, the land management factor P was derived from Wenner (1981) as follows:

$$P = 0.2 + 0.03 * s \tag{5}$$

The slope gradient s is ranging from 10 to 12% for the major soil units (Table 4.3).

The resulting model was validated against soil loss measurements from experiments in and around the district (Gachene, 1987; Kilewe et al., 1989; Tong'i and Mochoge, 1991). For each soil unit, N_{tot} and P_{tot} (Table 4.3) and K_{tot} (Table 4.5) were used to convert soil loss into nutrient loss. K_{tot} was calculated from K_{exch} and clay content, the range of 0.2-0.6 g K kg^{-1} soil being in accordance with the scarce literature (Pagel et al., 1982). The nutrient losses arrived at were finally multiplied by an 'enrichment' factor of 1.5 (Avnimelech and McHenry, 1984; Stocking, 1984). Erosion implies loss of surface soil. Meanwhile, at the root base, soil formation is taking place. To take that into account, it was assumed in calculating *OUT 5* that the net loss of P and K was only 0.75 times the calculated loss at the surface.

Table 4.5 Total K (K_{tot}) in the 0-20 cm layer as a function of clay content (<35, 35-55, >55%) and exchangeable potassium (K_{exch})

K_{exch} (mmol kg^{-1})	K_{tot} (g kg^{-1} soil)		
	<35	35-55	>55
<10	2	3	4
10-20	3	4	5
>20	4	5	6

FALLOW AND MULTIPLE CROPPING

In addition to monocropping (cash crops, pasture), the bimodal rainfall pattern also entailed periods of zero use (fallow) and double use (multiple cropping).

For year-round fallow (Fa-1), estimated to occupy 5% of the total arable land (Table 4.1), equilibrium conditions were assumed (IN - OUT = 0). The balance for the shorter seasonal fallow (Fa-2) was calculated similar to the other LUT components, as only a sparse vegetation cover is developed. Multiple cropping plays a role in LUTs with annual crops, with different percentages of total land use for the first and the second season (Table 4.1). In TZ 2, two crops of maize can be grown annually, but in TZ 1 only the more rapidly maturing beans can be cultivated during the second season.

THE NUTRIENT BALANCE QUANTIFIED

For the district as a whole, the sum of the four input factors minus the sum of the five output factors rendered the values -112 kg N, -3 kg P, and -70 kg K ha^{-1} yr^{-1}, implying net depletion of the soil nutrient pools, i.e. weatherable minerals and organic matter.

Average values for the various inputs and outputs are shown in Figure 4.3. For N, removal of harvested product (*OUT 1*) was the strongest negative contributor, followed by leaching (*OUT 3*) and erosion (*OUT 5*). For P and K, removal of harvested product and erosion were again the dominant factors in the nutrient balance. For P, nutrient losses were more or less offset by mineral fertilizers and manure. For K, however, the use of mineral fertilizers was negligible and the K export in removed crop residues was relatively high.

Table 4.6 shows the nutrient balance for each LUT component. Losses were particularly high under pyrethrum and, to a lesser extent, sugarcane and maize. The lowest depletion rates were found under tea. In Table 4.2, we indeed see that pyrethrum hardly receives any mineral or organic fertilizer, has a high nutrient content per unit harvested product and poorly protects the surface soil against erosion (C-factor 0.4). Tea, however, receives substantial amounts of mineral fertilizer and adequately protects the topsoil (C-factor 0.05). Under the described conditions, soil P status was even improved under tea and maize. However, the presence of fresh volcanic constituents in most soils rendered P largely unavailable to crops and responses to point-placed P fertilizers were high.

Table 4.7 shows the nutrient balance for the twelve land/water classes (LWCs) that exceed 5000 ha (Figure 4.2). Losses were highest in units Y-1 and lowest in Y-3. In Table 4.3, we indeed see that Y-1 has the highest N and P contents and a slope gradient of 12%, whereas Y-3 represents the poorer soils with slopes of 10%. The higher rainfall zones were, on average, more prone to nutrient losses than the drier zones.

The complete picture is only obtained by integrating the values from Tables 4.6 and 4.7, providing the nutrient balance for entire land use systems. Some indications for two LUS's are given in Table 4.8, showing a higher proportion of land under pyrethrum in Y-2, and under tea in I-1. This explains higher nutrient depletion in Y-2 (Table 4.7). As Y-2-1700 has more or less the same land use as Y-2-1500, rainfall is the major factor explaining the different depletion rates between these two LWCs. This difference does not show up between I-1-2050 and I-1-1900, as the latter LWC has less tea and more maize plus beans, which are stronger nutrient miners (Table 4.6).

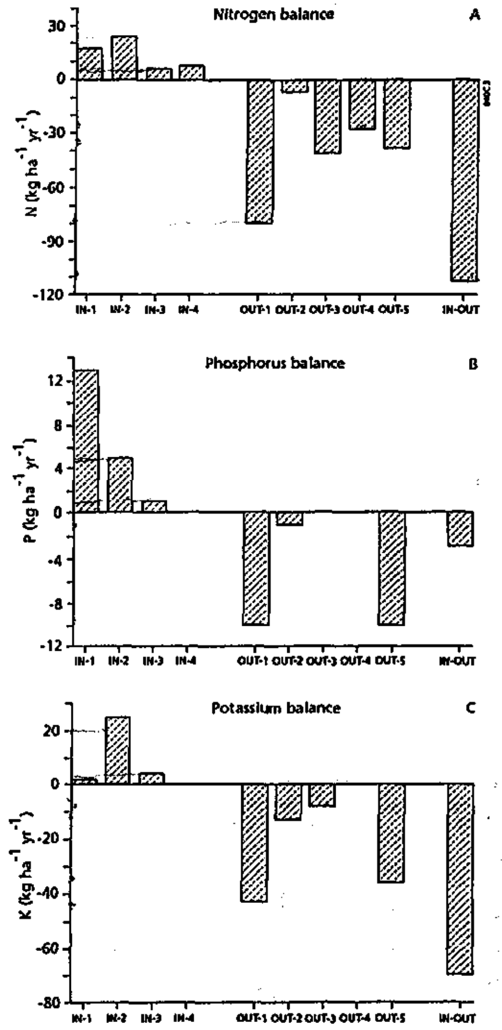


Fig. 4.3 Average inputs and outputs of N, P and K in the land use systems of the Kisii District

Table 4.6 Nutrient balance of the different land use type components; explanation of abbreviations in Table 4.1

LUT component	Area (ha)	Σ IN-Σ OUT (kg ha^{-1} yr^{-1})		
		N	P	K
Fa-1	8800	0	0	0
Ge	1800	-43	-1	-9
Pa	29200	-98	-6	-49
Te	19600	-67	6	-30
Py	17800	-147	-24	-96
Co	16500	-82	0	-34
Ba	2900	-87	-5	-48
Su	1500	-129	-10	-91
Ma-1	13400	-105	2	-83
Be-1	1900	-73	-6	-55
Ma + Be-1	42800	-83	11	-63
Tu-1	1600	-75	-6	-51
Ma-2	900	-102	-1	-80
Be-2	13800	-75	-13	-58
Ma + Be-2	9300	-78	4	-65
Fa-2	35600	-53	-7	-29
Mean	157700	-112	-3	-70

In the continental study (Stoorvogel et al., 1992), the nutrient balance for the 'good rainfall' LWC in Kenya for 1990 was approximately -75 kg N ha^{-1}, -5 kg P ha^{-1} and -56 kg K ha^{-1}. All the soils would have been in fertility class 2 (moderate) with 1 g N kg^{-1} soil and 0.2 g P kg^{-1} soil, whereas they are in fact richer (Table 4.3). Pyrethrum, the big nutrient miner in this study, was not included at the continental level as it is of minor importance at that scale.

Table 4.7 Nutrient balance of land/water classes (LWC) exceeding 5000 ha

LWC soil unit	rainfall (mm yr^{-1})	Area (ha)	Σ *IN*-Σ *OUT* (kg ha^{-1} yr^{-1}) N	P	K
Y-1	2050	7500	-185	-11	-100
	1900	11300	-175	-13	-90
	1700	5200	-170	-10	-98
Y-2	1700	6800	-121	-11	-88
	1500	8200	-111	-8	-84
Y-3	1500	5500	-58	8	-53
I-1	2050	8100	-103	6	-62
	1900	16900	-103	3	-61
	1700	8200	-97	4	-61
B-1	1900	9800	-109	-5	-75
	1700	21200	-101	-4	-71
B-2	1700	8600	-130	-3	-61

Y (acid), I (intermediate), and B (basic) parent material

Table 4.8 Relative occupation of land/water classes (LWC) by different land uses

LWC soil unit	rainfall (mm yr^{-1})	Area (ha) Pa	Relative occupation (%) Te	Py	Co	Su	Ma	Ma+Be	
Y-2	1700	6800	19	16	25	0	0	13	22
	1500	8200	19	14	26	0	0	13	23
I-1	2050	8100	19	28	11	3	1	11	24
	1900	16900	19	18	13	7	1	10	31

SENSITIVITY ANALYSIS

The procedure followed in this study has been to develop transfer functions to calculate the factors leaching, denitrification and erosion, including determinants generally recognized in literature. Parameter values and class limits were chosen such that agreement between calculated results and available data was as close as possible.

Table 4.9 Sensitivity analysis of some input-output determinants

Determinant	Variation	Σ *IN*-Σ *OUT* (kg ha^{-1} yr^{-1})		
		N	P	K
Mineralization rate	+0.5%	-10.5	0	0
N_{tot}	+0.5 g kg^{-1}	-15.5	0	0
P_{tot}	+0.1 g kg^{-1}	0	-1	0
K-factor	+0.01	- 5.5	-1.5	- 5.5
Slope gradient *s*	+2%	-15.5	-4	-15
Slope length *d*	+50 m	- 7.5	-2	- 8
C-factor	+0.05	- 6.5	-1.5	- 5.5
Enrichment factor	+0.25	- 6.5	-1.5	- 6

The nutrient balance described here, although further detailed than in the continental study, still relies on a number of assumptions and estimates. A sensitivity analysis is therefore indispensable to evaluate the impact of changes in values of the determinants of the nutrient balance factors. The results appeared not very sensitive to amount of mineral fertilizer and manure, yield level, nutrient content, and percentage residue removal. When increasing their values by 10%, changes in the nutrient balance did not exceed 4 kg N ha^{-1}, 1 kg P ha^{-1} and 4 kg K ha^{-1}. Results were neither very sensitive to exchangeable K, clay content, and the contribution of weathering to P and K supply.

The determinants having greater impact are listed in Table 4.9. Changing mineralization rate and total soil N content had a great impact on the N balance. An increase in soil N content of 0.5 g kg^{-1} for example caused a decrease in nitrogen balance (Σ *IN* - Σ *OUT*) of 15.5 kg ha^{-1}. Varying slope gradient *s* and slope length *d*, K-factor, C-factor and enrichment factor, however, affected the balance of all nutrients. These factors are all used in calculating erosion. Apparently, there is not only a need to intensify erosion control, but also to increase quantitative research on erosion.

RECOMMENDATIONS FOR SOIL FERTILITY CONSERVATION

In the continental study (Stoorvogel et al., in press), ways to conserve soil fertility were discussed, which may now be considered in relation to the actual situation in the Kisii District.

Increasing *IN 1* can be combined with a decrease in *OUT 3,4* and *5* by timely and possibly split application of modest amounts of the proper type of fertilizer, complying with recommendations that are specific for both LUT and LWC (Smaling and Van de Weg, 1990). In Kisii, mineral fertilizer is supplied by the Grain Growers Cooperative Union and the Tea Development Authority. The popular di-ammonium-phosphate is suitable for most P-deficient soils, but in the long run causes soil acidification.

Increasing *IN 2*, through better use of manure and household waste, provides nutrients and additional benefits such as increased water storage and nutrient retention. The long-term beneficial effect of organic manure on soil fertility has been demonstrated on a Nigerian sandy loam (Jones, 1971), where, after 18 years of continuous cultivation, the highest manure treatment (5 t ha^{-1}) gave a stable organic carbon level in the soil of 3.4 g kg^{-1}. In plots receiving no manure, however, it had decreased to 1.5 g kg^{-1}. In Kisii, there is limited scope for increasing input from animal manure as livestock mainly roams along roads and tracks, in bushland (Ge) and on pastures (Pa). Increasing herds is limited due to land shortage. Organic inputs such as urban or industrial refuse may be valuable, but the possibilities were little explored to date.

Introducing more nitrogen-fixing species in cropping systems may increase *IN 4*. Research on a Mollisol in the US showed that continuous maize yielded less grain (5.5 t ha^{-1}) than in rotation with a legume (7.6 t ha^{-1}). Also, maize following a legume in rotation produced maximum grain yield at 90 kg N ha^{-1}, while continuous maize required at least 180 kg N ha^{-1} for maximum yield (Peterson and Varvel, 1989). Research in Kenya has shown that maize-beans rotations outyield intercropping systems (Nadar and Faught, 1984; Kilewe et al., 1989). Although green manures, grain legumes and woody species may transfer up to 100 kg N ha^{-1} to a subsequent crop (Dommergues and Ganry, 1986), Phaseolus bean is the only N-fixing crop in the Kisii District. Owing to the low available P status of most soils, biological fixation is not very effective unless phosphatic fertilizers are applied. In TZ 1, planting beans during the short rainy season (Be-2) has the additional advantage that maize can be early-planted during the subsequent long rainy season (Ma-1 and Ma + Be-1).

OUT 2 can be reduced by grazing crop residues in the arable field, leaving residues as a mulch or ploughed into the soil. A Nigerian sandy loam, receiving a mulch of previous season groundnut shells each year had, after nine cropping seasons, an organic carbon content of 6.7 g kg^{-1}. Applying 52 kg N and 30 kg P ha^{-1} yr^{-1} as mineral fertilizers during the same period resulted in an organic carbon content of 5.3 g kg^{-1}, whereas that in the control plots was 4.5 g kg^{-1} (Jones, 1971). Treatments in which maize residues (4 t ha^{-1}) and weeds were burned during four seasons on a Plinthudult in Cameroon outyielded those in which crop residues were used as a mulch (2.7 vs. 2.3 t ha^{-1}) (Nguu, 1987). Such differences are generally ascribed to a short-lived pH increase and enhanced availability of mineral nutrients. In the longer run, however, burning practices lead to increased nutrient depletion in systems of continuous cultivation. Incorporating residues with a high C/N ratio, such as maize stover, causes temporary depressions in net N mineralization. The increased micropopulation uses soil and fertilizer N for its own sustainance until most of the residues have been decomposed (Smith and Sharpley, 1990). When leaving residues as a mulch in a monoculture, they may serve as host material for pests and diseases.

A considerable decrease in *OUT 5* can be realized when the conditions that determine erosion are adequately manipulated. This includes practices such as zero-tillage, mulching, strip cropping, alley or multi-storey cropping and terracing. In Kisii, zero-grazing systems are expanding, in combination with feeding of contour-planted tall grasses to stabled livestock. Most grass species, once established, grow vigorously, offer adequate soil protection and reduce slope length.

Long-term fertilizer trials on a deep Nitisol on relatively flat land near Nairobi showed trends which support the above aspects of integrated nutrient management (Qureshi, 1987). Figure 4.4 shows that during ten consecutive cropping years, maize received mineral fertilizers, manure and crop residues. Only when receiving a combination of these inputs, the mean yield in years 5-8 was 12% higher than the mean yield over the years 1-4.

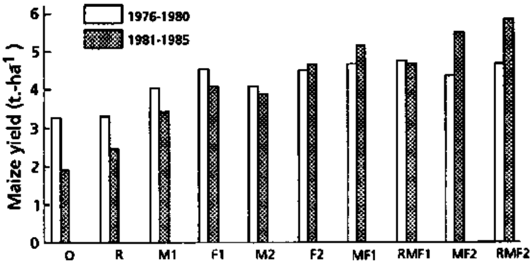


Fig. 4.4 Development of maize yields at different treatments on a Kenyan Nitisol (after Qureshi, 1987).
0 = control, R = crop residues of previous season, M = organic manure (1 = 5 t ha^{-1}; 2 = 10 t ha^{-1}), F = mineral fertilizer (1 = 60 kg N and 25 kg P ha^{-1}; 2 = 120 kg N and 50 kg P ha^{-1})

In view of the relatively high costs of imported fertilizers in Kenya, and the need to increase food production for a growing population, the importance of conserving the productive capacity of the soils cannot be overemphasized. The results of both the supra-national and the district study should be translated into packages to advice decision-makers at both levels in land use planning and extension. The methodology presented in this study can be applied and prove valuable in any area where researchers, policy makers and farmers are receptive to systems of integrated nutrient management.

ACKNOWLEDGEMENT

The Land and Water Division (AGL) of the UN Food and Agriculture Organization is acknowledged for initiating the search for quantitative data on nutrient balances in sub-Saharan Africa. The present study is a follow-up to this initiative. Soil scientist W.A. van Dooremolen provided assistance in quantifying factors of the nutrient balance.

References

Addiscott, T.M. and Wagenet, R.J., 1985. Concepts of solute leaching in soils: a review of modeling approaches. J. Soil Sci. 36: 411-424.

Ahn, P.M., 1977. Erosion hazard and farming systems in East Africa. In: Greenland, D.J. and Lal, R. (eds.). Soil conservation & management in the humid tropics. pp. 165-176. John Wiley & Sons.

Andriesse, W. and Van der Pouw, B.J.A., 1985. Reconnaissance Soil Map of the Lake Basin Development Authority, Western Kenya (scale 1:250,000). Wageningen and Nairobi: Netherlands Soil Survey Institute/Kenya Soil Survey.

Arora, Y. and Juo, A.S.R., 1982. Leaching of fertilizer ions in a kaolinitic Ultisol in the high rainfall tropics: leaching of nitrate in field plots under cropping and bare fallow. Soil Sci. Soc. Am. J. 46: 1212-1218.

Avnimelech, Y. and McHenry, J.R., 1984. Enrichment of transported sediments with organic carbon, nutrients and clay. Soil Sci. Soc. Am. J. 48: 259-266.

Barber, R.G., Moore, T.R. and Thomas, D.B., 1979. The erodibility of two soils from Kenya. J. Soil Sci. 30: 579-591.

Burns, I.G., 1975. An equation to predict the leaching of surface-applied nitrate. J. Agric. Sci. Camb. 85: 443-454.

Cooke, G.W., 1982. Fertilizing for maximum yield. London: English Language Book Society/Collins.

De Willigen, P., 1991. Nitrogen turnover in the soil-crop system; comparison of fourteen simulation models. Fert. Res. 27: 141-149.

Dommergues, Y.R. and Ganry, F., 1986. Biological nitrogen fixation and soil fertility maintenance. In Mokwunye, A.U. and Vlek, P.L.G. (eds.). Management of nitrogen and phosphorus fertilizers in sub-Saharan Africa. pp. 95-115. Dordrecht: Martinus Nijhoff.

Dubey, H.D. and Fox, R.H., 1974. Denitrification losses from humid tropical soils of Puerto Rico. Soil Sci. Soc. Am. Proc. 38: 917-920.

Ekpete, D.M. and Cornfield, A.H., 1964. Losses through denitrification from soil, of applied inorganic nitrogen even at low moisture contents. Nature 201: 322-323.

Food and Agriculture Organization/Unesco, 1974. Soil Map of the World, 1:5,000,000. Paris: Unesco.

Food and Agriculture Organization, 1988. Fertilizer yearbook 1987, Vol. 37. FAO, Rome.

Gachene, C.K.K., 1987. Nutrient losses in eroded soil material from some Kenyan soils. In: Soil and Water Conservation in Kenya. Proc Third National Workshop. pp. 34-37. University of Nairobi/Swedish International Development Agency.

Grant, R.F., 1991. A technique for estimating denitrification rates at different soil temperatures, water contents, and nitrate concentrations. Soil Sci. 152: 41-52.

Grimme, H. and Juo, A.S.R., 1985. Inorganic N losses through leaching and denitrification in soils of the humid tropics. In: Proc. Symp. Nitrogen Management in the Farming Systems in the Humid and Subhumid tropics. pp. 57-72. Ibadan: IITA.

Jaetzold, R. and Schmidt, H., 1982. Farm management handbook of Kenya, Volume II: Natural conditions and farm management information. Part A: West Kenya. pp. 83-126. Nairobi: Ministry of Agriculture.

Jones, M.J., 1971. The maintenance of soil organic matter under continuous cultivation at Samaru, Nigeria. J. Agric. Sci. Camb. 77: 473-482.

Kilewe, A.M., Kamau, F.N., Kariuki, F.N. and Kaiyare, J.M., 1989. The effect of crop cover and residue management on runoff and soil loss. In: Annual Report 1985. pp. 1-8. Nairobi: Kenya Agricultural Research Institute, Agric. Res. Dep.

Mitchell, J.K. and Brubenzer, G.D., 1980. Soil loss estimation. In: Kirkby, M.J. and Morgan, R.P.C. (eds.). Soil erosion. pp. 17-62. London: John Wiley & Sons.

Munyinda, K., Karamanos, R.E., Legg, J.O. and Sanogho, S., 1988. Nitrogen fixation by soybeans (Glycine max L.) in Zambia. Plant Soil 109: 57-63.

Nadar, H.M. and Faught, W.A., 1984. Maize yield response to different levels of nitrogen and phosphorus fertilizer application. In: Dryland Farming Research in Kenya, E. Afr. Agric. For. J. 44: 147-156.

Nguu, N.V., 1987. Effect of nitrogen, phosphorus and soil and crop residues management practices on maize (Zea mays L.) yield in ultisols of eastern Cameroon. Fert. Res. 14: 135-142.

Omoti, U., Ataga, D.O. and Isenmila, A.E., 1983. Leaching losses of nutrients in oil palm plantations determined by tension lysimeters. Plant Soil 73: 365-376.

Othieno, C.O., 1975. Surface runoff and soil erosion on fields of young tea. Trop. Agric. (Trinidad) 52: 299-308.

Pagel, H., Enzmann, J. and Mutscher, H., 1982. Pflanzennährstoffe in tropischen Böden. Berlin: VEB Deutscher Landwirtschaftsverlag.

Peterson, T.A. and Varvel, G.E., 1989, Crop yield as affected by rotation and nitrogen rate. III Corn. Agron. J. 81: 735-738.

Pichot, J., Al Zahawe, F. and Chabalier, P.F., 1977. Evolution d'un sol ferralitique de Cote d'Ivoire après la mise en culture. In: Soil organic matter studies. Proc Symp Braunschweig, 6-10 Sept 1976. pp. 83-96. IAEA/FAO.

Pilot, L. and Patrick, W.H., 1972. Nitrate reduction in soils: effect of soil moisture tension. Soil Sci. 114: 312-316.

Pieri, C., 1985. Bilans minéraux des systèmes de cultures pluviales en zones arides et semi-arides. Agron. Trop. 40: 1-20.

Pieri, C., 1989. Fertilité des terres de savanes. Bilan de trente ans de recherche et de développement agricole au sud du Sahara. Ministère de la Coopération et CIRAD-IRAT, Montpellier, 444 pp.

Qureshi, J.N., 1987. The cumulative effects of N-P fertilizers, manure and crop residues on maize grain yields, leaf nutrient contents and some soil chemical properties at Kabete. National Maize Agronomy Workshop, Nairobi: CIMMYT.

Smaling, E.M.A. and Van de Weg, R.F., 1990. Using soil and climate maps and associated data sets to select sites for fertilizer trials in Kenya. Agric. Ecos. Envir. 31: 263-274.

Smith, S.J. and Sharpley, A.N., 1990. Soil nitrogen mineralization in the presence of surface and incorporated crop residues. Agron. J. 82: 112-116.

Stocking, M., 1984. Erosion and soil productivity: a review. Consultants' Working Paper No.1. Rome: FAO.

Stoorvogel, J.J. and Smaling, E.M.A., 1990. Assessment of soil nutrient depletion in Sub-Saharan Africa, 1983-2000. Report 28. Wageningen: The Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO).

Stoorvogel, J.J., Smaling, E.M.A. and Janssen, B.H., in press. Calculating soil nutrient balances in Africa at different scales. I. Supra-national scale. Fert. Res.

Tisdale, S.L., Nelson, W.L. and Beaton, J.D., 1985. Soil Fertility and Fertilizers (4th ed.) New York: Macmillan Publishing Company.

Tong'i, E.R.N. and Mochoge, B.O., 1991. Soil and water loss through erosion from three Kenyan soils. Workshop on denudation processes and land use in tropical regions. Nairobi.

Ulsaker, L.G. and Onstad, C.A., 1984. Relating rainfall erosivity factors to soil loss in Kenya. Soil Sci. Soc. Am. J. 48: 891-896.

Uribe, E. and Cox, F.R., 1988. Soil properties affecting the availability of potassium in highly weathered soils. Soil Sci. Soc. Am. J. 52: 148-152.

Van der Noll, I.E. and Janssen, B.H., 1983. Cow dung slurry as an organic manure for fodder crops in Kilifi, Coast Province, Kenya. TPIP Prel. Report 5. Wageningen: Dep Soil Sci Plant Nut, Wageningen Agricultural University.

Van der Pol, F.. 1992. Soil mining. An unseen contributor to farm income in southern Mali. Bulletin 325. Amsterdam: Royal Tropical Institute (KIT).

Velly, J. and Longueval, C., 1977. Evolution d'un sol ferralitique sur gneiss de Madagascar sous l'influence d'apports annuels de paille et d'azote. In: Soil organic matter studies. Proc. Symp. Braunschweig, 6-10 Sept 1976. IAEA/FAO.

Von Rheinbaben, W., 1990. Nitrogen losses from agricultural soils through denitrification - a critical evaluation. Z. Pflanzenernähr Bodenk. 153: 157-166.

Wagenet, R.J., Bouma, J. and Grossman, R.B., 1991. Minimum data sets for use of soil survey information in soil interpretive models. In: Mausbach, M.J. and Wilding, L.P. (eds.). Spatial variability of soils and landforms. SSSA Special Publ. 28: 161-182.

Walters, D.T. and Malzer, G.L., 1990. Nitrogen management and nitrification inhibitor effects on nitrogen-15 urea: II. Nitrogen leaching and balance. Soil Sci. Soc. Am. J. 54: 122-130.

Wenner, C.G., 1981. Soil conservation in Kenya. Nairobi: Ministry of Agriculture, Soil Conserv Extension Unit.

Wetselaar, R. and Ganry, F., 1982. Nitrogen balance in tropical agrosystems. In: Dommergues, Y.R. and Diem, H.G. (eds.). Microbiology of tropical soils and plant productivity. pp. 1-36. Developments in Plant and Soil Sciences, Volume 5. Dordrecht: Martinus Nijhof.

Wielemaker, W.G. and Boxem, H.W., 1982. Soils of the Kisii area, Kenya. Agric Res Rep 922. Wageningen: Centre for Publication and Documentation (PUDOC-DLO).

Wild, A., 1972. Nitrate leaching under bare fallow at a site in northern Nigeria. J. Soil Sci. 23: 315-324.

Wischmeier, W.H. and Smith, D.D., 1978. Predicting rainfall erosion losses from cropland. A guide for selection of practices for soil and water conservation. Washington DC: Agricultural Handbook 282.

Wischmeier, W.H., Johnson, C.B. and Cross, B.V., 1971. A soil erodibility nomograph for farmland and construction sites. J. Soil Water Conserv. 26: 189-192.

Chapter 5

A decision-support model for monitoring nutrient balances under agricultural land use (NUTMON)

Submitted to Geoderma

5 A decision-support model for monitoring nutrient balances under agricultural land use (NUTMON)

E.M.A. Smaling[1] and L.O. Fresco[2]

[1] *DLO The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen (The Netherlands)*
[2] *Department of Tropical Crop Science, Agricultural University of Wageningen, P.O. Box 341, 6700 AH Wageningen (The Netherlands)*

ABSTRACT

A quantitative model of the balance between inputs and outputs of nitrogen, phosphorus and potassium in African land use systems (NUTBAL) was recently developed at two scales: supra-national (38 sub-Saharan African countries) and regional (Kisii District, Kenya). Calculating inputs (mineral fertilizer, organic manure, wet and dry deposition, biological nitrogen fixation, sedimentation) and outputs (removal of above-ground crop parts, leaching, denitrification, water erosion) led to the conclusion that there are considerable net fertility losses in each growing period.

In this paper, NUTBAL is elaborated into a decision-support model (NUTMON) to monitor the effects of changing land use, and suggest interventions that improve the nutrient balance. As input and output determinants cannot all be quantified equally well, the model recognizes primary data, estimates, and assumptions. The NUTMON determinants are mostly scale-neutral and can therefore be used to monitor nutrient balances at farm, regional, national and supra-national level. This is essential since the hierarchical levels interact. A number of recent interventions at the regional level (Kisii District, Kenya) are elaborated, including national fertilizer and produce price policies, fertilizer supply in small packages, zero-grazing, agroforestry, soil conservation measures, and increasing fertilizer use efficiency. It is shown that a major nutrient conservation effort in Kisii reduces

nutrient depletion by approximately 50%, but does not entirely redress the N and K balance. To achieve the latter without reducing crop production, 75% of the district would have to be converted to a rotation system of maize and green manure cover crops, whereas 25% can remain under tea.

NUTMON has the potential to become a dynamic tool for land use policies, geared towards a balanced nutrient status in African land use systems. It can assist decision makers in determining the effects of current and alternative land use scenarios, taking account of both the productivity as well as the long-term sustainability of agro-ecosystems.

INTRODUCTION

Between 1975 and 1988, Africa's population grew from 415 to 610 millions (FAO, 1989). This occurred in the absence of land use policies that address increased productivity simultaneously with sustainability of agro-ecosystems. Productivity is defined here as the output of valued product per unit of resource input, and sustainability as the capacity of a system to maintain output at a level approximately equal to or greater than its historical average (Conway, 1987; Lynam and Herdt, 1989).

As classical long-fallows have largely been replaced by systems of (semi)-permanent agriculture, maintenance of the soil nutrient balance has become a prominent requirement of agro-ecological sustainability. To follow on this theme, the UN Food and Agriculture Organization undertook to quantify the nitrogen (N), phosphorus (P) and potassium (K) balance in the root zone of 38 sub-Saharan African countries (Stoorvogel and Smaling, 1990; Stoorvogel et al., in press). Production figures of 35 crops were used to define land use systems (LUS), characterized by nutrient inputs by mineral fertilizers (*IN 1*), animal manure (*IN 2*), wet and dry deposition (*IN 3*), biological N fixation (*IN 4*) and sedimentation (*IN 5*), and nutrient outputs by harvested crop parts (*OUT 1*) and crop residues (*OUT 2*), leaching (*OUT 3*), denitrification (*OUT 4*), and water erosion (*OUT 5*). Mean values of the nutrient balance (Σ *IN* - Σ *OUT*) were -22 kg N, -2.6 kg P and -15 kg K per ha per yr for the period 1982-1984. Not included were fluxes of nutrients within the soil, i.e. mineralization and immobilization of N and P in organic matter, surface retention of P by kaolinitic clay minerals and oxides, precipitation of P in salts, and adsorption/desorption of K in mica-derived clay minerals.

As scale-inherent simplifications were inevitable in this continental study, a similar nutrient balance study (NUTBAL) was done for the well-inventoried Kisii District in Kenya (Smaling et al., in press). Table 5.1 shows that annual N and K depletion was severe, but the P balance was near equilibrium. Removal of nutrients in harvested product (*OUT 1*) was the strongest negative contributor to the balance, followed by water erosion (*OUT 5*) and, for N, leaching (*OUT 3*). In terms of land use, depletion was highest under pyrethrum (*Chrysanthemum cinerariaefolium*), with -147 kg N, -24 kg P, -96 kg K per ha per yr, and maize with -105 kg N, +2 kg P, -83 kg K per ha per cropping season. Both crops received little fertilizer and provide poor soil cover in the early growth stages. Depletion of N and K was lowest under tea (-67 kg N, +6 kg P, -30 kg K per ha per yr) and coffee (-82 kg N, 0 kg P, -34 kg K per ha per yr).

Table 5.1 Nitrogen, phosphorus and potassium inputs (IN) and outputs (OUT) in the Kisii District (in kg/ha,yr; after Smaling et al. (1992))

	IN 1	*IN 2*	*IN 3*	*IN 4*	*IN 5*	*OUT 1*	*OUT 2*	*OUT 3*	*OUT 4*	*OUT 5*	Total
N	17	24	6	8	0	55	6	41	28	37	-112
P	12	5	1	nr	0	10	1	0	nr	10	-3
K	2	25	4	nr	0	43	13	9	nr	36	-70

IN 1	mineral fertilizers	*OUT 1*	removal of harvested crop parts
IN 2	organic manure	*OUT 2*	removal of crop residues
IN 3	wet and dry deposition	*OUT 3*	leaching
IN 4	biological nitrogen fixation	*OUT 4*	denitrification
IN 5	sedimentation	*OUT 5*	water erosion

nr = not relevant

Both studies showed that the soil nutrient pool is exploited every cropping season in order to allow nutrient export through agricultural products. As the land use systems involved are currently not sustainable, it is relevant to monitor soil nutrient balances in order to suggest corrective agronomic and policy interventions. This requires data collection and the formulation of land use scenarios based on regularly updated databases, to be used by decision makers at different levels in the agro-ecosystem hierarchy.

Table 5.2 The structure of NUTMON

STEP	DESCRIPTION	UNIT	INPUT
1-1	Fertilizer sales in the district	ton fertilizers	
1-2	Fertilizer types and NPK content	ton NPK	
1-3	Fertilizer application in each LUS in each LUS	kg NPK per ha	*IN 1*
2-1	Livestock types and numbers in the district	x_i cows, y_j goats, z_k sheep, etc. stubble grazing,	
2-2	Livestock systems in the district	tethering browsing, pastoralism, etc.	
2-3	Number and systems in each LUS	x_1 cows, 20% zero-grazing graded 80% browsing (zebu), etc.	
2-4	Manure collection for agricultural use in each LUS related to livestock systems	ton dry manure per ha	
2-5	Manure NPK content and loss percentage (L) before application	(100 - L)% * kg NPK per ha	
2-6	Household waste and NPK content for each LUS	kg NPK per ha	*IN 2*
2-7	Town and industrial refuse and NPK content for each LUS	kg NPK per ha	
3-1	Available point data on wet and dry deposition of NPK in the district	kg NPK per ha	*IN 3*
3-2	Development of suitable transfer functions on data points outside district	TF 1	
4-1	Type and hectarage of N-fixing N fixing species in each LUS	a_1 ha groundnuts, b_1 ha wetland rice	
4-2	Percentage of N uptake (OUT 1+2) attributed to symbiotic fixation	e.g. groudnuts: 50%, wetland rice: 75%	*IN 4*
4-3	Contribution from non-symbiotic N-fixation via direct measurement or transfer functions	kg N per ha TF 2	
5-1	Quantities of flood and irrigation water reaching LUS	m^3 water	
5-2	NPK content of waters for each LUS	kg NPK per ha	*IN 5*

Tabel 5.2 (continued)

STEP	DESCRIPTION	UNIT	OUTPUT
6-1	Yields and hectarage of crops and pastures in the district	a_i tons coffee on p_i ha b_i tons maize on q_i ha	
6-2	Yields and hectarage of crops and pastures in each LUS	a_1 tons coffee on p_1 ha b_1 tons maize on q_1 ha	
6-3	Nutrient content of crops and grasses	kg NPK per ton coffee, maize etc.	
6-4	Nutrients in harvested parts per LUS	kg NPK per ha	*OUT 1*
7-1	Amount of crop residues per LUS	6-2 in combination with harvest index	
7-2	Destination of residues in each LUS (residue management)	r% complete removal (100-r)% left on the field	
7-3	Nutrient content in removed residues	kg NPK per ton coffee, maize etc.	
7-4	Nutrients in removed residues per LUS	r% * kg NPK per ha	*OUT 2*
8-1	Available point data on N and K leaching in the district	kg NK per ha	*OUT 3*
8-2	Development of suitable transfer functions from data points outside the district	TF 3	
9-1	Available point data on denitrification in the district	kg N per ha	*OUT 4*
9-2	Development of suitable transfer functions from data points outside the district	TF 4	
10-1	Available point data on soil loss by erosion in the district	kg soil per ha	
10-2	NPK content of eroded soil	kg NPK per ha	*OUT 5*
10-3	Development of suitable transfer functions	TF 5	

BASIC DATA

1 Size of the district and its arable land (ha)

2 Land use types: crops, livestock, forestry, game parks (LUT; ha)

3 Land units: rainfall and temperature zones, landforms and soils (LU; ha)

4 Land use systems: matching 2 and 3 (LUS; ha)

5 Population density (persons per km^2) and growth rate (% per yr)

The present article describes a multi-level decision-support model for monitoring the soil nutrient balance (NUTMON). The model is developed on the regional level, using data from the Kisii District, Kenya. The regional level is the most appropriate for establishment and operationalization of the model. Possible corrective actions can be judged in relation to both national as well as farming system levels. National agricultural policies (e.g., produce prices, fertilizer subsidies) act as boundary conditions at the regional and farm level, whereas regional policies have to take account of constraints at the farm level such as capital and labour availability and land ownership.

MATERIALS AND METHODS

The structure of NUTMON

NUTMON is fed by a number of basic data, and by nutrient input and output data (Table 5.2). Basic data include the hectarage of the arable land, and the spatial patterns of land use systems, i.e. the combination of prevailing soils and climate on the one hand, and cropping and livestock systems on the other hand. Nutrient input and output data are reflections of the processes *IN 1-5* and *OUT 1-5*. Each process has a certain value, and the nutrient balance is given by Σ *IN* - Σ *OUT*. This figure is the output of NUTMON for a given LUS at a given point in time. A second monitoring exercise at a later stage may yield different results, which may be due to changes in the LUS, or changes in the individual nutrient input and output values. As the changes have either aggravated or ameliorated the nutrient balance, NUTMON can support decision-making in the interest of sustainable forms of agriculture.

To determine nutrient input and output values, a step-wise approach is proposed, in which the different determinants of *IN 1-5* and *OUT 1-5* are calculated, estimated or assumed (Table 5.2). Some steps relate to data that are easily measured or obtained from agricultural offices (e.g. step 1-1, 6-1), but others relate to more complex processes (step 8-1, 9-1). Some data need continuous recording, while others are required irregularly, e.g. once in 5-10 years. It is therefore convenient to group the data according to type, source and frequency of collection, as indicated in Table 5.3.

Table 5.3 Data types, sources and required frequency of recording in NUTMON

Type	Source	Frequency
t-1	primary data	direct measurement or retrieval from existing data bases
t-2	estimates	combinations of primary data and empirical quantitative relations ('transfer functions')
t-3	assumptions	use of literature data and 'common sense', due to lack of primary data and transfer functions
source		
s-1	agricultural statistics	agricultural extension, research institutes, produce and marketing boards, fertilizer market
s-2	field observations	soil, climate and crop-related measurements and farming system analysis
s-3	laboratory analysis	soil, plant, water and fertilizer/manure analysis
s-4	specific research	amongst others: calibration and validation of transfer functions (TF 1-5 in Table 1)
frequency		
f-1	seasonal (dynamic)	properties that are dynamic over one growing period
f-2	seasonal (static)	properties that are static over one growing period, but dynamic over several growing periods
f-3	(multi)-annual	properties that are static over several growing periods

For *IN 2*, for example, the type of data required is livestock numbers and systems, the amount of manure reaching the arable field, and its nutrient content at the time of application. Similar information is needed on household waste and urban and industrial refuse, if applicable. With the necessary effort, steps 2-1 to 2-7 in Table 5.2 can thus all be measured (t-1 in Table 5.3). For *OUT 3*, however, primary data for all LUS are seldomly available. Yet, Burns (1975) has shown that N leaching can be predicted when data are available on rainfall, initial and field capacity moisture content, inorganic soil N content and fertilizer rates. The required data are all measurable, but the relation between leaching and these determinants is an empirical 'transfer function (TF)' (Addiscott and Wagenet, 1985; Bouma and Van Lanen, 1987), resulting from regression analysis on scattered point observations. Hence, the value for *OUT 3*, obtained when entering the collected primary data in the transfer function, is no more than an estimate (t-2 in Table 5.3). Specific research is needed to validate the pedotransfer functions. Those used in NUTBAL (Smaling et al., in press) are given in Table IV. Point data on, for example, atmospheric deposition (*IN 3*) may be non-existent in a country. NUTMON then uses assumptions based on supra-national point data (t-3 in Table 5.3).

Collection of data throughout the growing period (Table 5.3, frequency: f-1) is required on fertilizer sales in the region (Table 5.3, source: s-1), rainfall totals and intensities, temperature, development of leaf area index, and erosion rates (s-2). Data that are only to be monitored once per growing period (f-2) encompass hectarage of agricultural land, cropping and livestock systems with geographical distribution (s-1), fertilizer and manure application rates, hectarage and yields of crops with harvest indices, pastures and forests, residue removal from the field and destination, hectarage of N-fixing species, fallow percentage, soil conservation measures (s-2), nutrient content of soils, eroded sediment, fertilizers, manure, flood and irrigation water, and plant tissue (s-3). Multi-annual monitoring (f-3) relates to farm size distribution, organization of the agricultural extension service and produce and marketing boards, government produce and fertilizer price policies, and world market price development (s-1), and on some relatively stable soil properties, such as soil texture, bulk density and pH (s-3). Finally, literature search and specific regional research (s-4) is required on the different components of the nutrient balance. Examples are the deposition of nutrients in dust and rain (e.g. Poels, 1987), correlation between decomposition of organic matter and moisture and temperature (e.g. Jenkinson and Ayanaba, 1977), biological N-fixation in different agro-ecosystems (e.g. Giller and Wilson, 1991), solute leaching (e.g. Addiscott and Wagenet, 1985), denitrification rates under different soil and hydrological conditions (e.g. Von Rheinbaben, 1990), erosion under different slopes, cropping systems and land management, determination of the enrichment factor for eroded soil, and rates of soil formation by weathering (Ollier, 1979, Stocking, 1984; Lal, 1988).

Entering regional data into NUTMON

- Basic data

The analyses in this study used data prior to 1989. At this time, the Kisii District in Southwestern Kenya covered 220 000 ha of which 80% was considered suitable for agriculture (Government of Kenya, 1985-90)[1]. Population was estimated at 1.5 million (680 inhabitants per km^2), the growth rate was 3.8% per year, and there were approximately 110 000 farm holdings. Data on land and land use were taken from Wielemaker and Boxem (1982) and Jaetzold and Schmidt (1982).

Soil units and rainfall zones are indicated in Figure 1. Soils are predominantly well drained, very deep and rich in nutrients, with the exception of P (mainly Phaeozems and Nitisols; FAO, 1988). Mean annual rainfall ranges between 1350 and 2050 mm. Rainfall is bimodally distributed with peaks in April and November.

Farmers use approximately 0.5 ha of their holding for food crops, i.e. mainly intercropped maize and beans (*Phaseolus vulgaris*), and smaller portions of sweet potato, finger millet, and cabbages. Cash crops are grown on 0.2-0.5 ha and include tea and pyrethrum in the eastern parts, and coffee, banana and sugarcane, mainly in the western parts of the district. The remainder of the holding is occupied by homesteads, small improved pastures and, in the drier parts of the district, bushland for livestock. Due to population pressure, only about 5% of the cultivated land in the district is left fallow each year.

- Nutrient input data

IN 1. Table 5.5 shows that fertilizer consumption rose sharply during the 1980's. Moreover, there was a shift away from straight fertilizers such as triple superphosphate and calcium ammonium nitrate towards the compound fertilizers diammoniumphosphate, 20:20:0, and 25:5:5+5S. In 1991, the latter was entirely applied to tea, and the other fertilizers to maize (70%) and pyrethrum and horticultural crops (30%). Coffee was not fertilized due to very low produce prices.

The total tonnage of fertilizer, applied in 1991 in the 'new' Kisii District coincide with an average fertilizer input (*IN 1*) of almost 20 kg nutrients per ha. Real fertilizer use is still higher, as not all stocklists are included in the district records. Figure 2 shows that farmers apparently apply fertilizers during two periods of the year, in December-February for the long rains, and in July-August for the short rains.

---

[1] In 1989, the Kisii District was subdivided into Kisii and Nyamira District. The 'new' Kisii District (southern, western and central parts of the 'old' district) has an area of 131 500 ha, of which 102 600 ha is suited for agriculture.

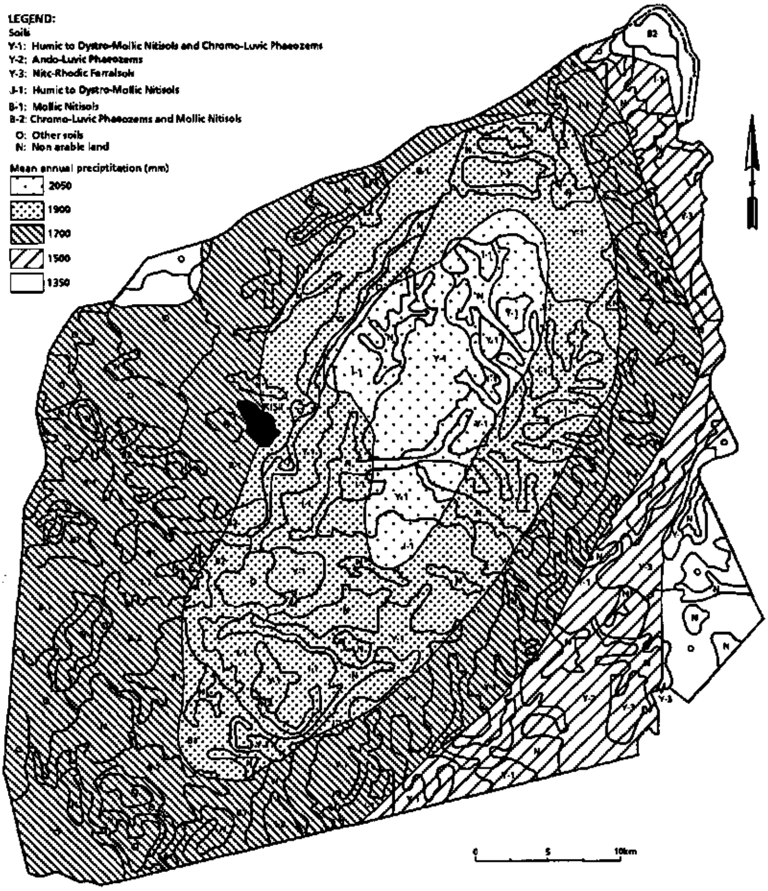


Fig. 5.1 Soil units and rainfall zones in the Kisii District

IN 2. The district accommodates approximately 600 000 cows (1/3 grade, 2/3 local zebu) and 250 000 goats and sheep, mainly in a form of 'semi-zero-grazing' (Government of Kenya, 1985-90). The animals stay overnight in kraals, where they feed on residues of maize and banana. The manure is collected and stored for later application on arable fields. During daytime, cows are generally tethered on small improved pastures, whereas goats and sheep roam along the roadside and in bushland. For pastures, it was assumed that an estimated percentage of what is exported through grazing is returned in manure. Nutrients in manure are partly lost during storage by leaching, denitrification and ammonia volatilization, whereas nutrients in urine are lost almost entirely. Household waste and other refuse with varying nutrient contents are applied to cabbages and vegetables in the homegarden.

IN 3. Due to lack of point data on wet and dry deposition in the district, transfer functions were used, as previously established during the supra-national study (Stoorvogel et al., in press), plotting nutrient input against the square root of average annual rainfall (Table 5.4).

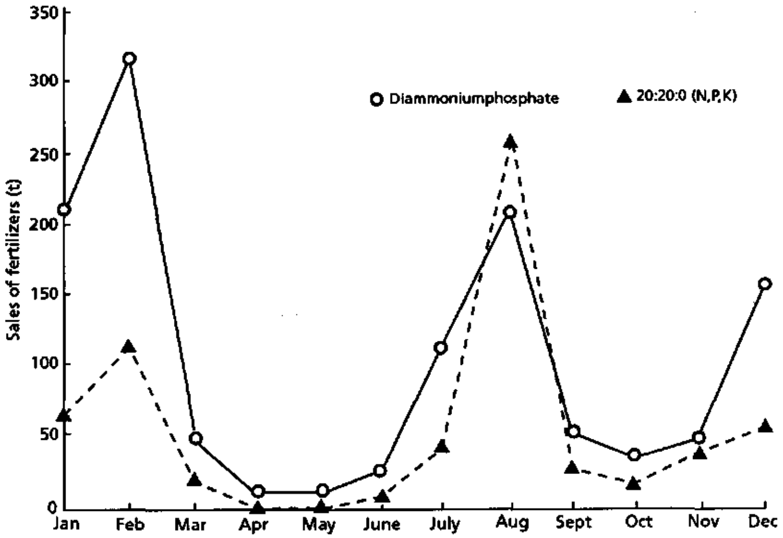


Fig. 5.2 Sales of DAP and 20:20:0 in the Kisii District through the year 1990

IN 4. The hectarage of beans in the different LUS was 34 200 ha in 1987-88 (Table 5.6). It was assumed that beans, the only N-fixing arable crop in the district, draw 50% of their total N requirement from the atmosphere, and 50% from the soil (Giller and Wilson, 1991). For asymbiotic fixation, a small rainfall-dependent contribution was assumed (Table 5.4).

IN 5. Sedimentation did not play a role, as all bottomlands and floodplains have periodic flooding and salinity and sodicity problems, and are thus not used for agriculture.

↑ Why? leaching

- Nutrient output data

OUT 1. Table 5.6 shows crop hectarages and yields. By 1985, 62 000 farmers planted coffee on 7000 ha, and 43 600 farmers planted tea on 13 000 ha. Pyrethrum occupied up to 20 000 ha in the mid-seventies, then declined sharply to rising

1000 ha, but recent price incentives caused a rapid resurgence to 2800 ha in 1988. All farmers grow maize, very often intercropped with beans. In the warmer parts of the district, two crops of maize and beans can be grown in a year. In the colder zones, however, maize takes at least six months to mature, and beans are grown solely during the second season. Bananas are popular as a result of low labour input requirements and instant payment by traders from outside the district. Nutrient contents of the different crops were taken from Wielemaker and Boxem (1982).

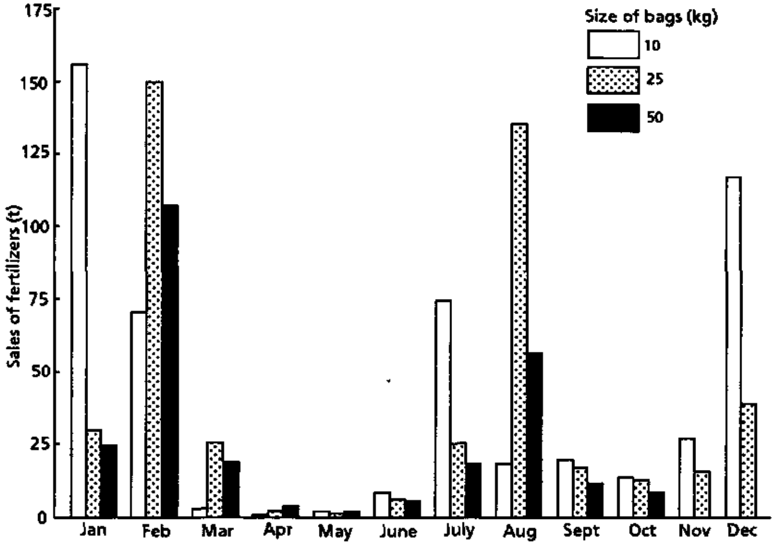


Fig. 5.3 Sales of DAP fertilizer in bags of different sizes through the year 1990

Table 5.4 Use of measurable determinants in transfer functions (after Smaling et al., in press)

	Transfer functions (TF)				
Measurable determinants	1	2	3	4	5
Mean ann. rainfall	x	x	x	x	x
NPK in mineral fertilizers			x	x	
NPK in manure at application			x	x	
Soil N mineralization			x	x	
Clay content			x	x	x
Total soil N			x	x	x
Total soil P					x
Total or exch. soil K			x		x
Rainfall intensity					x
Erodibility factor *K*					x
Slope gradient *S*					x
Slope length *L*					x
Land cover factor *C*					x
Land management factor *P*					x
Enrichment factor					x
Soil formation					x

TF 1: Nutrient input by wet deposition (*IN 3*; kg/ha.yr) is linked with the square root of average rainfall (m, in mm/yr):

$N = 0.14 * \sqrt{m}$

$P = 0.023 * \sqrt{m}$

$K = 0.092 * \sqrt{m}$

TF 2: A small rainfall-dependent contribution A (kg/ha.yr) from non-symbiotic N-fixers was accounted for in each LUS: $A = 2 + (m - 1350) * 0.005$

TF 3: Total mineral soil N in the 0-20 cm layer (N_{min}; kg per ha) was calculated from total soil N, assuming a fixed annual nitrogen mineralization rate M:

$N_{min} = 20 * N_{tot} * M$

Leaching of nitrogen, subdivided in LN_{soil} and LN_{fert}, ranges between 15 and 40% of N_{min} and (*IN 1*+*IN 2*) respectively, depending on rainfall and clay content.

TF 4: Denitrified soil N (DN_{soil}, percentage of N_{min}) and fertilizer N (DN_{fert}, percentage of *IN 1* + IN 2) are calculated from $DN = -9.4 + 0.13 * \text{clay }\% + 0.01 * m$

TF 5: Erosion in Kisii District was calculated along the lines of the Universal Soil Loss Equation (Wischmeier and Smith, 1978), which estimates annual soil loss per ha as a function of rainfall erosivity (*R*), soil erodibility (*K*), slope gradient (*S*) and slope length (*L*), land cover (*C*) and land management (*P*).

$R = 0.25$

K = f (clay content, organic matter content, permeability); range 0.06 - 0.08

$S = (0.43 + 0.3 * \text{slope }\% + 0.043 * (\text{slope }\%)^2)/6.613$

$L = (\text{slope length}/22.13)^{0.5}$

C = f (crop type and development); range 0.01 - 0.5

$P = 0.2 + 0.03 * \text{slope }\%$

Table 5.5 Fertilizer sales in Kisii between 1981 and 1991 (in tons)

	1981	1984	1987	1991*
25:5:5+5S	465	830	1500	2756
20:20:0 + CAN	65	95	522	884
DAP + TSP	106	185	283	2232
Other	18	63	60	24
Total	654	1173	2364	5896

* for the 'new' Kisii District, after subdivision (102 000 ha)

Table 5.6 Hectarage and yields (kg/ha) of major crops in Kisii; normative good yields (kg/ha) after Wielemaker and Boxem (1982)

Crop	1985-1986		1987-1988		Normative good yield	
	ha	yield	ha	yield		
Coffee	7 000	5 080	7 100	4 110	7 500	berries
Tea	13 400	4 190	14 400	4 290	5 000	green leaves
Pyrethrum	2 500	330	2 800	470	750	dried flowers
Maize	51 800	3 600	53 200	3550	6 000	
Beans	27 800	990	34 200	950	4 000	pulses
Finger millet	3 600	820	3 200	840	1 500	
Banana	20 800	17 000	21 900	18 400	30 000	
Sweet potato	2 500	7 000	1 700	17 500	17 500	
Cabbages	1 100	15 000	1 300	13 170	40 000	
Sugarcane	no data	no data	3 100	13 500	12 000	sugar

OUT 2. The bulk of the residues of maize and banana is fed to livestock outside the arable field. The remaining maize stover is applied as a surface mulch. Most of the beans and sugarcane residues also remain in the field. The latter is often burned, implying almost complete N loss. Husks of coffee beans are widely used as a mulch. Pyrethrum residues are partly turned into nutritious cattle feed (Government of Kenya, 1985-1990).

OUT 3, 4. Point data on leaching and denitrification are scarce in the tropics; hence, transfer functions were established, using recognized determinants such as rainfall, texture, soil N and K content, and fertilizer input (Table 5.4). A detailed description of the procedure is given by Smaling et al. (in press).

OUT 5. Erosion rates have been recorded in various parts of Kenya. They are mostly expressed in soil loss per ha, and still need to be converted into nutrient loss. In NUTBAL, the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978) was calibrated for the Kisii District. As Table 5.4 shows, a large number of determinants had to be measured to cover all the USLE factors. Values for N, P and K loss per ha still have to be multiplied with an estimated enrichment factor for eroded sediment, which is richer than soil *in situ*. Finally, a weathering factor is assumed for P and K (25% of *OUT 5*), representing new formation at the root base.

Assessing the effect of current agronomic practices and policy interventions using NUTMON

The above approach was followed to calculate the nutrient balance for the Kisii District. Attention was then turned to possible interventions, necessary to rectify or at least alleviate the unbalanced situation. A number of recent national and regional interventions are mentioned, which have had an impact on the nutrient balance, although not explicitly intended.

- National price policies

Fertilizer subsidies and the artificially low consumer prices for the major food crops were recently abolished. This affects entire LUS, and in the nutrient balance, mainly *IN 1* and *OUT 1*. The net effect of this national intervention on the nutrient balance follows from annual NUTMON updates.

- Fertilizer supply

A recent incentive to farmers has been the supply of fertilizers in small packages, increasing *IN 1*. Figure 5.3 shows that 10 kg-bags of fertilizer accounted for 41% of the total amount of diammoniumphosphate sold in 1990, with peak sales in January and July, prior to the rainy seasons. The subsequent decreases were the result of reduced availability, forcing farmers to buy 25 and 50 kg-bags.

- Zero-grazing

Owing to the virtual absence of idle land in the district, the scope for increasing stocking rates is limited. However, improvements in the quality and husbandry of livestock are supported by the government, in the form of establishment of zero-grazing units. The implications for NUTMON are an increase in *IN 2*, because of better storage opportunities, and a reduction in *OUT 5* when fodder grasses are planted on contour bunds.

- Nitrogen fixation in beans

No use is made of *Rhizobium* inoculant to increase *IN 4*, as farmers do not yet consider beans important enough. Nadar and Faught (1984) found that sequential maize and beans systems often outyielded intercropping systems, which are common in the Kisii District. If in rotation systems beans would withdraw 75% instead of 50% of their N requirement from the atmosphere (Giller and Wilson, 1991), an increase of 30 kg N per ha of maize/beans rotation can be obtained in *IN 4*. Such improvements are triggered by the application of P fertilizer, enhancing nodulation.

- Agroforestry

Planting of leguminous tree species has gained momentum in the past decade, although farmers often appreciate trees for other reasons (Kerkhof, 1990). *Calliandra calothyrsus*, *Sesbania sesban* and *Leucena leucocephala* are highly valued. *Grevillea robusta* is popular too, but is not a leguminous species. Approximately 50% of the farming community has adopted agroforestry practices, which can increase *IN 4*, reduce *OUT 3* and *OUT 5*, and add nutrients to the topsoil from layers not accessible for the roots of annual crops.

- Soil conservation

Soil conservation is gaining momentum as a result of active promotion by the government. A 'catchment' approach was adopted, where the inhabitants of an entire village collaboratively undertake the protection of their land. The output includes cut-off drains, terraces, stonewalls and waterways, but also low-input farm operations such as ploughed strips, grass strips, cover crops, intercropping and mulching. In addition to reducing *OUT 5*, the latter practices may also increase *IN 4* and reduce *OUT 2*.

- Fertilizer use efficiency

Most nutrients leave the LUS in the harvested crop parts (*OUT 1*). In a situation of land scarcity as in the Kisii District, lowering this output is tantamount to lowering crop production. Next, farmers only increase fertilizer use (*IN 1*) when they expect crop harvests (*OUT 1*) to increase as well. Economic and environmental gains can both be obtained by increasing the ratio *OUT 1/IN 1*, i.e. the fertilizer use efficiency. This can be achieved by synchronizing type and amount of fertilizer and timing of application to the prevailing chemical soil fertility and the requirements of the crops to be grown in well-defined agro-ecological units (Smaling and Van de Weg, 1990). Fertilizer use on the basis of prevailing agro-ecological conditions implies increases in *IN 1* and *IN 2*. This is offset by higher crop yields and nutrient withdrawal (*OUT 1*), but the net benefit for the nutrient balance is that more residues are produced which can be left in the field, thus reducing *OUT 2*, fewer inputs are lost through leaching (*OUT 3*) and denitrification (*OUT 4*), and better crop development with higher leaf area indices reduces erosion (*OUT 5*). A certain fraction of the fertilizer (mainly P) may remain in the soil and contribute to soil fertility restoration.

Different land use scenarios

Knowing the current developments in the district, realistic changes in land use can be proposed, and their effect on the nutrient balance assessed. Three NUTMON scenarios were described, including agro-forestry practices (Scenario 1), zero-grazing and soil conservation (Scenario 2), and changing LUS (Scenario 3). As the phosphorus balance is positive in all scenarios, the attention is focussed largely on the nitrogen and potassium balances.

NUTMON Scenario 1 has NUTBAL (Table 5.1) as a starting point. In addition, it encompasses agroforestry practices in 50% of the district, occupied by annual crops and pastures. The changes in the nutrient balance for this area are assessed at:

- *IN 4* : +100% (inclusion of leguminous tree species),
- *OUT 2*: -50% (tree mulch partly replacing residues as fuel/fodder),
- *OUT 3*: -75% (interception of leaching nutrients and pumping up of nutrients not accessible to roots of annual crops),

NUTMON Scenario 2 has Scenario 1 as a starting point. In addition, it includes zero-grazing and soil conservation practices. The changes brought about in the nutrient balance are assessed at:

- *IN 2* : +50%, in 50% of the district (better storage and efficient use of animal manure),
- *OUT 5*: -75%, for the entire district (successful catchment approach).

NUTMON Scenario 3 has Scenario 2 as a starting point. In addition, land use changes are proposed as follows: 25% of the district is to remain under tea, as it is a major foreign exchange earner. The changes brought about in the nutrient balance are assessed at:

- *IN 1*, *OUT 1*, *OUT 2*: data from Smaling et al. (in press) for tea
- *OUT 3*, *OUT 5*: -75% of the mean value for the district (deep rooting and soil protecting crop)
- *OUT 4*: -50% of the mean value for the district (rain water reaches the surface gently, low risk of ponding and local saturation of soil aggregates).

The remaining 75% percent of the cultivated area is converted into a rotation of maize and green manure cover crops. The changes brought about in the nutrient balance are assessed at:

- *IN 1* : 0 kg N and K per ha
- *IN 4* : +100% + 35 kg N per ha (N fixing capacity of the green manure crop)
- *OUT 1*: 41 kg N and 12 kg K per ha (Smaling et al., 1992)
- *OUT 2*: 39 kg N and 49 kg K per ha (Smaling et al., 1992)
- *OUT 3*: -75% (no fertilizer leaching)

RESULTS AND DISCUSSION

Impact of interventions on the nutrient balance

NUTBAL was calculated by Smaling et al. (in press), and shows that Σ *IN* - Σ *OUT* is -112 kg N, -3 kg P and -70 kg K per ha per yr, in the absence of corrective agronomic practices (Table 5.1). The results of the three alternative NUTMON scenarios are shown in Table 5.7. In Scenarios 1 and 2, improvements are considerable, but

N and K outputs still exceed the inputs. In Scenario 2, the annual N and K losses amount to approximately 50% of those in NUTBAL.

Table 5.7 Ameliorating the soil nutrient balance in the Kisii District, using NUTMON (Scenarios 1, 2 and 3).

	IN 1	*IN 2*	*IN 3*	*IN 4*	*IN 5*	*OUT 1*	*OUT 2*	*OUT 3*	*OUT 4*	*OUT 5*	Total
Scenario 1: Agro-forestry programme in 50% of the district											
N	17	24	6	12	0	55	5	26	28	28	-83
K	2	25	4	nr	0	43	10	5	nr	27	-54
Scenario 2: Soil conservation programme in 100% of the district; zero-grazing units in 50% of the district											
N	17	30	6	12	0	55	5	26	28	9	-58
K	2	31	4	nr	0	43	10	5	nr	9	-30
Scenario 3a: Tea in 25% of the district											
N	43	0	6	8	0	70	0	10	14	9	-46
K	5	0	4	nr	0	35	0	2	nr	9	-37
Scenario 3b: Maize/green manure rotation in 75% of the district											
I. Maize											
N	0	36	6	16	0	41	19	10	28	9	-49
K	0	37	4	nr	0	12	24	2	nr	9	- 6
II. Green manure											
N	0	36	6	65	0	0	0	5	14	9	+79
K	0	37	4	nr	0	0	0	1	nr	9	+31

In Scenario 3, a balanced situation is reached in the district with respect to N and K. Under tea and maize, nutrient outputs still exceed nutrient inputs, but the green manure crop is included to offset the negative balance. To equilibrate the N balance, the green manure crop, for example *Mucuna* or *Pueraria*, should fix 69 kg N per ha, on top of the N fixed by the leguminous tree species of Scenarios 1 and 2 (16 kg N per ha). According to Juo and Kang (1989) and Giller and Wilson (1991), a well-established green manure can even fix 100 kg N per ha and above. The average balance for the rotation system is now +15.5 kg N and +12 kg K per ha per yr. As this system comprises 75% of the total cultivated area, it offsets the

-46 kg N and -37 kg K that is realized in the tea-based system, as can be derived from Equation (1):

$$0.25 * BAL_{tea} + 0.75 * (0.5 * BAL_{maize} + 0.5 * BAL_{green\ manure}) \qquad (1)$$

Maintaining maize production in NUTMON Scenario 3

The common soil type I-1 (Fig. 1) has approximately 5000 kg N per ha, and is able to supply 150 kg N per ha at an annual mineralization rate of 3% (Smaling et al., in press). This is sufficient to replenish the negative nitrogen balance figures arrived at in Scenarios 1 and 2. Nitrogen is apparently not limiting crop production on this soil for a period of at least $(5000 - BAL_N/0.03)/BAL_N$ years, in which BAL_N is the absolute value of the nitrogen balance. For Scenarios 1 and 2, BAL_N is equivalent to 83 and 58 kg per ha, implying that soil I-1 can adequately replenish the nitrogen balance for periods of 27 and 53 years, respectively.

Meanwhile, fertilizer trials on the same soil revealed that maize yields were 2.7 t per ha (unfertilized), 4.4 t per ha (on applying 22 kg P per ha), and 5.8 t per ha (with an additional application of 5 t farmyard manure per ha) (Smaling et al., 1992). In other words, yields can be doubled by applying modest amounts of P fertilizer and manure. Maize yields in Scenario 3 can thus be maintained in spite of the reduction in cultivated area by 50%. The other 50% will recover recuperate under green manures, which, once established satisfactorily and fixing at least 69 kg N per ha, may partly be harvested to serve as a protein-rich cattle fodder. In such a way, the sustainable Scenario 3 may still appeal to farmers as crop production is not adversely affected, by virtue of the high P fertilizer use efficiency. Phosphorus is limiting production, and by applying it in fertilizer, more efficient use is made of the nitrogen and potassium reserves in the soil. As a consequence, no N and K fertilizers have to be applied to maize in Scenario 3, reducing total leaching losses. The rotation system does not have to be temporal. A farmer can accommodate 50% of both components at the same time, exchanging swapping them after every year. The tea system should also be included in the spatial rotation as soon as a tea stand has reached the end of its productive life cycle.

Applying NUTMON at different scales

Agro-ecosystems comprise various system levels that combine the biological hierarchy, ranging from the crop or pasture to the highest scale of the continent (or even the biosphere), with socio-economic units ranging from household to supranational political system (Fresco et al., 1990). The concept of nutrient balance applies at each level, from the crop (field) to the region or the country and, finally, the continent. The determinants in NUTMON are mostly scale-neutral and can therefore be used to monitor nutrient balances at each hierarchical level. This is essential since the hierarchical levels interact and cannot be studied in isolation. The interaction takes shape in two directions: (a) each level constitutes an aggregation of nutrient balances at lower levels, so that, for example national nutrient balances can be calculated from combined regional level data sets, and (b) higher level policies may shape actions at lower levels, as is the case in the Kisii District, where booming pyrethrum prices have led farmers to apply fertilizer, manure and erosion control measures. Interventions at the national level can have a direct impact on *IN 1* and *OUT 1* at regional level. In addition, regional policies can markedly improve *IN 2* and *IN 4*, and reduce *OUT 2* and *OUT 5*. This applies particularly to Kenya, where a district focus for rural development was launched in the recent past. Positive effects on *OUT 3* and *OUT 4* also occur, but are indirect and less visible. The farmer is, in principle, able to influence all these input and output processes, depending on the relative profitability of land use alternatives.

NUTMON can be used at national, regional, and farm level, and the data sets obtained can be interlinked. Monitoring of nutrient balances and the effects of interventions should be carried out in a comprehensive way, combining details from each of the levels. REGNUTMON, the regional level model elaborated in detail in this article, consists of a fixed data base and continuous updates. It indicates both the gaps in knowledge as well as the effects of possible interventions. Regional agricultural staff should be aware of the potential and receptiveness of local farming systems as regards integrated nutrient management. Translating nutrient loss in economic terms, as was done by Van der Pol (1992) in the southern region of Mali, may appeal to decision makers at this level.

FARMNUTMON, the farm level application of NUTMON, allows the inclusion of land use specifications that are insufficiently reflected in the regional model, such as individual farmers' deviations from average cropping patterns. It also permits the setting of different boundary conditions of holding size, labour and capital, that limit cropping patterns, and the introduction of alternative practices to redress the nutrient balance. FARMNUTMON can not only be used as a decision support tool for individual farms, but also as a technique to generate data on 'representative farm types' in a district, in order to produce more detailed specifications on relative losses per farm type and the flexibility of different farmers to absorb nutrient saving techniques. At farm level, considerable transfers of nutrients may take place through the application of manure or household waste. A seemingly stable balance may be achieved for plots surrounding the farm house, while at the same time nutrient depletion is rampant in the more distant parts of the farm. REGNUTMON can therefore not consist of a simple aggregation of farm level nutrient balances.

unchecked in spread

NATNUTMON, the application of NUTMON at national level, combines the standardized regional data bases on nutrient balances. As a policy tool, it sets objectives with respect to target production for each community, land tenure, subsidies and prices etc., and assesses their effects. It also reflects (multi)-annual dynamics in the national fertilizer industry, trade, consumption and handling in a country. The work done in this respect by the International Fertilizer Development Center in Togo and Burkina Faso deserves attention (André, 1990; André et al., 1991). Furthermore, the impact of large scale, subnational interventions such as reforestation or hydroelectric dams on the national nutrient balance can be estimated. NATNUTMON is most effective when updated regularly, say every 4-5 years. It can then be fed into a supra-national (subcontinental) model, not only to improve assessments of nutrient depletion at that scale, but also to determine priorities for international research, and to formulate policies that transcend national boundaries. In the longer term, it may be employed to monitor effects of global change on agro-ecological zones and the corresponding effects on land use, as well as the effects of changes in land use on global models (Scharpenseel et al., 1991).

CONCLUSIONS

1. Agricultural production systems are in a permanent state of change. As far as nutrient management is concerned, the direction and magnitude of this change is dictated by changes in any one or more of the NUTMON determinants discussed in this article. NUTMON indicates what types of data need to be monitored and priorities for data collection to refine it. Then, the effects of interven-

tions aimed at amelioration of the soil nutrient balance can be assessed. NUTMON can become a dynamic tool for land use policies, geared towards a balanced nutrient status in agricultural LUS. The model is scale-neutral and links data at farm, regional, national and supra-national levels.

2. At the regional level (Kisii District, Kenya), some current interventions were shown to alleviate a strained nutrient balance, but they do not entirely redress it in a situation of continuous cultivation. An attempt to balance all nutrients in the arable land implies that 25% of the district can remain under tea, whereas another 75% should be put to a spatial or temporal rotation of 50% annual cropping and 50% green manuring. The latter land use scenario does not necessarily have to be 'socially unacceptable', as it was found that modest applications of P fertilizer and manure can raise maize yields from 2.7 to around 5 t per ha. Continuous cultivation without interventions is definitely 'environmentally unacceptable', as crop yields will decline with time. The playground in between such social and environmental boundaries is what we call 'integrated nutrient management systems', which can be quantified with the help of NUTMON.
3. Many of the ways of influencing the nutrient balance discussed here are feasible in the Kisii District by virtue of favourable soil and climatic conditions. The potential for agroforestry and zero-grazing systems, for example, is much higher in the Kenyan highlands, than in a situation of low biomass production such as in Mali (Van der Pol, 1992). In such areas, however, topography is much flatter and soils are less fertile, thus having less to lose than soils enriched by volcanic materials in areas with rolling topography.
4. Data requirements for NUTMON are considerable and demand a serious investment. Nonetheless, in many parts of the world numerous sources of LUS data exist that have hardly been integrated into a decision tool. At the same time, however, in spite of the wealth of information on a district like Kisii, many data are only available in the form of assumptions or estimates. Whatever the situation, the integration of existing information and a continuous updating of NUTMON will assist decision makers in determining the effects of current and improved land use scenarios.
5. NUTMON takes account of both productivity as well as sustainability, operationalized here as the maintenance or improvement of the soil nutrient status (Conway, 1987; Fresco and Kroonenberg, 1992). Decisions on sustainable land use require a calculation of the effects of alternative scenarios at different hier-

archical levels, including specific sets of boundary conditions acceptable to different groups of users (farmers, extensionists, conservationists, politicians) in their spatial and temporal perspective. Once tested and operational, NUTMON may be turned into a decision-support system, comparing and advocating 'nutrient-friendly' land use alternatives through optimization procedures.

ACKNOWLEDGEMENT

The authors thank soil scientists W. Andriesse, J. Bouma, C.A. van Diepen and B.H. Janssen for their critical comments on the manuscript. The UN Food and Agriculture Organization (FAO) is acknowledged for initiating the calculations of the soil nutrient balance under agricultural land use in Africa. The present article is a follow-up to that initiative.

References

Addiscott, T.M. and Wagenet, R.J., 1985. Concepts of solute leaching in soils: a review of modeling approaches. J. Soil Sci. 36: 411-424.

André, M., 1990. Approvisionnement, commercialisation et demande des engrais en République du Togo. International Fertilizer Development Center, 165 pp.

André, M., Gerner, H. and Dahoui, K., 1991. Approvisionnement, commercialisation et demande des engrais au Burkina Faso. International Fertilizer Development Center, 149 pp.

Bouma, J. and Van Lanen, H.A.J., 1987. Transfer functions and threshold values: from soil characteristics to land qualities. In: K.J. Beek, P.A. Burrough, and D.E. McCormack (Editors), Quantified Land Evaluation Procedures, ITC Publication 6, pp. 106-110.

Burns, I.G., 1975. An equation to predict the leaching of surface-applied nitrate. J. Agric. Sci. Camb. 85: 443-454.

Conway, G.R., 1987. The properties of agro-ecosystems. Agric. Systems 24: 95-117.

FAO, 1988. Soil Map of the World, Revised Legend. World Soil Resources Report 60, Food and Agriculture Organization/Unesco/ISRIC, 138 pp.

FAO, 1989. Production yearbook 1988, Vol. 42. Food and Agriculture Organization, Rome, 350 pp.

Fresco, L.O. and Kroonenberg, S.B., 1992. Time and spatial scales in ecological sustainability. Land use policy 9: 155-168.

Fresco, L.O., Huizing, H., Van Keulen, H., Luning, H. and Schipper, R.A., 1990. Land evaluation and farming systems analysis for land use planning. FAO/ITC/WAU, Rome/Wageningen. 207 pp.

Giller, K.E. and Wilson, K.J., 1991. Nitrogen fixation in tropical cropping systems. CAB International, Wallingford, UK, 313 pp.

Government of Kenya, 1985-1990. Ministry of Agriculture. Annual Reports of the Kisii District Agricultural Office.

Jaetzold, R. and Schmidt, H., 1982. Farm management handbook of Kenya. Volume II: Natural conditions and farm management information. Part A: West Kenya. Ministry of Agriculture, Nairobi, pp. 83-126.

Jenkinson, D.S. and Ayabana, A., 1977. Decomposition of carbon-14 labelled plant material under tropical conditions. Soil Sci. Soc. Am. J. 41: 912-915.

Juo, A.S.R. and Kang, B.T., 1989. Nutrient effects of modification of shifting cultivation in West Africa. In: J. Proctor (Editor), Mineral nutrients in tropical forest and savanna ecosystems. Blackwell Scientific Publishers, pp. 289-300.

Kerkhof, P., 1990. Agroforestry in Africa. A survey of project experience. The Panos Institute, London, 216 pp.

Lal, R., 1988. Soil erosion research methods. Soil and Water Conservation Society, Ankeny, Iowa, 244 pp.

Lynam, J.K. and Herdt, R.W., 1989. Sense and sustainability: sustainability as an objective in international agricultural research. Agric. Economics 3: 381-398.

Nadar, H.M. and Faught, W.A., 1984. Effect of legumes on yield of associated and subsequent maize in intercropping and rotation systems. East African Agric. For. J. 44: 127-136.

Ollier, C.D., 1979. Weathering (4th edition). Longman, London, 304 pp.

Poels, R.L.H., 1987. Soils, water and nutrients in a forest ecosystem in Suriname. PhD.thesis. Agric. Univ. Wageningen, 253 pp.

Scharpenseel, H., Schomaker, M. and Ayoub, A. (Editors), 1991. Soils on a warmer earth. ISSS/UNEP/Elsevier, Amsterdam, 274 pp.

Smaling, E.M.A. and Van de Weg, R.F., 1990. Using soil and climate maps and associated data sets to select sites for fertilizer trials in Kenya. Agric. Ecos. Envir. 31: 263-274.

Smaling, E.M.A., Stoorvogel, J.J. and Windmeijer, P.N., in press. Calculating soil nutrient balances in Africa at different scales. II. District scale. Fert. Res.

Smaling, E.M.A., Nandwa, S.M., Prestele, H., Roetter, R. and Muchena, F.N., 1992. Yield response of maize to fertilizers and manure under different agro-ecological conditions in Kenya. Agric. Ecos. Envir. 41: 241-252.

Stocking, M., 1984. Erosion and soil productivity: a review. Consultants' Working Paper No.1. AGLS, FAO, 102 pp.

Stoorvogel, J.J. and Smaling, E.M.A., 1990. Assessment of soil nutrient depletion in Sub-Saharan Africa, 1983-2000. Report 28, Winand Staring Centre, Wageningen, The Netherlands, 137 pp.

Stoorvogel, J.J., Smaling, E.M.A. and Janssen, B.H., in press. Calculating soil nutrient balances in Africa at different scales. I. Supra-national scale. Fert. Res.

Van der Pol, F., 1992. Soil mining. An unseen contributor to farm income in southern Mali. Bulletin 325. Royal Tropical Institute, Amsterdam, 48 pp.

Von Rheinbaben, W., 1990. Nitrogen losses from agricultural soils through denitrification - a critical evaluation. Z. Pflanzenernähr. Bodenk. 153: 157-166.

Wielemaker, W.G. and Boxem, H.W., 1982. Soils of the Kisii area, Kenya. Agric. Res. Rep. 922. Centre for Publication and Documentation (PUDOC-DLO), Wageningen, The Netherlands, 208 pp.

Wischmeier, W.H. and Smith, D.D., 1978. Predicting rainfall erosion losses - a guide to conservation planning. Agriculture Handbook 537. U.S. Department of Agriculture, Washington DC, 58 pp.

Wolf, J., De Wit, C.T. and Van Keulen, H., 1989. Modeling long-term crop response to fertilizer and soil nitrogen. I. Model description and application. Plant and Soil 120: 11-22.

PART III AGRO-ECOLOGICAL CONDITIONS AS A BASIS FOR FERTILIZER RECOMMENDATIONS

6. Using soil and climate maps and associated data sets to select sites for fertilizer trials in Kenya

7. Yield response of maize to fertilizers and manure under different agro-ecological conditions in Kenya

Chapter 6

Using soil and climate maps and associated data sets to select sites for fertilizer trials in Kenya

Published in: Agriculture, Ecosystems and Environment 31 (1990): 263-274

Using Soil and Climate Maps and Associated Data Sets to Select Sites for Fertilizer Trials in Kenya

E.M.A. SMALING and R.F. VAN DE WEG

The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen (The Netherlands)

(Accepted for publication 3 October 1989)

ABSTRACT

Smaling, E.M.A. and van de Weg, R.F., 1990. Using soil and climate maps and associated data sets to select sites for fertilizer trials in Kenya. *Agric. Ecosystems Environ.*, 31: 263–274.

In Kenya during 1985 a comprehensive fertilizer trial programme for annual crops was launched. The aim was to contribute towards securing the country's self-sufficiency in food supplies in the medium and high potential areas. This article reports on the methodology adopted to arrive at judicious decisions on where to establish the trial sites.

The chosen procedure encompassed a profound scrutiny of all the available maps and associated data sets of Kenya, regarding climate, landforms, geology and soils. A limited number of soil and climatic properties, relevant to crop production, was then selected from the database.

Using the values of these key properties, existing land mapping units are then transformed and, whenever possible, combined on newly compiled district soil and agro-climate maps. By overlaying these respective maps, new land units were delimited, characterized by a specific set of biophysical conditions. They are called 'Agro-Ecological Units' (AEUs). Thereafter, the locations for trial sites are chosen so they are representative of the most important AEUs.

After 5–10 years of experimentation, the trial results form the basis for fertilizer recommendations, which are not just crop-specific but also AEU-specific. Only then will they be meaningful to the farming community.

INTRODUCTION

Application of mineral fertilizers and/or farmyard manure is a way of increasing crop yields per unit area. Relatively few farmers in sub-Saharan Africa apply fertilizers. The reasons vary from lack of cash and lack of incentive because of unfavourable national price policies, to unreliability of seasonal rainfall and low responses owing to poor crop husbandry practices. If farmers do opt for fertilizers, the type and amount of fertilizer purchased are often prone to arbitrariness. Fertilizer recommendations in tropical countries are often based on very general crop-specific guidelines. Trials are conducted on few research stations, and little effort is made to make these observations meaningful to a wider range of environments. For example, an extension officer hardly knows about the prevailing soil types around his duty-station, whereas he still advises the farmer on the use of fertilizer. The problem here relates to the discussion on the transfer of technology from an experimental location with its controlled environment, to wider regions with mainly reconnaissance-scale information. This topic has been discussed by several experts (Brinkman and Stein, 1987; Nix, 1987) during a special meeting on the characterization, classification and mapping of agricultural environments (Bunting, 1987). It is also a key topic of interest to the International Benchmark Soils Network on Agro-Technology Transfer (Silva, 1985).

A thorough review of past fertilizer trials on annual foodcrops in Kenya revealed that the trials do not provide sufficient information on which to base reliable fertilizer recommendations (FURP, 1987). The main reasons encompass the lack of basic data on climatic and soil conditions at the site and the fact that many trials were carried out for only one or a few consecutive growing seasons; rare exceptions are fertilizer studies in Kitale and Katumani (e.g. Nadar and Faught, 1984). Also, trials have so far mainly been conducted on research stations, whereas there is no clear-cut consistency or repeatability of technology performance between research stations and farmers' fields. These findings formed part of the justification, in 1985, for launching a comprehensive fertilizer-trial research programme in Kenya, for rain-fed annual crops. The programme is confined to the medium and high potential areas. A major aim is that the production functions arrived at the trial sites must be transferable and applicable to 70–80% of these areas. The objective of this text is to provide a cost-efficient methodology to transfer results from these fertilizer trials to wider ranges of similar environment. The methodology advocated here includes:

(1) gathering data from existing maps and reports on climate, landforms, geology and soils;

(2) transformation of existing soil and climate mapping units on the basis of a limited number of properties that are strongly related to crop production, and compiling new soil and agro-climate maps for the 32 Kenyan districts involved;

(3) overlaying, for each district, these two maps and delimiting the resulting overall land units, which are characterized by a specific set of biophysical conditions (Agro-Ecological Units (AEUs));

(4) determining the location of trial sites in the field so that they adequately represent most of these AEUs; the trial results will eventually be converted into fertilizer recommendations for the entire AEU represented by a trial.

MATERIALS

Soils

Most soil maps consulted in this study were produced by the Kenya Soil Survey. This institute conducts soil surveys at different scales and for different users. The output comprises soil maps and reports, related resource maps, thematic maps and land suitability maps (Kenya Soil Survey, 1988). A major achievement has been the compilation of the Exploratory Soil Map of Kenya. This map provides soil information on a 1:1 000 000 scale (Sombroek et al., 1982).

The soil pattern of Kenya is very intricate because of marked differences in altitude, landforms, geology and climate. The legend of the soil maps in Kenya reflects landform at the first level (e.g. coastal plains) and lithology at the second level of distinction (e.g. sandstones). Soil mapping units emerge at the third level of distinction, and include a brief description of drainage, depth, colour, texture, consistency, stoniness, slope class and FAO/UNESCO soil classification. Survey reports provide a more elaborate listing of land and soil properties. Data are presently stored in the KSS soils database (van Engelen, 1987). The predominant soil orders in the medium and high potential areas of Kenya are: Nitisols; Phaeozems; Luvisols; Acrisols; Ferralsols. Of secondary importance are, in terms of acreage: Cambisols; Andosols; Vertisols; Planosols (FAO/UNESCO, 1974).

Climate and agro-ecological zones

Studies on the water balances and temperatures for the whole of Kenya were done by the Kenya Soil Survey, which resulted in the 1:1 000 000 Agro-Climatic Zones Map (Braun, in Sombroek et al., 1982). Meanwhile, a more detailed system of agro-ecological zonation was established (Jaetzold and Kutsch, 1982), aiming at the assessment of land-use potential on a district scale (Jaetzold and Schmidt, 1982/3). This information base was used in the present study, and recognizes main zones at the first level of distinction. They are, like Braun's classification, made up of characteristic temperature and moisture availability limits, but they also show the 66% probability of meeting the water requirements of the leading crops in the various zones. At the second level of distinction, subzones are reflected. They accommodate the length, intensity, and seasonal distribution of the growing periods and are, as such, largely determining cropping possibilities.

METHODS AND BASIC ASSUMPTIONS

It was decided that the methods of compiling the district soil and agro-climate maps, must be based on a small but relevant data set representing soil and climatic conditions. Nine properties are assumed to portray the biophysical setting adequately, because they are:

(1) available in most of the spatially referenced data sets scrutinized;

(2) relatively static in time;

(3) relevant to crop production, or, in land evaluation terminology, are the constituents of the five land qualities, moisture, nutrient and oxygen availability, rootability and temperature.

The five selected soil properties are: (i) drainage conditions; (ii) effective soil depth; (iii) inherent nutrient availability (parent material); (iv) topsoil properties (organic matter content, base saturation); (v) moisture storage capacity. The climatic properties are: (i) mean annual temperature; (ii) mean minimum or maximum temperature; (iii) rainfall (exceeded at least in 20 out of 30 seasons); (iv) agro-ecological subzone (length + pattern of growing periods). For the transformation of soil data, the Exploratory Soil Map served as the background database, but its small scale does not make it the most suitable data set to be drawn upon. However, the multitude of existing reconnaissance and semi-detailed maps proved to be very useful.

Three situations arose in the 32 districts considered:

(1) there is little or no reconnaissance or semi-detailed information in the district: only data from the Exploratory Soil Map are used;

(2) part of the district is covered by reconnaissance maps and semi-detailed maps: an example is the Kilifi District, where three different reconnaissance maps (on a 1:100 000 scale) cover large parts of the district (van Wijngaarden and van Engelen, 1985; Michieka et al., 1986; Boxem et al., 1987); the rest of the district is covered by the Exploratory Soil Map;

(3) districts are entirely covered by reconnaissance and semi-detailed maps, for instance the Lake Basin districts, which were all mapped on a 1:250 000 scale (Andriesse and van der Pouw, 1985).

The interpretation of boundaries between soil mapping units is a delicate matter because they all suggest abrupt changes in the values of their inherent properties. Figure 1 provides an adequate picture of the different sorts of boundaries, faced during the transformation exercise (Burrough, 1986).

(1) A boundary on a soil map separates, for example, a Planosol from a Nitisol; this soil boundary generally coincides with a geomorphological boundary, and is discrete and abrupt (Fig. 1a).

(2) Elsewhere on the map, haplic and vertic Phaeozems and pellic Vertisols occur in a toposequential pattern. A boundary should be recognized, because the three soils have different functional properties. It is, however, not very clear where to draw this boundary. There is a 'fuzzy' zone, in which the soils contain some elements from both soil classification units (Fig. 1b).

(3) Orthic Acrisols and orthic Luvisols are separated by a boundary. They differ only because of base saturation values in the subsoil. Sampling variation has unfortunately been such that 'units' could be distinguished. This separa-

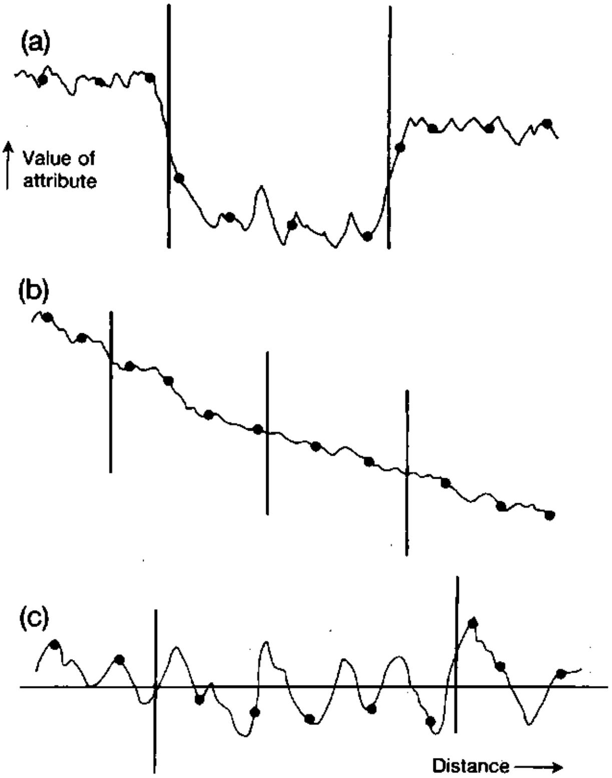


Fig. 1. Types of boundaries encountered when mapping natural resources: (a) abrupt, (b) dividing a trend, (c) resulting from sample variation.

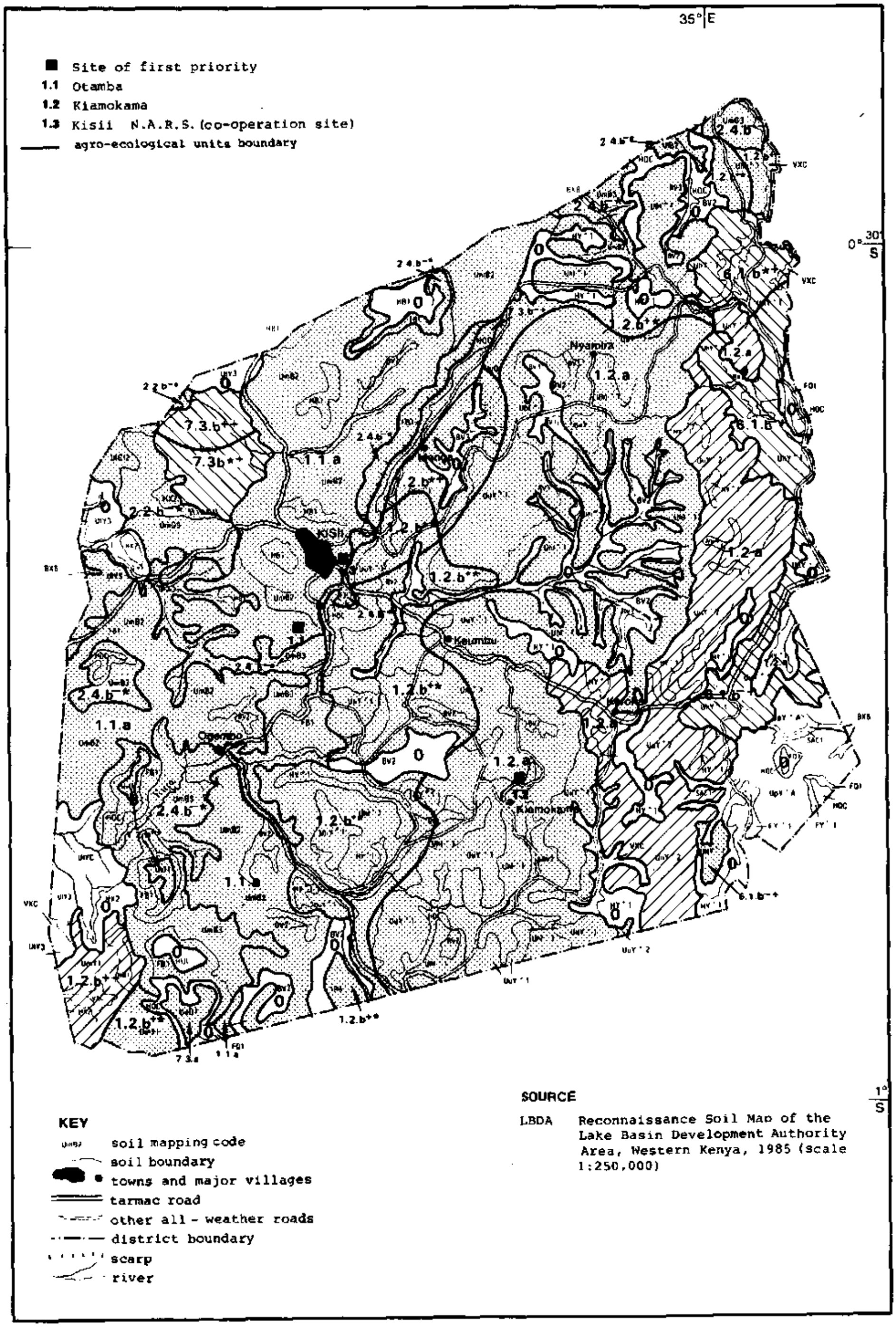
tion, however, has no agricultural significance whatsoever. During district soil map compilation, the boundary in Example 1 will be maintained. Both the Nitisol and the Planosol should be represented by separate trial sites. In Example 2, the trial site must be located in one of the constituents of the toposequence but not in the 'fuzzy' zones. For the present purpose the boundary in Example 3 can be deleted, as the two units will fall in one group when adhering to the data set used in this study.

The Agro-Ecological Zones maps by Jaetzold and Schmidt (1982/3) were used for the combination of climatic data. This data set was updated with figures of recent years and improvements in quantitative interpretation. A detailed account of procedures is beyond the scope of this text.

RESULTS

Delimitation of AEUs

The new district soil and climate maps are overlayed, entailing many soil–climate combinations, which here are AEUs. As the boundaries on soil and



■ Site of first priority
1.1 Otamba
1.2 Kiamokama
1.3 Kisii N.A.R.S. (co-operation site)
—— agro-ecological units boundary

KEY

UmB2 soil mapping code
soil boundary
towns and major villages
tarmac road
other all - weather roads
district boundary
scarp
river

SOURCE

LBDA Reconnaissance Soil Map of the Lake Basin Development Authority Area, Western Kenya, 1985 (scale 1:250,000)

Soil Codes

░ = A = highly representative

▧ = B+ = moderately representative
(soils of map unit are slightly more favourable than soils at the trial site)

▨ = B- = moderately representative
(soils of map unit are slightly less favourable than soils at the trial site)

Trial sites

1.1 Otamba - Kisii District
1.2 Kiamokama - Kisii District
1.3 Kisii NARS - Kisii District
2.2 Rongo - South Nyanza District
2.4 Oyuis-Ober - South Nyanza District
(2.5) between Rongo and Migori - South Nyanza District
6.1 Kamakoiwa - Bungoma District
7.3 Vihiga-Maragoli - Kakamega District
9.2 Chebunyo - Kericho District

Climatic Codes

a highly representative,i.e. same Agro-Ecol.Zones Belt and long rains (+/-10%) as at trial site

b moderately representative

++ = 1 AEZ Belt warmer, long rains 10-20% higher
+* = 1 AEZ Belt warmer, long rains similar (+/-10%)
+- = 1 AEZ Belt warmer, long rains 10-20% lower
-+ = 1 AEZ Belt cooler, long rains 10-20% higher
-* = 1 AEZ Belt cooler, long rains similar (+/-10%)
-- = 1 AEZ Belt cooler, long rains 10-20% lower
*+ = AEZ Belt the same, long rains 10-20% higher
*- = AEZ Belt the same, long rains 10-20% lower
xx = 2 AEZ Belts warmer, long rains 20-30% higher
x̲x̲ = 2 AEZ Belts cooler, long rains 20-30% lower

Areas not represented

0 = not represented by soils and/or climate

Fig. 2. AEUs represented by trial sites in the Kisii District (with explanatory note).

TABLE I

Major soil properties and climatic conditions of the AEUs in the Kisii District

Agro-Ecological Unit			Soil properties						Climatic conditions				
Site no.	Soil code	Climate code	Drainage	Eff. depth	Nutr. avail.	Top soil	Moist. st. cap.	Classification	Temp. mean ann.	Temp. mean min.	Rainfall 66% prob.	Agro-Ec. sub-zone	Agro-Ec. zone
1.1	A	a	W	ed	h	2h	vh	mo Ni	18–21	11–14	760–940	p or l-m	UM 1
1.2	A	a	W	vd-ed	h	2h-2ah	vh	hu + dy-mo Ni	15–18	8–11	740–900	p or l-m	LH 1
		b+*							18–21	11–14	740–900	p or l-m	UM 1
		b*+							15–18	8–11	900–980	p or l-m	LH 1
		b++							18–21	11–14	900–980	p or l-m	UM 1
		b+–							18–21	11–14	660–740	l/m-m/s	UM1-2
1.2	B–	a	W	d-ed	m-h	1h-2h	h-vh	hu + moNi + ch-lu + an-lu Ph	15–18	8–11	740–900	p or l-m	LH 1
		b+*							18–21	11–14	740–900	p or l-m	UM 1
		b++							18–21	11–14	900–980	p or 1-m	UM 1
2.2	A	b–*	W	md-d	1	1ah	m	hu Ac	18–21	11–14	850–1050	p or 1-m	UM 1
2.4	A	b––	W	md-vd	h	1h-2h	h-vh	ch-lu Ph + mo Ni	18–21	11–14	760–940	p or 1-m	UM 1
		b––							18–21	11–14	650–760	l/m-m/s	UM 1-2
(2.5)	A		W	md-d	m	0–1h	m-h	lu Ph + or Lu	depends on final selection of the site				
6.1	B+	b*+	W	vd	1	0	vh	ni-rh Fe	18–21	11–14	750–820	p or l-m	UM 1
		b–+							15–18	8–11	750–820	p or l-m	LH 1
7.3	A	a	W	d-vd	1	1 ah	h-vh	hu Fe	18–21	11–14	720–880	p or two	UM 1
		b–+							15–18	8–11	880–960	p or two	UM 1

7.3	B+	b*+	w	vd	1	2ah	vh	ni-hu Fe	18-21	11-14	880-960	p or two	UM 1
		b++							21-24	>14	880-960	p or two	LM 1
9.2	A		p	sh-md	l-m	0	l-m	ch Ve+eu Pl	climate not representative				
	C			soil not representative									
	0			soil and/or climate are not representative									

Effective soil depth

ed	extremely deep	>180 cm.
vd	very deep	120-180 cm.
d	deep	80-120 cm.
md	moderately deep	50- 80 cm.
sh	shallow	25- 50 cm.
		<25 cm.

very shallow

Nutrient availablity

h	high
m	moderate
l	low
vl	very low

Topsoil properties

h	humic (base saturation >50%)
ah	acid humic (base saturation <50%)
2	thick (30-60 cm.)
1	thin (<30 cm.)
0	non-humic

Moisture storage capacity

vh	very high	>160 mm.
h	high	120-160 mm.
m	moderate	80-120 mm.
l	low	<80 mm.

Drainage

w	well
p	poor

Soil classification

Ni	Nitisols	ch	chromic
Ph	Phaeozems	lu	luvic
Ac	Acrisols	dy-mo	dystro-mollic
Fe	Ferralsols	ch-lu	chromo-luvic
Ve	Vertisols	an-lu	ando-luvic
Pl	Planosols	rh	rhodic
mo	mollic	ni-rh	nito-rhodic
hu	humic	eu	eutric
ni-hu	nito-humic		

climate maps do not generally coincide, the number of AEUs turned out high in most districts. For reasons of programme management, however, the total number of trial sites was not to exceed 65. Because of this practical constraint, three groups of AEUs can be recognized:

(1) AEUs that have a trial site within their boundaries, and those that have no trial site but have the same values for the selected properties; the AEU code should reflect the high degree of representativeness of the trial site;

(2) AEUs that finish up having no trial site, even though their properties are similar to one of the trial sites; the AEU code should reflect the moderate degree of representativeness of this trial site;

(3) AEUs that have no trial site and are not represented by one; they are coded 0.

Trial sites representing AEUs in the Kisii District

The soil map of the Kisii District (not shown) recognizes 30 units, and the agro-climatic map of the Kisii District (not shown) recognizes six units. The result of overlaying these two maps is shown in Fig. 2 and its explanatory note. In the district, there is a total of 18 AEUs, represented by eight trial sites and one unit, coded 0. The representativeness of soils (A, B^+, B^-) is shown by means of screens, and the representativeness of climate is part of the map code (a, b). The 18 AEUs are specified in Table I. In this Table, the values of the nine selected properties are listed for each AEU. A large unit in the Kisii District is AEU 1.2.A.a (in Fig. 2, this is the unit coded 1.2.a with a spotted screen). According to Table I, this AEU has well-drained, very deep to extremely deep soils with a high inherent fertility, a thick (acid) humic topsoil and a very high moisture storage capacity. The mean annual temperature ranges between 15 and 18°C, mean minimum temperature from 8 to 11°C, rainfall probability (20 out of 30 years) is in the range 740–900 mm, and the subzone is coded p or l–m (permanent growing season or a long and medium growing season separated by an indistinct dry period). As Trial Site 1.2 has all these features, the AEU is well represented by the trial site.

AEU 1.2.B-.b^{++} is, in Fig. 2, the unit coded 1.2.b^{++} with a striped screen. It occurs in the south-eastern corner of the district, and has well drained, deep to extremely deep soils with a moderate to high inherent fertility, a (thick) humic topsoil and a high to very high moisture storage capacity. With regard to soils, there is some similarity to Trial Site 1.2, as two diagnostic soil properties rank one class less favourable than at the site itself. This is why the code B– has been used. The trial results at Site 1.2 can be used for south-eastern Kisii District, but the B– code indicates moderate representativeness only.

With regard to climate, the b^{++}-code indicates that both temperature and rainfall are both one class higher (warmer and wetter), compared to trial site 1.2 and AEU 1.2.A.a (Table 1). Areas which show neither high nor moderate similarity with respect to soils or climate are coded 0. Land coded as such mainly reflects areas with soils which are shallow, saline, or calcareous, and soils of bottomlands and floodplains, which have too high a spatial variability to justify any extrapolation at the reconnaissance level.

DISCUSSION

The procedure described in this article does not claim to represent the best way to transfer site information to a district level. 'How far can we go in extrapolation' is the question in many articles dealing with the problem of technology transfer and spatial variability of resources (Bunting, 1987). Still, it is felt that the present methodology can greatly improve the presently low efficiency of fertilizer use in Kenya. It is a methodology which is time- and cost-efficient, it makes optimal use of systematically gathered information on natural resources, and subjectivity is mainly confined to the selection of key properties for the transformation exercise. The procedure can be greatly facilitated with the help of a geographical GIS information system, provided maps and associated data sets are available in digitized format.

More than 60 fertilizer trials have become operational in 1988. They are located in 32 districts. Most sites are located on farmers' fields. The randomized complete block design includes the factors N, P, K, S, lime, and farmyard manure. Because of the many sources of soil heterogeneity, scores of farms were considered before a final decision on the location of the trial site was taken. The sites had to meet requirements related to farm size, accessibility, demonstration effect, spatial homogeneity of the plot surface, and the values of the selected soil and climatic properties.

After approximately 5 years of experiments, the trials should start providing a good basis for fertilizer recommendations, which are not just crop-specific but also area-specific. Results will be published in separate articles.

ACKNOWLEDGMENT

The authors are indebted to Professor Dr. R. Jaetzold, Mr. R. Leyder and Mr. R. Roetter for their critical comments on the manuscript.

REFERENCES

Andriesse, W. and van der Pouw, B.J.A., 1985. Reconnaissance Soil Map of the Lake Basin Development Authority, Western Kenya (scale 1:250,000). Netherlands Soil Survey Institute, Wageningen/Kenya Soil Survey, Nairobi, 56 pp + 1 MAP.

Boxem, H.W., de Meester, T. and Smaling, E.M.A., 1987. Soils of the Kilifi Area, Kenya. Agric. Res. Report 929. Centre for Publication and Documentation, Wageningen; Reconnaissance Rep. R11, Kenya Soil Survey, Nairobi, 249 pp + 8 annexes.

Brinkman, R. and Stein, A., 1987. Linking site information and geographically distributed data at different scales and levels of detail. In: A.H. Bunting (Editor), Agricultural Environments, Characterization, Classification and Mapping. CAB International, Wallingford pp. 119–126.

Bunting, A.H., 1987. Agricultural Environments, Characterization, Classification and Mapping. CAB International, Wallingford, 335 pp.

Burrough, P.A., 1986. Principles of Geographical Information Systems for Land Resources Assessment. Clarendon Press, Oxford, 193 pp.

FAO-UNESCO, 1974. Soil Map of the World, 1:5,000,000, Volume I: Legend. UNESCO, Paris, 59 pp.

FURP, 1987. The Fertilizer Use Recommendation Project. Final Report. Annex I: Fertilizer trial documentation (FERDOC). Min. of Agriculture, Nairobi.

Jaetzold, R. and Kutsch, H., 1982. Agro-Ecological Zones of the Tropics with a sample from Kenya. Tropenlandwirtschaft, 83: 15–34.

Jaetzold, R. and Schmidt, H., 1982/83. Farm management handbook of Kenya. Volume II: Natural conditions and farm management information. Min. of Agriculture, Kenya.

Kenya Soil Survey (1988). List of Publications, Kenya Soil Survey, Ministry of Agriculture, Nairobi, 35 pp.

Michieka, D.O., van der Pouw, B.J.A. and Vleeshouwer, J.J., 1986. Soils of the Kwale–Mombasa–Lunga Lunga area. Reconnaissance Rep. R3, Kenya Soil Survey, Nairobi, 300 pp.

Nadar, H.M. and Faught, W.A., 1984. Maize yield response to different levels of nitrogen and phosphorus fertilizer application. In: Dryland Farming Research in Kenya, E. Afr. Agric. For. J., 44: 147–156.

Nix, H., 1987. The role of crop modelling, minimum data sets and geographic information systems in the transfer of agricultural technology. In: A.H. Bunting (Editor) Agricultural Environments, Characterization, Classification and Mapping. CAB International, Wallingford, pp. 113–118.

Silva, J.A., (Editor), 1985. Soil-based agrotechnology transfer. Benchmark Sites Project, University of Hawaii, 269 pp.

Sombroek, W.G., Braun, H.M.H. and van der Pouw, B.J.A., 1982. Exploratory Soil Map and Agroclimatic Zones Map of Kenya, scale 1:1 000 000. Report E1, Kenya Soil Survey, Nairobi, 56 pp + 4 maps.

van Engelen, V.W.P., 1987. KSS Soil Information System. User manual and guidelines for the description and coding of soil data. Internal Comm. 27, Kenya Soil Survey, 44 pp + 4 annexes.

van Wijngaarden, W. and van Engelen, V.W.P., 1985. Soils and vegetation of the Tsavo area. Reconnaissance Rep. R7, Kenya Soil Survey, Nairobi, 246 pp + 9 annexes.

Chapter 7

Yield response of maize to fertilizers and manure under different agro-ecological conditions in Kenya

Published in: Agriculture, Ecosystems and Environment 41 (1992): 241-252

Yield response of maize to fertilizers and manure under different agro-ecological conditions in Kenya

E.M.A. Smaling[a], S.M. Nandwa[b], H. Prestele[b], R. Roetter[b] and F.N. Muchena[b]
[a]*DLO The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen, Netherlands*
[b]*National Agricultural Research Laboratories, P.O. Box 14733, Nairobi, Kenya*

(Accepted 24 March 1992)

ABSTRACT

Smaling, E.M.A., Nandwa, S.M., Prestele, H., Roetter, R. and Muchena, F.N., 1992. Yield response of maize to fertilizers and manure under different agro-ecological conditions in Kenya. *Agric. Ecosystems Environ.*, 41: 241–252.

In Kenya, 70 long-term fertilizer trials were established in which the response of the major annual crops to nitrogen, phosphorus and farmyard manure was tested. As the sites all represent well-defined agro-ecological units, the trial results can be used as a basis for area-specific fertilizer recommendations. Results of 4 years (1987–1990) of fertilizer and manure application to maize at three sites were evaluated. The selected sites are at altitudes of 2020 m (Nitisol), 1160 m (Phaeozem), and 130 m (Alisol). All the sites are in maize-growing environments, but farmers use different hybrids. Analysis of variance revealed that maize on the Nitisol responded vigorously to phosphorus and manure, with even a significant interaction. On the Phaeozem, it was solely nitrogen that limited yields, and on the Alisol there was a response to both nitrogen and phosphorus. At a relatively low level of fertilizer input (Sh. 825–1125), farmers can, in 3 out of 4 years, earn an extra Sh. 3000 from the Nitisol (value/cost 4.5), Sh. 4000 from the Phaeozem (value/cost 4.2), but only Sh. 425 from the Alisol (value/cost 1.5). The study clearly shows the need to (i) recommend fertilizers according to the agro-ecological diversity of agricultural land, and (ii) support systems of integrated nutrient management, particularly in areas of low soil fertility, where the farmer has too few economic incentives to rely solely on mineral fertilizers.

INTRODUCTION

Many African farmers are aware of the potential contribution of mineral fertilizers to crop production. Yet, fertilizer use in the region is very low compared with the world average, as is shown in Fig. 1 (adapted from FAO, 1988a). The main reasons why African farmers refrain from using fertilizer

---

Correspondence to: E.M.A. Smaling, DLO The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen, Netherlands.

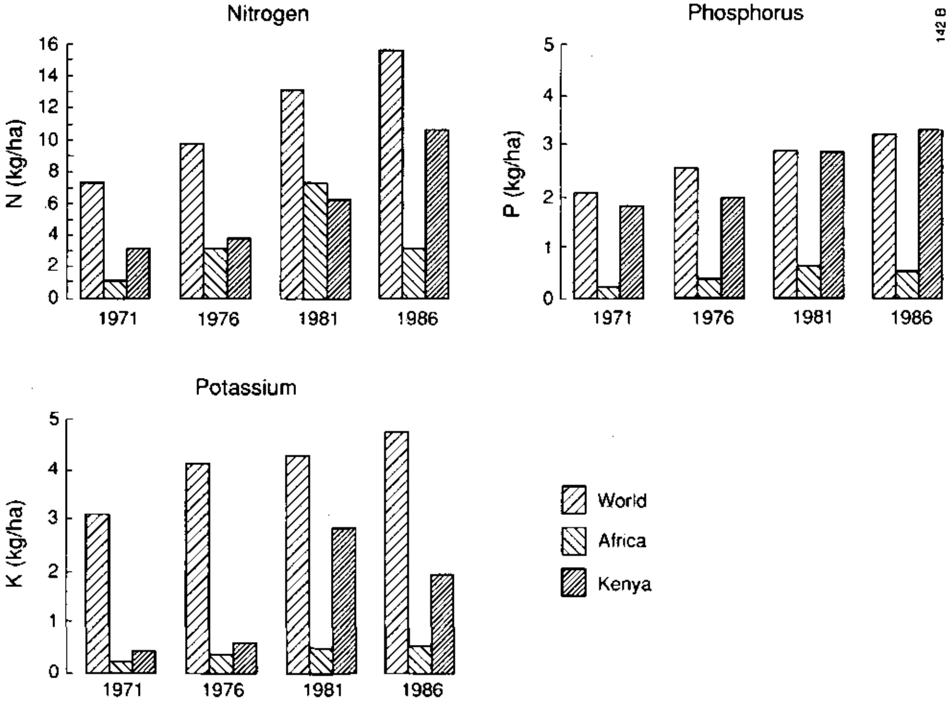


Fig. 1. Nitrogen, phosphorus, and potassium consumption (in kg ha^{-1} agricultural land) in the world, in Africa, and in Kenya (1971–1986)

are lack of confidence in the economic returns to fertilizing food crops, and lack of knowledge as to which kinds and rates of fertilizers are recommended for their specific crops, soils, and agro-climatic conditions. Such recommendations have either not been transferred from research to extension departments or, more often, just do not exist (FAO, 1983; Mudahar, 1986; Vlek, 1990). Hence, the farmer acts according to inappropriate blanket recommendations, such as 'one bag per acre' of the most readily available kind of fertilizer.

In Kenya, land with a high agricultural potential is densely populated and most households of five to eight persons nowadays have less than 1 ha to grow their crops (Ssali et al., 1986). In the semi-arid areas, farmers have more, but less productive, fragile land. As the possibilities of extending the arable land have almost been exhausted, the production per area of land has to be increased, amongst others, by applying mineral fertilizers and manure.

Kenya rapidly increased its fertilizer consumption during the past two decades, particularly of nitrogen (Fig. 1), and is well above the African average. Fertilizer in Kenya is sold at subsidized prices and its distribution is largely organized through the Kenya Grain Growers Cooperative Union, with branches in most district headquarters. The Ministry of Agriculture, through its Department of Extension, has qualified technical field staff, who visit the farmers to encourage the use of fertilizers and manure. Contacts in the field being so intense, it would be a waste of scarce resources to continue to apply mineral fertilizers haphazardly. The importance of organic manure in maintaining soil fertility and increasing crop yields is evident. Soils benefit from its relatively lasting effects, as it is both a source of nutrients and a soil-physical amendment increasing water storage (Sanchez, 1976; Van Faassen and Smilde, 1985).

Kenya's agricultural land stretches from sea level to altitudes of over 2500 m, with an intricate pattern of climates, soils and cropping systems (Sombroek et al., 1982; Jaetzold and Schmidt, 1982/83). For the present study, the arable land was classified into so called Agro-Ecological Units (AEU), characterized by a specific set of biophysical conditions, and delimited after a profound scrutiny of all the available maps and associated data sets of Kenya, regarding climate, landforms, geology, and soils (Smaling and Van de Weg, 1990). Based on these AEU, 70 fertilizer trials were established in which the response of annual crops to nitrogen, phosphorus and farmyard manure was tested. The results obtained are used as a basis for fertilizer recommendations within the entire AEU. In this article, we present and evaluate the results of 4 years (1987–1990) of fertilizer and manure application to maize at trial sites in three different AEU.

MATERIALS AND METHODS

Study areas

The selected sites are in Kiamokama (Humic Nitisols; FAO, 1988b) in the Kisii Highlands at an altitude of 2020 m, Homa Bay (Haplic Phaeozems), on the shores of Lake Victoria, at 1160 m, and Shimba Hills (Haplic Alisols), 30 km from the coast, at 130 m. Basic data on soils, climate, and crop varieties of the three sites are listed in Table 1. In spite of the differences in altitude, all the sites are in maize-growing environments, but farmers use different hybrids and composites.

Unfertilized soils in Kiamokama are clayey with a high N content, but acid and low in available P, as this element is strongly retained by the soil's fresh volcanic constituents. Homa Bay has heavy clay soils, with moderate N and high P and K contents, and Shimba Hills has sandy loam soils with very low N, P, and K contents. Sites and surroundings have been described in more detail by Wielemaker and Boxem (1982), Michieka et al. (1986), and the Fertilizer Use Recommendation Project (1987).

All the sites are in areas with a bimodal rainfall pattern. The short rainy season (August–December) is unreliable and feeble in Homa Bay and Shimba

inadequate

TABLE 1

Characteristics of the three trial sites (soil data refer to the upper 20 cm only)

Site (and district)	Altitude (m)	Mean temp. (°C)	Mean rainfall (mm year^{-1})	66% Probability		Org. C (g kg^{-1})	N total (g kg^{-1})	P-Olsen (mg kg^{-1})	Exch. K (mmol kg^{-1})	pH (H_2O)	Sand (%)	Silt (%)	Clay (%)	Dry bulk density (g cm^{-3})	Maize variety	Emergence to maturity (d)
				First rains	Second rains											
Kiamokama (Kisii) 34°53′E; 0°48′S	2020	19.2	1491	800	430	27.0	2.6	2.3	5.5	5.2	25	32	43	0.9	H 614/625	165–180
Homa Bay (S. Nyanza) 34°29′E; 0°32′S	1190	22.5	1222	500	280	27.3	2.0	9.7	14.2	7.9	25	10	65	1.0	H 512	105–125
Shimba Hills (Kwale) 39°23′E; 4°21′S	130	25.7	1301	700	150	6.5	0.4	0.5	1.6	6.0	76	14	10	1.5	Coast Comp.	95–115

TABLE 2

Measured rainfall (mm) at the three sites between emergence and physiological maturity in 1987, 1988, 1989, and 1990

Trial site	1987	1988	1989	1990
Kiamokama	811	1137	828	1176
Homa Bay	629	820	586	647
Shimba Hills	753	524	746	346

Hills, as is indicated by the seasonal totals that are exceeded in 20 out of 30 years (Table 1). In this article, only yields obtained during the long rainy season (February–July) are considered. Rainfall recorded at the sites between emergence and physiological maturity of the maize crops is given in Table 2. In 1988, a year with excessive rainfall in most parts of western and central Kenya, 912 mm came down in Kiamokama during the first half of the growing period, and 757 mm in Homa Bay, resulting in spells of poor aeration, low soil temperatures, and slow initial growth in Kiamokama, and considerable surface runoff and erosion in Homa Bay. In Shimba Hills, 1987 had a wet start (600 mm in May), but there was a yield-depressing moisture deficit during the reproductive stage. Through the seasons, the average rate of dry-matter accumulation and the length of the growing period, which are mainly dependent on the level of solar radiation and temperature conditions, differed somewhat (±10%) for Kiamokama, but not for Homa Bay and Shimba Hills. For the individual seasons included in this study, no absolute rainfall deficits were observed. Weather-related yield depressions were caused by unfavourably distributed rains and associated features such as runoff, leaching, and temporary moisture excess or deficit.

Trial design

Researcher-managed factorial maize trials were laid out in a randomized complete block design (two replications) at a spacing of 0.75 m × 0.60 m, two plants per hole after thinning, with a harvest area of 21.6 m^2. Husbandry practices were the same at the three sites, including application of pesticides against African maize stalkborer (*Buseola fusca* fuller), and returning crop residues. The crop was subjected to four levels of nitrogen: 0, 25, 50 and 75 kg ha^{-1} (single topdressing of calcium ammonium nitrate (CAN)), and four levels of phosphorus: 0, 11, 22, and 33 kg ha^{-1} (at planting as triple super phosphate (TSP)). In a second experiment, maize received 5 t of farmyard manure (FYM) ha^{-1}.

Methods of evaluation

Yield data from the factorial trials were grouped according to seven aggregated treatments (TMT), coded as follows.

TMT 1: control (zero fertilizer)
TMT 2: N-0 (mean of N-0 P-0, N-0 P-11, N-0 P-22, N-0 P-33)
TMT 3: N-1 (mean of N-50 P-0, N-50 P-11, N-50 P-22, N-50 P-33)
TMT 4: P-0 (mean of N-0 P-0, N-25 P-0, N-50 P-0, N-75 P-0)
TMT 5: P-1 (mean of N-0 P-22, N-25 P-22, N-50 P-22, N-75 P-22)
TMT 6: FYM-1 NP-0 (only farmyard manure)
TMT 7a (Kiamokama): FYM-1 N-0 P-1 (farmyard manure + P-22)
TMT 7b (Homa Bay): FYM-1 N-1 P-0 (farmyard manure + N-50)
TMT 7c (Shimba Hills): FYM-1 N-1 P-1 (farmyard manure + N-50 + P-22).

Analysis of variance of the entire factorial experiment was used to determine significance as to treatment effects at the three sites. The profitability of the use of fertilizer and manure was determined by evaluating the farmer's net return to fertilizer and the value/cost ratio (v/c). The latter was determined by the yield increment per unit fertilizer, prices of fertilizer, and the price of the crop. The calculations in the present study are based on 1990 prices, i.e. Sh. 30 kg^{-1} N, Sh. 50 kg^{-1} P, Sh. 0.25 kg^{-1} FYM and Sh. 2.50 kg^{-1} maize. (US\$ 1 = Sh. 30).

RESULTS

Agronomic analysis

Grain yields of maize (at 12.5% moisture) are shown in Table 3. During the 4 years of experimentation, the Nitisol (Kiamokama) gave unfertilized maize yields (TMT 1) of 2.1–3.8 t ha^{-1} (excluding 1988 because of excessive wetness). Applying 16.5 kg P ha^{-1} (TMT 2), increased yields to 3.8–5.3 t ha^{-1}, and with only manure (TMT 6), 4.5–5.7 t ha^{-1} were harvested. A combination of manure and P (TMT 7) gave the highest yields, 5.6–5.9 t ha^{-1}.

The Phaeozem (Homa Bay) gave unfertilized yields of 3.0–3.6 t ha^{-1} and in 1990 4.6 t ha^{-1}. Here it was an N application of 37.5 kg ha^{-1} (TMT 4) that increased yields to 4.5–6.5 t ha^{-1}. High yields were realized when N was combined with manure (TMT 7), giving 5.3–7.0 t ha^{-1}.

Unfertilized maize yields on the sandy Alisols (Shimba Hills) ranged between 1.3 and 2.1 t ha^{-1}. Applying both N and P (TMT 5) was needed to raise yields to 2.3–3.3 t ha^{-1}. Applying manure as well (TMT 7) brought yields to higher levels of 3.8–4.2 t ha^{-1} in 3 out of 4 years.

Analysis of variance of the entire factorial experiment revealed significant treatment effects at all the sites. The response of maize differed largely between sites, as shown in Table 4. The maize in Kiamokama responded vigor-

TABLE 3

Yields (t ha^{-1}) of maize grain (12.5% moisture) at the three sites at different fertilizer treatment levels

Site	TMT	1987	1988	1989	1990
Kiamokama	1	2.3	1.2	3.8	2.1
	2	3.8	1.6	5.3	4.2
	3	4.2	1.9	5.6	4.3
	4	2.4	1.0	3.6	2.1
	5	4.7	1.8	6.6	4.9
	6	4.5	1.7	5.5	5.7
	7a	5.6	2.0	5.8	5.9
	Mean	3.9	1.6	5.2	4.2
Homa Bay	1	3.2	3.0	3.6	4.6
	2	3.9	3.0	3.9	4.8
	3	6.3	5.4	6.9	7.1
	4	5.1	4.5	5.8	6.5
	5	5.9	4.8	6.5	6.4
	6	5.9	3.7	5.8	6.6
	7b	6.6	5.3	6.9	7.0
	Mean	5.3	4.2	5.6	6.1
Shimba Hills	1	1.6	2.1	1.3	1.3
	2	1.8	2.8	1.8	2.2
	3	2.1	3.1	2.5	2.9
	4	1.3	2.4	1.5	1.4
	5	2.3	3.3	2.6	3.2
	6	1.2	1.7	1.6	1.4
	7c	2.4	3.8	3.9	4.2
	Mean	1.8	2.7	2.2	2.4

ously to P and manure, with even a significant interaction. The P-effect can probably be attributed to the high P-fixing amorphous oxide content of the soils. In Homa Bay it was solely N that significantly limited yields. Although TMT 6 gave considerable yield increases, the overall response to treatments including manure in the factorial trial was not significant in 1987–1989. Maize grown on the Alisol showed a response to both N and P and also, to a lesser extent, to manure.

Manure was particularly effective in the phosphorus-fixing soils of Kiamokama. On mineralization, the manure probably acts as a relatively slow-release phosphorus fertilizer. In Homa Bay and Shimba Hills, FYM became significant with time.

Economic analysis

As the essence of this text lies in the agro-ecological concept, the following economic evaluation follows the discrete path adhered to in the previous section, not aiming at the calculation of nutritional and economic optima.

TABLE 4

Significant treatment effects and their interactions in analysis of variance for N, P and manure (FYM)

Site	Year	N	P	N·P	FYM	N·FYM	P·FYM
Kiamokama	1987	ns	***	ns	***	*	ns
	1988	*	***	ns	***	*	**
	1989	**	***	*	**	ns	***
	1990	ns	***	ns	***	ns	***
Homa Bay	1987	***	ns	ns	ns	ns	*
	1988	***	ns	ns	ns	ns	ns
	1989	***	ns	ns	ns	ns	ns
	1990	***	ns	ns	**	ns	ns
Shimba Hills	1987	*	***	ns	ns	ns	ns
	1988	*	**	ns	ns	ns	ns
	1989	***	***	**	**	ns	ns
	1990	***	***	*	*	ns	ns

ns = not significant, *, significance at 5%, **, significance at 1%, ***, significance at 0.1%.

Table 5 shows the net return to fertilizer and value/cost ratios for the different treatments. The following results refer to revenues obtained in 3 out of the 4 years of experimentation (75% probability). The Kiamokama farmer gets a net return to fertilizer of approximately Sh. 3000 when applying P according to TMT 2, or only manure (TMT 6). Given the investment, applying only P gives a high value/cost ratio of 4.5. In the case of manure, this value is at least 3.4.

The Homa Bay farmer has a net return of Sh. 3625 when N is applied according to TMT 4. The fertilizer investment needed is Sh. 1125, resulting in a value/cost of at least 4.2. Applying only manure (TMT 6), gives the farmer a profit of Sh. 3750, at the also attractive value/cost ratio of 4.0.

The Shimba Hills farmer earns Sh. 775 from fertilizer when applying N and P according to TMT 5. The annual investment being as much as Sh. 2225, a value/cost ratio of only 1.3 is realized. The cheaper option of applying P only (TMT 2) leaves the farmer with a revenue of Sh. 425, and a slightly higher v/c of 1.5 in 3 out of 4 years.

In all cases, high input-TMT 7 seems too expensive, given the present price ratios. In good years, net returns of Sh. 3000–7000 were realized on the three sites, but on the basis of 75% probability, value/cost ratios did not exceed 2.2, whereas net returns were always lower than those obtained with lower-input treatments.

TABLE 5

Investment (Sh.), net return (Sh. ha^{-1}), and value/cost ratio at the three sites at different fertilizer treatment levels

Site	TMT	Investment	Net return to fertilizer				Value/cost ratio			
			1987	1988	1989	1990	1987	1988	1989	1990
Kiamokama	1	0	0	0	0	0				
	2	825	2925	175	2925	4425	4.5	1.2	4.5	6.4
	3	2325	2425	−575	2175	3175	2.0	0.8	1.9	2.4
	4	1125	−875	−1625	−1625	−1125	0.2	−0.4	−0.4	0.0
	5	2225	3775	−725	4775	4775	2.7	0.7	3.1	3.1
	6	1250	4250	0	3000	7750	4.4	1.0	3.4	7.2
	7a	2350	5900	−350	2650	7150	3.5	0.9	2.1	4.0
Homa Bay	1	0	0	0	0	0				
	2	825	925	−825	−75	−325	2.1	0.0	0.9	0.6
	3	2325	5425	3675	5925	3925	3.3	2.6	3.5	2.7
	4	1125	3625	2625	4375	3625	4.2	3.3	4.9	4.2
	5	2225	4525	2275	5025	2275	3.0	2.0	3.3	2.0
	6	1250	5500	500	4250	3750	5.4	1.4	4.4	4.0
	7b	2750	5750	3000	5500	3250	3.1	2.1	3.0	2.2
Shimba Hills	1	0	0	0	0	0				
	2	825	−325	925	425	1425	0.6	2.1	1.5	2.7
	3	2325	−1075	175	675	1675	0.5	1.1	1.3	1.7
	4	1125	−1875	−375	−625	−875	−0.7	0.7	0.4	0.2
	5	2225	−475	775	1025	2525	0.8	1.3	1.5	2.1
	6	1250	−2250	−2250	−500	−1000	−0.8	−0.8	0.6	0.2
	7c	3850	−1850	400	2650	3400	0.5	1.1	1.7	1.9

DISCUSSION

Agro-economic considerations

An important assumption in the economic analysis was that the cost of (family) labour was fixed at zero, assuming the farmer would have no other opportunity to generate income during the time spent on applying fertilizers and manure. This may be doubtful in the case of Kiamokama, where most farmers also have tea or pyrethrum to attend to. The cost of hybrid seeds and insecticides were not included either. Consequently, the real net profit for the farmer will be below the ones following from this study, and a value/cost ratio of at least three may be needed to make smallholders invest in fertilizers.

The prices used in this paper were valid for 1990, and the ratio between maize price and input prices was approximately equal in the other years. It is obvious that changing price policies, such as, for example, lifting subsidies, will have a tremendous impact on the readiness of farmers to buy inputs.

In the economic analysis, it is further assumed that farmers have to buy manure. Although 5 t ha^{-1} exceeds what most farmers have available, it should be reckoned considered with that they can supply at least 1 t ha^{-1} from their own farmyard. Still, there is much scope for stepping up the use of different sorts of household waste, or even urban and industrial refuse. Next, many Kenyan farmers opt for applying multi-nutrient fertilizers, as this saves labour. Diammonium-phosphate (DAP; 18% N, 20% P) is particularly popular, but as it is a strongly acidifying fertilizer, continuous application is detrimental to soil fertility.

Translating the results to practice

Table 5 shows that in Kiamokama, the recommendation '16.5 kg P ha^{-1}' (TMT 2) seems appropriate for smallholders. To become meaningful to extension staff and farmers, it should be translated into bags per acre, and be used in the entire AEU that is represented by the trial site, as depicted by Smaling and Van de Weg (1990). Treatment 2 can also be read as TSP-82.6. As TSP is sold in bags of 50 kg, the proper recommendation for the smallholder investing only at a high value/cost ratio, is 82.6/50 bags ha^{-1}, which is approximately three-quarters of a bag of TSP for one acre.

Recommendations on a district scale are constrained by the spatial variability of soil properties which is often high, even within a single field. Around farmhouses, fertility is generally higher than further away from the homestead. Also, there is the influence of extraneous factors such as spotty waterlogging or infestation of Striga weed (Smaling et al., 1991). Extension staff should therefore use the AEU-specific fertilizer recommendation as a general yardstick, which takes no account of farm-scale heterogeneity. Also to be considered is the fact that various farm types occur within the same AEU, and the profitability and applicability of fertilizer recommendations depends a lot on capital and labour resources at the farm. A stratification of farms based on yield level, and farm size and income within each AEU would be most useful.

Application of fertilizers should not be recommended as a sole practice. In order to sustain the nutrient base, one should also call for measures that combat the loss of nutrients. Such an integrated package of recommendations should include: (1) application of modest amounts of the proper type of fertilizer, complying with recommendations that are specific for both crop and agro-ecological zone; (2) efficient use of animal manure and household waste; (3) adopting more nitrogen-fixing species in cropping systems; (4) grazing of crop residues on the field, leaving residues as mulch or ploughing them into the soil; (5) properly-timed, if needed split application of mineral fertilizers to combat leaching; (6) appropriate tillage and soil conservation measures to combat erosion.

Starting, managing and evaluating fertilizer trials throughout the agricultural land of a country involves vast amounts of funds, manpower development, and organizational capacity. Simulations models can help to (1) fully exploit the data generated, and (2) search for functional relationships to predict crop yields. Articles are being prepared on the testing and calibration of the models WOFOST (Van Diepen et al., 1989) and QUEFTS (Janssen et al., 1990) for the different agro-ecological conditions and crop varieties. Climate data, soil physical factors and soil and plant analytical data constitute the building blocks of these models. When proving useful in predicting yields, a next fertilizer research effort in a tropical country does not need to be as comprehensive as the one in Kenya.

REFERENCES

Fertilizer Use Recommendation Project (FURP), 1987. Final Report. Description of First Priority Trial Sites in the Various Districts. Vol. 1. Kisii District; Vol. 2. South Nyanza District; Vol. 31. Kwale District. National Agricultural Research Laboratories, Nairobi, Kenya.

Food and Agriculture Organization (FAO), 1983. Maximizing fertilizer use efficiency. Fertilizer and Plant Nutrition Bulletin 6, FAO. Rome.

Food and Agriculture Organization (FAO), 1988a. Fertilizer yearbook 1987, Vol. 37, FAO, Rome.

Food and Agriculture Organization (FAO), 1988b. FAO-Unesco Soil map of the world: revised legend. World Soil Resources Report 60, FAO, Rome.

Jaetzold, R. and Schmidt, H., 1982/83. Farm management handbook of Kenya. Volume II: Natural conditions and farm management information. Ministry of Agriculture, Kenya.

Janssen, B.H., Guiking, F.C.T., van der Eijk, D., Smaling, E.M.A., Wolf, J. and van Reuler, H., 1990. A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma, 46: 299–318.

Michieka, D.O., van der Pouw, B.J.A. and Vleeshouwer, J.J., 1986. Soils of the Kwale-Mombasa-Lunga Lunga area. Reconn. Rep. R3, Kenya Soil Survey, Nairobi, 300 pp.

Mudahar, M.S., 1986. Fertilizer problems and policies in sub-Saharan Africa. In: A.U. Mokwunye and P.L.G. Vlek (Editors), Management of Nitrogen and Phosphorus Fertilizers in Sub-Saharan Africa, Martinus Nijhoff, Dordrecht, pp. 1–32.

Sanchez, P.A., 1976. Properties and Management of Soils in the Tropics. Wiley, New York, 618 pp.

Smaling, E.M.A. and van de Weg, R.F., 1990. Using soil and climate maps and associated data sets to select sites for fertilizer trials in Kenya. Agric. Ecosystems Environ., 31: 263–274.

Smaling, E.M.A., Stein, A. and Sloot, P.H.M., 1991. A statistical analysis of the influence of Striga hermonthica on maize yields in fertilizer trials in South-western Kenya. Plant and Soil, 138: 1–8.

Sombroek, W.G., Braun, H.M.H. and van der Pouw, B.J.A., 1982. Exploratory Soil Map and Agro-climatic Zones Map of Kenya, scale 1 : 1 000 000. Report E1, Kenya Soil Survey, Nairobi, 56 pp.

Ssali, H., Ahn, P.M. and Mokwunye, A., 1986. Fertility of soils of tropical Africa: a historical perspective. In: A.U. Mokwunye and P.L.G. Vlek (Editors), Management of Nitrogen and Phosphorus Fertilizers in Sub-Saharan Africa, Martinus Nijhoff, Dordrecht, pp. 59–82.

Van Diepen, C.A., Wolf, J., van Keulen, H. and Rappoldt, C., 1989. WOFOST: a simulation model of crop production. Soil Use Manage., 5(1): 16–24.

Van Faassen, H.G. and Smilde, K.W., 1985. Organic matter and nitrogen turnover in soils. In:

B.T. Kang and J. van der Heide (Editors), Nitrogen Management in Farming Systems in Humid and Subhumid Tropics. IITA, Ibadan, Nigeria; IB, Haren, Netherlands, pp. 39–55.

Vlek, P.L.G., 1990. The role of fertilizers in sustaining agriculture in sub-Saharan Africa. Fert. Res., 26: 327–339.

Wielemaker, W.G. and Boxem, H.W., 1982. Soils of the Kisii area, Kenya. Agric. Research Rep. 922, Centre for Publication and Documentation (PUDOC), Wageningen, Reconn. Rep. R4, Kenya Soil Survey, Nairobi, 208 pp.

PART IV FIELD-SCALE HETEROGENEITY

8. Bypass flow and leaching of nitrogen in a Kenyan Vertisol at the onset of the growing season

9. A statistical analysis of the influence of *Striga hermonthica* on maize yields in fertilizer trials in Southwestern Kenya

Chapter 8

Bypass flow and leaching of nitrogen in a Kenyan Vertisol at the onset of the growing season

Published in: Soil Use and Management 8 (1992): 44-48

Bypass flow and leaching of nitrogen in a Kenyan Vertisol at the onset of the growing season

E. M. A. Smaling[1] & J. Bouma[2]

Abstract. Bypass flow and concurrent leaching of nitrogen were studied on a Vertisol in south-western Kenya under rangeland and bare, manually tilled cropland. Showers of 30 mm/hr were simulated, causing bypass flow of 47–62% in rangeland topsoils and 19–49% in cropland topsoils. Volumetric water contents after experimentation increased from 28 to 35% and from 24 to 38%, respectively, for the two land-use types.

In rangeland samples up to 3.4 kg N/ha was found in the leachate of unfertilized soil. With a fertilizer application of 50 kg N/ha, up to 5.7 kg N/ha was lost from a pre-wetted soil, and more than 20 kg N/ha from dry soil. In cropland topsoils up to 2.2 kg N/ha was lost from unfertilized soil, and only up to 2.9 kg N/ha from both dry and prewetted fertilized soil. Although Vertisols are often linked with excess water, the phenomenon of bypass flow can cause water stress to crops in their early growth stages. Nitrogen leaching losses were large from dry grassland, but prewetting helped to decrease them. On intensively cultivated cropland there was little nitrogen leaching; the tilled topsoil was able to retain most of the supplied nitrogen.

INTRODUCTION

THE AVAILABILITY of water plays a pivotal role in the evaluation of land for agricultural purposes. It can be determined by calculating the fluxes of water which enter and leave the rooted volume of soil (Bouma, 1984). In soils with continuous macropores, such as cracking clays, water availability is a dynamic land quality. Swelling and shrinking alternate through the seasons, causing constantly changing pore size distributions and pore-continuity patterns (White, 1985; Bouma & Loveday, 1988; Bronswijk & Evers-Vermeer, 1990). At the onset of the growing season, when soils are relatively dry, rainwater partly infiltrates along the vertically continuous cracks and macropores. As this water bypasses an unsaturated soil matrix, the process has become known as 'bypass flow' or 'short-circuiting' (Bouma *et al.*, 1981). Figure 1 shows a schematic representation of the different types of water flow in the root zone of a dry, cracked clay.

As a result of a build-up of inorganic nitrogen during the preceding dry months and a flush of nitrogen mineralization in the topsoil at the start of the rains, the bypassing water contains soil-derived nitrogen (Birch, 1958; Sanchez, 1976); mineralized nitrogen must first diffuse from within the aggregates towards the larger channels (Wild, 1972). Fertilizer nitrogen applied at planting may be leached quickly when washed into draining macropores. When fertilizer is applied as a topdressing several weeks after

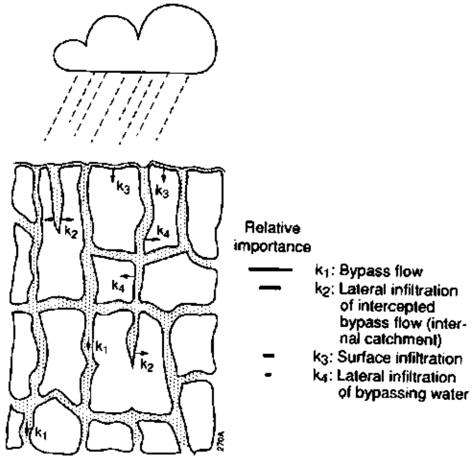


Fig 1. Schematic representation of water flow in the root zone of a dry, cracked clay. k_1: bypass flow, leaving the root zone, k_2: lateral infiltration from bypass flow, caught inside discontinuous cracks within the root zone (internal catchment), k_3: surface infiltration into aggregates, k_4: lateral infiltration of bypassing water that is in contact with the pore walls.

---

[1] DLO The Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), PO Box 125, 6700 AC Wageningen, The Netherlands.

[2] Wageningen Agricultural University, Department of Soil Science and Geology, PO Box 37, 6700 AA Wageningen, The Netherlands.

planting, the chances of nitrogen being intercepted by the crop are greater as roots have started to develop.

Bypass flow and concurrent nitrogen fertilizer leaching were studied in Dutch pastures on cracking, riverine Fluvisols (Bouma *et al.*, 1981; Dekker & Bouma, 1984). These processes have hardly been studied in tropical environments, although there are large areas of cracking clays, mostly classified as Vertisols (IBSRAM, 1989). In Kenya, there are 2.8 million hectares of Vertisols in areas that range from marginally to very productive, with average annual rainfall of 500–1200 mm; on these soils there are good crop responses to fertilizer nitrogen (Ikitoo, 1989).

This paper describes the amount and spatial variability of bypass flow and leaching of nitrogen in a Kenyan Vertisol at the onset of the major rainy season. It is part of an attempt to formulate fertilizer recommendations for annual crops in Kenya that are based on agro-ecological concepts (Smaling & Van de Weg, 1990).

MATERIALS AND METHODS

Study area

The study area was one hectare of flat land near Rodi Kopany, south-western Kenya (0°35′S, 34°30′E). The soils are developed on Tertiary alkali basalts (Wielemaker & Boxem, 1982); the 0–20 cm layer has 54% clay, 2.4% organic carbon, and a pH of 6.2. Between 20 and 50 cm depth, the clay content is 67%. Rotten basaltic rock predominates below a depth of 70 cm. Groundwater was absent within 100 cm. The soils are classified as Eutric Vertisols (Food and Agriculture Organization, 1988) or Typic Pelluderts (Soil Survey Staff, 1975). The rainfall distribution pattern is bimodal with, in 20 out of 30 years, 820 mm between early March and late July and 550 mm between late August and early January. Experiments were conducted in rangeland under perennial grasses and in the adjacent bare cropland manually tilled to a depth of 10–15 cm. Fifteen profiles were sampled: three in rangeland and 12 in cropland. At the end of the growing season, it was observed that the roots of maize in the cropland did not reach deeper than 40 cm. The roots of the perennial grasses, however, followed ped surfaces to 60 cm and below.

Soil morphology

The soils of the rangeland had a strong, angular blocky structure in the topsoil with thin continuous cracks, the aggregates tightly kept together by coarse roots, typical of tropical perennial grasses. The subsoil had coarse prisms, 8–15 cm wide, separated by vertical cracks 0.5–2 cm wide. In the cropland topsoils intensive tillage destroyed macropores but increased total porosity. Below the depth of tillage, the soil had a coarse prismatic structure with slickensides. Vertical cracks were 0.5–1.5 cm wide and continuous to a depth of 60–80 cm.

Bypass flow

Experiments were in late February, at the onset of the rainy season. Showers of 20 and 30 mm were simulated at intensities of 20 and 30 mm/hr. Daily rainfall totals at the site revealed that the applied amounts were exceeded 8–20 times (20 mm) and 4–8 times (30 mm) in the period 1987–89. The intensities were chosen after consulting the Rainfall Frequency Atlas of Kenya, which shows an hourly rainfall intensity in the area of 55–65 mm/hr once in 5 years. In total, there were four groups of samples (Table 1, Part I): (A) 12 rangeland topsoils, receiving 30 mm on day 1, and

Table 1. Summary of experimental data on bypass flow and nitrogen leaching

		I Water application at Day no.			II Bypass flow upon application				III Water content		IV Water content (vol%) at pressure head		V Nitrogen leaching‡ (kg/ha)		
					1		2								
Sample	n†	1	2	3	mm	%	mm	%	before appl. 1 (vol%)	after appl. 2 (vol%)	−100 cm	−500 cm	N_0	N_1	N_2
A*	12	30	—	30	14.2 ±5.3	47	18.6 ±2.1	62	28	35	n/d	n/d	1.4–3.4	21–60	1.9–5.7
B	24	30	—	30	5.7 ±2.4	19	14.6 ±2.4	49	24	38	n/d	n/d	1.6–2.2	1.3–1.8§	1.6–2.9
C	16	20	20	—	1.5 ±1.6	7	8.7 ±2.6	44	22	35	68	38	0.8–1.0§	0.9–1.6§	n/d
D	8	20	20	—	11.2 ±1.8	56	14.4 ±1.0	72	38	43	55	51	n/d	n/d	n/d

*A = rangeland, topsoil; B = cropland, topsoil; C = cropland, topsoil; D = cropland, subsoil.

†n = number of cylinders tested.

‡N_0 = no fertilizer applied.

N_1 = 50 kg N/ha applied immediately **before** first water application.

N_2 = 50 kg N/ha applied immediately **after** first water application.

§Leaching load found at low bypass flow (< 10 mm); other values at bypass flow of 10–20 mm; n/d = not determined.

again 30 mm on day 3, (B) 24 cropland topsoils, treated like A, (C) 16 cropland topsoils, receiving 20 mm on day 1, and again 20 mm on day 2, (D) eight cropland subsoils, treated like C.

Bypass flow was measured largely according to the field technique of Bouma *et al.* (1981). Four undisturbed samples were excavated from each profile and placed side by side (Fig. 2). PVC cylinders, 25 cm long and 20 cm in diameter, were used. They were sharpened at the bottom and greased prior to sampling to avoid edge-flow along the walls. This method was shown to be effective by checking the fate of a staining agent applied during experimentation. The recent method of Cameron *et al.* (1990), who successfully prevented edge-flow with a watertight seal between soil and casing, however, deserves future consideration. In the filled cylinder, the original soil surface was approximately 5 cm below the upper rim. Grass in the rangeland samples was left in place.

Fig. 2. Excavated soil columns (4 replicates) ready for testing.

Water was gently sprinkled from a measuring cylinder through a fine-meshed sieve held approximately 25 cm above the cylinders. Every 5 min one full minute was spent applying 1/12 of the total volume. The water leaving the base of the column was led through a funnel into measuring flasks, and was recorded every 5 min. Between the showers on Day 1 and Days 2 or 3, the cylinders were left to evapotranspire. The area has a potential evaporation in February of 6 mm/day (Jaetzold & Schmidt, 1982). The mass of the soil-filled cylinder was determined before and after experimentation. The oven-dry mass was measured at the end, allowing calculation of bulk density and volumetric water content. Also, on samples C and D, water content at pressure heads of −100 and −500 cm was determined. Methyl red was applied as a staining agent to the columns to allow recognition of water-conducting macropores (Bouma & Dekker, 1978).

Nitrogen leaching
Of the 60 cylinders, 32 received no fertilizer (N_0). Sixteen cylinders received the equivalent of 50 kg N/ha, applied as calcium ammonium nitrate, just **before** the first shower (N_1). Twelve cylinders received 50 kg N/ha just **after** the first shower and were sprinkled again on day 2 or 3 (N_2). Treatment N_1 implied immediate subjection of the fertilizer to leaching, whereas N_2 allowed the fertilizer to be adsorbed on soil particles or taken up by grass roots prior to the second shower. As different forms of nitrogen may have been displaced, the leachate was analysed for total nitrogen by a semi-micro Kjeldahl procedure (Bremner & Mulvaney, 1982).

RESULTS

Physical measurements
Table 1 (Part II) shows that, on applying 30 mm, bypass flow in rangeland topsoils (A) was 14.2 mm on Day 1 and 18.6 mm on Day 3. The same amount applied to cropland topsoils (B) gave bypass flow of 5.7 mm on Day 1 and 14.6 mm on Day 3. Cropland topsoils receiving 20 mm (C) yielded 1.5 mm of bypass flow on Day 1 and 8.7 mm on Day 2. Cropland subsoils receiving 20 mm (D) had 11.2 mm on Day 1 followed by 14.4 mm on Day 2.

Volumetric water content of the topsoils at the start of the experiment was 28% (rangeland) and 22–24% (cropland), whereas the final water content was 35% (rangeland) and 35–38% (cropland). In the subsoils these values were 38% before and 43% after experimentation (Table 1, Part III). According to conventional flow theory, water can only leave the columns after saturation has been reached at the base of the column. The top of the column should then have a pressure head of −20 cm. When comparing Parts III and IV of Table 1, however, it seems that the volumetric water contents after experimentation still fall short of those corresponding to a pressure head of −500 cm. Anisotropy of the cracking clays was also indicated by the staining test, showing a marked decrease from 60% red surface at a soil depth of 20 cm to about 20% red surface at a depth of 40 cm. At this depth, one or two continuous macropores were entirely responsible for the drainage in the cylinder.

Nitrogen leaching
Table 1 (Part V) shows how much nitrogen was leached. In the rangeland samples (A) up to 3.4 kg N/ha was lost from unfertilized soil (N_0), and up to 5.7 kg N/ha from fertilized, moist soil (N_2). From dry soil (N_1), however, not less than 21–60 kg N/ha was lost.

Losses from the cropland samples were very different, and differences between treatments were small: up to 2.2 kg N/ha from unfertilized soil, up to 1.8 kg N/ha after treatment N_1 (bypass flow < 10 mm) and up to 2.8 kg/ha after treatment N_2 (bypass flow 10–20 mm). As bypass flow in the C-samples was small (< 8 mm), there was also little N leaching: up to 1 kg N/ha in unfertilized plots, and up to 1.5 kg N/ha after treatment N_1.

DISCUSSION AND CONCLUSIONS

In The Netherlands, Bouma *et al.* (1981) recorded 36–47% bypass flow for dry clay soils under grass at input rates of 17–25 mm/hr. They measured final water contents of 30–40% by volume, whereas saturation coincided with 46%. Dekker & Bouma (1984) found final water contents of 38–50%, whereas saturation was reached only at 55%. In the present study, we found 47% bypass flow at an application rate of 30 mm/hr in dry Vertisols under grass. On the final water content, conclusions were similar to those of the studies in The Netherlands, namely that water left the columns long before the soil was saturated.

In the Vertisols, tillage largely disrupted crack continuity in the topsoils. Consequently bypass flow in the tilled topsoils (samples B) was much less than in the rangeland topsoils receiving the same amount of water (samples A), particularly during the first application. This was partly because of the greater initial water content of the rangeland samples, attributable to their strong coarse structure, with water tightly bound inside aggregates; however, water content after experimentation was less in these samples as the total pore volume in the cropland topsoils had been increased by tillage.

Cropland subsoils (samples D) allowed more bypass flow than corresponding topsoils (samples C), again indicating less absorption and a larger macropore continuity in the absence of tillage. Also the subsoils have a larger clay content, less organic matter and less biological activity than topsoils. The effect on bypass flow is evident when comparing the subsoil samples (D) with the non-tilled rangeland topsoils (A), which received larger amounts of water but showed less bypass flow.

Total bypass flow was not only greater in non-tilled samples A and D than in the tilled samples B and C, but also started earlier – 5–8 minutes after application as opposed to 35–45 min after application on Day 1, and 21–27 min after application on Days 2 and 3 in the tilled samples. Man-induced spatial variability can be detected from the standard deviations during the second applications, which are less for the non-tilled samples (7–11%) than for the tilled samples (16–30%). Manual tillage seems to have given each sample some 'random' pore size distribution, resulting in different responses even to the second water application.

Comparison of the tilled topsoils that received different amounts and rates of water (samples B and C) shows that bypass flow increased with increasing water application. Moreover, bypass flow during the second shower was greater in all samples than during the first shower. It apparently increased at greater water contents of the soil as long as cracks were vertically continuous, which is in agreement with Bouma & Loveday (1988).

The large leaching losses of nitrogen (more than 20 kg N/ha) found on dry grassland and the fact that prewetting helped to decrease these losses (up to 6 kg N/ha) agree with earlier findings (Dekker & Bouma, 1984). Apparently, cracks in between the dry strong, coarse aggregates were wide enough to prevent fertilizer from even partly diffusing into the soil. However, intensive tillage, twice prior to planting and once after harvesting to plough in crop residues, decreased nitrogen leaching from a freshly fertilized Vertisol to less than 3 kg N/ha. The tilled topsoil seems able to retain the supplied nitrogen, probably in the smaller and discontinuous pores and through surface infiltration of rapidly dissolving nitrogen (mechanisms k_2 and k_3 in Fig. 1).

This study shows that simple field techniques can enhance our understanding of water availability and nitrogen displacement in Vertisols used as rangeland and as cropland around planting time. Much of the rain water percolates as bypass flow and is thus not available to emerging crops and poorly available to grasses. However, losses of soil- and fertilizer-derived nitrogen are modest as long as the topsoil is carefully tilled. For the farmer and the ecosystem, this is good news, but the researcher waits for the rains to increase and the Vertisol to start swelling, because the next possible loss mechanism, i.e. denitrification, may be just around the corner.

ACKNOWLEDGEMENTS

We thank L. W. Dekker for his helpful comments on the manuscript, and E. M. Muya, B. G. Mwangi and S. Wataka of Kenya Soil Survey for assistance during the fieldwork.

REFERENCES

BIRCH, H.F. 1958. The effect of soil drying on humus decomposition and nitrogen availability. *Plant and Soil* **10**, 9–31.

BOUMA, J. 1984. Estimating moisture-related land qualities for land evaluation. In: *Land Use Planning Techniques and Policies. Proceedings of a Symposium at Atlanta, Georgia, 1981.* Soil Science Society of America, Madison, Wisconsin, pp. 61–76.

BOUMA, J. & DEKKER, L.W. 1978. A case study on infiltration into dry clay soil. 1. Morphological observations. *Geoderma* **20**, 27–40.

BOUMA, J., DEKKER, L.W. & MUILWIJK, C.J. 1981. A field method for measuring short-circuiting in clay soils. *Journal of Hydrology* **52**, 347–354.

BOUMA, J. & LOVEDAY, J. 1988. Characterizing soil water regimes in swelling clay soils. In: *Vertisols: their distribution, properties, classification and management* (eds L.P. Wilding & R. Puentes). Technical Monograph 18, Soil Management Support Services, Texas A&M University Printer, pp. 83–97.

BREMNER, J.M. & MULVANEY, C.S. 1982. Nitrogen-total. In: Methods of soil analysis. Part 2. 2nd ed. (ed. A.L. Page). *Agronomy* **9**, 595–624.

BRONSWIJK, J.J.B. & EVERS-VERMEER, J.J. 1990. Shrinkage of Dutch clay soil aggregates. *Netherlands Journal of Agricultural Science* **38**, 175–194.

CAMERON, K.C., HARRISON, D.F., SMITH, N.P. & MCLAY, C.D.A. 1990. A method to prevent edge-flow in undisturbed soil cores and lysimeters. *Australian Journal of Soil Research* **28**, 879–886.

DEKKER, L.W. & BOUMA, J. 1984. Nitrogen leaching during sprinkler irrigation of a Dutch clay soil. *Agricultural Water Management* **9**, 37–45.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, 1988. *FAO-UNESCO Soil map of the world: revised legend.* World Soil Resources Report 60. FAO, Rome.

IBSRAM, 1989. *Vertisol management in Africa.* International Board on Soil Research and Management Proceedings 9. Funny Publishing Limited Partnership, Bangkok.

IKITOO, E.C. 1989. Some properties of Vertisols in Kenya and their current level of management for crop production. In: *Vertisol Management in Africa.* International Board on Soil Research and Management Proceedings 9, Bangkok, pp. 193–208.

JAETZOLD, R. & SCHMIDT, H. 1982. *Farm management handbook of Kenya. Volume II: Natural conditions and farm management information. Part A: West Kenya.* Ministry of Agriculture, Nairobi, pp. 127–177.

SANCHEZ, P.A. 1976. *Properties and management of soils in the tropics.* John Wiley & Sons, New York.

SMALING, E.M.A. & VAN DE WEG, R.F. 1990. Using soil and climate maps and associated data sets to select sites for fertilizer trials in Kenya. *Agriculture, Ecosystems and Environment* 31, 263–274.

SOIL SURVEY STAFF, 1975. *Soil Taxonomy, a basic system of soil classification for making and interpreting soil surveys.* Agricultural Handbook 436. USDA, Washington DC.

WHITE, R.E. 1985. The influence of macropores on the transport of dissolved and suspended matter through soil. *Advances in Soil Science* 3, 95–121.

WIELEMAKER, W.G. & BOXEM, H.W. 1982. *Soils of the Kisii area, Kenya.* Agricultural Research Report 922. Centre for Publication and Documentation, Wageningen.

WILD, A. 1972. Nitrate leaching under bare fallow at a site in northern Nigeria. *Journal of Soil Science* 23, 315–324.

Chapter 9

A statistical analysis of the influence of *Striga hermonthica* on maize yields in fertilizer trials in southwestern Kenya

Published in: Plant and Soil 138 (1991): 1-8

A statistical analysis of the influence of *Striga hermonthica* on maize yields in fertilizer trials in Southwestern Kenya

E.M.A. SMALING, A. STEIN and P.H.M. SLOOT
DLO The Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO), P.O. Box 125, 6700 AC Wageningen, The Netherlands and Department of Soil Science and Geology, Wageningen Agricultural University, P.O. Box 37, 6700 AB Wageningen, The Netherlands

Received 20 August 1990. Revised May 1991

Key words: fertilizer trials, Kenya, maize, *Striga hermonthica*, sunflower

Abstract

The adverse effect of the parasitic weed *Striga hermonthica* on yield of maize was studied in a fertilizer trial in Southwestern Kenya. In two years of experimentation (1987 and 1988), the weed had a highly significant, negative impact on maize yields. The spotty incidence of Striga disturbed the fertilizer trials. Inclusion of the degree of Striga infestation in a regression model caused an increase in the fraction of experimental variation that could be explained by the model.

Several methods were tested to combat Striga. Hand-pulling reduced Striga incidence and increased grain yields during the following growing season. No clear effect was obtained from the trap crop sunflower, although such an effect may have been concealed by the success of hand-pulling. Application of mineral fertilizers or farmyard manure did not significantly reduce Striga infestation.

Introduction

In many African countries, maize, sorghum and millet are badly affected by the incidence of the parasitic weed *Striga hermonthica*. Between the roots of Striga and those of its host a connection is formed through which Striga extracts water and nutrients from the host xylem, leading to stunted growth of the host plant and symptoms resembling drought damage. Crop-loss data due to Striga vary from 10% yield reduction to total crop failure. In the soil, mature seeds of Striga may remain dormant between 6 months and 20 years (Doggett, 1988; Efron et al., 1989; FAO, 1989; Vasudeva Rao et al., 1989).

In fertilizer trials, it is essential that all other factors apart from the treatments be maintained uniformly for all experimental units (Gomez and Gomez, 1984). For the extraneous factor Striga infestation, it is impossible to meet this requirement. Striga emerges in a spotty, unpredictable pattern and it does most harm to the host prior to its own emergence. In Southwestern Kenya, Striga struck on a number of fertilizer trials. These trials are part of a national network in which annual crops are subjected to different rates of mineral and organic fertilizer (Smaling and Van de Weg, 1990). All sites around Lake Victoria, indicated in Figure 1, suffered from Striga.

The objectives of the present study were to statistically analyse the effect of Striga incidence on maize yields in the fertilizer trial near Oyugis (site 5, Fig. 1), and to test means to combat Striga, in particular hand-pulling, cultivation of a trap crop, and application of fertilizers and farmyard manure.

Timely hand-pulling before the weed flowers reportedly reduces Striga incidence (Doggett, 1988; FAO, 1989). Carson (1989) and Laycock

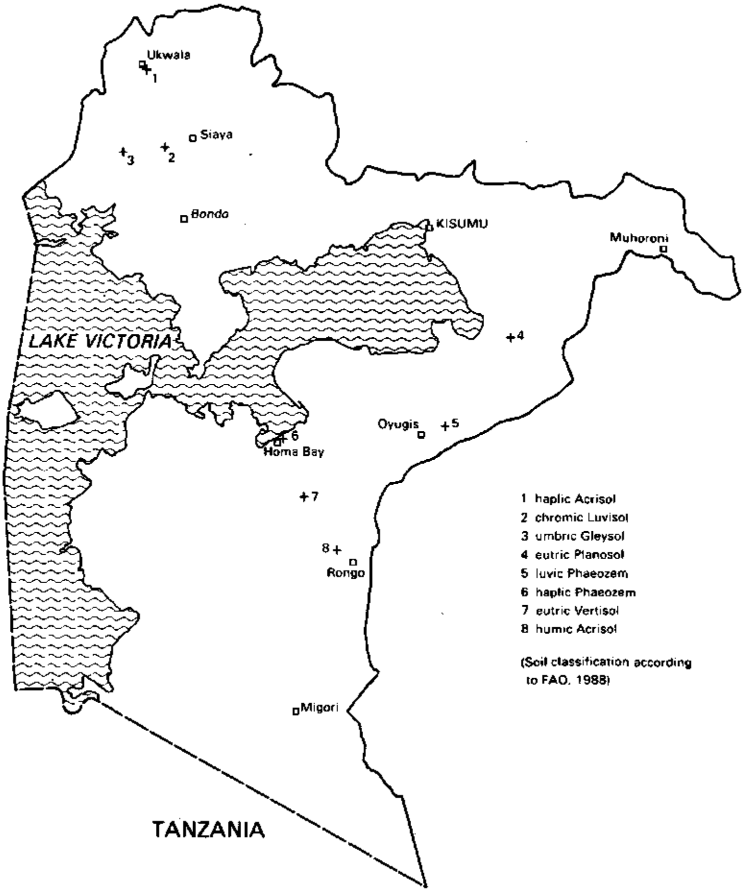


Fig. 1. Striga-infested trial sites, with different fertility levels, in Southwestern Kenya (scale 1:1 000 000).

(1989) reduced Striga infestation and increased yields of sorghum and millet through hand-pulling in The Gambia and Niger. Trap crops are false hosts. They produce exudates that lure Striga into germination, but are not parasitized. Consequently, Striga perishes soon after germination. The next crop grown on such a field will benefit, as shown by Parkinson et al. (1989). They planted soybean as a trap crop, resulting in a considerable reduction in Striga infestation in a following maize crop. Sunflower, a rather popular crop in West Kenya, is mentioned as a possible trap crop (Hosmani, 1978; Bebawi, 1987; Doggett, 1988). It was used in this study.

Yield losses due to Striga occur at all fertility levels (FAO, 1989; Vasudeva Rao et al., 1989). Also in Kenya, Striga is rampant on soils of different fertility levels (Fig. 1). Reports on the beneficial effects of nitrogen fertilizer are numerous (Agabawi and Younis, 1965; Bebawi, 1987; Bebawi and Farah, 1981; Last, 1961; Ogborn, 1984). Experiments often report high quantities of fertilizer needed to suppress Striga infestation and increase grain yields. This was confirmed by reports from Chad, Ghana, Mali and Niger (FAO, 1989; Laycock, 1989). On the other hand, Osman et al. (1991) found high Striga infestation at nitrogen levels up to 100 kg ha^{-1} (urea), but the host plants (sorghum) did not lose vigor. Calcium ammonium nitrate, the fertilizer used in the present study, is said to be effective in controlling Striga (Ogborn, 1987). Application of farmyard manure can help to combat Striga (Sudan Report, in FAO, 1989). It reduced Striga incidence in West Kenya (Watt, 1936), but West African experts warn against the risk of spreading Striga seeds by applying manure (FAO, 1989).

Materials and methods

Field methods

The research site, approx. 0,5 ha, was located near Oyugis (site 5, Fig. 1) on a farmer's field. Prior to experimentation, the land, tilled by hoe, was used for maize and cassava with occasional fallow seasons. The soils were well drained and had a rootable depth of 80–100 cm. The upper 20 cm has 56% clay, a dry bulk density of 1250 kg m^{-3} and an organic carbon content of 17 g kg^{-1}. The pH(H_2O) is 5.7, available P (Olsen's method) is 4 mg kg^{-1}, and exchangeable K is 9 mmol kg^{-1}. Soils are classified as luvic Phaeozems (FAO, 1988) or Typic Argiudolls (Soil Survey Staff, 1975). Rainfall during the period of experimentation (early March to early August) was 1088 mm in 1987 and 1564 mm in 1988, whereas the 66%-probability rainfall during this period is 920 mm only.

The area was subdivided into two so-called modules (Table 1). In Module 1 continuous maize was grown (hybrid 622, at a spacing of 0.75 m × 0.60 m, 2 plants per hill after thinning), and in Module 2 a maize/Phaseolus beans (var. GLP 2) intercrop was grown in the major growing season, and the trap crop sunflower during the short rainy season. The crops were subjected to two experiments. Experiment 1 is a 2^4 factorial with N applied at rates of 0 and 50 kg ha^{-1}, P at 0 and 22 kg ha^{-1}, S at 0 and 40 kg ha^{-1}, and farmyard manure at 0 and 5 t ha^{-1}. Experiment 2 is a refinement as regards the N and P effects on maize. It is a 4^2 factorial including four levels of N: 0, 25, 50 and 75 kg ha^{-1}, and four levels of P: 0, 11, 22, and 33 kg ha^{-1}. The maize and sunflower crops received N as a single topdressing of calcium ammonium nitrate, whereas P was applied at planting as triple superphosphate. The intercropped beans did not receive separate doses of fertilizer. Experiments were repeated in two blocks, according to a randomized complete design, yielding a total of 128 plots. The location of these plots in the blocks, experiments and modules is shown in Table 2.

Table 1. Cropping patterns in Modules 1 and 2

Growing season[a]	Module 1	Module 2
1987/1	maize	maize + beans
1987/2	maize	sunflower
1988/1	maize	maize + beans

[a] 1 = major growing season, 2 = short rainy season.

Table 2. Distribution of the 128 plots of fertilizer trial Oyugis

Experiment	Module 1		Module 2	
	Block 1	Block 2	Block 1	Block 2
1	1–16	17–32	33– 48	49– 64
2	65–80	81–96	97–112	113–128

Emerged Striga, assumed to represent parasitizing Striga, was recorded 4 and 8 weeks after planting. The number of affected plant hills in the harvest area of each plot (maximum of 24 hills) was used to indicate Striga infestation. Table 3 provides a classification reflecting the average infestation observed during one season. After counting, we practised hand-pulling along with the regular weeding practices.

Table 3. Rating of Striga incidence in plant hills (maximum number of plant hills is 24)

Affected no. of hills	Striga rating
0– 4	0 (very low)
5– 9	1 (low)
10–14	2 (moderate)
15–19	3 (severe)
20–24	4 (very severe)

Statistical methods

The statistical methods applied in this study follow the lines of Snedecor and Cochran (1980). Experiment 1 was analysed according to the model:

$$Y_{ijkl} = (N)_i + (P)_j + (S)_k + (M)_l \qquad (1)$$

in which experimental variation is explained by N (nitrogen), P (phosphorus), S (sulphur) and M (farmyard manure), each at two application levels, and Y_{ijkl} is the maize grain yield. A comparative model was formulated, in which the quantitative Striga effect (X) was also included as an explanatory variable, yielding:

$$Y_{ijkl} = (N)_i + (P)_j + (S)_k + (M)_l + b \times X \qquad (1')$$

Significance of the parameter b and increase in R^2 when transgressing from 1 to 1′ testify to a pronounced Striga effect.

For Experiment 2, maize yield was explained by only two treatments, i.e. the amounts of fertilizer N and P. Since there are four application levels, a linear regression model was used:

$$Y_i = \beta_0 + \beta_1 \times N + \beta_2 \times P \qquad (2)$$

where N and P are the amounts of nutrients applied in the i^{th} experiment, and Y_i is the grain yield. β_0, β_1 and β_2 are coefficients to be determined.

Like in Model 1′, the Striga infestation was included as an explanatory variable, yielding the comparative model:

$$Y_i = \beta_0 + \beta_1 \times N + \beta_2 \times P + \beta_3 \times X \qquad (2')$$

in which X is the Striga rating, obtained from Table 3. Again, the significance of the parameter β_3 and the increase in R^2 value are indicators of the importance of Striga. All four models, first ignoring and later including Striga, were worked out for the two blocks, the two modules and for both years.

Finally, Experiment 1 was used to analyse the effect of the different treatments on Striga incidence for both years, yielding model:

$$X_{i\ldots m} = (\text{Block})_i + (N)_j + (P)_k + (S)_l + (M)_m \qquad (3)$$

The coefficient of variation of the trials was used as an indicator of its reliability. We considered values below 20% to represent a well executed and relatively little disturbed trial. Values exceeding 30%, however, testify to poor trial execution or the interference of non-treatment factors.

Results and conclusions

Effect of Striga on maize yields

Table 4 shows the maize grain yields and the Striga ratings for all 16 plots of the two blocks of Experiment 2, Module 1, realized during the major growing seasons of 1987 and 1988. Averages of the two blocks are visualised in Figure 2a (1987) and 2b (1988). Figure 2a shows a highly uncorrelated picture. The impact of Striga is so high, that it seems as if neither N nor P has any consistent effect on maize yields. In 1988, after two seasons of hand-pulling, Striga incidence was brought back to zero (Table 4). Figure 2b shows a clear response of maize to N, which, applied at a rate of 50–75 kg ha^{-1}, increases maize yield from 3 t ha^{-1} to about 5 t ha^{-1}. There is a slight response to P, when applied at a rate of 11–22 kg ha^{-1}.

Mean maize yields and Striga ratings for the whole trial are listed in Tables 5 and 6. The mean maize yield in 1987 was 2675 kg ha^{-1}, with a Striga rating of 1.85; in 1988, maize yield increased to a mean value of 3780 kg ha^{-1}, whereas the Striga rating decreased considerably to 0.43.

Tables 5 and 6 also show the results of the statistical analyses of Experiments 1 and 2, respectively. In Experiment 1, the first set of results (Striga ignored) is highly erratic for 1987 (mean c.v. = 65%), but reasonable for 1988 (mean c.v. = 27%). Including Striga in the model decreases mean c.v. values to 51% and 24% for 1987 and 1988, respectively. The effect of Striga on maize yields is significant in both years and in both modules. Significance of N and P increased from 1987 to 1988, but S and manure were not

Table 4. Maize grain yields and Striga rating in Experiment 2, Module 1, as affected by variation in fertilizer application

N (kg ha^{-1})	P (kg ha^{-1})	Grain yields (kg ha^{-1}) and Striga ratings							
		1987				1988			
		Block 1		Block 2		Block 1		Block 2	
		yield	Striga	yield	Striga	yield	Striga	yield	Striga
0	0	3490	1	3910	1	2970	0	3480	0
25	0	1740	2	4460	1	2780	0	4080	0
50	0	5300	1	5160	2	4300	0	4200	0
75	0	4740	1	5340	1	4930	0	4680	0
0	11	4810	1	4080	1	3800	0	3130	0
25	11	4880	1	4880	1	4330	0	4490	0
50	11	2250	3	5860	1	4960	0	5370	0
75	11	2500	3	5930	2	5220	0	4950	0
0	22	3490	1	1740	2	2740	0	3070	0
25	22	4330	1	4740	2	3570	0	4880	0
50	22	860	2	5160	1	5420	0	5100	0
75	22	4670	1	5300	1	5810	0	4720	0
0	33	2370	2	6700	1	3660	0	4630	0
25	33	1880	1	1930	2	3360	0	3340	0
50	33	3420	1	5130	1	4130	0	4730	0
75	33	2960	2	5650	2	4820	0	5540	0

significant. In Experiment 2, with only N and P applied at four levels, the data are slightly less erratic, both in 1987 (mean c.v. = 44%, mean $R^2 = 0.23$), and in 1988 (mean c.v. = 20%, mean $R^2 = 0.59$). A marked improvement is obtained when Striga is included in the statistical analysis: mean c.v. values decrease to 34% and 18% for 1987 and 1988, respectively, whereas mean R^2 values move up to 0.55 and 0.65. Again, the Striga effect proves highly significant in three cases, and there is a response of maize to N and P, which is again higher in 1988 than in 1987.

Including Striga in statistical models 1 and 2 lowered the c.v. of the maize trials and increased R^2 values, thus better explaining experimental variation of the trial results.

Effects of hand-pulling, trap crop, mineral fertilizers, and manure on Striga

The effects of hand-pulling and the trap crop sunflower can also be derived from Tables 5 and 6. Hand-pulling strongly reduced the incidence

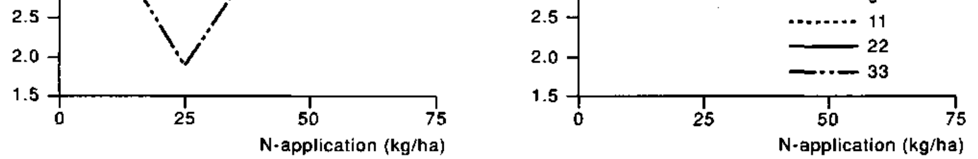


Fig. 2. Effect of N and P applications on maize yield in Experiment 2, Module 1, in 1987 (**a**) and 1988 (**b**).

Table 5. Maize yields and Striga ratings and the coefficients of variation (c.v.), regression coefficients (R^2), and significances resulting from the statistical analysis of Experiment 1, i.e. Models 1 (Striga ignored) and 1′ (Striga included)

Year	Module	Mean yield ($kg\,ha^{-1}$)	Mean Striga rating	Striga ignored				Striga included				
				c.v. (%)	R^2	significance[a]		c.v. (%)	R^2	significance[a]		
						N	P			N	P	X
1987	1	2570	1.8	52.1	0.38	0.01	n.s.	31.9	0.78	0.05	n.s.	0.001
1987	2	1690	2.4	78.6	0.11	n.s.	n.s.	70.7	0.31	n.s.	n.s.	0.05
1988	1	3440	0.4	27.0	0.52	0.001	n.s.	24.4	0.62	0.001	n.s.	0.05
1988	2	3870	0.8	26.7	0.34	n.s.	0.01	23.0	0.53	0.05	0.05	0.01

[a] n.s. = not significant.

NB: no response to sulphur (S) and farmyard manure (M).

Table 6. Maize yields and Striga ratings and the coefficients of variation (c.v.), regression coefficients (R^2), and significances resulting from the statistical analysis of Experiment 2, i.e. Models 2 (Striga ignored) and 2′ (Striga included)

Year	Module	Mean yield ($kg\,ha^{-1}$)	Mean Striga rating	Striga ignored				Striga included				
				c.v. (%)	R^2	significance[a]		c.v. (%)	R^2	significance[a]		
						N	P			N	P	X
1987	1	4052	1.4	32.5	0.31	n.s.	n.s.	26.3	0.56	0.05	n.s.	0.001
1987	2	2387	1.8	55.8	0.15	n.s.	0.05	41.7	0.54	n.s.	0.05	0.001
1988	1	4287	0	13.1	0.62	0.001	n.s.	13.1	0.62	0.001	n.s.	n.s.
1988	2	3525	0.5	26.3	0.56	n.s.	0.001	23.3	0.67	n.s.	0.01	0.01

[a] n.s. = not significant.

of Striga, the mean rating going down from 1.85 in 1987 to 0.43 in 1988.

Any extra positive effect on Module 2 in 1988 should be ascribed to the trap crop sunflower. In Module 1 the mean Striga rating went down from 1.6 (1987) to 0.2 (1988), and in Module 2 from 2.1 (1987) to 0.65 (1988). Although the decreases in number of emerged Striga plants are of the same magnitude, Striga was observed to emerge and subsequently perish in the sunflower field. Hand-pulling being so effective, the impact of sunflower on Striga may have been concealed. We can, however, not conclude that planting sunflower in the second growing season of 1987 significantly reduced Striga infestation in 1988.

The outcome of statistical Model 3, in which the effects of N, P, S and farmyard manure on Striga were examined, was disappointing. None of them could suppress Striga significantly, and R^2 values were below 0.3. Possibly, the application rates were too low.

Discussion

The present study shows that *Striga hermonthica* is highly responsible for erratic trial results during the 1987 and, to a lesser extent, the 1988 major growing seasons in SW Kenya. Yet, other factors cannot be fully excluded. Apart from Striga, the higher yields in 1988 may be explained by higher rainfall. This hypothesis is, however, to be rejected because surrounding sites suffering less from Striga but receiving equal rainfall, had lower yields in 1988 than in 1987. Furthermore, Tables 5 and 6 show that the results for intercropped Module 2 have a higher c.v. and lower R^2 than those for Module 1. This may largely be due to the fact that mean Striga rating is higher in Module 2, but some experimental error may be caused by competition of the intercropped beans. Yields of beans were low: below 200 $kg\,ha^{-1}$ on average. Only in 1987 (Experiment 1) 380 $kg\,ha^{-1}$ was realized, as maize was very badly affected by Striga (rating 2.4 in Table 5). The beans, which had to scavenge on fertilizer applied to the maize, hardly responded to any fertilizer, but were not affected by Striga. Still, they may have biologically fixed and released N as maize in Module 2 responded better to P and less to N, whereas in monocropped Module 1 the reverse was the case.

In 1988, yield responses to N and P were markedly higher than in 1987. This may point to a rapid decline in inherent soil fertility on continuous cultivation. Long-term yield response data are needed to investigate this hypothesis further. In the literature, trial results are published too often without attention paid to extraneous effects. Results are simply evaluated as if such effects do not exist. In Kenya, however, fertilizer effects on maize and sorghum in the districts bordering Lake Victoria cannot be properly evaluated without taking Striga into account (Enserink, 1982). When Striga was included in regression analysis, the percentage explained variation increased. This simple technique can be used for any poorly manageable extraneous factor (for example, waterlogging, lodging, pests), as long as the phenomena are monitored during the growing season. Vasudeva Rao et al. (1989) successfully used regression analysis in a somewhat comparable way. Their aim was to formulate response prediction equations so that loss of income due to Striga could be calculated for different parts of India.

The present study further calls for a critical look on conclusions drawn from one-season fertilizer trials, and stipulates the need for pre-trial uniformity crops to level out initial soil heterogeneity.

Striga constitutes a problem to a farmer and should be dealt with from a farming system's perspective. Hand-pulling proved to be an effective means of eradicating Striga. Yet, it is labour-intensive and therefore not very economical, as was shown by Doggett (1988) and Carson (1989). Moreover, it requires a common effort from all farmers in an infested area. In other words, hand-pulling can never be the only solution. The inclusion of trap crops in a rotation, though not substantiated by this study, seems to be the most promising and ecologically sound way to overcome the Striga problem, as it guarantees the farmer a crop and an income, whereas no extra labour input is required. The effectiveness of sunflower as a trap crop needs further investigation, in which rooting patterns and production of stimulants should be compared with those of other trap crops. Soybean did well as a trap crop (Parkinson et al., 1989), but it is not very popular in Kenya.

Although maize yields respond to modest amounts of fertilizer, the fertilizer itself does not seem to be very effective in suppressing Striga. This is in line with recent findings by Osman et al. (1991). There is, however, not much point in testing higher amounts, as farmers in the region are not inclined to use more fertilizer than the rates applied in this study.

The Striga problem should be looked at from different disciplines. Quantitative data on Striga-soil-plant relationships are still scarce, often subjective and sometimes inconsistent. With mode of emergence still being Striga's best kept secret, it remains difficult to design field trials in such a way that the parasite's potentially harmful effects are circumvented.

Acknowledgement

The authors are greatly indebted to soil scientists J Bouma and B H Janssen and weed scientist S J ter Borg of Wageningen Agricultural University, for their comments on the manuscript.

References

Agabawi K A and Younis A S 1965 Effect of nitrogen application on growth and nitrogen content of *S. hermonthica*, Benth. and *Sorghum vulgare*, Lur. grown on forage. Plant and Soil 23, 295.

Bebawi F F 1987 Cultural practices in witchweed management. *In* Parasitic Weeds in Agriculture, Volume I: Striga. Ed. L J Musselman. p 159. CRC Press, Boca Raton, FL.

Bebawi F F and Farah A F 1981 Effects of patterns and methods of sowing on sorghum/Striga relations. Exp. Agric. 17, 337.

Carson A G 1989 Research and development strategies for the control of *Striga hermonthica* in the Gambia. *In* Striga-improved Management in Africa. pp 101–118. FAO, Plant Production and Protection paper 96.

Doggett H 1988 Witchweed (Striga). *In* Sorghum, 2nd ed.

Ed. G Wirgley. pp 368–404. Longman Sc and Tech, London/Wiley, New York.

Efron Y, Kim S K, Parkinson V and Bosque-Perez N A 1989 IITA's strategies to develop Striga resistant maize germplasm. *In* Striga-improved Management in Africa. pp 141–153. FAO, Plant Production and Protection paper 96.

Enserink H J 1982 Sorghum agronomy investigations in Western Kenya. UNDP Assignment Report KE/78/016, Busia, Kenya.

FAO 1988 FAO-Unesco soil map of the world: Revised legend. World Soil Resources Report 60. FAO, Rome, Italy.

FAO 1989 Striga-improved Management in Africa. Plant Production and Protection paper 96.

Gomez K A and Gomez A A 1984 Statistical Procedures for Agricultural Research. Wiley, New York.

Hosmani M M 1978 Striga, a noxious root parasitic weed. Royal Printers and Univ. Agric. Sciences, Bangalore.

Last F T 1961 Direct and residual effects of Striga control treatments on sorgum yields. Trop. Agric. 38, p. 49.

Laycock D 1989 Recent results of Striga investigations in the CILSS integrated pest management project with special reference to Niger. *In* Striga-improved Management in Africa. pp 119–135. FAO, Plant Production and Protection paper 96.

Ogborn J E A 1984 Research priorities in Agronomy. *In* Striga Biology and Control. Eds. E S Ayensu et al. p 195. Int. Council of Scientific Unions Press, symposium series no. 2, Paris.

Ogborn J E A 1987 Striga control under peasant farming conditions. *In* Parasitic Weeds in Agriculture, Volume 1: Striga. Ed. L J Musselman. p 145. CRC Press, Boca Raton, FL.

Osman M A, Raju P S and Peacock J M 1991 The effect of soil temperature, moisture and nitrogen on *Striga asiatica* (L.) Kuntze seed germination, viability and emergence on sorghum (*Sorghum bicolor* L. Moench) roots under field conditions. Plant and Soil 131, 265–273.

Parkinson V, Kim S K, Efron Y, Bello L and Dashiell K 1989 Potential trap crops as a cultural measure in Striga control for Africa. *In* Striga-improved Management in Africa. pp 136–140. FAO, Plant Production and Protection paper 96.

Smaling E M A and Van de Weg R F 1990 Using soil and climate maps and associated data sets to select sites for fertilizer trials in Kenya. Agric. Ecos. Envir. 31, 263–274.

Snedecor G W and Cochran W G 1980 Statistical Methods, 7th ed. Iowa State Univ. Press, Ames.

Soil Survey Staff 1975 Soil Taxonomy, a basic system of soil classification for making and interpreting soil surveys. Agric. Handbook 436. USDA, Washington, DC.

Vasudeva Rao M J, Chidley V L and House L R 1989 Estimates of grain yield losses caused in sorghum (*Sorghum bicolor* L. Moench) by *Striga asiatica* (L.) Kuntze obtained using the regression approach. Agric. Ecos. Envir. 25, 139–149.

Watt W L 1936 Control of Striga weed in Nyanza Province, Kenya. East Afr. Agric. For. J. 1, 320.

PART V MODELLING MACRONUTRIENTS IN SOILS AND PLANTS AS RELATED TO MAIZE YIELDS

---

10. Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices

Chapter 10

Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices

Submitted to Geoderma

10 Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices

E.M.A. Smaling[1] and B.H. Janssen[2]

[1] DLO The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen (The Netherlands)

[2] Department of Soil Science and Plant Nutrition, Wageningen Agricultural University, P.O. Box 8005, 6700 EC Wageningen (The Netherlands)

ABSTRACT

The model QUEFTS (QUantitative Evaluation of the Fertility of Tropical Soils) was calibrated using data from maize fertilizer trials in Kenya. QUEFTS describes, in four steps, relations between (i) chemical soil test values, (ii) potential NPK supply from soils and fertilizer, (iii) actual NPK uptake, and (iv) maize grain yield, acknowledging interactions between the three macronutrients. All steps were calibrated separately, and yield a modified version of QUEFTS. Major changes were the inclusion of ambient temperature and clay content in explaining potential nitrogen supply, and the replacement of the parabolic relation between potential supply and actual uptake by an exponential relation. The regression coefficient relating measured and calculated yield was improved from 0.66 in the original version to 0.78 in the modified version of QUEFTS and, when including a boundary condition for harvest index, to 0.88. A satisfactory validation was conducted with input data from fertilizer experiments in other parts of Kenya. Sensitivity analysis revealed that changing the parameters pH and organic N by 20% caused yield differences of at least 10%.

The basic thinking and theoretical concepts underlying the original version of QUEFTS still apply to the modified version. Agronomists in tropical environ-

ments are encouraged to collect the relatively few input data to further validate the two versions of the model. As a consequence, QUEFTS can contribute to a more efficient procurement and use of mineral fertilizers at both regional and farm level.

INTRODUCTION

In 1985, a network of seventy long-term fertilizer trials for rainfed, annual crops was established in Kenya. Interpretation of soil and climate maps was instrumental in deciding where to site the experiments, as the major goal was to formulate fertilizer recommendations that are specific for well-defined agro-ecological units (Smaling and Van de Weg, 1990). The trials generated a vast amount of data, and maize indeed responded differently to nitrogen, phosphorus and farmyard manure in the different agro-ecological units (Smaling et al., 1992). The results prove Sumner and Farina (1986) right in that "crops do not respond to a fertilizer application *per se*, but rather to the soil's response to that application".

Running such a number of fertilizer trials requires long-term commitment as regards financing, institutional infrastructure, and human resource development. As this can seldomly be afforded, cheaper alternatives must be sought. A nowadays much-valued alternative is the use of computer models that translate measurable climatic, soil and plant parameters into an output variable such as crop yield. Burrough (1989) recognizes (i) empirical models, describing a relation between a model output variable and its original determinants, without referring to underlying processes, and (ii) mechanistic process-models, describing a particular process in terms of known physical laws.

Researchers use a variety of mathematical models to empirically predict crop response to nutrients supplied in fertilizer. Cochrane (1988) described an exponential yield prediction model, whereas Waugh et al. (1975) obtained satisfactory results with a linear-plateau model. Cerrato and Blackmer (1990) discussed why one model is selected over others and found the quadratic-plus-plateau model best describing yield responses in their study. Next to fertilizer, Mombiela et al. (1981) included initial soil nutrient level in their model. The pathways of the different nutrients were, however, left unstudied.

Of a very different nature are dynamic nutrient uptake models as described by Kovar and Barber (1988) and Chen and Barber (1990). They did in-depth studies on the pathways of phosphorus, predicting its uptake by plant roots from size and morphology of the root system, kinetics of P absorption by the root and mass flow and diffusion rates. Hoffland (1991) used similar inputs to describe the effect of organic acid exudation on (rock) phosphate uptake by rape *(Brassica napus).* Caassen and Barber (1976) predicted K uptake from diffusion coefficients, initial K^+ concentration in soil solution, and buffering capacity. De Willigen (1991) evaluated fourteen dynamic models, describing turnover of nitrogen in the soil-crop system.

Sumner and Farina (1986) denounce the 'spread and measure' approach followed in the empirical models. They do not contribute anything to our understanding of the processes involved in the measured yield responses, and they are valid only for soils on which the experiments were conducted. The mechanistic models are very meaningful from an academic point of view, considerably increasing our knowledge on processes in the soil-plant interface. Their main disadvantage is their complexity and associated lack of practical significance, especially for tropical countries, as they often require input data that are hard to gather on a routine basis. Moreover, rural development programmes in these countries are largely geared towards proper management of agricultural resources rather than to research *per se*. For such purposes, models are required that have few and easily measurable input parameters, but are still as much process-based as possible. Wolf et al. (1989) tried to find this balance in modelling crop response to soil and fertilizer nitrogen. Next to external inputs such as mineral and organic N fertilizer, supply of N by rainfall, flood and irrigation water and biological fixation, data were needed on internal fluxes between labile and stable nutrient pools, their initial sizes, and the time constants of conversion between pools. Osmond et al. (1992) recently applied this model for soils in different parts of the tropics and obtained satisfactory results.

Most models describing relations between nutrient supply, uptake and crop yield address a single nutrient. In agricultural practice however, at least the three macronutrients should be taken into account. This principle is the major cornerstone of the model QUantitative Evaluation of the Fertility of Tropical Soils (QUEFTS), which takes N, P and K into consideration, as well as the interactions between them (Janssen et al., 1990). QUEFTS has both empirical and theoretical components, and describes relations between (i) chemical soil tests, (ii) potential NPK supply from soils and fertilizer, (iii) actual NPK uptake, and (iv) maize grain yield.

In this article, QUEFTS is run with input data from fertilizer experiments, conducted in 1990, in different agro-ecological units in Kenya. As some soils do not meet the boundary conditions of the model, the results are only partly satisfactory. Consequently, the data are employed in a major calibration exercise, so as to widen the applicability of QUEFTS. Finally, a validation is done using input and yield data from fertilizer trials in other parts of Kenya and from different years, and a sensitivity analysis then reveals to what extent changes in input parameters affect model output.

MATERIALS AND METHODS

Theoretical background of QUEFTS

QUEFTS calculates the yield of maize on tropical soils as a function of the availability of soil and fertilizer N, P and K. A value for potential grain yield must be entered (standard setting is 10 000 kg/ha at 12% moisture), but below this level, maize production must be limited by the supply of N, P and K only. In other words, water supply during the growing season, and other extraneous factors such as waterlogging, deficiencies of other nutrients or weed infestation, should not adversely affect crop development.

The calculation procedure in QUEFTS consists of four successive steps. The essential equations for each step are given in Table 10.1 (Part A).

Step I. The potential supply of soil nitrogen, phosphorus and potassium (SN, SP, SK), i.e. the maximum quantity of those nutrients that can be taken up by maize if no other nutrients or other growth factors are limiting, is derived from empirical equations with soil chemical properties of the 0-20 cm soil layer as independent determinants. Soils should be well drained and deeply rootable, with a pH(H_2O) of 4.5-7.0, organic C < 70 g/kg, organic N < 7 g/kg, total **P** < 2000 mg/kg, P-Olsen < 30 mg/kg, and exchangeable K < 30 mmol/kg.

Table 10.1 Relations between soil and climatic parameters, potential nutrient supply, actual nutrient uptake and maize grain yields for the original QUEFTS (after Janssen et al., 1990)

Step I

$SN = 17 * (pH - 3) * org.N$, or $1.7 * (pH - 3) * org.C$

$SP = 0.014 * (1 - 0.5 * (pH - 6)^2) * total\ P + 0.5 * P\text{-}Olsen$, or
$0.35 * (1 - 0.5 * (pH - 6)^2) * org.C + 0.5 * P\text{-}Olsen$

$SK = 250 * (3.4 - 0.4 * pH) * exch.K / (2 + 0.9 * org.C)$

Step II

Situation	Condition
A	$S1<r1+(S2-r2)(a2/d1)$
C	$S1>r1(S2-r2)(2*d2/a1-a2/d1)$
B	S1 in between

	Equation for U1(2):
A	$U1(2)=S1$
C	$U1(2)=r1+(S2-r2)(d2/a1)$
B	$U1(2) = S1 - \frac{0.25[S1-r1-(S2-r2)(a2/d1)]^2}{(S2-r2)(d2/a1-a2/d1)}$

Nutrient	Value of constants:		
	a	*d*	*r*
N	30	70	5
P	200	600	0.4
K	30	120	2

Step III

YNA = 30 * (UN - 5)   YND = 70 * (UN - 5)
YPA = 200 * (UP - 0.4)   YPD = 600 * (UP - 0.4)
YKA = 30 * (UK - 2)   YKD = 120 * (UK - 2)

Step IV

YE = (YNP + YNK + YPN + YPK + YKN + YKP) / 6

Step II. If the supply of one nutrient is enhanced, it can positively influence the uptake of other nutrients. There are many documented examples of such interactions (e.g. Van Keulen and Van Heemst, 1982; Sumner and Farina, 1986; Kamprath, 1987). In QUEFTS, these interactions are reflected in the way actual uptake of each nutrient (UN, UP, UK) is calculated, namely as a function of the potential supply of that nutrient, taking into account the potential supply of the two other nutrients. It is a theoretical relation, assuming a linear decrease of dU/dS from 1 to 0. Integration of this differential equation results in a parabolic curve (Situation *B*), bounded by a linear relation between potential supply and actual uptake when the supply of the particular nutrient is low compared to the two other nutrients (Situation *A*), and a plateau value at a relatively high potential supply of the nutrient, implying that increased supply does not lead to any further uptake of that nutrient (Situation *C*).

Step III. When the potential supply of a nutrient is low compared to the two other nutrients, the particular nutrient is growth-limiting, and its internal concentration in the plant is low, eventually reaching a stage of maximum dilution. Nutrient use efficiency (NUE), i.e. the economic yield produced per unit of nutrient in the above-ground dry matter, is then maximum. Values of maximum NUE for maize are 70, 600, and 120 kg grain per kg N, P and K. When the supply of a nutrient is large and growth is not limited by the uptake of that nutrient, the crop takes up more than required until *maximum accumulation* is reached, coinciding with *NUE* values of 30, 200, and 30 kg grain per kg N, P and K. Moreover, there has to be a minimum uptake (5 kg N, 0.4 kg P, 2 kg K per ha) before any grain filling can take place. At this point, three yield (Y) ranges can be calculated, represented by maximum dilution (D) and accumulation (A) of N, P and K in the plant tissue: YND-YNA, YPD-YPA, and YKD-YKA.

Step IV. The final yield estimate (YE) is found by comparing the three ranges. The yield range that follows from N uptake is narrowed to the overlap with the range YPD-YPA, leading to a combined estimate YNP, and to the overlap with the range YKD-YKA, with a combined estimate YNK. The same procedure is followed for P and K, and provides six estimates: YNP, YNK, YPN, YPK, YKN, YKP. The final yield estimate is the average value of these six combined estimates, and lies in the common overlap of the three yield ranges.

The potential supply of a nutrient is enlarged by application of fertilizers. Part of the fertilizer is made unavailable, either temporarily (immobilization, retention) or permanently (leaching, gaseous losses, erosion). The fraction recovered by the crop is a function of soil, weather and crop properties. The relation between the amount of N fertilizer applied and N uptake is often a straight line over a considerable range of applications. For phosphorus, the situation is more complex, as the reactions between P in soil solution and the solid phase are not of simple first-order kinetics. Potassium takes an intermediate position. Continuous additions change the K equilibrium between the adsorption complex and the soil solution, thus affecting the amount available for uptake.

Similar to the concept of potential supply, QUEFTS uses the concept of maximum fertilizer recovery (Janssen and Guiking, 1990). Nitrogen recovery, for example, is calculated as the difference in N uptake between an experimental unit receiving NPK and an unit receiving PK, divided by the amount of applied N. If no field data of maximum recovery fractions are available, QUEFTS uses standard values of 0.5 for N and K, and 0.1 for P.

The literature shows little consensus with respect to methodology of measuring fertilizer recovery (FAO, 1983; Harmsen and Moraghan, 1987; Morel and Fardeau, 1990; Walters and Malzer, 1990). The difference method, used in the present study, tends to overestimate recovery because of (i) increased root proliferation and (ii) a priming effect on N and P mineralization caused by fertilizer application. Several authors strongly advocate isotope-dilution techniques to follow the fate of the labelled nutrient. An important methodological disadvantage, however, is that substitution of a nutrient between pools (mineralization-immobilization turnover) is not accounted for and leads to underestimation of recovery. A practical disadvantage is the difficulty of applying the isotope-dilution method under field conditions.

In long-term experimentation, P recovery may be overestimated considerably as a result of a gradual build-up of residual fertilizer P, applied during previous seasons. A model was developed, calculating P accumulation and residual P recovery under such circumstances (Wolf et al., 1987). It was found that each year, 20% of labile residual fertilizer phosphorus is transferred to stable residual phosphorus (Janssen et al., 1987). The P recovery in year t (R_t) can then be calculated, at least for about 4 to 5 years (Janssen and Wolf, 1988), as a function of recovery during the first year of application (R_1), as shown in Equation (1):

$$R_t = (0.8 - R_1)^{t-1} * R_1 \qquad (1)$$

Model calibration

The calibration of QUEFTS was based on fertilizer trials (4^2 NP randomized complete block design, four replications) in Nyanza and Coast Province. Data on soils

Calibrating Step IV implied comparison of the measured yields with the average value of the six yield estimates YNP, YNK, YPN, YPK, YKN, YKP, as derived from the measured uptakes and the yield/uptake relations of Step III.

Table 10.4 Model input of sites i, j and k for validation, and of reference soils x and y for sensitivity analysis

Site	Org. C (g/kg)	Org. N (g/kg)	Total P (mg/kg)	Exch. K (mmol/kg)	pH (H_2O)	Temp. factor*	Clay factor*	Recovery fraction N	Recovery fraction P	Maximum yield (kg/ha)
i	34	3.0	750	2.0	4.8	1.90	2.60	0.28	0.08	12 000
j	30	2.4	1000	12.0	5.9	2.10	2.40	0.44	0.22	10 000
k	28	1.5	440	10.0	6.0	2.30	2.60	0.38	0.12	7 000
x	20	1.5	350	5.0	6.7	3.00	2.75	0.00	0.00	10 000
y	10	0.8	100	1.5	6.7	2.50	2.75	0.00	0.00	10 000

* See Table 10.7 for calculation of temperature and clay factors

Model validation and sensitivity analysis

The version of the model obtained after calibration (modified QUEFTS) was validated with 1988 data from sites **b** and **d**, and with 1990 data from sites **i**, **j**, and **k**, located in the Embu District, east of Mount Kenya. Table 10.4 shows the input data, used to run the model.

For sensitivity testing, two reference soils were defined: **x** and **y** (Table 10.4). All individual parameter and coefficients, employed in the different steps of QUEFTS, were varied by 20%, in order to test their individual impact on model output.

RESULTS AND DISCUSSION

Maize yields and nutrient uptake

Table 10.5 shows, for each treatment mean, maize grain yield (12% moisture), harvest index, above-ground NPK uptake, and 1000-grain weight of treatments N_0P_0 and $N_{75}P_{33}$. Grain yields and response to N and P differed largely between

Table 10.5 Grain yield (at 12% moisture), harvest index, total above-ground nutrient uptake, and 1000-grain weight at different fertilizer rates; each figure is average value of four replications.

Site	Treatment		Grain yield (kg/ha)	Harvest index	Nutrient uptake (kg/ha)			1000-grain weight (g)
					N	P	K	
a	N_0	P_0	2108	0.41	41.8	4.7	29.8	350
	N_{50}	P_0	2290	0.42	49.5	5.6	35.5	
	N_0	P_{22}	4862	0.48	79.2	12.3	58.4	
	N_{50}	P_{22}	5251	0.52	79.4	10.8	58.0	
	N75	P_{33}	5726	0.51	no data			408
b	N_0	P_0	1308	0.26	28.7	13.2	55.4	241
	N_{50}	P_0	2589	0.33	41.7	14.6	91.2	
	N_0	P_{22}	1128	0.23	27.6	11.2	65.3	
	N_{50}	P_{22}	3143	0.35	53.1	19.2	110.2	
	N_{75}	P_{33}	3693	0.33	59.2	15.0	131.1	302
c	N_0	P_0	1892	0.29	40.3	12.0	54.3	281
	N_{50}	P_0	3057	0.37	66.8	13.6	64.7	
	N_0	P_{22}	2657	0.33	55.3	14.4	56.0	
	N_{50}	P_{22}	3879	0.37	81.6	19.4	85.5	
	N_{75}	P_{33}	4676	0.45	no data			316
d	N_0	P_0	1235	0.33	18.2	8.8	26.2	231
	N_{50}	P_0	2182	0.33	38.0	13.1	42.4	
	N_0	P_{22}	934	0.27	15.3	6.8	24.0	
	N_{50}	P_{22}	2176	0.36	27.2	10.6	42.2	
	N_{75}	P_{33}	3142	0.37	51.7	15.5	49.5	215
e	N_0	P_0	4569	0.42	62.8	23.7	94.6	375
	N_{50}	P_0	6299	0.42	108.5	35.0	126.3	
	N_0	P_{22}	4719	0.40	70.4	22.7	105.7	
	N_{50}	P_{22}	7187	0.45	113.8	37.9	133.1	
	N_{75}	P_{33}	7589	0.47	132.5	42.3	133.9	437
f	N_0	P_0	1187	0.36	25.5	3.1	25.7	264
	N_{50}	P_0	1672	0.45	36.2	4.1	29.8	
	N_0	P_{22}	2952	0.46	46.9	10.8	34.4	
	N_{50}	P_{22}	3029	0.43	59.1	11.7	50.6	
	N_{75}	P_{33}	3755	0.50	74.8	14.0	53.9	320
g	N_0	P_0	3965	0.34	91.8	16.2	95.8	253
	N_{50}	P_0	4174	0.35	109.7	18.9	90.1	
	N_0	P_{22}	3344	0.29	91.8	15.7	107.4	
	N_{50}	P_{22}	4482	0.36	111.2	20.5	108.9	
	N_{75}	P_{33}	3728	0.29	109.8	17.4	121.7	260
h	N_0	P_0	2553	0.45	37.6	6.8	42.4	265
	N_{50}	P_0	2243	0.44	44.9	6.6	46.8	
	N_0	P_{22}	2267	0.37	37.9	11.1	68.0	
	N_{50}	P_{22}	3731	0.45	66.1	16.1	77.4	
	N_{75}	P_{33}	4193	0.46	79.9	20.2	89.5	300

sites. Maize at **a**, for example, responded mainly to P and hardly to N, whereas the reverse was true for **e**. At **g**, there was hardly any response at all, whereas at **h**, maize only responded to the application of both N and P. The sites with retarded crop development (**b** and **d**) had low harvest indices and a negative response to the application of P only. Maize at the two Vertisols (**d** and **g**) had the lowest 1000-grain weight, and no weight increase upon fertilizer application, as opposed to all other sites. Growth conditions during grain filling must thus have been suboptimal here. Table 10.5 further shows that fertilizer application had a positive influence on harvest index. Maize in treatments that included both N and P had higher harvest indices than the control plots in the highland varieties (**a-e**), but this was less convincing at the coast (**f-h**). Table 10.5 also shows various interactions between nutrients as a result of fertilizer application. Treatment N_0P_{22}, for example, had considerably higher N uptake than N_0P_0 at **a** and **f**. Similarly, treatment $N_{50}P_0$ increased P uptake, compared to uptake with treatment N_0P_0 at **d** and **e**. K uptake was enhanced by application of nitrogen (**b**, **d**), phosphorus (**a**), or both (**c**, **e**, **f**, **g**, **h**).

Fertilizer recovery

Table 10.6 shows that the apparent N recovery fractions ranged between 0.00 for **a**, and 0.87 for **e**. The extremely high value at **e** could be explained by increased root proliferation, which was observed (but not quantified) in plots of maize that received N fertilizer. Phosphorus recovery fractions ranged between 0.00 for **d**, and 0.43 for **h**, and were negatively related to clay content ($r^2 = 0.64$), and to SP ($r^2 = 0.29$). The negative effect of clay can be ascribed to P fixing properties of fine soil particles. The negative effect of SP is due to the fact that the crop's demand for fertilizer P decreases with increasing P supply from the soil. Because clay content and SP were also correlated ($r^2 = 0.45$), it was impossible to unravel their individual effects on P recovery. High P recovery values at some trials are explained by a build-up of residual phosphorus in soils, as shown in Table 10.6. Measured P recovery thus consisted of the first-year recovery of the application in 1990 and the residual recoveries of the applications in 1989, 1988 and 1987. Using Equation (1), the total recovery (R) in 1990 can be calculated as:

$$R_{90} = ((0.8 - R_{87})^3 + (0.8 - R_{87})^2 + (0.8 - R_{87})^1 + (0.8 - R_{87})^0)*R_{87}$$

A high recovery of 0.43 (site **h**) should thus be interpreted as the sum of 0.04 + 0.07 + 0.12 + 0.20; hence, the recovery of the 1990 application is only 0.20, which is a plausible value for a sandy soil.

Table 10.6 Measured potential supply, maximum apparent fertilizer recovery fraction, and build-up of phosphorus between 1987 and 1990

Site	Potential supply (kg/ha)			Recovery fraction		Total P (mg/kg)*	
	SN	SP	SK	N	P	P_0	P_{22}
a	95.7	7.5	76.3	0.00	0.24	528	560
b	31.0	18.2	174.7	0.54	0.21	734	790
c	77.2	16.3	96.1	0.53	0.26	358	372
d	21.8	19.9	65.2	0.24	0.00	1072	1152
e	100.1	41.1	146.4	0.87	0.13	1645	1669
f	50.9	4.7	80.4	0.24	0.35	74	90
g	110.0	21.8	137.6	0.39	0.07	358	385
h	43.9	8.8	96.1	0.56	0.43	112	118

* Average P content of plots that received 0 and 22 kg P per ha respectively; sites a-e received 154 kg P per ha, sites f-h received 88 kg P per ha

Model calibration

Monitoring growth conditions at the sites during the 1990 season revealed that maize at site **b** was partly parasitized by witchweed *(Striga hermonthica)*, and at site **d**, a Vertisol on flat land, excessive downpour in March and April (860 mm) had caused spells of poor aeration. These extraneous influences adversely affected crop development, reflected in a low ratio between nitrogen uptake and organic soil nitrogen, and also in low harvest indices (Table 10.5). The two sites were thus left out of the calibration exercise; hence, only data from the remaining six sites were used for that purpose.

Step I. Soil test values of sites **a**, **c**, **e**, **f**, **g**, and **h** were entered into QUEFTS. Figure 10.1a, 10.1b and 10.1c show that the correlation between measured and calculated potential supply was poor for all three nutrients ($r^2 < 0.5$). One reason is that the original data set used to develop QUEFTS comprised few high-pH soils; hence, the previous testing of QUEFTS on such soils was rather weak. Of the present data set, however, three soils had a pH > 7, thus exceeding the boundary condition.

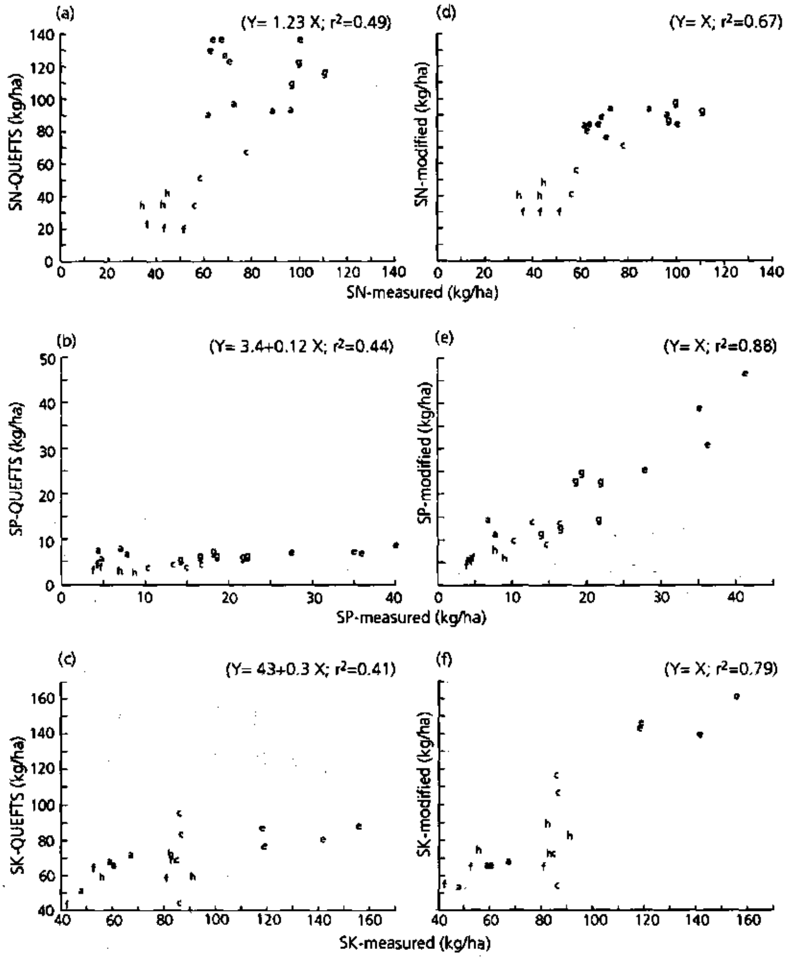


Fig. 10.1 Relation between measured and calculated potential NPK supply, determined by soil and climatic factors when employing regression equations of Step I (a-c: original version; d-f: modified version)

Table 10.7 Relations between soil and climatic parameters, potential nutrient supply, actual nutrient uptake and maize grain yields for the modified QUEFTS

Step I

$\mathrm{SN} = 45 * \mathrm{org.N} * \{2^{(T-9)/9} / \log (15 * \mathrm{clay}\%)]$

$\mathrm{SP} = (0.0375 * \mathrm{total\ P} + 0.45 * \mathrm{org.C}) * (1 - 0.25 * (\mathrm{pH} - 6.7)^2)$

$\mathrm{SK} = 0.35 * (2 + \mathrm{exch.K}) * (55 - \mathrm{org.C})$

Step II

Situation *A*: non-existent

Situation *B*:

$$\mathrm{U1} = \mathrm{S1} * e^{\{0.5 * (c_1 * \mathrm{S1/S2} + c_2 * \mathrm{S1/S3})\}}$$

N	P	K	c_1	c_2
1	2	3	-0.05	-0.35
2	1	3	-1.15	-0.40
2	3	1	-0.35	-0.07

Situation *C*: $\mathrm{U1} = \mathrm{U1}_{max}$

The curve has a maximum uptake $\mathrm{U1}_{max}$, when $\mathrm{S1} = |0.5 * (c_1/\mathrm{S2} + c_2/\mathrm{S3})|$. At this point, it is assumed that the exponential curve changes into a plateau, i.e. increased supply of nutrient (1) does not affect its actual uptake. Hence, if $\mathrm{S1} > |0.5 * (c_1/\mathrm{S2} + c_2/\mathrm{S3}|$, $\mathrm{U1} = \mathrm{U1}_{max}$.

Step III

YNA = 30 * (UN - 5)	YND = 80 * (UN - 5)
YPA = 160 * (UP - 0.4)	YPD = 600 * (UP - 0.4)
YKA = 30 * (UK - 2)	YKD = 120 * (UK - 2)

Step IV

YE = (YNP + YNK + YPN + YPK + YKN + YKP) / 6

Boundary condition: harvest index is approximately 0.4; if harvest index > 0.45, YE must be multiplied by 0.5/0.4.

A second reason for the poor correlation is that some of the soils at the trial sites did not meet boundary conditions of free drainage (g), and P-Olsen (individual plots). A third reason is that in the present calibration of Step I, N and P fertilizer applications were modest and K was not applied at all. Hence, potential supply may in some cases still exceed the measured values listed in Table 10.6.

The calibrated equations for the potential supply of N, P and K, following from multiple regression analysis are shown in Table 10.7. Correlation between measured and calculated potential supply was much improved, particularly with respect to P and K (Fig. 10.1d-f). Potential nitrogen supply (SN) was primarily determined by the organic N content of the soil, as in the original version of QUEFTS. Next, the data set showed that at the coastal sites (**f**-**h**), with temperatures around 26°C, the ratio of measured SN (Table 10.6) to organic soil N (Table 10.2) was markedly higher than at the highland sites (**a**-**e**), with temperatures around 21°C. In the original version this difference was accounted for indirectly by pH, which ranged between 4.7 and 6.2 in the highlands, and between 5.8 and 7.0 in the lowlands (Janssen and Van der Eijk, 1990). In the present calibration, temperature was used instead, as it proved to give a better correlation with SN than pH. The parameters employed in Table 10.7 reflect research on the correlation between temperature and mineralization of organic nitrogen by Jenkinson and Ayanaba (1977) and Ladd and Amato (1985). They found that mineralization rate was doubled at an increase in temperature of 9°C. Lastly, the ratio between SN and total N was higher for coarse-textured soils (**c**, **f**, **h**) as compared to the fine-textured ones. This is in agreement with the fact that the latter soils provide a better protection against microbial decomposition (Sörensen, 1975; Lynch, 1983). Therefore, clay percentage was also included as a variable explaining SN.

Janssen and Van der Eijk (1990) interpreted the original equation for SP in Table 10.1 as follows. P is supplied to the crop by a labile pool, related to P-Olsen, and by a stable pool related to f * total P, in which $f = (1 - 0.5 * (\mathrm{pH} - 6.0)^2)$. The remainder of soil phosphorus was considered inert. At pH 6.0, $f = 1$, and all phosphorus is in either the labile pool or the stable pool. The new equation in Table 10.7 differs from the original one in three ways. Firstly, P-Olsen is left out as it did not contribute to explaining SP. Apparently, the influence of labile P was satisfactorily dealt with in the other terms of the equation. The second difference between the original and the modified equations is that the parabolic pH curve is flatter (parameter value of 0.25 instead of 0.5), with an optimum pH of 6.7 instead of 6.0. This seems plausible, as phosphates still have a high solubility at this pH (Novozamsky and Beek, 1976). At pH 6.7, the expression $(1 - 0.25 * (\mathrm{pH} - 6.7)^2)$ in Table 10.7 equals 1.0, and SP reaches a maximum value. The third difference is that the new equation includes both total P and organic C, whereas in the original version they were used as alternatives.

The new version more explicitly takes contributions from both organic and inorganic P to potential P supply into account.

Potential potassium supply (SK) was explained by the amount of exchangeable potassium and organic carbon content. Equilibrium between K^+ in soil solution and in the adsorbed fraction is controlled to a large extent by the degree of K selectivity of the adsorption complex. At increasing organic carbon content, cation exchange capacity (CEC) is also increased but, at a given exchangeable K, the relative K saturation at the adsorption complex decreases, rendering potassium less available to plants (Van Diest, 1978; Mengel and Kirkby, 1980). Higher values of CEC are also brought about by an increase in clay content. Because organic carbon and clay contents are usually positively correlated, only organic carbon was included in the equation for SK. The approach follows the now commonly accepted view that not just exchangeable K, but rather the K buffering capacity of soils is a sound measure of the K availability in soils (Uribe and Cox, 1988). On sandy soils, small applications of K increase the K^+ concentration in the soil solution appreciably and may thus result in substantial yield increases, but on fine-textured soils, K fertilizer applications hardly affect K^+ concentration in the soil solution. In the original version, the influence of organic carbon on SK was also taken into account, but the mathematical expression was different. Contrary to the original version, pH no longer contributes to explaining SK in the modified version of QUEFTS (Table 10.7).

Step II. Figures 10.2a, 10.2b and 10.2c are reflections of the way QUEFTS calculates actual N, P and K uptake from the potential supply measured at the sites. Calculated and measured uptake were well-correlated for P, but the model overestimated N and K uptake, particularly at low values. Figures 10.2d, 10.2e and 10.2f show the relations after calibration. Instead of the linear-parabolic-plateau model used in the original version (Situation *A*, *B* and *C* in Table 10.1), an exponential model better reflected the observations at the trials. Ln(UN/SN) was plotted against SN/SP and SN/SK, ln(UP/SP) against SP/SN and SP/SK, and ln(UK/SK) against SK/SN and SK/SP. Each pair of regression functions was averaged, yielding new descriptions for UN, UP and UK. Rewriting the new equations gave an exponential-plateau model, still explaining uptake of each nutrient as a function of the supplies of all three (Table 10.7). At low supplies, the uptake of an element approaches this supply asymptotically, unlike the original version of QUEFTS, where the two have the same value until the nutrient is not maximally diluted any more (Situation *A*). Once the maximum uptake has been realized, it is not affected by further supply of the nutrient, and the exponential relation turns into a plateau (Situation *C*).

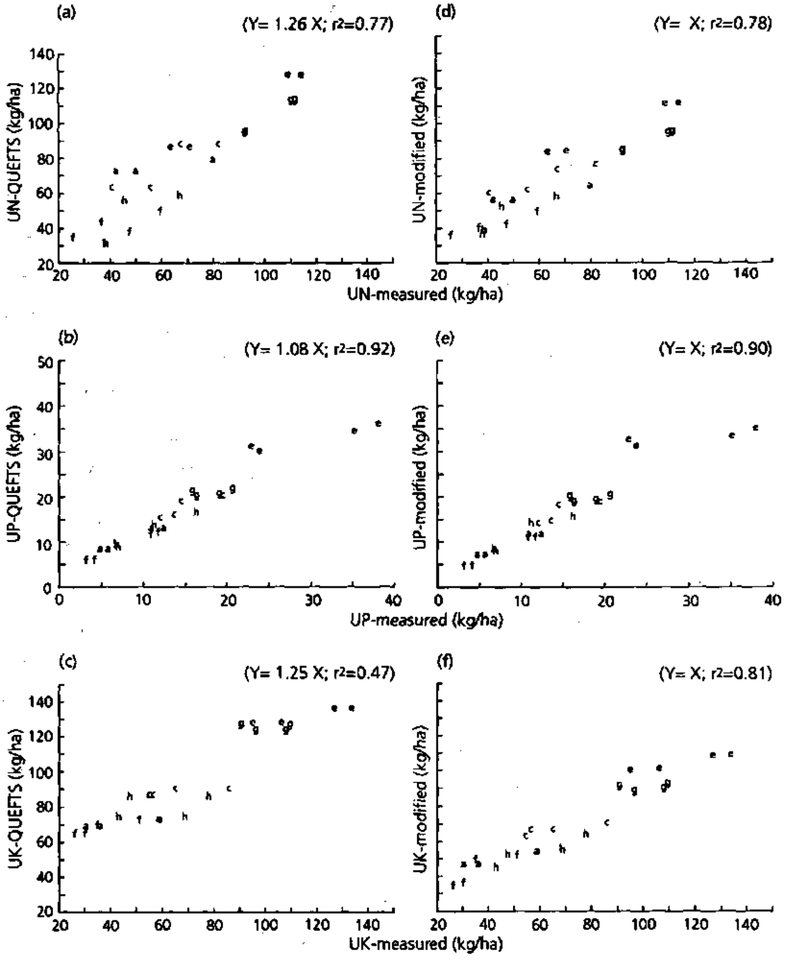


Fig. 10.2 Relation between measured and calculated actual NPK uptake, as determined by measured potential supply when using Step II equations (a-c: original version; d-f: modified version)

Step III and IV. Calibration of Steps III and IV, using actual uptake as input values, gave approximately the same correlation for QUEFTS (Fig. 10.3a; $r^2 = 0.78$) and the modified version (Fig. 10.3b; $r^2 = 0.79$). Most yield/uptake ratios were well within the ranges corresponding with maximum dilution and maximum accumulation. For a number of plots, N dilution and P accumulation required a widening of YND from 70 (UN - 5) to 80 (UN - 5), and of YPA from 200 (UP - 0.4) to 160 (UP - 0.4) (Table 10.7).

Figure 10.3b shows two marked outliers, in which measured yield exceeds calculated yield, i.e. treatments including phosphorus at site **a**. Table 10.5 shows that the maize crop realized here had high harvest indices of approximately 0.5. Boxman and Janssen (1990), who conducted numerous fertilizer trials in Suriname, found that a harvest index of 0.4 can be regarded as a 'normal' value for a properly managed maize crop. They also found a relation between harvest index and nutrient use efficiency. Based on these findings, maize plants with a harvest index of approximately 0.5 were multiplied by 1.25, i.e. 0.5/0.4, causing r^2 to increase to 0.86 (Fig. 10.3c). Lower harvest indices than 0.4 also occurred, but as this may be due to extraneous influences that were not observed, no correction was deemed justified.

Entering the input data for Step I into the original version of QUEFTS and running the model all the way without considering the different steps separately, gave a moderate correlation between measured and calculated yield ($r^2 = 0.66$; Fig. 10.4a). When applying the modified version the same way, correlation coincided with r^2 of 0.78 (Fig. 10.4b). When taking account of the correction factor for high harvest indices, as introduced in Step IV, r^2 is even 0.88 (Fig. 10.4c).

Model validation

Figure 10.5 shows a good correlation between measured and calculated yields for fields **b** and **j**. The calculated yields for fields **d**, **i**, and **k**, however, were too high which can be ascribed to several unfavourable circumstances. Maize at site **i** was adversely affected by a very low pH, and at site **k** by dry spells during the growing season. Maize yields at site **d** (1988) fell short of the calculated values, indicating that the QUEFTS boundary condition that soils should at least be moderately well drained, is to be maintained.

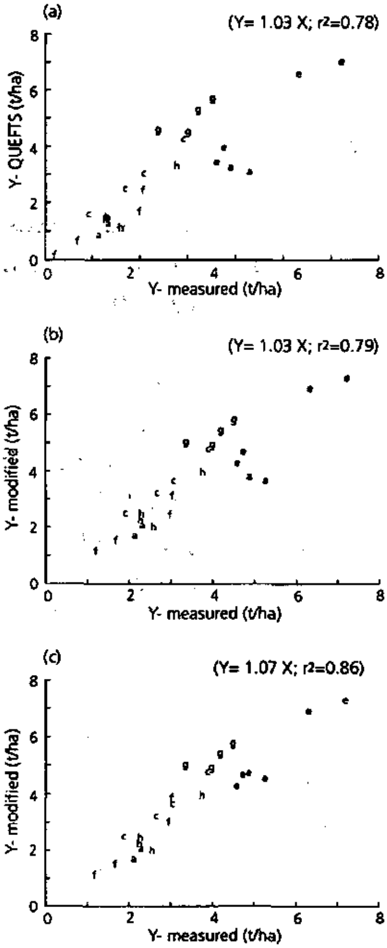


Fig. 10.3 Relation between measured and calculated maize yield, as determined by measured actual uptake when using yield/uptake ratios of Step III and combination of yield ranges of Step IV (a: original version; b and c: modified version, without (b) and with (c) harvest index correction factor)

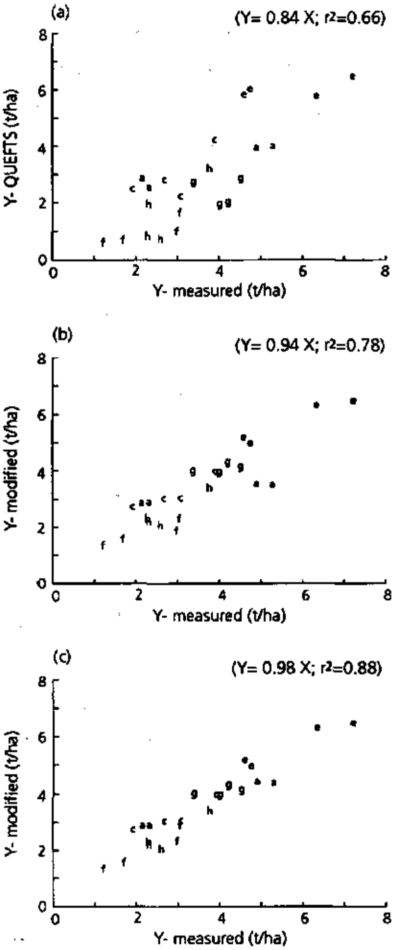


Fig. 10.4 Relation between measured and calculated maize yield when entering input data and running QUEFTS through the four Steps (a: original version; b and c: modified version, with out (b) and with (c) harvest index correction factor)

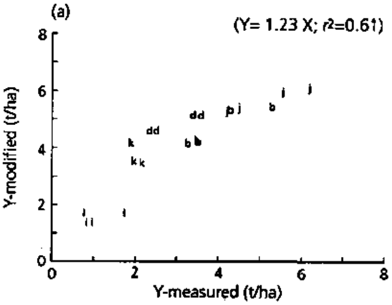


Fig. 10.5 Validation of the modified version of QUEFTS using data from five fertilizer experiments in Kenya (input data in Table 10.1 and 10.4)

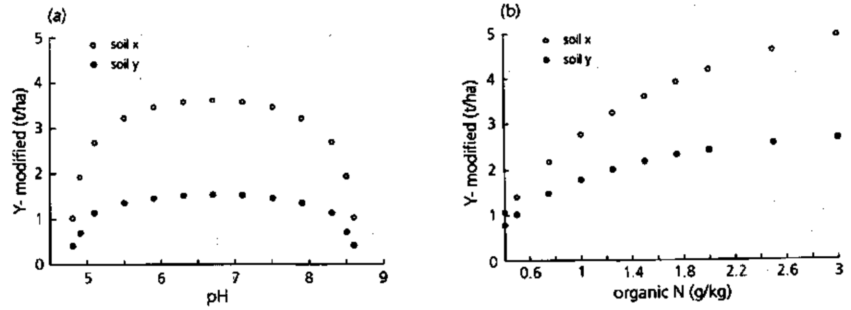


Fig. 10.6 Sensitivity analysis: effect of changing pH (a) and organic N (b) on maize yield calculated by the modified version of QUEFTS

Sensitivity analysis

On employing the modified QUEFTS, calculated yields for the reference soils of Table 10.4 were 3616 kg per ha (soil x) and 1544 kg per ha (soil y). The most sensitive parameters causing maize yield to differ by at least 10% from the reference value were organic N, pH, and temperature. All other parameter and coefficient changes caused yield changes of less than 5%. Figures 10.6a and 10.6b show how maize yields at the two reference sites varied when changing pH and organic N. Figure 10.6a shows that as long as pH is in between 5.5 to 7.9, effects on yield were modest; however, when pH approaches its outer limits, i.e. 4.7 and 8.7, the modified version gave considerable yield declines, even when pH was varied by a mere 0.1. In the present data set, sites **a** and **i** approach the lower pH limits. Figure 10.6b shows that organic N had a considerable impact on maize yield, and that this impact is greater at low values of organic N. This applies to site **f** and **h** of the present data set.

CONCLUSIONS

1. This article shows a calibration of the QUEFTS model, based on data collected from fertilizer trials in Kenya. The calibration involved some major parameter changes (Step I and II), but minor changes in the values of coefficients (Step III and IV). Although new relations were found, the basic structure and theoretical concepts of QUEFTS stood firm. With the modified version, the regression coefficient relating measured and calculated yield was improved from 0.66 to 0.78. When employing a correction factor for maize with a high harvest index, r^2 was even improved to 0.88.
2. In analyzing the different steps in QUEFTS, the largely empirical Step I gave a relatively low correlation (Fig. 10.1a-c). Upon calibration, new relations were established which gave a much higher correlation (Fig. 10.1d-f). Boundary conditions in the modified version are that $4.7 < pH < 8.0$, and soils should at least be moderately well drained.
3. Parameters employed to calculate SN had a relatively high sensitivity with respect to model output. As calibration of Step I for N did not give a very high correlation either (Fig. 10.1d; $r^2 = 0.67$), there is a need to further study this relation, and possibly include components of a model by Wolf et al. (1989), who conducted a somewhat more process-based modelling of crop response to the supply of nitrogen, including a partitioning into stable and labile pools.
4. In Step II, the assumption that the decrease of the N and K uptake/supply ratio was linear at increasing supply rates appeared to be an overestimation, causing relatively low correlation (Fig. 10.2a-c). It was replaced by a exponential model, which adequately describes a more rapid decrease of N and K uptake at increasing supply (Fig. 10.2d-f). Moreover, in the modified version, the uptake of an element is always lower than the supply, unlike the original version of QUEFTS, where the two have the same value until a certain threshold is surpassed.

5. Steps III and IV did not need major calibration as such, but were extended with an extra boundary condition for high harvest indices, which appeared to affect yield/uptake relations. Normal crop development is assumed to bring about harvest indices of approximately 0.4.
6. The development of a modified version does not imply that the original version of QUEFTS has become obsolete. Both versions require thorough validation in different tropical environments. Agronomists in the tropics should be encouraged to collect the relatively few data that are needed to run both versions of QUEFTS; only then can the model become a management tool to assist agronomic and policy decisions in land use planning and fertilizer use at farm and regional level. Increased efficiency of fertilizer use has many beneficiaries, including the farmer, the national economy, and the environment.
7. Interpretation of soil test values and, to a lesser extent, plant analysis is hampered by the often high inherent spatial variability of soil properties, which is not entirely random (Trangmar et al., 1985), and inter- and between-laboratory variability in the quality of analysis (Pleysier, 1989). As QUEFTS to a large extent uses soil test values as model input, sampling and analytical quality is of utmost importance for a successful model run. In addition, a lot more understanding of the relations between nutrient supply and uptake and crop yield is gathered when plant analysis would be carried out on routine basis in fertilizer trials.

ACKNOWLEDGEMENT

Support from Peter Dohme, who made QUEFTS fit for use in Lotus, and from Reimund Roetter on discussing modelling issues in agro-climate and soil fertility, and for providing agro-climatic data, is gratefully acknowledged.

REFERENCES

Boxman, O. and Janssen, B.H., 1990. Availability of nutrients and fertilizer use. In: B.H. Janssen and J.F. Wienk (Editors), Mechanized annual cropping on low fertility acid soils in the humid tropics. A case study of the Zanderij soils in Suriname. Wageningen Agricultural University Paper 90.5, pp. 73-99.

Burrough, P.A., 1989. Matching spatial databases and quantitative models in land resource assessment. Soil Use and Manage. 5: 3-8.

Caassen, N. and Barber, S.A., 1976. Simulation model for nutrient uptake from soil by a growing plant root system. Agron. J. 68: 961-969.

Cerrato, M.E. and Blackmer, A.M., 1990. Comparison of models for describing corn yield response to nitrogen fertilizer. Agron. J. 82: 138-143.

Chen, J.H. and Barber, S.A. 1990. Soil pH and phosphorus and potassium uptake by maize evaluated with an uptake model Soil Sci. Soc. Am. J. 54: 1032-1036.

Cochrane, T.T., 1988. A differential equation to estimate fertilizer response curves. Soil Sci. Soc. Am. J. 52: 525-529.

De Willigen, P. 1991. Nitrogen turnover in the soil-crop system; comparison of fourteen simulation models. Fert. Res. 27: 141-149.

FAO, 1983. Maximizing fertilizer use efficiency. Fertilizer and Plant Nutrition Bulletin 6. Food and Agriculture Organization, Rome, 50 pp.

FAO, 1988. FAO-Unesco Soil map of the world: revised legend. World Soil Resources Report 60. Food and Agriculture Organization, Rome, 138 pp.

Harmsen, K. and Moraghan, J.T., 1987. A comparison of the isotope recovery and difference methods for determining nitrogen fertilizer efficiency. Plant and Soil 105, 55-67.

Hoffland, E., 1991. Mobilization of rock phosphate by rape (Brassica napus L.). Ph.D. thesis, Agricultural University Wageningen, 93 pp.

Janssen, B.H. and Guiking, F.C.T., 1990. Modelling the response of crops to fertilizers. In: M.L. Van Beusichem (Editor), Plant nutrition - physiology and applications. Kluwer Academic Publishers, pp. 699-703.

Janssen, B.H. and Van der Eijk, D., 1990. Phosphorus supply to plants predicted from chemical soil properties. Transactions 14th Internat. Congress of Soil Science, Kyoto, pp. II-325-326.

Janssen, B.H. and Wolf, J., 1988. A simple equation for calculating the residual effect of phosphorus fertilizers. Fert. Res. 15: 79-87.

Janssen, B.H., Lathwell, D.J., and Wolf, J., 1987. Modelling long-term crop response to fertilizer phosphorus: II. Comparison with field results. Agron. J. 79: 452-458.

Janssen, B.H., Guiking, F.C.T., Van der Eijk, D., Smaling, E.M.A., Wolf, J., and Van Reuler, H., 1990. A system for Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS). Geoderma 46: 299-318.

Jenkinson, D.S. and Ayabana, A., 1977. Decomposition of carbon-14 labelled plant material under tropical conditions. Soil Sci. Soc. Am. J. 41: 912-915.

Kamprath, E.J., 1987. Enhanced phosphorus status of maize resulting from nitrogen fertilization of high phosphorus soils. Soil Sci. Soc. Am. J. 51, 1522-1526.

Kovar, J.L. and Barber, S.A., 1988. Phosphorus supply characteristics of 33 soils as influenced by seven rates of phosphorus addition. Soil Sci. Soc. Am. J. 52: 160-165.

Ladd, J.N. and Amato, M., 1985. Nitrogen cycling in legume-cereal rotations. In: B.T. Kang and J. Van der Heide (Editors), Nitrogen management in farming systems in humid and subhumid tropics. Soil Fertility Research Institute (IB-DLO), Groningen, and International Institute of Tropical Agriculture (IITA), Ibadan, pp. 105-127.

Lynch, J.M., 1983. Soil biotechnology. Microbiological factors in crop productivity. Blackwell Scientific Publications, Oxford, 191 pp.

Mengel, K. and Kirkby, E.A., 1980. Potassium in crop production. Adv. in Agronomy 33: 59-110.

Mombiela, F., Nicholaides, J.J., and Nelson, L.A., 1981. A method to determine the appropriate mathematical form for incorporating soil test levels in fertilizer response models for recommendation purposes. Agron. J. 73: 937-941.

Morel, C. and Fardeau, J.C., 1990. Uptake of phosphate from soils and fertilizers as affected by soil P availability and solubility of phosphorus fertilizers. Plant and Soil 121: 217-224.

Novozamsky, I. and Beek, J., 1976. Common solubility equilibria in soils. In: G.H. Bolt and M.G.M. Bruggenwert (Editors), Soil Chemistry. A. Basic elements. Developments in Soil Science 5A, Elsevier, Amsterdam, pp. 96-125.

Osmond, D.L., Lathwell, D.J., and Riha, S.J., 1992. Prediction of long-term fertilizer nitrogen requirements of maize in the tropics using a nitrogen balance model. Plant and Soil 143: 61-70.

Pleijsier, L.K., 1989. Variability in soil data. In: J. Bouma and A.K. Bregt (Editors). Land qualities in space and time. Proc. ISSS Symposium, Wageningen, 22-26 Aug. 1988. Centre for Agricultural Publishing and Documentation, Wageningen, pp. 89-100.

Roetter, R., in press. Simulation of the limitations to maize production in various agro-ecological zones in Kenya. PhD. thesis, University of Trier/Centre for Agrobiological Research (CABO-DLO), Wageningen.

Smaling, E.M.A. and Van de Weg, R.F., 1990. Using soil and climate maps and associated data sets to select sites for fertilizer trials in Kenya. Agric. Ecos. Envir. 31: 263-274.

Smaling, E.M.A., Nandwa, S.M., Prestele, H., Roetter, R. and Muchena, F.N., 1992. Yield response of maize to fertilizers and manure under different agro-ecological conditions in Kenya. Agric. Ecos. Envir. 41: 241-252.

Sörensen, L.H., 1975. The influence of clay on the rate of decay of amino acid metabolites synthesized in soils during decomposition of cellulose. Soil Biol. Biochem. 7: 171-177.

Sumner, M.E. and Farina, M.P.W., 1986. Phosphorus interactions with other nutrients and lime in field cropping systems. Adv. in Soil Science 5: 201-236.

Trangmar, B.B., Yost, R.S., and Uehara, G., 1985. Application of geostatistics to spatial studies of soil properties. Adv. in Agronomy 38: 45-94.

Uribe, E. and Cox, F.R., 1988. Soil properties affecting the availability of potassium in highly weathered soils. Soil Sci. Soc. Am. J. 52: 148-152.

Van Diepen, C.A., Wolf, J., van Keulen, H., and Rappoldt, C., 1989. WOFOST: a simulation model of crop production. Soil Use and Manage. 5: 16-24.

Van Diest, A., 1978. Factors affecting the availability of potassium in soils. Proc. 11th Congr. Int. Potash Inst., Berne, pp. 75-97.

Van Keulen, H. and Van Heemst, H.D.J., 1982. Crop response to the supply of macronutrients. Agric. Res. Rep. 916. Centre for Agricultural Publishing and Documentation, Wageningen, 46 pp.

Walters, D.T. and Malzer, G.L., 1990. Nitrogen management and nitrification inhibitor effects on nitrogen-15 urea: II. Nitrogen leaching and balance. Soil Sci. Soc. Am. J. 54: 122-130.

Waugh, D.L., Cate Jr., R.B., Nelson, L.A., and Manzano, A., 1975. New concepts in biological and economical interpretation of fertilizer response. In: E. Bornemisza and A. Alvarado, (Editors), Soil management in tropical America. North Carolina State University, Raleigh, pp. 484-501.

Wolf, J., De Wit, C.T., Janssen, B.H., and Lathwell, D.J., 1987. Modeling long-term crop response to fertilizer phosphorus: I. The model. Agron. J. 79: 445-451.

Wolf, J., De Wit, C.T. and Van Keulen, H., 1989. Modeling long-term crop response to fertilizer and soil nitrogen. I. Model description and application. Plant and Soil 120: 11-22.

FUTURE PERSPECTIVE

Major conclusions of this thesis

Integrated nutrient management in this thesis involves the manipulation of the different ingredients (inputs and outputs) of the macronutrient balance in the root zone of sub-Saharan African land use systems. The five nutrient input processes are application of mineral fertilizer (*IN 1*) and organic manure (*IN 2*), atmospheric deposition (*IN 3*), biological nitrogen fixation (*IN 4*), and sedimentation from natural flooding and irrigation water (*IN 5*). The five nutrient output processes are removal of harvested product (*OUT 1*) and crop residues (*OUT 2*) from the arable field, leaching (*OUT 3*), gaseous losses (*OUT 4*), and water erosion (*OUT 5*). *The agro-ecological framework* advocated in this thesis implies that land use systems must be geographically referenced, both as regards soils and climate (land units), and crops, trees, animals and grasses (land use types).

The *agro-ecological framework for integrated nutrient management* covers different spatial scales and hierarchical policy levels: macronutrient balances are quantified at (supra)national and regional level, and a decision-support model is proposed that can be used at all levels, enabling users to scale up and down. At the regional level, the relation between efficient fertilizer use and crop production is elaborated, both being components of the nutrient balance. Recommendations following from this part of the thesis should guide extension officers working at regional and village levels. Yet, many geostatistical studies have shown that soil heterogeneity at these levels can not be ignored; hence, two studies are included addressing spatial variability on a field scale. The model QUEFTS, linking macronutrient supply and uptake with crop yields can also be used at different levels, the options being (i) advice to farmers, (ii) calculation of fertilizer requirements by regional wholesale and retail traders, and (iii) national and regional land use planning using yield levels calculated by QUEFTS as a yardstick. Field variability studies on the input parameters of QUEFTS can be used to see how sensitive the model is in this respect and the impact it has on predictions made for regions.

The thesis follows three lines of thinking on agricultural production and resource management in tropical countries, all applying to components of the nutrient balance. (1) The first and foremost concern of a smallholder farmer is the *productivity* of his land. In traditional bush fallows, where land is not scarce, the farmer leaves a plot as soon as its productivity dwindles, and he subsequently shifts to a neighbouring plot that has been idle during the previous years, gaining some fertility from atmospheric deposition (*IN 3*) and biological fixation (*IN 4*). This farmer aims solely at a satisfactory *OUT 1*, without consciously paying attention to the balance between nutrient inputs and outputs. Any deficit in the nutrient balance of the cultivated plot is offset by the soil nutrient pool, but may be fully replenished if fallow periods are long enough.

(3) When land becomes increasingly scarce, productivity has to be maintained artificially, for example by using mineral fertilizers (*IN 1*). Fertilizer nutrients are largely converted to useful (*OUT 1*) as well as non-useful outputs (*OUT 2-5*). The farmer has an interest to obtain a high ratio between *OUT 1* and *IN 1*, i.e. a high *fertilizer use efficiency*. For this to be realized, soil and climatic properties of the land should be known, as they largely dictate the kinds and amounts of fertilizer to be applied. High fertilizer use efficiency may but does not necessarily imply that a strained nutrient balance is alleviated, as it is mainly the reflection of a within-balance shift from non-useful to useful outputs. Yet, when production in one area can be increased by judicious fertilizer use, other areas, due for cultivation, may be left to recover recuperate.

(3) This brings us to the farmer's third goal, i.e. *sustainability* of land use systems: farmers aim at high *OUT 1*, but their land use systems are such that the sum of inputs more or less equals the sum of outputs, thus maintaining productivity over time. Chapters 3 and 4 have shown that the macronutrient balance in sub-Saharan African agricultural systems, calculated at supra-national and at regional scale, is strongly negative. In other words, actual land use systems are not sustainable: at some point in time, soils will have been depleted to the extent that they can no longer equilibrate the annual nutrient deficit in the prevailing land use systems. A strained nutrient balance can be alleviated along two lines. First, it can be influenced by selecting land units that are agro-ecologically less vulnerable, for example to erosion (*OUT 5* is reduced), and by selecting land use types with lower nutrient requirements (*OUT 1* is reduced). This option is, physically, easier to achieve in regions with low or moderate demographic pressure than in densely populated areas. Second, the balance can be influenced by manipulating the individual input and output values. This is largely in the hands of farmers and, more indirectly a reflection of regional, national and even supra-

national agricultural policies and infrastructure. Examples are: land management aimed at reduction of leaching and erosion, and proper crop residue management (field and farm level), adoption of agro-forestry, zero-grazing, soil conservation, and N fixing species in rotations (field, farm and regional level), policies on pricing of agricultural produce and input subsidies, credit facilities, incentives to meet export targets (national level), and, hopefully soon, international agreements on financial incentives for debt-ridden countries that see no alternative than depleting their national nutrient reserves by exporting agricultural and forest products (supra-national level).

There is an urgent need to develop systematic means of nutrient balance monitoring, which can suggest and evaluate agronomic and policy interventions, geared towards alleviation and redressing of the nutrient balance. Chapter 5 shows that for a densely populated, and (still) highly productive district such as Kisii in Kenya, one option to reach a balanced nutrient status is the adoption of rotations that include not-to-be-harvested green manures, and strict practices of manuring, soil conservation, agroforestry and zero-grazing. By virtue of high phosphorus fertilizer use efficiency, total crop production in the district can remain more or less constant, even when using a mere 50% of the agricultural land.

Chapter 6 shows that soil and climate maps are indispensable for geographical referencing of land use systems. It is essential to know where to find which soils and which climate types in a country. Reversely, we need to know to which soils, and which climate types, research results can be extrapolated. For this to be achieved, soil and climatic properties, functional to crop production, are derived from map unit descriptions and are combined to form agro-ecological units. Experimental results can then be extrapolated to the entire unit in the interest of integrated nutrient management, or, as a component of it, efficient fertilizer recommendations. It is clearly shown in Chapter 7 how differently maize responds to fertilizers and manure in different agro-ecological units. Types and amounts should be tailored to both crop and soil characteristics. The resulting increases of *OUT 1* at certain rates of *IN 1* and the concurrent exceedence of minimum value/cost ratios will positively influence farmers' attitude to modest investment in external inputs such as mineral fertilizer. In addition, high fertilizer use efficiency is not only advantageous to the farmer's wallet, but also to the environment (reduction of *OUT 3-5*), and to the national economy (foreign exchange spent on procurement of *IN 1* leads to increased *OUT 1*, replacing food imports).

Chapters 8 and 9 address spatial heterogeneity at the field level, i.e. occurrence of bypass flow and nitrogen leaching in cracking clays, and the spotty incidence of *Striga hermonthica*, both in areas of less than 1 hectare. It is shown that extrapolation of results, obtained on a field, to a regional level, is a precarious undertaking. Between field and regional level is still the farm level, not particularly addressed in this thesis. At this level, typical patterns of variability in, for example, slope angle, soil fertility or soil water flow may exist which could be used to characterize farm types as an aggregation of fields with typical heterogeneity patterns. For the extension service, carrying 'regional' messages to the farmer, this intermediary level may also be helpful.

As fertilizer trial networks in Africa are few and require considerable time and investment, a model such as the QUantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) is a sound alternative to predict maize yields from native soil fertility and fertilizer application. The model has few input requirements and is based on a mosaic of tropical soils, ranging from (sandy) Arenosols to (heavy clay) Vertisols. Though non-mechanistic, the model is underlain by worthy [illegible] plausible theoretical concepts, it has pedotransfer functions with few and easy-to-measure parameters, and it integrates all three macronutrients, unlike any other model (Chapter 10). It differs markedly from the response prediction models referred to in Chapter 2.5, which hardly take the local biophysical conditions into consideration. The regression equations arrived at when using such models are only meaningful for the particular soil for which they were developed, and the curve fitting which accompanies this work is rather arbitrary. The complex mechanistic models on nutrient uptake processes and crop yield have, however, not proved to be helpful either in resource management in tropical countries. So far they have been meaningful only from an academic point of view, helpful as they are in increasing our understanding of processes.

Research agenda

The nutrient balance is quantified using primary data, estimates and assumptions. To improve the quality and reliability of a decision-support model for monitoring nutrient balances, further research is primarily needed on nutrient losses by processes which have been poorly quantified in the field, and which at the same time have a substantial impact on the nutrient balance. Processes referred to are the uptake of nutrients by different crop species under different agro-ecological conditions (part of *OUT 1*), leaching (*OUT 3*), denitrification (*OUT 4*) and erosion (*OUT 5*). The latter have been calculated from transfer functions, using widely recognized and easily measured determinants of these outputs as independent variables in the regression equations (e.g. rainfall, slope angle and length, texture, bulk density, organic nitrogen, pH). Research should be focused on the validation and calibration of these relations in different agro-environments, as it will be impossible to measure the three outputs on a routine basis. An ambitious plan would be to perform nutrient balance studies in a well-characterized watershed, using labelled fertilizers, crop residues, and manure to assess the specific pathways and degrees of nutrient losses in different land use systems. In order to live up to agro-ecological principles, such a programme should actually be run in different agro-ecological units.

Research on agro-ecosystem performance should be increasingly judged on its contribution to sustainability, implying both collection of technical results (species performance, contribution from N fixation), and data on farmers' adoption rates. The latter should be compared with performance of indigenous systems, in order to assess whether suggested additional investments by farmers will endure once project structures are abolished.

Soil and agro-climatic surveys at reconnaissance scale proved indispensable for this thesis. Data collection should be increasingly geared to properties that are functional to agricultural production and resource management, rather than serving taxonomic purposes only. The approach will also imply that researchers who are not familiar with soil science do not immediately lose appetite when confronted with soil maps. It is for this reason that the introduction of data base management systems and geographical information systems in African soil survey and related organizations deserves priority, provided that there are reliable data to be entered. If this is the case, relevant soil and agro-climatic files can be overlaid to pinpoint the agro-ecological units, which form the geographic reference for fertilizer recommendations and integrated nutrient management at large.

The model QUEFTS (Chapter 10) urgently needs further validation, which should not be too difficult as it uses few and easy-to-obtain input parameters. Many validations and possibly new calibrations will definitely improve its predictive value for a wider range of soils. Comparison with mechanistic models is important to see whether other diagnostic parameters can be incorporated in QUEFTS, and whether they could be measured on a routine basis as developments in field and laboratory equipment progress. Modelling approaches in general should be centred more on implementation and user application, to ensure proper management decisions. Too few models are actually used by others than the developer.

Spatial variability at field level showed that extrapolation of research results to a regional level is difficult. Vertisols, for example, are more heterogeneous than Arenosols, although both occur as distinct land units on regional soil maps. Adapted research is needed (and, in fact, taking place by geostatisticians) on how to tackle this variability in order to still extrapolate survey results. Between two hierarchical levels, other less-distinct levels with recognizable spatial patterns may be identified that can be helpful in relating levels that are too distant. 'Scaling up and down' is not only a challenge to geoscientists dealing with spatial and temporal variability, but also to agronomic and policy decision-makers at the different hierarchical levels in the agricultural society.

Policy agenda

Sustainability should become an integral part of land use policies in African countries. Integrated nutrient management should become common practice, and projects that address components of integrated nutrient management (increased fertilizer use efficiency, agroforestry, soil conservation, zero-grazing, rotations with N-fixing species) should be appreciated as serving sustainable land use. Farmers' indigenous practices should also be seen in this context. Further development of a model proposed in Chapter 5 to monitor nutrient balances and suggest and evaluate interventions (NUTMON) should be supported as a matter of priority, so it can be tested and institutionalized in different regions.

To do away with blanket fertilizer recommendations and obtain high fertilizer use efficiency, there is a continued need for resource inventories at different scales, and improved agricultural and market infrastructure. Farmers should be advised according to the requirements of both their crops and soils. Fertilizer and produce price updates should indicate to farmers what profits they can expect upon the use of certain kinds and amounts of fertilizer for specific crops.

The model QUEFTS (Chapter 10) should be operationalized in agricultural research organizations and laboratories. Input data are easy to gather, and serve to further develop and improve the predictive value of the model. Laboratories should be equipped to measure the required input data, and quality control should be ensured through international networking.

Problem-solving: the need to bridge gaps between research, survey, extension and farming

Many geoscientists involved in (inter)national research tend not to appreciate the value of soil maps, as it is an aggregated bunch of non-functional information. Likewise, many of their fellow desk-economists tend to label farming systems analysis as only providing anecdotes, not being of sufficient quantitative value for economic modelling. Similarly, soil and farming systems surveyors blame the inhabitants of the 'Ivory Tower of Science' for not really being interested in the problems farmers actually face, as long as it does not yield a publication. Their general contempt for research is equally detrimental to problem-solving as the contempt researchers have for the meagre academic record of the surveyor, who is often not aware of the most recent developments in his field, and can easily be 'out-scienced' by the researcher. If we, for example, take a farmer's field in an irrigation scheme which has started to develop patchy salinity problems, the surveyor will try to make the best of it, based on his expert knowledge. He will probably take a few samples for EC analysis, advise the farmer to grow salt-tolerant species, level the plot, apply more water if available, or leave the field completely. The geostatistician will, however, not sleep well until his semi-variograms have featured on the monitor, and the soil physicist is entirely taken up by his calculations on the proper sample size and column diameter required to quantitatively describe soil water flow in this plot. Chapter 2.1 of this thesis provides some examples in the same line of thinking. Whereas Kang et al. (1990) have managed to collect a lot of research data on different species in agro-forestry systems, Kerkhof (1990) visited a large number of agro-forestry projects and denounced the often faulty concepts researchers use on farmers' receptiveness to techniques which have proven effective only on the research station.

The examples show that there is a serious need for agronomists and agro-economists from both within and outside tropical countries, who have an up-to-date academic background, and who have been 'around' in tropical countries long enough to assess what farmers regard as priority issues and problems, and how they may respond to the different options to solve them. Only then can the gap between researchers, surveyors, extension staff and the farming community be bridged, and can research and policy agendas be streamlined. This is a challenge which hopefully appeals to international organizations, such as the Consultative Group of International Agricultural Research (CGIAR), the UN Food and Agriculture Organization (FAO), the International Board for Soil Research and Management (IBSRAM), to regional networks in Africa such as the Southern African Development Community Council (SADCC), the Economic Community for West African States (ECOWAS), and the Intergovernmental Authority on Drought and Development (IGADD), but also to the many universities and other training institutes, national agricultural research institutes and government departments, involved in tropical agriculture and resource management.

SAMENVATTING

Geïntegreerd beheer van bodemnutriënten in een agro-ecologisch kader, met speciale aandacht voor Kenia.

In dit proefschrift worden lijnen uitgezet om te komen tot een geïntegreerd beheer van de bodemvruchtbaarheid in Afrikaanse landbouwgronden ten zuiden van de Sahara. Het integratie-aspect zit hem in het feit dat het verschil in bodemvruchtbaarheid tussen twee opeenvolgende jaren een resultante is van diverse aan- en afvoerprocessen van nutriënten. De meeste van deze processen zijn beïnvloedbaar. Aanvoerprocessen zijn: de toediening van kunstmest (*IN 1*) en organische mest (*IN 2*), atmosferische depositie (*IN 3*), biologische stikstofbinding (*IN 4*) en sedimentatie uit bevloeiingswater (*IN 5*). De afvoer wordt bepaald door de verwijdering van het oogstproduct (*OUT 1*) en gewasresten (*OUT 2*), uitspoeling (*OUT 3*), denitrificatie (*OUT 4*), en watererosie (*OUT 5*). Drie kernbegrippen staan centraal in deze geïntegreerde benadering: (korte termijn) produktiviteit, (lange termijn) duurzaamheid en efficiëntie van meststoffen. Deze begrippen worden nadrukkelijk geografisch gekoppeld aan goed gedefinieerde en op kaarten geïdentificeerde landeenheden met specifieke bodem- en klimaatseigenschappen (agro-ecologische eenheden). Dit agro-ecologisch kader maakt dat aan uitspraken en aanbevelingen m.b.t. de drie begrippen een ruimtelijke betekenis toegekend kan worden, waarmee ze waardevol worden voor de boer, de regio en het land: ze kunnen bijdragen aan agronomische en beleidsbeslissingen die op deze niveaus genomen worden.

Het in dit proefschrift besproken onderzoek vond grotendeels plaats in Kenia, hetgeen mogelijk werd dankzij de Kenya Soil Survey waar, in tegenstelling tot vele andere Afrikaanse landen, in ruime mate klimaats- en bodemkaarten op overzichtsschaal (1:100 000 tot 1:250 000) voor handen zijn.

Deel I van dit proefschrift bevat een algemene introductie, waarin het onderwerp van studie in een maatschappelijke context wordt geplaatst (Hoofdstuk 1). Vervolgens wordt per deelonderwerp een literatuuroverzicht gepresenteerd (Hoofdstuk 2).

Deel II gaat van start met de berekening van de stikstof-, fosfor- en kaliumbalansen in de wortelzône van de landbouwgronden in 38 Afrikaanse landen ten zuiden van de Sahara (Hoofdstuk 3). Op grond van gegevens van de Voedsel- en Landbouworganisatie van de Verenigde Naties (FAO) is het gebied verdeeld op basis van klimaat, bodem, en landgebruik. Aangevuld met gegevens uit de literatuur zijn vervolgens landgebruikssystemen vastgesteld, waarvoor de nutriëntenbalans is berekend als de som van *IN 1-5* minus de som van *OUT 1-5*. In totaal blijkt er in praktisch alle landen aanzienlijke nutriëntenuitputting op te treden. In het geaccidenteerde en relatief vruchtbare Oost-Afrika zijn de verliezen hoger dan in het vlakkere en bodemchemisch toch al armere West-Afrika. Gemiddelde waarden voor het subcontinent zijn 22 kg N, 2.6 kg P en 15 kg K ha^{-1} per jaar voor de periode 1982-1984.

Een beperking bij deze studie is de kleine, nationale schaal. Aannames, aggregaties en simplificaties zijn onvermijdelijk om een uniforme benadering van de verschillende landgebruikssystemen te handhaven. Verder blijkt de beschikbare informatie ongelijk verdeeld over de landen en ook daarbinnen en betreft het dikwijls puntgegevens, die niet geografisch-bodemkundig gecorreleerd zijn. Dientengevolge is de studie nogmaals uitgevoerd op regionale schaal (1:250 000) in een goed geïnventariseerd gebied: het Kisii District in Kenia (Hoofdstuk 4). Ook hier blijkt sprake te zijn van een negatieve nutriëntenbalans: -112 kg N, -3 kg P en -70 kg K ha^{-1} per jaar. Om deze negatieve waarden aan te vullen en constante opbrengsten te blijven realiseren moet de bodem elk jaar uit voorraad leveren. Afhankelijk van de chemische rijkdom en de mineralisatiesnelheid van een bodem komt er een moment dat het jaarlijks tekort op de nutriëntenbalans niet meer kan worden aangevuld. Het gevolg is een daling van de gewasopbrengst, ofwel een daling van *OUT 1*, waarbij een nieuwe, minder negatieve balans ontstaat, waarvan de waarde correspondeert met de hoeveelheid nutriënten die de bodem gedurende dat jaar nog kan leveren.

De cijfers zijn alarmerend en wijzen op de noodzaak om te komen tot een systematische vorm van controle van de nutriëntenbalans op verschillende schaalniveaus en suggesties voor gerichte agronomische en beleidsinterventies, die bodemuitputting kunnen afremmen. Voor het Kisii District worden in Hoofdstuk 5 dergelijke scenario's gedefinieerd. Sommige scenario's vormen een weerslag van activiteiten op dit gebied die op het moment in het district reeds plaatsvinden, maar het uiteindelijke toekomstscenario leidt tot een evenwichtssituatie, waarbij de totalen van aanvoer en afvoer gelijk zijn: $\Sigma\ (IN) = \Sigma\ (OUT)$.

In Deel III wordt verder ingegaan op de relatie tussen *IN 1* en *OUT 1*, ofwel de relatie tussen meststoffen en gewasproductie. Minerale meststoffen zijn schaars in de meeste Afrikaanse landen, waaronder Kenia, en onder de huidige filosofie van structurele aanpassing worden de subsidies op kunstmest in hoog tempo geschrapt. Het wordt voor een Afrikaanse boer dus steeds belangrijker om het maximale rendement uit een investering in meststoffen te halen. Dit vertaalt zich in een toenemende noodzaak om soort, hoeveelheid, tijdstip en plaats van toediening van de meststof zo goed mogelijk te kiezen. Naast de specifieke nutriëntenbehoefte van een gewas, betekent dit dat er informatie vereist is over bodemeigenschappen. Is dit het geval, dan leidt optimaal beheer tot een situatie waarbij zoveel mogelijk meststof (*IN 1*) omgezet wordt in nuttig produkt (*OUT 1*), in plaats van verloren te gaan via verwijderde gewasresten, uitspoeling, denitrificatie of erosie (*OUT 2-5*). Dit was één van de voornaamste redenen om in 1985 in Kenia een netwerk van 70 bemestingsexperimenten op te zetten, waarin de reactie van maïs op diverse meststoffen werd gemeten. De proefopzet omvat een 4^2 experiment met bemesting met 0, 25, 50 of 75 kg N ha^{-1} als calciumammoniumnitraat, toegediend op het moment dat het gewas kniehoogte heeft bereikt, en 0, 11, 22 of 33 kg P ha^{-1} als tripelsuperfosfaat, toegediend vlak voor het planten. In een tweede, 2^4 experiment is maïs bemest met 0 of 50 kg N, 0 of 22 kg P, 0 of 5000 kg organische mest ha^{-1} plus een vierde factor (kalium, zwavel of kalk). De proefvelden zijn geïnstalleerd na een grondige analyse van de Keniaanse bodem- en klimaatskaarten ten aanzien van hun functionele eigenschappen voor gewasgroei. Het besluit ten aanzien van de proefveldlokatie is genomen op grond van het feit of ze 'de bodem' en 'het klimaat' van die specifieke agro-ecologische zône bezaten. Alleen onder die voorwaarden kan men resultaten extrapoleren naar bedrijven binnen die zone, en zijn ze relevant voor de boerengemeenschap.

De methode van proefveldselectie, met als voorbeeld het Kisii District, wordt beschreven in Hoofdstuk 6. Vervolgens wordt in Hoofdstuk 7 aangetoond dat deze methode hout snijdt. Drie proefvelden in geheel verschillende agro-ecologische eenheden zijn gedurende 4 jaar gevolgd op hun reactie op minerale en organische mest. Op één van de proefvelden blijkt maïs zeer sterk te reageren op toediening van fosfor, maar nauwelijks op stikstof. Op het tweede veld is dit juist andersom. Maïs op het derde veld daarentegen blijkt behoefte te hebben aan beide elementen. In economische zin is de verbouw van maïs op de eerste twee velden zeer aantrekkelijk voor een boer die laag wil investeren. Een gerichte, lage mestgift staat borg voor een meeropbrengst die overeenkomt met een baten/kosten verhouding van 5-10. Voor het derde veld geldt dit niet: naast het feit dat beide meststoffen moeten worden toegediend, is de meeropbrengst van dien aard, dat kunstmest in de meeste jaren geen verantwoorde investering is. Dit kan verbeteren indien naast de meststof andere componenten van de nutriëntenbalans beïnvloed worden (combinatie met organische mest en stikstofbinders in het bouwplan). Deel III toont indirect aan hoe groot het belang van bodem- en klimaatskaarten is om althans op regionaal niveau tot een redelijke nuancering te komen in de bemestingsadvisering.

Het extrapoleren van proefveldresultaten zoals beschreven in Deel III heeft betrekking op een regionale of districtsschaal. Het houdt echter geen rekening met variabiliteit tussen en binnen individuele velden. Deze variabiliteit op veldschaal is het thema van Deel IV van dit proefschrift. Een indicatie van de heterogeniteit binnen proefvelden wordt verkregen uit de variatiecoëfficiënt (CV). Op een totaal van acht proefvelden bedraagt voor twee velden de gemiddelde CV tussen 1987 en 1990 ongeveer 30%. De andere proefvelden hebben een gemiddelde CV < 20%. De hoge CV op het eerste veld is te wijten aan het feit dat het hier een Vertisol betreft, een scheurende, zware kleigrond op vlak terrein. De zwel- en krimpprocessen die periodiek optreden in deze bodems veroorzaken een met het seizoen sterk variërende poriëngrootte en -conituïteit. Gedurende het regenseizoen blijkt periodiek en zeer verspreid wateroverlast op te treden op dit proefveld, hetgeen de gewasontwikkeling nadelig en, in ruimtelijke zin, op niet-uniforme wijze beïnvloedt. Bij de start van de regentijd is de grond relatief droog en heeft de Vertisol talrijke poriën, die gedeeltelijk met lucht gevuld zijn. Deze fungeren als preferente stroombanen en veroorzaken een proces dat als 'kortsluiting' te boek staat: het proces van snelle verticale waterbeweging door continue macroporiën in een onverzadigde bodemmatrix. Om de ruimtelijke variabiliteit binnen dit in bodemfysische zin 'lastige' proefveld te kwantificeren is deze kortsluiting gemeten aan het begin van de regentijd, alsmede de stikstofverliezen die hierbij optreden. Het geploegd bouwland op het proefveld blijkt aanzienlijk minder water en stikstof te verliezen dan het naburige grasland. De ruimtelijke variabiliteit van deze verliezen binnen het veld is aanzienlijk en verschilt voor de geploegde bovengrond bovendien in hoge mate van de sterk prismatisch gestructureerde laag eronder (Hoofdstuk 8).

Op het tweede proefveld wordt de hoge CV veroorzaakt door de aanwezigheid van het parasitaire onkruid *Striga hermonthica*. Dit onkruid ontkiemt in een onvoorspelbaar patroon en berokkent de waardplant de meeste schade vóór de eigen ontkieming. Dit maakt het tot een moeilijk te bestrijden plaag, en het gevaar bestaat dat de proefveldresultaten eerder een Striga-effect dan een bemestingseffect vertonen. Om dit te ondervangen is, naast de meststoffen, het voorkomen van Striga als verklarende variabele opgenomen in een regressiemodel. Hoofdstuk 9 laat zien dat deze manier van werken een forse bijdrage levert aan de verklaring van de experimentele variatie, waarmee het proefveld ondanks het voorkomen van Striga toch bruikbare resultaten oplevert. Methoden ter bestrijding van Striga zijn ook bestudeerd, waaronder het gebruik van een zogenaamde 'trap crop'. Deze doet Striga wel ontkiemen, maar fungeert niet als waardplant. Ook het effect van toediening van minerale mest is hierbij bekeken.

Hoewel buitengewoon nuttig, is de opzet en het onderhoud van een proefveldnetwerk een geld- en tijdverslindende aangelegenheid. Het is daardoor niet in elke situatie de meest aantrekkelijke oplossing. Een alternatief dat heden ten dage hoog wordt aangeslagen is het gebruik van computermodellen, die gewasopbrengst berekenen uit een aantal meetbare grootheden. Deel V beschrijft een model dat bekend staat als QUEFTS, acroniem voor QUantitative Evaluation of the Fertility of Tropical Soils. Het model beschrijft, in vier stappen, relaties tussen (i) een aantal chemische bodemeigenschappen (ii) het potentiele aanbod van N, P en K door bodem en meststof, (iii) de actuele opname van N, P en K door maïs, en (iv) de korrelopbrengst. Karakteristiek voor het QUEFTS model is dat daarin alle drie macronutriënten zijn inbegrepen, alsmede hun interacties. Voorts stelt het model lage eisen aan de invoergegevens, waardoor het eenvoudig toegepast en getest kan worden in tropische gebieden.

QUEFTS wordt in dit proefschrift getoetst met invoergegevens, verkregen van 8 proefvelden in verschillende agro-ecologische eenheden. De correlatie tussen de gemeten en de berekende opbrengsten blijkt matig te zijn. Een belangrijke reden hiervoor is dat de originele set gegevens, gebruikt om QUEFTS te ontwikkelen, slechts weinig bodems bevat met een hoge pH, terwijl in de huidige set drie gronden voorkomen met een pH > 7. Bovendien voldoen sommige bodems uit de huidige set gegevens niet aan andere randvoorwaarden van QUEFTS. Op grond van deze overwegingen wordt de gegevensset aangewend voor een calibratie van QUEFTS, met het doel de bruikbaarheid van het model te verruimen. Hoofdstuk 10 geeft de bodemvruchtbaarheidscijfers, nutriëntenopname en korrel- en droge stofopbrengst, zoals gemeten op de 8 proefvelden. Alle vier stappen in het model worden gecalibreerd en een uiteindelijke vergelijking van gemeten en berekende opbrengst voor het complete model geeft een hoge correlatie. Hoewel nieuwe relaties worden beschreven, blijft het theoretisch concept van QUEFTS overeind. Er is nu een dringende behoefte aan verdere validatie van beide versies en landbouwkundigen in de tropen worden aangemoedigd juist díé gegevens te verzamelen die nodig zijn om QUEFTS operationeel te maken. Het model moet een belangrijk instrument gaan vormen in de besluitvorming over aanschaf van meststoffen op agro-ecologische basis, zowel op bedrijfsniveau als op regionaal niveau. De hogere meststofefficiëntie die aldus kan worden verkregen is gunstig voor zowel de boer, het milieu als de nationale economie.

CURRICULUM VITAE

Eric Marc Alexander Smaling werd op 18 augustus 1957 geboren in Amsterdam. In 1975 behaalde hij het diploma gymnasium-ß aan het Spinozalyceum in Amsterdam.

In september 1975 begon hij zijn studie bodemkunde en bemestingsleer aan de Landbouwhogeschool (LH) Wageningen. De praktijktijd (1979/'80) werd doorgebracht in het LH-project Training Project in Pedology, Kilifi, Kenia. In september 1982 studeerde hij af als landbouwkundig ingenieur met als hoofdvak de tropische bodemkunde, en als bijvakken de bodemvruchtbaarheid en de ontwikkelingseconomie.

In 1983 werkte hij in opdracht van het International Institute for Aerospace Surveys and Earth Sciences (ITC) in een plattelandsontwikkelingsproject in Atjeh, Indonesië. Voor twee provincies werd een bodemkartering en landevaluatie uitgevoerd. Vervolgens schreef hij in dienst van de LH als co-auteur aan het rapport 'Soils of the Kilifi Area, Kenya'. Tot medio 1985 volgden korte opdrachten voor het International Institute for Land Reclamation and Improvement, de Stichting voor Bodemkartering en het International Institute of Tropical Agriculture in het kader van het Wetlands Utilization Research Project (Nigeria, Sierra Leone, Benin, Burkina Faso). Het werk bestond uit de bodemkundige karakterisering van kleine valleien en hun directe omstreken, ten behoeve van de lokale, door rijst gedomineerde teeltsystemen. Van september 1985 tot eind 1987 volgde een tijdelijke aanstelling bij de Stichting voor Bodemkartering en detachering in Nairobi, Kenia bij het Fertilizer Use Recommendation Project. De voornaamste opdracht was tot een zodanige lokatie voor proefvelden voor bemestingsexperimenten te komen, dat de proefveldresultaten representatief geacht kunnen worden voor grotere, op een districtskaart aan te geven gebieden met dezelfde bodem- en klimaatseigenschappen. Later werd ook gewerkt aan de inrichting en operationalisering van een twintigtal proefvelden.

Sinds 1988 werkt hij in Wageningen bij de Stichting voor Bodemkartering, welke in 1989 met drie andere instituten opging in het DLO-Staring Centrum voor

Onderzoek van het Landelijk Gebied. Als medewerker bij de Afdeling Internationale Samenwerking verleent hij, in opdracht van het Directoraat-Generaal Internationale Samenwerking (DGIS), technische en wetenschappelijke steun aan bodemkundige organisaties in o.a. Kenia en Mozambique en is hij actief betrokken bij landbouwkundige onderzoeksprojecten in Oost- en West-Afrika in opdracht van DGIS, EG en FAO.