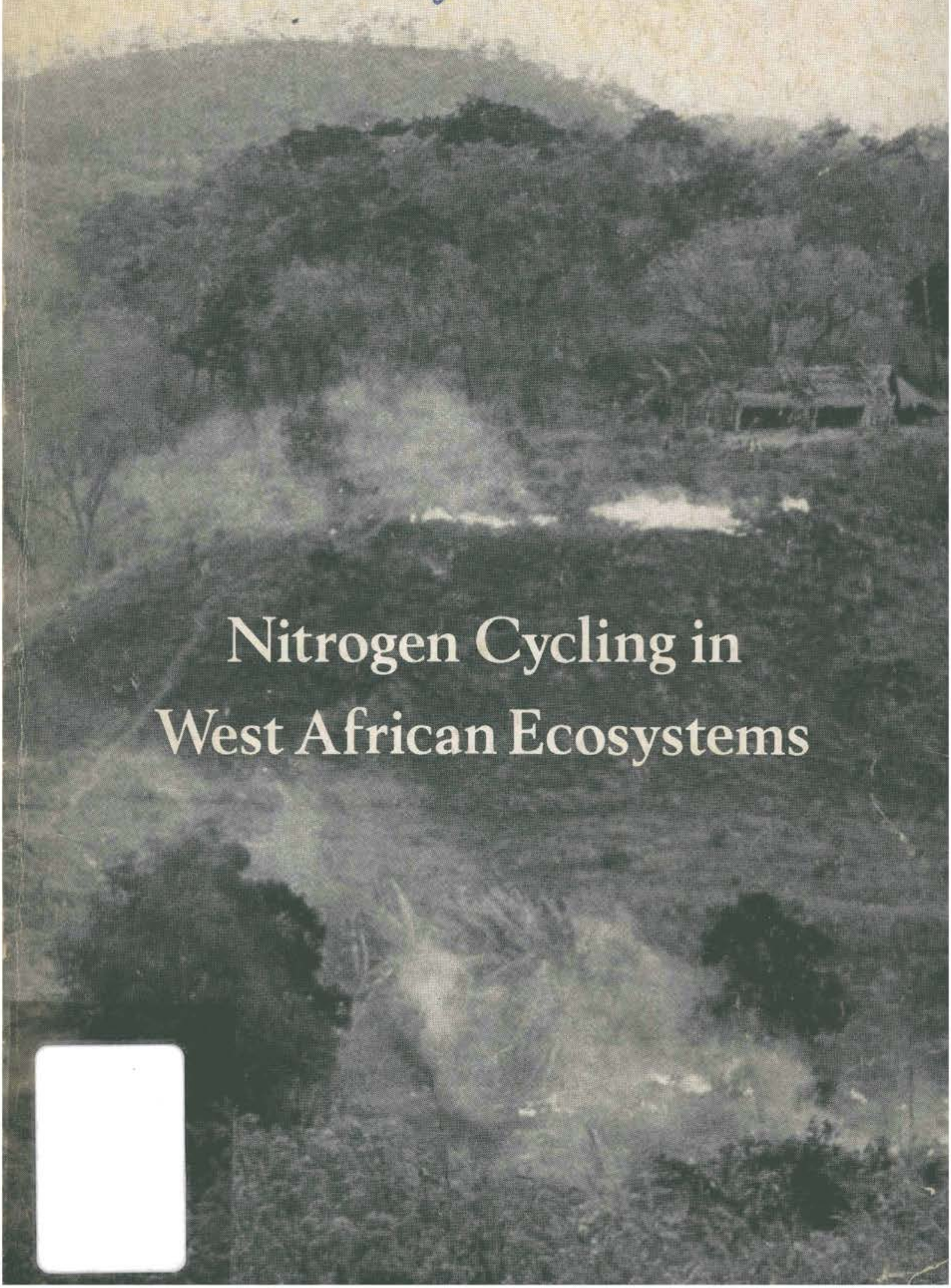

Nitrogen Cycling in West African Ecosystems

Nitrogen Cycling in West African Ecosystems

T. Rosswall (Editor)

Proceedings of a workshop arranged by the SCOPE/UNEP International Nitrogen Unit in collaboration with MAB (Unesco) and IITA
at
the International Institute for Tropical Agriculture, Ibadan, Nigeria
11–15 December, 1978

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PREFACE

The present volume reports on the first regional meeting arranged by the SCOPE/UNEP International Nitrogen Unit. The volume contains invited key note papers as well as papers contributed by other participants in the workshop. A major part of the meeting was devoted to discussions of present knowledge of nitrogen cycling in three major ecosystem types in West Africa, viz., savannas, forests and agro-ecosystems. The reports from these work group discussions are included together with a report on the final discussion on research priorities and future cooperation.

The SCOPE/UNEP Nitrogen Unit asked L.C. Nwoboshi and N.O. Adedipe in Nigeria and P. Berg in Sweden to prepare bibliographies on published articles dealing with nitrogen cycling in West African ecosystems. These bibliographies have been extended and are included in this volume.

The meeting was financially supported by the United Nations Environment Programme (UNEP), the Scientific Committee on Problems of the Environment (SCOPE) and the Man and the Biosphere programme (MAB) of Unesco. We are very grateful for their generous support, as well as for the sponsorship of the meeting by the Nigerian national committee for SCOPE.

The meeting was held at the International Institute of Tropical Agriculture (IITA), and all the facilities of IITA were put at our disposal thanks to the generosity of its Director General, Dr. W.K. Gamble. Dr. A. Ayanaba served as the local organizer and the hard and efficient work of the IITA staff was a very important reason for the success of the meeting.

Ms G. Sunnerstrand and Mr P. Wigren did the artwork and photography, while Ms M. Kågesson and C. Ribbing were helpful in the editing of the volume, Mr N. Robertson was responsible for the important linguistic editing. To all those, and especially to Ms G. Sundt, who was responsible for the production of the camera-ready copy, I would like to express my gratitude.

The publication has unfortunately been very delayed for a variety of reasons, and I would only like to cite Hofstadter's law: *It always takes longer than you expect, even when you take into account Hofstadter's Law.*

Stockholm December, 1980

Thomas Rosswall

Project Coordinator
SCOPE/UNEP International Nitrogen Unit

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OPENING REMARKS

T. Rosswall
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Mr Chairman, Dr Gamble, Mr Iyamabo, Ladies and Gentlemen,

At a meeting between the management of UNEP (United Nations Environment Programme) and the Executive Committee of SCOPE (Scientific Committee on Problems of the Environment) of ICSU (International Council of Scientific Unions) last week in Nairobi, it was decided to prepare a joint statement, to be signed by the Executive Director of UNEP, Dr M. Tolba, and the President of SCOPE, Professor G.F. White. The statement will deal with the importance of further studies of major biogeochemical cycles and call for a world-wide co-operative effort in this area.

The cycles of carbon, water and such nutrients as nitrogen, phosphorus and sulphur are fundamental to the working of the biosphere. Man-made perturbations of these cycles may, in many instances, cause unwanted and sometimes unforeseen effects. By way of example, it will suffice to mention the increasing levels of carbon dioxide in the atmosphere and their possible impact on climate, the probability of catalytic destruction of the global ozone layer as one consequence of the increased use of nitrogen fertilizers, the eutrophication of water bodies by nitrogen and phosphorus, and the acidification of rainwater by sulphur and nitrogen compounds emitted into the atmosphere as a result of combustion. There is a growing need for scientific risk assessment as one component in the complicated process leading to political and socio-economic decisions on the utilization of the world's finite resources. Many of the risks that man is facing originate from the cycling of chemical substances in the biosphere and the technosphere. Any risk assessment of the consequences of chemical compounds in the environment must be based on an in-depth knowledge of the biogeochemical cycles of such elements – their sources, transformations, transport pathways and sinks.

The web of carbon and nutrient flows is the basis for the production of food, fodder, fibre and fuel, and together with the flow of solar energy it interlinks all parts of the biosphere. With regard to the biogeochemical cycles, the slogan of "Only One Earth" expresses reality. Disturbances of these cycles on a regional scale can cause global and possibly irreversible changes. A further understanding of these cycles, qualitatively and quantitatively, should be an important component of UNEP's programme on outer limits and basic human needs. It is, furthermore, an area of study which needs a truly interdisciplinary approach, with the participation among others, of meteorologists, oceanographers, hydrologists, limnologists, pedologists, ecologists and microbiologists. It is thus an area eminently suitable for study and support by such organizations as UNEP and SCOPE, which are truly interdisciplinary bodies.

The SCOPE project on biogeochemical cycles was initiated in 1974, in realization of the large gaps in our knowledge of the cycles of some major nutrients. It was also recognized that man was influencing these cycles to a major extent. It was decided to make an attempt at quantifying the global cycles of nitrogen, phosphorus, sulphur and carbon. In considering global cycles, one advantage is that inputs and outputs must be balanced – an output from one system must be an input to another. The final report on the global nitrogen, phosphorus and sulphur cycles was published in 1976 (Svensson & Söderlund, 1976). The work on the nitrogen cycle was continued, resulting in a UNEP-sponsored Nobel Symposium on "Nitrogen – An Essential Life Factor and a Growing Environmental Hazard", the proceedings of which were published in early 1977 (Bolin & Arrhenius, 1977). The results of the first phase of the carbon project will be published in the very near future (Bolin *et al.*, 1979).

In 1977, SCOPE decided to continue with the second phase of its project on the biogeochemical cycles. In 1978, the SCOPE/UNEP International Nitrogen Unit was established at the Royal Swedish Academy of Sciences in Stockholm with financial support from UNEP, SCOPE, MAB and Swedish funding agencies. The primary goals of this unit are:

- to collect, analyse and disseminate data on the biogeochemical nitrogen cycle
- to prepare a revised version of the global nitrogen cycle
- to focus on regional studies of nitrogen cycles in tropical and subtropical areas; the present meeting is the first of two addressing this question
- to initiate training courses on applied aspects of the nitrogen cycle in co-operation with the UNEP/Unesco/ICRO Panel on Microbiology. The first of two such training courses is scheduled for West Africa
- to investigate the need for environmental monitoring of nitrogenous substances.

At the UNEP meeting last week it was decided to try to make a synthesis bringing the major biogeochemical cycles together in an integrated framework, which would be a contribution to the UNEP Report "State of the Environment – 10 years after Stockholm", which will be presented in 1982. Such a synthesis of the interdependences of major biogeochemical cycles must be based on a thorough understanding of the individual cycles. This meeting is an important first step in gaining an in-depth understanding of nitrogen cycles in equatorial areas of the world. The aims of the workshop are:

- to assemble scientists working in the region on various aspects of the nitrogen cycle
- to present overview papers on certain aspects of nitrogen cycling
- to give regional participants the opportunity to present data on their work in this area
- to discuss the present state of knowledge of nitrogen cycles of some major ecosystems of the region
- to discuss research needs and set priorities concerning future work.

Right away, at the outset of this meeting, I would like to thank IITA and its Director-General, Dr Gamble, for their generosity in hosting this meeting. Had it not been for the unfailing assistance of Mrs Boshoff, the IITA Conference Coordinator, and Dr Ayanaba, the local organizer, this meeting could never have taken place. We are very grateful for their continuous interest in and support of this meeting.

On behalf of SCOPE, I would like to bid you a warm welcome to this meeting, and trust that you will find it rewarding. I hope that, in an atmosphere of give-and-take, we will gain new insight into nitrogen cycling processes in West African ecosystems. All of us will, no doubt, make new contacts, which will be important in our future work. This workshop might well prove to be a starting point for increased co-operation between West African scientists concerned with nitrogen-cycling studies.

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OPENING REMARKS

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On behalf of IITA, I am pleased to welcome all participants in this workshop, the theme of which is closely allied to interests within IITA's own research programme. My sincere thanks to SCOPE and UNEP for sponsorship of the workshop as well as to all the institutions which have supported its planning and initiation.

The meeting comes at an appropriate time in programme planning of an expansion of our research in nitrogen studies. To date we have concentrated our studies on Rhizobium, the effects of forest clearing and management techniques on soil biological activity, and the rate of breakdown of organic matter. The work will be continued and expanded particularly in the research work on maximizing nitrogen fixation in cowpeas and soybean.

Nitrogen is an element that is often a limiting factor in crop production. The possibility of increasing nitrogen through natural means is directly allied to the focus of the research of IITA. It is concerned with millions of resource-poor farmers in the humid and subhumid tropics who have little access to commercial nitrogen fertilizer. One of the key objectives of our work is to "develop soil and crop management practices and farming systems for millions of small farmers that will make possible a stable, permanent and productive agriculture in place of the centuries old shifting cultivation and bush fallow systems". It should be obvious to all that increasing nitrogen through natural means is a key element to help achieve the objective.

I am pleased that during the workshop you will be examining various aspects of nitrogen cycling from the viewpoint of a number of scientific disciplines. Through this interaction we should be able to analyze what is known and what is not known on the subject and thereby form a basis for continued research and development on the most important issues. This multidisciplinary approach to analyzing the problem corresponds well with that of IITA which uses a multidisciplinary team approach in all its major research.

It is our pleasure to host this workshop which brings together eminent scientists and we look forward to cooperating with you in the research ahead.

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JOINT FAO/IAEA/FEDERAL REPUBLIC OF GERMANY INTERNATIONAL COORDINATED PROGRAMME OF RESEARCH ON AGRICULTURAL NITROGEN RESIDUES WITH PARTICULAR REFERENCE TO THEIR CONSERVATION AS FERTILIZERS AND BEHAVIOUR AS POTENTIAL POLLUTANTS

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Abstract

The Joint FAO/IAEA Division in Vienna has responsibility for an ongoing and extensive programme of research on agricultural nitrogen residues with particular reference to their conservation as fertilizers and behaviour as potential pollutants. This programme, therefore, concerns a vital aspect of nitrogen cycling in the agricultural ecosystem.

Background

The global use of fertilizers has increased dramatically in recent decades because "unfertilized soils no longer can provide the food necessary to meet the needs of expanding populations" (Nelson, 1972). Usage in 1954 was estimated at 17.4 million tons ($N + K_2O + P_2O_5$), 70 million tons in 1971 and is estimated to reach 115 million tons by 1980. Current annual usage of ca. 40 million tons of nitrogen alone is actually approaching the order of total nitrogen fixed biologically according to some authors (e.g., Söderlund & Svensson, 1976). In this connection there has been some concern with the evidence of rising nitrates of certain ground and surface waters, problems of eutrophication, as well as the toxicological implications of high nitrates and their derivatives such as nitrites, nitrosamines in food, feed and water. The possible role of intensive agricultural practices in these problems has attracted attention at international level. In 1972, with the support of the Swedish International Development Authority (SIDA), FAO convened an Expert Consultation on the subject (SIDA/FAO, 1972). One outcome was the question as to whether nitrogen fertilizers were in fact a significant input as a pollutant and there was a need for more data on the overall fate of nitrogen residues.

A panel of experts was jointly convened by IAEA and FAO in 1973 because of the important role of isotopic tracer techniques, especially the use of ^{14}N and ^{15}N-labelled fertilizer, for studying the behaviour of fertilizer N residues and because of the existing IAEA laboratory facilities. Copies of the report from the panel meeting may be requested by writing to the Publishing Section, IAEA in Vienna. This panel of experts recognized that there was not only the potential of water pollution by fertilizer nitrogen residues but loss from the root zone represented a critical loss of a costly agricultural input for a developing country. The panel recommended that FAO and IAEA should jointly initiate an international programme to study these problems, especially in developing countries, and involving the facilities (e.g., those for ^{15}N-isotopically labelled fertilizer studies) and expertise of advanced institutes.

The panel especially recognized possible conflict of interests between need for food production and environmental quality and resources protection. In this context I should like to quote from the report: "In making its recommendations the panel wished to record its unanimous view that studies of these problems are an essential prerequisite to the development of any national controls or recommendations for modified agricultural practices. Otherwise, there is a danger that vital agricultural practices may be impaired with little or no benefit to environmental quality". A modest start on the recommended programme was made in 1974 within the resources then available to the Joint FAO/IAEA Division. However, thanks to the generosity of the Federal Republic of Germany, on the basis of a formal agreement with the International Atomic Energy Agency, this programme was greatly expanded in 1975.

Current status and objectives

Objectives of the programme are, "To contribute to the control of the pollutant potential of fertilizer nitrogen residues as undesirable nitrate in food, feed or water, and to improve their conservation in soil as useful plant nutrients. Particular attention will be given to these problems in developing countries". It was expected to continue for at least five years. Overall coordination, liason, organization of meetings, collection and dissemination of information, reports, etc., are undertaken by the Joint FAO/IAEA Division in Vienna. Investigations within the Federal Republic of Germany are financed and coordinated through the Gesellschaft für Strahlen- und Umweltforschung. Collection of information and data on soil and water nitrate levels and trends and their correlation, if any, with agricultural practices or alternative nitrogen sources is an important feature. This is undertaken in close collaboration with colleagues of the Land and Water Development Division of FAO in Rome.

The main emphasis of the experimental investigations under contract is on behaviour of ^{15}N-labelled fertilizers below the root zone. How much and how fast does it get leached downwards, how much is lost through denitrification, as ammonia, etc. Contractual investigations have been undertaken in the Arab Republic of Egypt, Brazil, Chile, India (2 contracts), Israel, Mauritius, Pakistan, Peru, Romania and Yugoslavia.

Services for contractors, development of standardized methodology, e.g., sampling of leachate, centralized purchase of ^{15}N fertilizers, ^{15}N assays by mass spectrometry and emission spectrometry are provided by the IAEA Seibersdorf Laboratory near Vienna. In addition, the Seibersdorf Laboratory also undertakes supporting research, e.g., methods of measurement of denitrification under field conditions by gas-liquid chromatography applied to "undisturbed" soils.

In addition to the investigations under contract, investigators of advanced institutes are collaborating on a number of complementary aspects on a cost-free basis on subjects such as nitrate toxicology (Israel), development of nitrate-sensitive electrodes (Denmark), behaviour of animal waste nitrogen residues (Japan and New Zealand), mathematical models for describing and predicting nitrogen residue behaviour (Netherlands), accurate measurement of natural $^{14}N/^{15}N$ isotopic ratios in soil and water as N source and behaviour indicators (USA and Canada), chemical and fertilizer nitrogen residue interactions (USA), leaching of NO_3 and other soluble ions as a function of soil irrigation and hydrodynamics (Australia, Japan, UK and USA).

We have no illusions about the size and complexity of the problems. As best we shall get some of the answers to some of the questions. Nevertheless, some useful and important information and data have already been generated by the programme. In particular, important changes in the soil nitrogen were not only a function of fertilizer nitrogen addition and irrigation but of agricultural practices as a whole, clearance, crop rotation, etc.

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THE NITROGEN CYCLE – GENERAL CONSIDERATIONS

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Abstract

Nitrogen must be considered not only a vital factor for regulating primary productivity but also as a potential pollutant. Better knowledge is needed to determine the fate of nitrogen added as fertilizers. The research should continue a traditional agronomic approach with due attention to the fundamentals of ecology and microbiology. The paper finally stresses the importance of obtaining better knowledge of the factors regulating nitrogen losses from terrestial ecosystems.

Man made perturbations of major biogeochemical cycles pose an increasing threat to the global environment. Such impacts can be traced back to the early times of man, when he developed strategies whereby the natural environment was managed to meet his needs. Such impacts have for millenia been negligible and the natural ecosystems showed a remarkable resilience to such increasing impacts. The major effect created by man was brought about through the introduction of agriculture and the establishment of small communities. Land was cleared for production of crops, and the activity pattern of man changed from one of hunting and collecting to one of active utilization of ecosystems through the introduction of agriculture. Agriculture is by definition manipulation of a native ecosystem. Food was brought back to the small villages with the resulting accumulation of less mobile nutrients, e.g., phosphorus, in the soils of the settlements. As a matter of fact, the accumulation of unusually high concentrations of phosphorus has been used as an archaeological indicator for early human settlements (Eriksson & Rosswall, 1976).

Through experience, man has learnt to utilize available resources. From a total dependence on the productivity of virgin ecosystems, man has slowly, but at an accelerating rate, interfered with the environment producing until now ever increasing amounts of food, fodder and fibre.

The management by man with the aim of increasing agricultural production to meet the needs of a growing population has in some ways been unsuccessful not only because there is an increasing gap between those who have and those who have not, but also due to the fact that the concommitant environmental problem is a cause for concern. Some of the problems experienced as a result of attempts to meet world food needs are outlined in Table 1. Many of the land management techniques directly affect the cycles of some of the major elements, i.e., carbon, nitrogen, phosphorus and potassium.

Table 1. **Environmental consequences of agriculture and forestry with regard to nutrient cycles. The process and elements mainly regulated by microbial transformations are given in italics.**

Activity	Environmental consequence	Major element involved
Cultivation	*Decrease in soil organic matter*	*C, N*
	Erosion losses	C, N, P
	Mining of nutrients	N, P, K
Clear cutting	*Leaching losses*	*N*
	Mining of nutrients	N, P, K
Irrigation	*Leaching losses*	*N*
	Salinization	K, Ca, Na
Fertilization	*Decrease in soil organic matter*	*C, N*
	Leaching losses	*N*
	Losses of gaseous forms of nitrogen	*N*
Grazing	Ammonia volatilization	N
	Erosion losses	C, N, P
Drainage	*Decrease in soil organic matter*	*C, N*
	Leaching losses	*N*

Nitrogen is an element which limits productivity in many ecosystems, and it is a nutrient which has been added to ecosystems in rapidly increasing amounts (Fig. 1), with Africa having a projected increase in consumption by 125 % over the seven years period 73/74 to 80/81. Man is thus adding combined nitrogen in substantial amounts to terrestrial ecosystems, and it has been estimated that this addition will be equivalent to 140 Tg (Tg = 10^{12} g) in 1990 (Söderlund & Svensson, 1976), which is as much as biological ni-

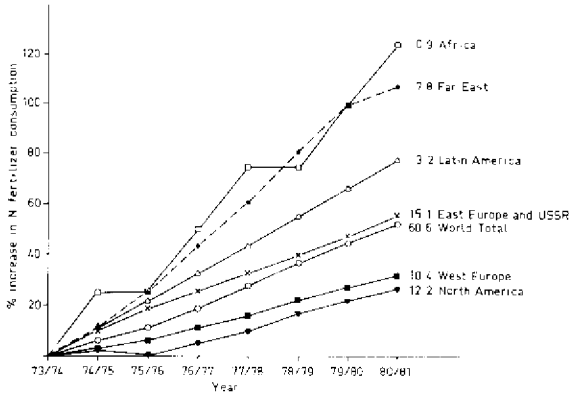

Figure 1. Predictions of increase in use for nitrogen fertilizers in certain regions until 1980/81. Figures give predicted consumption in Tg yr^{-1}.

trogen fixation in all terrestrial ecosystems. The possible impact of this doubling of the annual input of combined nitrogen has not yet been assessed.

Nitrogen is an element which in an intricate way links the activities of the microorganisms with those of the plants. Nitrogen is involved in the most complex and perhaps also most interesting of all biogeochemical cycles, with nitrogen occurring in valence states from -3 to + 5. In contrast to the sedimentary biogeochemical cycles (e.g., Ca, Mg, K, P), nitrogen occurs in important gaseous forms (N_2, NH_3, nitrogen oxides).

Although nitrogen has been a topic of intensive research for over a century, still surprisingly little is known about the regulation of the cycle, and only recently have attempts been made to link the knowledge of the physiology of some of the microorganisms involved with observation of nitrogen behaviour at the ecosystem level. The traditional agricultural approach to nitrogen cycling research has provided us with a firm data base, but it has failed to link these observations with ecological theory and ecosystem research on the behaviour of nutrients in biogeochemical cycles. It is remarkable that the detailed analyses on nitrogen cycles available come from natural ecosystems and not from those influenced by agriculture and silviculture in view of the paramount importance that nitrogen has for high yields in these managed systems.

Nitrogen cycling studies thus far generally started from one of the following two approaches:

- a simple input/output analysis without any regard for nitrogen not immediately involved in crop production

or

- basic research on nitrogen cycling without taking the effects on crop production into account.

Only by combining these two approaches it will be possible to advance our knowledge of the behaviour of nitrogen in ecosystems and enable us to quantitatively assess the positive and negative effects of present-day and future use of nitrogen as fertilizer.

Negative effects of extensive nitrogen fertilizer use are becoming increasingly evident. Eutrophication of water bodies can occur as a result of nitrogen and phosphorus transport from agroecosystems, high levels of nitrate in groundwater can become a health hazard causing methemoglobinemia in infants and there is also a risk of production of carcinogenic nitrosamines from nitrates and nitrites. The possibility of denitrification of fertilizer nitrogen to nitrous oxide, which can result in catalytic destruction of the global ozone layer is a concern which has recently been receiving much attention. It should thus be realized that nitrogenous substances are both essential nutrients and potential pollutants (Bolin & Arrhenius, 1977).

Nitrogen as an element will never become limiting, as the amount of dimolecular nitrogen in the atmosphere is 2500 times larger than the global amount of combined nitrogen (Fig. 2). Microorganisms are responsible for most nitrogen transformations in the biota, both qualitatively – certain transformations like nitrogen fixation and nitrification can be carried out by microorganisms only – and quantitatively – about 2.4 times more nitrogen is circulated through microorganisms in terrestrial ecosystems than through the vegetation (Rosswall, 1976). However, only a very small proportion of the total ($7 \cdot 10^{-6}$ %) is contained in terrestrial microbial biomass at any one time. It is thus

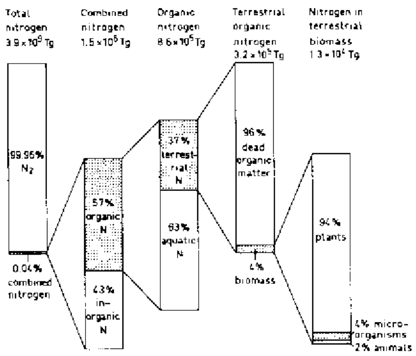

Figure 2. Partitioning of the global amounts of nitrogen. Total amounts for nitrogen in Tg (10^{12} g) given for each column (Rosswall, 1979)

Table 2. **Turnover time (yr) of nitrogen in various parts of the global terrestrial system and some selected terrestrial ecosystems. PP = primary producers, PL = plant litter, SOM = soil organic matter, MO = microorganisms, IN–N = soluble and exchangeable inorganic N.**

Ecosystem	PP	PL	SOM	MO	IN-N	Reference
"World"	4.9	1.1	177	0.09	0.53	Rosswall (1976)
Tundra mire	9.3	5.8	290	0.28	7.5	Rosswall & Granhall (1980)
Oak-hickory forest	4.1	2.9	150	0.15	0.19	Mitchell *et al.* (1975)
Mixed deciduous forest	4.0*	5.1	109	0.02	0.23*	Henderson & Harris (1975); Burgess & O'Neill (1976)

* Recalculated from data in the references.

important to consider not only the distribution of nitrogen in various components of the biosphere but also its turnover times. Table 2 gives the estimated turnover times for nitrogen in certain major components of terrestrial ecosystems. It can be seen that nitrogen in soil microorganisms and soil inorganic nitrogen have turnover times in the order of only 0.1–0.5 yr, while it is over 100 yr in soil organic matter.

In recent years increased attention has been given to research in fundamental and applied aspects of nitrogen fixation research. Interest in nitrogen-fixation has been focussed both on symbiotic systems, mainly the *Rhizobium* symbiosis and *Azolla*, and on free-living microorganisms such as blue-green algae and *Azospirillum* in the rhizosphere of certain plants. Research on nitrogen fixation is being carried out in most West African countries, specialized regional symposia have been held as well as training courses on the use of nitrogen fixing microorganisms in agriculture. It is important, however, not only to know the inputs of combined nitrogen to a given system but also the losses.

Only by considering both inputs and losses it is possible to estimate amounts of plant available nitrogen. Input/output budgets should be attempted in various types of systems at various levels, i.e., global, regional and ecosystem levels. In most attempts to make nitrogen budgets for particular systems a steady-state is assumed, and this assumption is made for two reasons; one is that long-term observations are very rarely available to show if such a steady-state exists and the second is that a steady-state approach must be used, since the budget is balanced by assuming that any nitrogen not accounted for has been lost through denitrification. In many cases it can be shown that the systems are not in a steady state.

In summary, I would like to stress the following four points, as I consider them essential in attempts to evaluate the importance of the biogeochemical nitrogen cycle.

- Nitrogen is an essential element but also one which can form potentially hazardous compounds.
- Nitrogen research must combine a traditional agronomic approach with a fundamental ecological/microbiological approach.
- Focus must not only centre on the distribution of nitrogen in the ecosystem but also on processes and turnover times.
- An understanding of the availability of nitrogen for crop production must be based on an in depth understanding of both inputs to and losses from a given system.

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ASPECTS OF NITROGEN CYCLING FROM AN ATMOSPHERIC CHEMIST'S VIEWPOINT

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Abstract

The atmospheric part of the nitrogen cycle for ammonia (NH_3), nitric oxide (NO) and nitrogen dioxide (NO_2) is briefly described. This includes natural sources such as ammonia volatilization, lightning and soil exhalation. The tropospheric abundance and examples of photo-chemical reactions, deposition rates of these gases and particulate matter formed from these gases are given.

Introduction

Some of the important processes which determine the amounts of nitrogen compounds that are circulated in the atmosphere will be reviewed. A brief description of the sources, transformations and transport of ammonia and of nitrogen oxides will be included.

In this paper only the lower part – approximately 10 km – of the atmosphere, i.e., the troposphere will be considered. In this part 75 % of the total mass of the atmosphere is found and it can be considered to be rather well mixed. The typical transport time of matter from the ground to the top of the troposphere is approximately one month, depending somewhat on the geographical area. In tropical areas the transport time is slightly shorter.

Figure 1 is a schematic drawing showing some of the processes which influence the transport and transformation of a compound on its way through the atmosphere. All of these processes will not be discussed; the focus will be on the photochemistry as well as sources and scavenging, with special relation to nitrogen compounds.

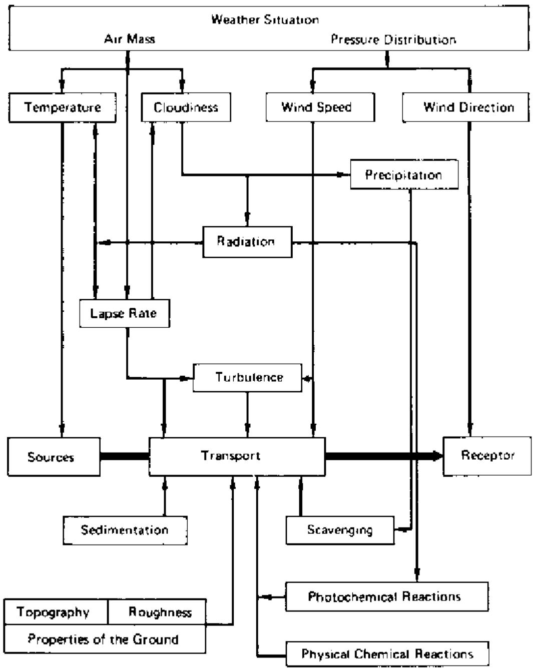

Figure 1. Processes of importance for the transport and transformations of compounds in the troposphere (NAS, 1977).

Nitrogen compound concentrations

Both inorganic and organic nitrogen compounds are present in ambient air. Typical values for the inorganic compounds are given in Table 1. Reliable data on organic nitrogen compounds in nonpolluted air are lacking.

Table 1. Concentrations of inorganic compounds in the lower atmosphere. (s) = solid, (g) = gas.

Compound	Typical concentration	
N_2	78 % (v)	dinitrogen, molecular nitrogen
N_2O	0.3 ppm (v)	nitrous oxide
NH_3 (g)	0.1–6 ppb (v)	ammonia
NO_2 (g)	0.1–5 ppb (v)	nitrogen dioxide
NO (g) NO_x (g)	0.1–5 ppb (v)	nitric acid
HNO_3 (g)	? ppb (v)	nitric acid
NH_4^+ (s) (g)	1–50 μg N m^{-3}	ammonium compounds
NO_3^- (s)	1–20 μg N m^{-3}	nitrates

The discussion will focus on NO, NO_2, HNO_3 and NO_3^-, generally called the NO_x compounds.

Photochemical reactions

Solar radiation triggers a series of reaction in the atmosphere between gaseous organic molecules and nitrogen oxides (Fig. 2). Thus, a wide variety of by-products are produced. The major chemical characteristic of this mixture is its oxidative properties.

At the centre is shown the NO_x-ozone engine, which is surrounded by peripheral chemical reactions involving hydrocarbons. This processing results in noxious products, such as ozone, peroxy compounds, nitrates and sulphates. When the sunlight ceases, the central cycle is stopped and NO_2 accumulates during the dark period. In the morning, the sun quickly starts these reactions again.

The variety of nitrogen compounds from the photochemical reaction is great. The likely occurrence of nitric acid in a gaseous phase is noteworthy. This form of nitrogen is more easily scavenged from the atmosphere than the gases NO and NO_2, as will be discussed more thoroughly later.

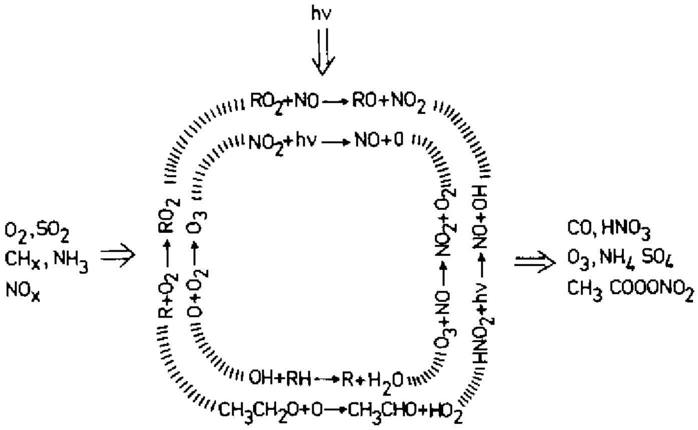

Figure 2. A few important photochemical reactions for the turnover of nitrogen compounds in a sunlit atmosphere.

Source of ammonium compounds in the atmosphere

On a global scale, volatilization of ammonia from natural sources on land (and possibly the sea) dominates over the anthropogenic (man-made) sources. The sources are unevenly distributed both in time and space:

- On a local to regional scale the emission from feed lots represents a significant source.
- From heavily grazed pastures, substantial amounts of ammonia are volatilized. However, most of the volatilized ammonia is being reabsorbed by the plant canopy (Denmead *et al.*, 1974, 1978).

The role of aquatic environments as a source or sink for ammonia has not been well studied. At pH values above 8.3, which can occur during algal blooms, the water acts as a source of ammonia for the atmosphere. Stratton (1969) reported losses at rates of 35 and

98 mg m^{-2} d^{-1} from two eutrophic lakes with pH greater than 9. At lower pH levels absorption of ammonia will occur, dependent on the ambient concentration of ammonia.

Sources of NO_x compounds

On a global scale, the man-made sources of NO_x are likely to be smaller than the natural sources (Söderlund & Svensson, 1976).

Man-made sources are mainly the combustion of fossil fuels in power plants, automobiles and house heating.

Nitric-oxide exhalation from soil systems is believed to be another important source. Galbally & Roy (1978) measured the NO flux from some Australian soils. The fluxes amounted to a typical rate of 2.2 (range 0.5–6) mg NO_x-N ha^{-1} d^{-1}. This could be compared with the average global rate of 3–16 mg NO_x-N ha^{-1} d^{-1} derived from a mass balance study by Söderlund & Svensson (1976). In this study the contribution from lightning was not considered. Recent estimates of this source give the range of 10–40 Tg (10^{12} g; million metric tons) over the globe annually (Tuck, 1976; Chameides *et al.*, 1977). If this amount is deducted from the previous estimate on a global scale, the rates of NO_x emission from the soil will decrease to 0–15 mg NO_x-N ha^{-1} d^{-1}, a value which fits well with the observations from the Australian investigation.

The distribution of lightning is by no means equal over the globe, as can be seen in Fig. 3. The frequency is much higher in tropical areas as compared to elsewhere. The principal form of NO_x being formed from this source is NO. Due to the poor solubility of NO in water and the convective character of thunderstorms, no good correlation between thunder activity and nitrate in precipitation should be expected. The nitrogen oxides have to be either in the form of nitric acid or nitrogen dioxide to be easily removed from the atmosphere by precipitation. The transformation rate to form nitric acid from nitric oxide at these altitudes is small, and it takes 1–3 days before the major part of the NO is transformed into HNO_3, and could by then be spread over large areas. Thunderstorms could be a substantial source of NO_x.

Wet deposition

Measurements of the content of inorganic nitrogenous substances in precipitation have been conducted over the globe for many decades. For a comprehensive review, see, e.g., Eriksson (1952). In a few investigations the organic nitrogen content has been estimated. Readily available data on deposition rates of nitrogen compounds from the African continent are summarized in Table 2. The reported values are generally somewhat lower for nitrate and higher for ammonium as compared with data from temperate regions. Data from highly industrialized regions, e.g., NW Europe, show higher deposition rates. In these regions most of the NO_x found in the atmosphere is believed to be of anthropogenic origin (Söderlund, 1977). This indicates a rather short lifetime in the order of days, and even shorter for emissions during precipitation events have been indicated for NO_x. The scavenging of the NO_x substances is dependent upon their solubility. NO is only slightly soluble in water and will not easily be removed from the atmosphere, while NO_2 and HNO_3 are easily soluble in water.

Ammonia is also very soluble in water, and it is expected that ammonia would be completely removed from an air mass during precipitation.

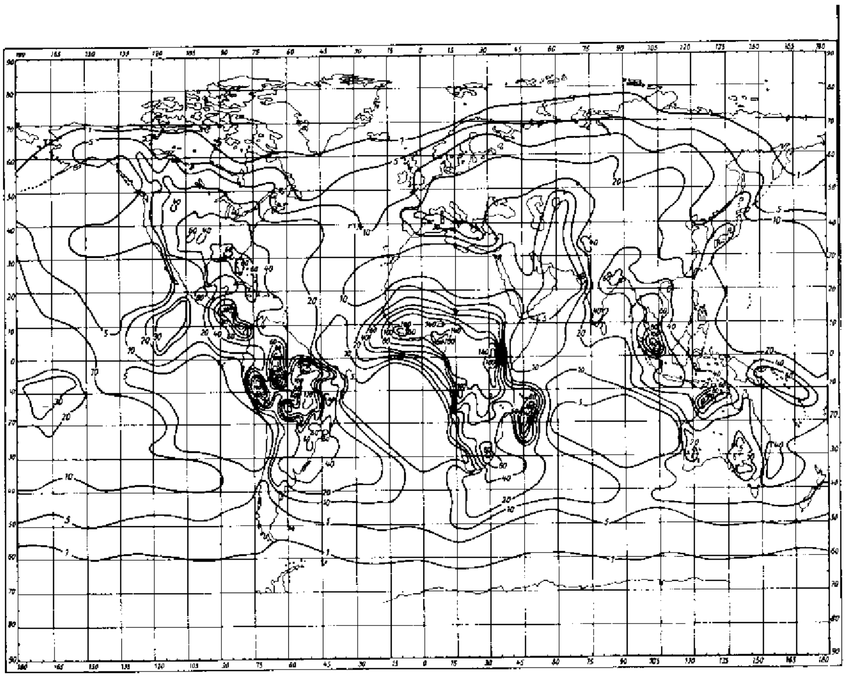

Figure 3. Number of days per year with lightning (Liljequist, 1970).

Table 2. Deposision rates for nitrogen compunds on the African continent (kg M ha^{-1} yr^{-1}) (Steinhart, 1973).

Location	NO_3^-	NH_4^+	Total inorg.	Total nitrogen
Nigeria	–	–	2.5–3.5	–
Gambia	–	–	–	14–47
Zaire	2.2–4.6	0.7–5.3	–	–
Ghana	2.5	11.5	–	–
Uganda	4.9	6.6	–	91.1

Dry deposition

Gases and particulate matter are removed at ground level by a large number of processes, such as, for gases: active biological uptake and surface reactions on the ground and vegetation; for aerosols; inertial impact on obstacles and gravitational settling.

A common way to estimate the flux of a compound to the Earth's surface is by using the concepts of dry deposition velocity (Vg). The observed ambient concentrations of the gas or particulate matter are multiplied by deposition velocity, and an estimate of the flux of the substance is obtained. 1/Vg is called the resistance.

The resistance can be subdivided into:

- resistance in the atmosphere (turbulence)
- resistance in a thin layer in the order of a few mm close to the surface
- resistance due to surface characteristics.

The numerical value of Vg for gases depends largely on the solubility of the gas. For particulate matter, size is the determining factor.

Some conclusions – temporal and spatial variations

The turnover time (T) of a compound in a reservoir is a simple form in which time characteristics of the compounds can be described. The turnover time is defined as T = M/F where M is the mass of the compound in the reservoir and F is the flux to or from that reservoir. The mean tropospheric turnover times for the compunds discussed are given in Table 3.

The gaseous compounds have a shorter turnover time than the particulate, reflecting a more effective sink for the former than for the latter. The gaseous form has a sink in the atmosphere, i.e., the formation of particulates. Due to the short turnover time and uneven distribution of the sources for the NO_x and ammonia compounds, highly variable concentrations of these compounds are found. This means that if one wants to estimate the flux of these compounds with any certainty to the ground system, direct measurements must be performed.

Table 3. Turnover time for NO_x and ammonia compounds (from Söderlund & Svensson, 1976).

Compound	Turnover time (days)
NO_x (g)	2– 8
NO_x (s)	4–20
NH_3 (g)	1– 4
NH_4 (s)	7–19

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Nitrogen Cycling in West African Ecosystems

LOSSES OF PLANT NUTRIENTS IN RUNOFF AND ERODED SOIL

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Abstract

Field experiments conducted on an Alfisol in southwest Nigeria indicate significant nutrient loss of economic importance in water runoff and seepage, and with eroded sediments. Total nutrient loss in water runoff has been estimated to be 55, 17, 12, 2, and 4 kg ha^{-1} yr^{-1}, for bare fallow, maize-maize (ploughed), cowpea-maize (ploughed), maize-maize (mulched), and maize-cowpea (no-tillage), respectively. The loss of NO_3–N in water runoff for the same cropping systems was 10, 3, 2, 0.5, and 0.6 kg ha^{-1} yr^{-1}, respectively. Nitrate concentration in seepage water was 2 to 3 times that in the water runoff. The enrichment ratio of eroded sediments is generally 2:1–5:1 for organic carbon, total nitrogen, Bray-P, and exchangeable cations. The mean annual nutrient loss in the eroded soil, for slopes ranging from 1 to 15 %, was 2540 kg organic carbon, 210 kg N, 11 kg P, 19 kg K, 140 kg Ca and 11 kg Mg ha^{-1} yr^{-1} for the bare fallow plot. Similar losses for the maize-maize (ploughed) rotation were 330 kg organic carbon, 29 kg N, 1 kg P, 3 kg K, 19 kg Ca and 2 kg ha^{-1} yr^{-1} Mg. The nutrient concentration in runoff and seepage water also depends on the quality of the mulched material used, and on the methods of fertilizer application.

Introduction

Intensification of arable farming in the humid tropics, now predominantly under bush fallow and related systems, is inevitable (Boerma, 1975). Large-scale deforestation for arable farming in these areas can cause accelerated runoff and soil erosion (Pereira, 1973; Lal, 1956; Greenland & Lal, 1977). The consequences of an ecological imbalance resulting from deforestation and introduction of large scale commercial farming in the tropics have not yet been adequately investigated. It has been estimated that the total area of degraded soil that was biologically productive at one time is $2 \cdot 10^9$ ha, of which about 30 % is due to water erosion (Kovda, 1974). Continuous degradation of land by mismanagement and increase in population may result in a decrease in per capita arable area of 0.31 ha to 0.15 ha by the year 2000.

Sustained production on highly leached soils of the tropics with low inherent fertility will necessitate inputs of fertilizers and other agricultural chemicals; including herbicides and pesticides. The effects of large doses of these chemicals on pollution and eutrophication (Stewart & Rohlich, 1977) of natural waters in the tropics need to be investigated prior to the initiation of large-scale agricultural development schemes.

Recovery of nitrogenous fertilizers by crops is hardly 50 % and a maximum of 10 % is recovered by the succeeding crop. Most of the fertilizer is lost in water runoff and seepage water. The fate of applied N has been discussed in some recent reviews (Bartholomew, 1972; Fox, 1972; C.A.B. 1962; Porter, 1975).

The magnitude and quality of water runoff and seepage from a watershed depends on many factors, including land use, soil characteristics, tillage and soil management, intensity and frequency of rainfall events, crop management, and type and mode of fertilizer application. Research information on the effects of these parameters on quality of water runoff and sediments from watersheds in the tropics is scanty.

Land use factors affecting nutrient loss

Data on nutrient loss in water runoff and eroded soil from tropical regions are scanty. A recent survey from the United States indicates that more than 50 million tons of plant nutrients, with a cost of about $6.8 to $7.75 billion are lost each year (Biswas & Biswas, 1978).

The quality of water runoff from a forested watershed may be different from that coming from land use for arable farming. Pereira (1973) reported significant increase in water and sediment yields by replacement of tropical forest in Kenya with plantation crops, and by forest fire in the Australian Alps. Decomposing leaf litter on the surface of the forested land increases the concentration of basic cations and organic nitrogen in runoff. Timmons & Holf (1977) and Timmons *et al.* (1977) reported that organic N and P comprised 68 and 82 % of the respective annual loss in water runoff from a forested prairie and an aspen-birch forest. The quantities of cations in the surface runoff were Ca > K > Mg > Na. Similar observations were made by White and Williamson (1973).

The nutrient concentration in water runoff and eroded soil from an underutilized forested plot on an Alfisol in Ibadan, Nigeria has been compared in Table 1 with a cleared plot growing maize with commercial fertilizer. The nutrient concentration in water runoff and eroded soil from the fertilized maize plot was more than that of the unfertilized forested plot.

Table 1. Nutrient concentration (ppm) in water runoff and eroded soil from forested and maize plots located on natural slopes (Lal, 1976)

	Water runoff								Eroded soil					
Slope	Maize				Forest				Maize			Forest		
%	P	Na	Ca	K	P	Na	Ca	K	P	Ca	K	P	Ca	K
1	0.1	1.5	21.8	5.2	0.1	1.3	2.7	1.7	18.1	985	58	3.9	475	105
5	0.2	2.3	14.5	8.4	0.1	1.5	2.6	2.1	18.1	788	98	5.5	725	70
10	0.7	1.7	5.6	7.9	0.4	2.2	1.6	2.8	28.1	995	102	8.2	790	90
15	0.5	1.1	1.8	3.0	0..6	1.6	1.4	2.3	65.3	1515	154	14.7	1135	82

Soil management as it effects nutrient loss

Tillage systems and other soil conservation measures affect the quality of water runoff and eroded sediments. Barnett *et al.* (1972) reported from their studies on some Puerto Rican soils that the average concentration of N in runoff ranged from 0.01 to 0.02 ppm, and that of K from 0.01 to 2.29 ppm. In northern Nigeria, Kowal (1972) reported average annual losses of Ca, Mg, and Na in runoff water and eroded soil to be 14 and 30 kg ha^{-1} depending on the soil and crop management practices adopted.

Similar investigations in temperate regions indicate a significant effect of soil conservation measures and tillage systems on the quality of water runoff (Burwell *et al.*, 1974; Klausner *et al.*, 1974). Nutrient losses can be held at low levels by suitable conservation practices. Schuman *et al.* (1973) reported from an agricultural watershed in Missouri Valley loess that terracing reduced the runoff and sediment yields. With contour cultivation, 92 % of the N loss was associated with the eroded sediments.

Romkens *et al.* (1973) observed significant effects of tillage systems on the N and P concentrations in surface runoff. The coulter and chisel system controlled soil loss, but runoff water contained high levels of soluble N and P from surface applied fertilizer. The conventional tillage systems had high losses of soil and water but lower concentrations of nutrient losses.

Data in Fig. 1 show the significant effect of surface mulch on nutrient concentration in water runoff. The concentrations of Ca and Mg were generally higher under bare fallow and that of K higher in mulched compared with other treatments. The effects of a range of mulch material on quality of water runoff are shown in Table 2. Unmulched plots lost relatively more fertilizer nutrients compared with the mulched plots.

Relative nutrient concentrations in water runoff and eroded soil are associated with crop, fertility level, and the type of fertilizer used (White & Williamson, 1973; Klauser *et al.*, 1974; Dunigan *et al.*, 1976; Durwell *et al.*, 1977; Shelton & Lessman, 1978; Klepper, 1978). Edwards *et al.* (1972) reported NO_3-N concentration of < 2 mg l^{-1} in barnlot runoff water. Most of the soluble N was in a reduced form with a maximum monthly concentration of < 70 mg l^{-1}. Long *et al.* (1975) observed that NO_3 levels in runoff water were not affected by manure application at $45 \cdot 10^3$ kg ha^{-1} yr^{-1} and were < 2 mg l^{-1}.

There are also differences in water quality of surface runoff compared with sub-surface flow (Jackson *et al.*, 1973; Lal, 1976). Burwell *et al.* (1976) reported that NO_3 in sub-surface discharge accounted for 84 to 95 % of the total annual soluble N discharge in stream flow.

The effect of soil characteristics on nutrient loss

Sandy soils with low nutrient and water retention capacity lose more nutrients in water runoff and sub-surface flow compared with heavy textured soils (Avnimelech & Raveh, 1976; Jones *et al.*, 1977). Symakov (1975) observed that nutrient concentration in water runoff depends on the agro-chemical properties and availability of various forms of these compounds in the underlying genetic horizons forming the plough layer instead of the eroded horizon. The water quality is affected by the water regime of the soil prior to the runoff event and whether the water passes through macro or micro-pores. Kissel *et al.* (1976) observed that concentrations of NO_3-N were usually highest just after fertilizer

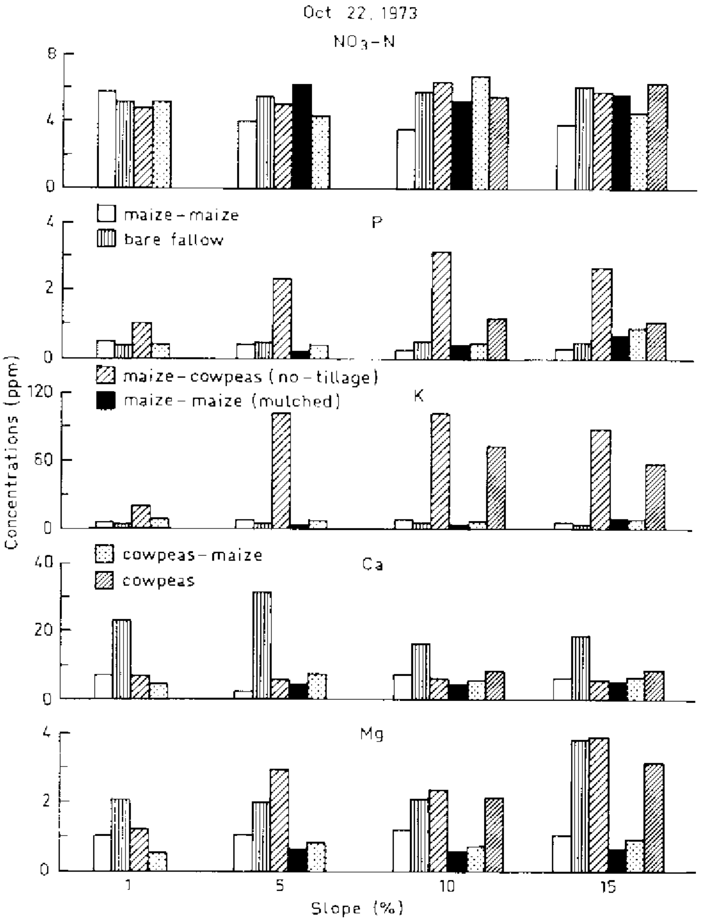

Figure 1. Effect of cropping systems and residue management on nutrient concentration in water runoff (Lal, 1976)

application and when the soil was near field capacity, and lowest when large amounts of water infiltered into dry soil immediately before runoff. During runoff-producing storms, just after fertilizer application, the concentrations were observed to be lowest in the initial runoff and highest near the end of the runoff event (Kissell *et al.*, 1976). Similar observations were made by Peverill *et al.* (1977).

Leaching is one of the principal mechanisms of inorganic N loss in tropical soils. The loss of NO_3-N with the mass flow of water causes significant leaching losses in the tropics. Reliable data on leaching losses monitored over a long period using monolithic lysimeters are few from tropical regions. Losses of 70–107 kg N ha^{-1} yr^{-1} have been reported from bare fallow unfertilized plots in India, compared with 329–511 kg ha^{-1} from bare fallow and 3–156 kg ha^{-1} from cropped plots in Peradeniya, Sri Lanka (Martin & Skyring, 1962). Suarez & Rodrigues (1958) reported from lysimetric investigations in the high rainfall regions of Colombia that an average of 360 kg ha^{-1} yr^{-1} of inorganic N

Table 2. Nutrient concentration (ppm) in water runoff, from maize receiving recommended dose of fertilizer as affected by mulch material (unpublished data of Lal & Okigbo)

Mulch	NO_3-N	PO_4-P	K	Ca	Mg
Cassava stem chipped	13.2	0.82	1.9	2.1	0.72
Ridges	12.4	0.84	2.8	5.1	1.40
Pigeon pea stem	11.7	0.72	1.9	5.0	1.81
Ploughed Guinea grass	11.0	1.70	1.9	1.7	1.03
Maize cobs	10.4	0.94	1.7	3.5	1.40
Saw dust	10.1	0.94	1.9	1.0	0.68
Oil Palm leaves	9.8	0.70	1.7	3.2	1.19
Flat	9.3	0.72	1.5	2.5	0.45
Typha	9.3	0.70	1.3	1.7	0.53
Rice husk	9.3	1.00	0.9	2.4	0.65
Legume husk	9.3	0.90	2.2	2.0	1.05
Mixed twigs	8.8	0.82	0.6	1.5	0.60
Pennisetum	8.6	1.26	1.5	2.2	0.54
Transparent polythene	8.3	1.26	0.6	1.3	0.31
Gravel	8.1	0.70	1.1	2.2	0.64
Rice straw mulch	7.7	0.44	1.7	1.5	0.74
Soybean straw	7.7	0.76	0.7	1.3	0.55
Guinea grass	7.5	0.68	0.6	2.1	0.31
Control	7.3	0.96	0.6	0.7	0.33
Mounds	7.1	0.84	6.0	3.5	0.85
Eupatorium	6.5	0.70	2.4	2.9	1.29
Andropogan	6.2	0.88	0.4	0.7	0.27
Mounds no mulch	5.8	0.76	2.1	8.3	2.75
Pigeon pea branches	5.7	1.28	0.9	3.0	0.80
Water lettuce	5.4	0.76	1.7	1.5	0.38
Ridges with apanicum	5.1	1.36	0.4	0.5	0.30
Maize stover	4.9	1.60	0.5	0.8	0.21

Fertilizer applied at the rate of 120 kg N, 13 kg P and 30 kg K/ha.

was lost in the leachate from bare soil, whereas only 62 kg ha^{-1} yr^{-1} was lost when the legume *Indigfera endecaphylla* was grown. High leaching losses of N have also been reported from a sandy soil in Malaya (Bolton, 1968), Martin & Cox (1956) reported leaching losses of 27 kg N ha^{-1} from a black earth in a sub-humid environment of Queenland, Australia.

The effect of soil type on the amounts of fertilizers leached out of the profile is shown in Table 3. Fertilizer losses from sandy Apomu soil were significantly higher compared with those from heavy textured Egbeda.

The stage of crop growth and the time of fertilizer application can also affect the quality of water runoff. Alberts *et al.* (1978) observed that most of the average annual total N and P losses were associated with the initial establishment period of crop growth.

Table 3. Leaching losses of plant nutrients from different soils growing maize (unpublished data of Lal & Kang)

Soil	Fertilized treatment	Leaching losses (kg ha^{-1} yr^{-1})					
		NO_3-N	NH_4-N	P	K	Ca	Mg
Egbeda	F	7.4	0.66	0.42	36.1	32.4	1.6
Egbeda	UF	0.7	0.04	0.07	2.7	8.2	0.2
Alagba	F	1.3	0.16	1.3	4.5	2.0	0.9
Alagba	UF	0.3	T	0.5	1.3	1.5	0.4
Onne	F	0.2	T	0.5	0.9	0.7	0.3
Onne	UF	T	T	0.04	0.4	0.2	0.1
Apomu	UF	50.6	0.79	3.5	12.7	41.0	13.5
Apomu	F	58.3	0.78	2.9	12.9	78.6	11.0

F = fertilizer at the rate equivalent to 100 kg N, 13 kg P and 30 kg K per hectare
UF = unfertilized
T = traces

Table 4. Relative nutrient loss in water runoff and eroded soil from a bare fallow Alfisol on 15 % slope (Lal, 1976)

Nutrient	Nutrient loss (kg ha^{-1} yr^{-1})	
	Water runoff	Eroded soil
N	9.6	3.4
P	2.9	13.1
K	13.2	29.4
Ca	29.0	203.1
Mg	7.3	18.1

Nutrient loss in water runoff and eroded sediments

Most of the annual nutrient loss is generally associated with the eroded sediments (Table 4). Most nutrients are absorbed on the exchange sites on soil and organic matter and are transported with the solid particles. Similar observations have been made by Alberts *et al.* (1978). Schuman *et al.* (1973) observed that N losses associated with sediments in the runoff accounted for 92 % of the total loss.

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Nitrogen Cycling in West African Ecosystems

NITROGEN LOSSES FROM DISTURBED ECOSYSTEMS – ECOLOGICAL CONSIDERATIONS

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Abstract

Perturbations which interrupt the soil-plant-vegetation nitrogen cycle cause increased losses of nitrate from many terrestrial ecosystems. The increase varies among systems, but in some cases disturbance has a significant effect on downstream water quality. These responses to perturbation are separable into components of: i) resistance to displacement, which is related to rates of nitrogen cycling before perturbation; ii) delay, which is caused by nitrogen immobilization, lags in nitrification and a number of abiotic processes in the soils of disturbed ecosystems; and iii) resilience, which is related to the rate of reestablishment of plant nitrogen uptake. All of these appear to be controlled in part by site fertility, with the most substantial nitrogen losses expected in fertile sites.

Introduction

With phosphorus, nitrogen is the most important of the nutrient elements in both terrestrial and aquatic ecosystems. In terrestrial ecosystems, its importance is demonstrated by the observations that: i) the production of many terrestrial ecosystems is nitrogen limited; ii) many plants make a large energetic investment in supporting symbiotic nitrogen fixation; and iii) nitrogen is circulated highly efficiently within plants and within ecosystems. In aquatic ecosystems, nitrogen can play a significant role in controlling shortterm productivity and hastening eutrophication, and nitrate concentrations can reach levels where they pose a significant hazard to human health.

Nitrogen cycling has been studied intensively for many years. Nonetheless, generalizations on the ecological regulation of the nitrogen cycle must be regarded as preliminary. Nitrogen concentrations of many plants and soils are well established, and nitrogen pools and fluxes within and between a number of ecosystems have been measured. Research into the mechanisms controlling ecosystem-level fluxes is relatively recent, however, and data adequate for the examination of the ecosystem-level regulation of nitrogen cycling are not yet complete.

Fig. 1 is a coarse-grained model of the nitrogen cycle in a linked terrestrial-aquatic ecosystem. Nitrogen cycles within each of the system compartments, between compartments, and into and out of the system as a whole. Ecological aspects of the nitrogen cycle can be productively examined at any point in this cycle, from the regulation of biological nitrogen fixation to the ecological effects of nitrate in aquatic systems. I will emphazise the transport of nitrogen out of disturbed terrestrial ecosystems. Particular emphasis will be placed upon losses of dissolved nitrate, as i) nitrate is mobile in most soils, ii) nitri-

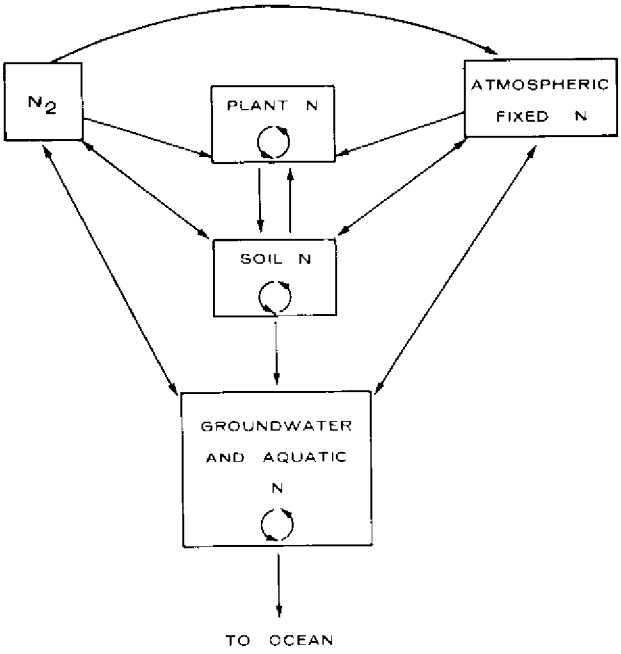

Figure 1. A schematic diagram of nitrogen flux in a linked terrestrial-aquatic ecosystem. Nitrogen cycles within compartments and between the compartments as indicated.

fication produces hydrogen ions in addition to mobile anions, thus increasing the potential for loss of cations (Nye & Greenland, 1960; Likens *et al.*, 1969), and iii) other papers in this volume examine the other pathways of nitrogen losses from terrestrial ecosystems. Volatilization losses probably predominate following disturbance in grassland and desert ecosystems (West & Skujins, 1977; Woodmansee, 1978).

The linkage between terrestrial and aquatic ecosystems can be crucial to the functioning of both systems. Losses of fixed nitrogen from terrestrial ecosystems can reduce soil fertility and impair the recovery of vegetation following disturbance. Aquatic ecosystems may be dependent on terrestrial systems for inputs of small amounts of nitrogen, but large inputs can hasten the growth of nuisance plants and algae and deleteriously affect water quality.

The nitrogen cycle in disturbed ecosystems

It has long been recognized that nitrate production can be accelerated in ecosystems subjected to destructive disturbance (Hesselman, 1917, a, b; cited in Stålfeldt, 1972). A number of studies have also reported increases in nitrate mobility in disturbed systems (Nye & Greenland, 1960; Firsova, 1965). More recently, detailed input-output budgets of watershed ecosystems before and after disturbance have been measured. The results of these studies have differed significantly among sites. At the Hubbard Experimental

Table 1. **Nitrate-nitrogen losses from control and disturbed forest ecosystems. Unless otherwise indicated, all of the results for disturbed ecosystems reflect the first year following disturbance.**

Site	Disturbance	NO_3-N loss ($kg\ ha^{-1}\ yr^{-1}$) control	NO_3-N loss ($kg\ ha^{-1}\ yr^{-1}$) disturbed	Reference
Hubbard Brook, New Hampshire	Clearcutting without vegetation removal, herbicide inhibition of regrowth	2.0	97	Likens *et al.*, 1970
Gale River, New Hampshire	Clearcutting	2.0	38	Pierce *et al.*, 1972
Fernow, West Virginia	Clearcutting	0.6	3.0	Aubertin & Patric, 1974
Coweeta, North Carolina	Complex	0.05	7.3[1]	Swank & Douglass, 1977
H.J. Andrews, Oregon	Clearcutting	0.08	0.26	Fredriksen, 1971
Alsea River, Oregon	Clearcutting with slash burning, alder succession	3.9	15.4	Brown *et al.*, 1973

[1] This value represents the second year of recovery following a long-term disturbance.

Forest, New Hampshire, forest cutting and herbicide inhibition of regrowth increased nitrate concentrations to levels in excess of established water quality standards (Likens *et al.*, 1970). In several other sites, little or no increase in nitrate loss has been observed.

The results of a number of North American studies of disturbance effects on nitrate losses are summarized in Table 1. Other studies have reported only changes in nitrate concentrations, and the results of these studies range from no increase in nitrate concentrations (Cole & Gessel, 1965; McColl, 1978) to very high concentrations like those observed at Hubbard Brook (Hibbert *et al.*, 1974; Edwards & Ross-Todd, 1979).

These highly significant differences between systems have no obvious climatic or vegetational correlates, and their causes are not now known. Even the systems which do have increased nitrate losses differ in the form and timing of the response. Nitrate lossses at Hubbard Brook increased rapidly, then decreased to levels below those in control watersheds by the fourth year of vegetation (Likens *et al.*, 1978). On the other hand, nitrate losses following disturbance at the Coweeta Hydrolic Laboratory never approached the high levels observed at Hubbard Brook, but significantly elevated nitrate losses persisted through twenty years of revegetation (Swank & Douglass, 1977).

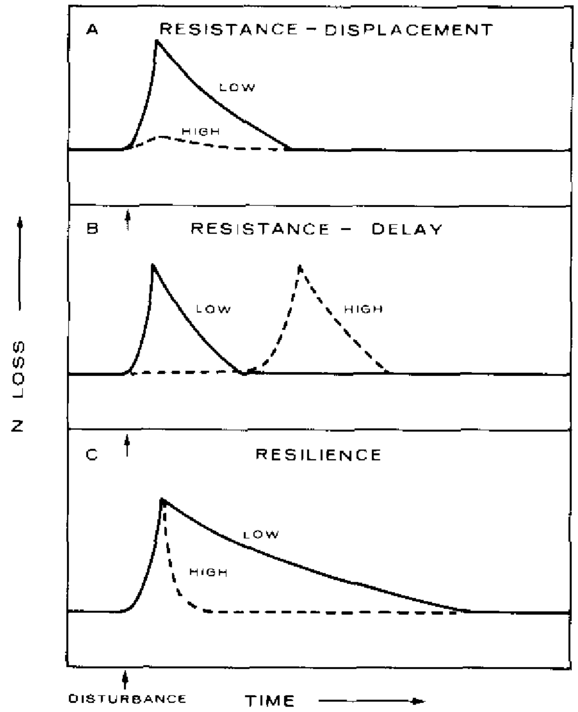

Figure 2. The components of response to disturbance in a terrestrial ecosystem. A) Resistance to displacement is the amplitude of ecosystem response to a given perturbation. Resistance to displacement is high when the perturbation causes a small system response. B) Delay is the length of the lag before the peak response to perturbation is observed. C) Resilience is the rate of return to the initial state following perturbation. A system with high resilience recovers rapidly.

Components of response

Population and ecosystem responses to perturbation can be separated into components of resistance and resilience (Holling, 1973; Webster *et al.*, 1975). Resistance is defined as the ability to withstand perturbation without change, while resilience is the ability to recover rapidly following perturbation. Although responses to perturbation are dependent in part on the type and severity of disturbance as well as the properties of the system, this separation has proved useful in the analysis of population and ecosystem stability.

This approach is directly applicable to the analysis of nitrogen losses from disturbed ecosystems. For this analysis, resistance should be further separated into components of displacement and delay. Resistance to displacement can be determined from the amplitude of peak nitrogen losses following a disturbance which interrupts plant nitrogen uptake. High losses of nitrogen indicate a low resistance to displacement (Fig. 2A). Delay is determined by the length of the lag between disturbance and peak nitrogen losses (Fig. 2B). Resilience can be determined from the time required for nitrogen losses to return to or below predisturbance level. A highly resilient system is one which rapidly returns to predisturbance nitrogen losses (Fig. 2C).

The overall pattern of nitrogen losses from any system is a function of all three of the components outlined in Fig. 2. Nonetheless, division of the response into components greatly simplifies the analysis of nitrogen losses from disturbed ecosystems. A reasonably small group of processes can be associated with each component, and the general nature and ecological regulation of each can be examined.

Processes contributing to resistance to displacement

Relatively little of the nitrogen utilized annually within undisturbed ecosystems comes directly from biological nitrogen fixation or atmospheric inputs – most is recycled within plants or within the soil-plant-microbial system (Rosswall, 1976; Ellenberg, 1977). Rosswall (1976) estimated that on a global basis annual inputs and outputs of nitrogen in terrestrial ecosystems are less than 10 % of plant nitrogen uptake and net mineralization and less than 4 % of the total annual biological cycling of nitrogen. Nitrogen cycling is thus relatively efficient, with large amounts passing through the biotic cycle relative to the amounts lost to a system.

The soil-plant-microorganism cycle can be interrupted by natural or human-caused disturbance. Destructive disturbance decreases or eliminates plant nitrogen uptake, while at the same time the rate of nitrogen mineralization can be temporarily enhanced by increased soil temperature and moisture (Stone, 1973; Aber *et al.*, 1978) and possibly by the elimination of competition with mycorrhizae (Gadgil & Gadgil, 1975). This excess of nitrogen mineralized over nitrogen uptake can lead to increased soil inorganic nitrogen concentrations and/or increased nitrogen losses.

The amount of excess nitrogen mineralized depends upon the severity of disturbance, the amount of nitrogen mineralized prior to disturbance, and the extent that disturbance accelerates rates of nitrogen mineralization. Assuming for comparative purposes a perturbation which eliminates plant nitrogen uptake, and assuming that the acceleration of nitrogen mineralization is a constant proportion of mineralization prior to disturbance, then the maximum potential amplitude of the increase in nitrogen losses after disturbance would be proportional to the rate of nitrogen mineralization prior to disturbance.

Table 2 reports nitrogen mineralization rates and nitrogen losses under undisturbed conditions in four well-studied North American watershed ecosystems. The results from deciduous forests are comparable with the results from Central European deciduous forests reported by Ellenberg (1977). While the forests in Table 2 differ significantly in annual nitrogen mineralization, they do not represent extremes. Bazilevich (1974) reported that the nitrogen required to support annual plant production varied from 65 kg N ha^{-1} yr^{-1} in boreal forests to 467 kg N ha^{-1} yr^{-1} in humid tropical forests. These values are not equivalent to annual nitrogen mineralization, however, since some of the annual nitrogen requirement can be met by translocation within plants (Turner, 1977). Nye (1961) reported nitrogen return in litterfall of 239 kg N ha^{-1} yr^{-1} in a 40-year old humid tropical forest; nitrogen mineralization must have been somewhat greater. Rhan (1970; cited by Ellenberg, 1977) measured nitrogen mineralization rates averaging 148 kg ha^{-1} yr^{-1} in the top of 5 cm of soil in humid forests in Ivory Coast; again, total nitrogen mineralization must have been somewhat greater.

The excess nitrogen mineralized following disturbance will not necessarily be lost from

Table 2. Rates of nitrogen mineralization and nitrogen outputs in several North American watershed ecosystems. All values in kg ha^{-1} yr^{-1}.

Ecosystem	Nitrogen mineralized	Nitrogen outputs
Hubbard Brook	100 (A)	2. 3 (B, H)
Coweeta	139 (C)	0.09 (D, H)
Walker Branch	115 (E)	3.1 (E)
H.J. Andrews	19 (F, I)	0.5 (G)

A. Melillo (1977)
B. Likens *et al.* (1977)
C. Mitchell *et al.* (1975)
D. Swank & Douglass (1977)
E. Henderson & Harris (1975)
F. Grier *et al.* (1974)
G. Fredriksen (1972)
H. Does not include outputs of organic nitrogen
I. Does not include the rapid turnover of fine roots

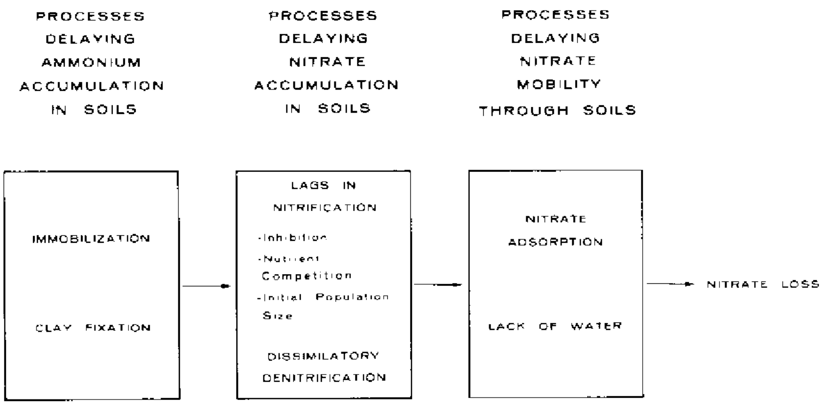

Figure 3. The mechanisms which can delay solution losses of nitrogen from disturbed ecosystems. Other processes which could be important include denitrification and ammonia volatilization, which are discussed elsewhere in this volume.

a system; the processes responsible for delay and for resilience (discussed below) usually reduce or prevent such losses. The rate of nitrogen cycling prior to disturbance provides an index of the amplitude of nitrogen losses in the absence of other processes, however, and hence it provides an estimate of the relative resistance to displacement of different ecosystems. In these terms, humid tropical forests have a very low resistance (a high amplitude of potential losses), temperate deciduous forests are intermediate, and temperate and boreal evergreen forests are the most resistant to displacement. Within latitudinal belts, the potential amplitude of nitrogen losses is greatest in humid areas and less in more arid areas (Bazilevich, 1974).

Processes contributing to delays

Several processes can reduce or delay hydrological outputs of the nitrogen mineralized following destructive disturbance. These processes can cause nitrogen losses in gaseous forms (which are examined in other papers in this volume), or they can cause the accumulation of nitrogen in some pool within the ecosystem. The latter group of mechanisms could reduce or delay solution losses of nitrate at three points in the nitrogen cycle: i) the net production and accumulation of biologically available ammonium could be slowed; ii) nitrification could be reduced or delayed, and iii) the leaching loss of any nitrate produced could be slowed. The processes which could retain nitrogen in a disturbed system are summarized in Fig. 3 and briefly discussed below.

Nitrogen immobilization

Decomposers obtain nitrogen from their substrate and from available nitrogen in the soil. Above a substrate carbon: nitrogen (C:N) ratio of 20-25:1, the net result of decomposition is nitrogen immobilization, while below a C:N ratio of 10-12:1, nitrogen is returned to the soil (Black, 1968). Immobilization and the loss of carbon in decomposition reduce the substrate C:N ratio, leading eventually to net nitrogen mineralization. Nitrogen immobilization can thus delay nitrogen losses from disturbed ecosystems, but it cannot prevent them entirely. Substantial delays can be expected in ecosystems with large amounts of nitrogen-poor organic matter, however.

Any disturbance which leaves behind large masses of nutrient-poor woody detritus will lead to substantial nitrogen immobilization in the disturbed system. Aber *et al.* (1978) estimated that of the 850 kg N ha^{-1} mineralized in the five years following clear cutting in a relatively fertile deciduous forest, 215 kg N ha^{-1} are immobilized, mostly in the decomposition of wood. Swift (1977) demonstrated the importance of fungi in translocating nitrogen into decaying wood. The burning of woody detritus can thus increase nitrogen losses both by volatilization during combustion and by accelerated leaching afterwards.

Efficient internal recycling of nitrogen by vegetation in nutrient-poor sites can also increase immobilization. At least some evergreens have the ability to translocate nitrogen from old to young leaves. Deciduous trees and even ruderal herbs can also withdraw nitrogen (and phosphorus) from senescent leaves prior to leaf abscission. By adding urea to increase nitrogen availability and a sawdust-sucrose mixture to widen the soil C:N ratio and thus decrease nitrogen availibility, Turner (1977) experimentally demonstrated that the efficiency of internal translocation can be altered by external nutrient availability in Douglas-fir. When nitrogen is in short supply, the trees withdraw most of their nitrogen prior to leaf abscission, producing litter with a wide C:N ratio. This litter then causes additional nitrogen immobilization in the soil, further decreasing nitrogen availability. Immobilization in litter can substantially delay nitrogen losses following disturbance in such an ecosystem. In sites with adequate nitrogen, the trees withdraw less from the leaves prior to abscission, so the litterfall C:N ratio is narrowed and the amount of nitrogen cycling through the soil-plant-microorganism system is increased.

Fire volatilizes nitrogen as it mineralizes most other nutrient elements (Grier & Cole, in press). Without vigorous nitrogen fixation, areas which burn frequently consequently have low levels of nitrogen. Efficient internal cycling, substantial nitrogen immobilization, and a considerable lag in the net mineralization of nitrogen following disturbance other than fire would thus be expected in fire-dominated ecosystems. Low rates of decomposition and nitrogen mineralization in cold-dominated ecosystems can also favor the development of efficient internal cycling and substantial nitrogen immobilization following disturbance.

This efficient internal nitrogen recycling must be experimentally documented in other plant species. If it can be substantiated, it will aid considerably in predicting nitrogen cycle responses to destructive disturbance.

Ammonium fixation by clays

Ammonium, like potassium, can be non-exchangeably bound into the interlattice area of illite, montmorillonite, and vermiculite clays (Brady, 1974). In this form, its biological availability is substantially reduced (Faurie *et al.*, 1975) and it is only susceptible to loss from an ecosystem through erosion. Ammonium fixation by clays could be significant in preventing nitrogen losses from disturbed ecosystems which contain large enough quantities of the appropriate clays (Kudeyarov & Bashkin, 1975).

Lags in nitrification

Due to the relative mobility of the nitrate anion, nitrification can be the critical step in regulating nitrogen losses from disturbed ecosystems. If excess nitrogen mineralized after disturbance remains in the form of ammonium, nitrogen losses will be relatively slight. Once it is converted to nitrate, the probability of substantial losses is increased.

Nitrification rates in incubated soils follow the pattern outlined in Fig. 4. A similar pattern is observed in the soils of disturbed ecosystems. The length of the lag phase differs markedly between systems, being absent in some and very long in others. A substantial lag in nitrification clearly could delay solution losses from a destructively disturbed ecosystem.

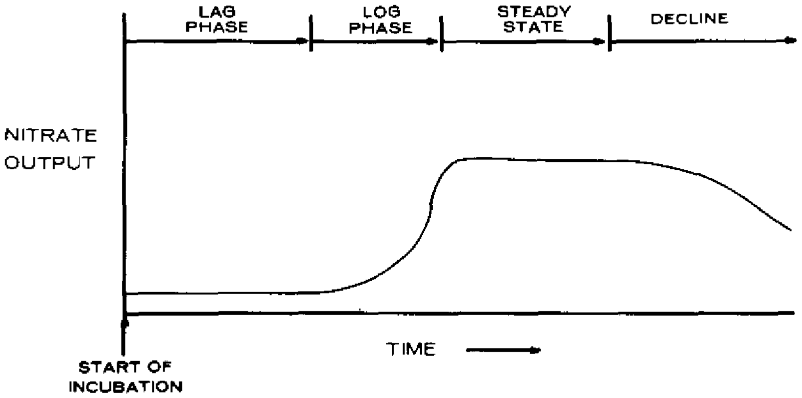

Figure 4. The general pattern of nitrate production in an incubated soil. The lag phase can be absent, or it can be very long. After Sabey *et al.* (1969).

Nitrification could be delayed by a lack of available ammonium substrate, which could in turn be caused by nitrogen immobilization (discussed above). Lags have also been observed where adequate ammonium was available, however. Three mechanisms have been suggested to explain lags in nitrification in such cases.

1. Meiklejohn (1962) and others have suggested that lags are caused by allelochemic inhibition of nitrifying bacteria by secondary plant compounds. Such compounds could be produced as metabolic byproducts, as herbivore defense mechanisms, or even as a means of affecting nitrogen cycling (Rice, 1974).
2. Competition between nitrifiers and heterotrophs for some other limiting nutrient, most likely phosphorus, could delay the growth and activity of nitrifiers (Purchase, 1974a, b). Nitrification could be delayed until the C:P ratio was reduced sufficiently to permit net mineralization of phosphorus.
3. Competition for ammonium between plant root-mycorrhizae complexes and nitrifiers prior to disturbance could lead to very low initial populations of nitrifiers. Following destructive disturbance, there would be a lag in nitrification as nitrifier populations became established and increased in population (Sabey *et al.*, 1969).

It seems reasonable to speculate that all three of these mechanisms would be most important in nutrient-poor sites. The production of potentially inhibitory secondary plant compounds in tropical forests is apparently much greater in acid, nutrient-poor sites (McKey *et al.*, 1978), possibly because trees in such forests could be severely damaged by herbivory. Lags resulting from insufficient phosphorus and from intense competition for ammonium would clearly be most important in nutrient-poor ecosystems.

Nitrification by heterotrophic microorganisms has received increased attention in recent years. Nitrification in a broad variety of acid forest soils can proceed relatively rapidly through the action of heterotrophic nitrifiers (Focht & Verstraete, 1977) and possibly through acid-adapted strains of autotrophic nitrifiers (Weber & Gainey, 1962; Melillo, 1977). If heterotrophic nitrifiers can be important in producing nitrate in disturbed ecosystems, information on their growth kinetics and particularly on their susceptibility to the delays outlined above must be obtained.

Nitrate reduction

Although denitrification to nitrous oxide and dinitrogen will not be discussed in this paper, the possible importance of the non-assimilatory reduction of nitrate to ammonium should be mentioned. Stanford *et al.* (1975) demonstrated that a large proportion of applied $^{15}NO_3$ was rapidly recovered as $^{15}NH_4$. Focht & Verstraete (1977) considered this to result from assimilatory nitrate reduction, but Tiedje (pers. comm.) suggests that the reduction (termed electron sink denitrification) is non-assimilatory. He further suggests that it could be important in preventing nitrogen losses from terrestrial ecosystems, since its effect is the conversion of inorganic nitrogen from a mobile to a relatively immobile form.

Nitrate adsorption

Although cation exchange is quantitatively more important, anion adsorption can significantly affect the mobility of particular anions in the soil solution. Nitrate, chloride, and bicarbonate are the least strongly adsorbed (and hence the most mobile) anions in most soils (Johnson & Cole, 1977). Nonetheless, nitrate adsorption has been demonstrated in tropical soils (Singh & Kanehiro, 1969; Kinjo & Pratt, 1971). Although such adsorption is relatively weak, it could reduce the mobility of soil nitrate and thus reduce or delay nitrate losses from disturbed ecosystems.

Insufficient water for nitrate transport

Neither nitrogen mineralization nor nitrification proceeds rapidly in very dry soils, but if soils are moist enough for microbial activity yet receive insufficient precipitation for leaching, nitrate can be produced and accumulated within soils without losses to downstream ecosystems. This process could be particularly important in sites with summer-dry climates, where the most favorable temperatures for nitrogen mineralization and nitrification occur during relatively dry seasons (Miller, 1974).

Summary

The processes which can reduce or delay solution losses of nitrate from disturbed ecosystems can be classified as biotic (immobilization, lags in nitrification, nitrate reduction) and abiotic (clay fixation, nitrate adsorption, lack of water). Although the abiotic processes are not yet completely understood, they are relatively predictable from the climate and soils of an area. Immobilization and lags in nitrification are more variable, more dynamic, and (at least in temperate forests) quantitatively more important. At this time, it seems reasonable to hypothesize that overall delays in solution losses of nitrogen should be most pronounced in relatively infertile sites, where both substantial immobilization (due to internal recycling within vegetation) and lags in nitrification can be expected. Fertile sites should experience little or no delay in nitrogen losses.

Processes contributing to resilience

The resilience component of nitrogen losses from disturbed ecosystems is caused by the regrowth of vegetation, which has both direct and indirect effects on resilience. The major direct effect is the reestablishment of plant nitrogen uptake, which again completes the soil-plant-microorganism cycle. During recovery, nitrogen uptake can increase to rates well above current mineralization while the excess nitrogen mineralized during the period of disturbance is utilized (Marks, 1974), and it can remain at levels slightly above nitrogen mineralization for long periods of time as the nitrogen capital of the ecosystem is rebuilt (Vitousek & Reiners, 1975; Vitousek, 1977).

The indirect effects of revegetation on resilience include shading and protecting the soil surface and chanelling soil water into evapotranspiration rather than percolation and runoff (Marks & Bormann, 1972; Harcombe, 1977). The acceleration in nitrogen mineralization and nitrification caused by increased soil temperature and moisture levels in disturbed ecosystems is thus reversed, often more rapidly than significant rates of nitrogen uptake are established (Stone, 1973). Chanelling soil water to evapotranspiration also reduced leaching losses of nitrogen and decreases the loss of organic, exchangeable, and clay-fixed nitrogen in erosion and mass soil movements (Swanston & Swanson, 1976).

The control of rates of revegetation in different ecosystems is not well understood. It is reasonable to speculate that fertile sites are more resilient than infertile sites, since revegetation should proceed more rapidly with high nutrient availability. Additionally, the historical frequency and type of disturbance in an area would be important. Resilience should be high in sites where the vegetation reproduces itself primarily by root or stump sprouting (Richardson & Lund, 1975), and frequent destructive disturbance would select for species with this capability. Resilience should also be high in sites with an abundance of species specialized in colonizing disturbed habitats, either by rapid dispersal following disturbance or by the maintenance of dormant seeds in undisturbed sites (Marks, 1974; Foster *et al.*, 1980). A long-term history of frequent disturbance would favor the evolution of such species (Pickett, 1976), while recent disturbance in the immediate area would increase their representation in the local flora. Resilience would be lower in sites where nutrient uptake was reestablished by slower-growing species.

Overall patterns

The processes responsible for resistance to displacement, delay, and resilience can be discussed most easily in isolation, but in practice all of them act simultaneously and overall ecosystem responses to disturbance are a function of all three. The joint effects of resistance, delay, and resilience are illustrated in Fig. 5. This figure shows the effects of two rates of predisturbance nitrogen mineralization (high mineralization and thus low resistance to displacement, and low mineralization), two levels of delay (zero and two years), and two rates of resilience (two and six years to the reestablishment of predisturbance rates of nitrogen uptake).

Fig. 5 contains the assumption that resistance to displacement, delay, and resilience are independent of one another; that any combination of the three could be observed. In practice, all three interact, restricting the set of results that would actually be observed. In previous sections, it was suggested that all three components are dependent, at least in part, upon site fertility. If so, three broad categories of site responses to destructive disturbance might be expected:

1. Sites with low levels of nitrogen availability should be resistant to displacement and have relatively long delays in nitrogen losses due to both nitrogen immobilization and lags in nitrification. They should have low resilience, however. Destructive disturbance in such sites should not have a substantial impact on downstream ecosystems, but any increase in nitrogen losses could have a negative impact on the terrestrial ecosystem.

2. Fertile sites should have low resistance to displacement and little or no delay in nitrogen losses. Such sites should be relatively resilient, however, due to favorable conditions for vegetation regrowth. Destructive disturbance in such sites should yield a high amplitude but short duration increase in nitrogen losses, with the possibility of deleterious consequences for downstream water quality. Prolonged disturbance could cause a severe reduction in site quality.

3. Sites with adequate nitrogen but low fertility due to low availability of other

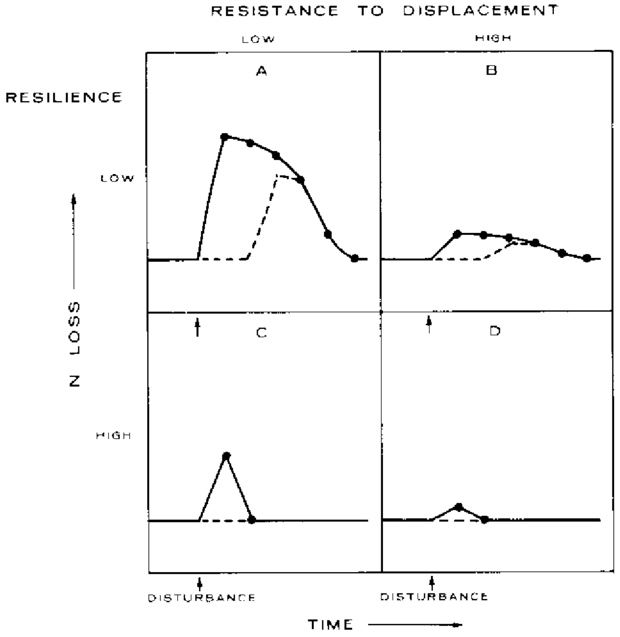

Figure 5. The combined effects of two levels of resistance to displacement, delay, and resilience on nitrate losses from disturbed ecosystems. The solid lines represent the possible combinations with no delay, while the broken lines represent the combinations with a two-year delay.

nutrients would of course be controlled primarily by those nutrients. Delays in nitrogen losses would most likely occur, however, since lags in nitrification (due to nitrifier-heterotroph competition and possibly secondary plant compounds) and probably reduced nitrogen mineralization could be expected.

Clearly, fertile sites are likely to present the most serious problems. The consequences of disturbance in such sites can be severe, and human disturbance is of course concentrated in such sites wherever they are available.

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Nitrogen Cycling in West African Ecosystems

MICROBIOLOGICAL CONSIDERATIONS OF THE NITROGEN CYCLE IN WEST AFRICAN ECOSYSTEMS

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Abstract

The review is an attempt to specify particular features of the biological processes involved in the nitrogen cycle as they occur in the following categories of West African ecosystems : flooded rice fields, rain-fed agroecosystems, and forests.

In rice fields in Senegal the nitrogen input through blue-green algae was reported to be in the range of 1–30 kg ha^{-1} yr^{-1}. Figures for heterotrophic rhizosphere N_2-fixation in the rice rhizosphere should be reassessed. In rain-fed ecosystems, symbiotic N_2-fixation is often impeded by such limiting factors as moisture stress (in semi-arid areas), nematode attacks, soil acidity and toxicity, mineral deficiencies (especially phosphorus deficiency), inadequacy of *Rhizobium* populations and competition between native and introduced strains. Inoculation with *Rhizobium* is futile if even one of the above-mentioned limiting factors is still operating. No reliable evaluation has been published thus far of N_2-fixation in forests.

Nitrification and denitrification are limited by soil acidity in rice soils as well as in non-fertilized rain-fed agrosystems. However, when nitrogen fertilizers are applied to the soil, losses through denitrification were reported to be ca. 30 %, whereas losses through leaching were only 10 %. In West African forest ecosystems, nitrification is potentially much more active than in temperate conditions. Data on denitrification is lacking.

Mineralization rates are high, except in acid rice fields, as long as the soil is flooded. In arid conditions, mineralization is slowed down but still persists as long as the soil pF is not higher than 5.2, which corresponds to relatively dry conditions.

Introduction

A voluminous amount of literature has been accumulated concerning nitrogen transformations in soil, but, unfortunately, most of the information is limited to temperate conditions. Many of the general concepts applicable to temperate soils are applicable to tropical soils, but the special conditions which prevail in tropical environments lead to considerable modifications of the transformation rates and nitrogen transfers. The present paper is a review of our current knowledge of the role of microorganisms in nitrogen transformations occurring in different ecosystems which are typical of West Africa, attempting to specify the particular features of the biological processes in such conditions.

Table 1. Distribution of bacteria, fungi and actinomycetes in different fractions of a typical sandy soil (Dior) from Central Senegal (Panthier & Feller, unpublished data)

Fractions	Weight (%)	Bacteria (%)	Fungi (%)	Actinomycetes (%)
Organic matter				
>2.0 mm	0.02	0.7	2.0	0.4
0.2–2.0 mm	0.33	20.0	33.3	4.3
0.2–0.05 mm	0.67	13.3	16.6	2.2
Total	1.02	34.0	51.9	6.9
Organo-mineral fraction				
(<0.05 mm)	15.41	66.0	47.1	92.9
Mineral fraction				
>2.0 mm	0	0	0	0
0.2–2.00 mm	33.50	0	0.5	0
0.2–0.05 mm	49.50	0	0.5	0.2
Total	83.00	0	1.0	0.2

Total number of bacteria, fungi and actinomycetes were respectively 3.3×10^6, 4.8×10^3, 1.3×10^4 per g (d.w.) soil.

Two preliminary remarks should be made here. The first relates to the soils. In West Africa, sandy to coarse loamy structures prevail in surface layers and the organic matter content is usually very low in cultivated soils. For example, in the AP horizon of a typical sandy soil from central Senegal (Dior Soil) the clay and carbon contents are respectively 3 -6 % and 0.2–0.3 %. Since the microbial populations are mainly located on the organic and organo-mineral particles, which make up the organic and organo-mineral fractions (Table 1), and since the organic matter content of these sandy soils is low, the total microbial numbers are low (10^6–10^7 g^{-1}). But such data do not mean that there is less microbial activity than in temperate conditions. Actually, it can be very high (see examples below) but it is located in habitats which represent only a relatively small volume of the soil: (1) in soil organic and organo-mineral particles and (2) in plant rhizospheres, i.e., the soil-plant root interface, including the surface of the root tissues and the surrounding soil (Yoshida, 1975). Another characteristic of the sandy soils of West Africa is their normally high acidity, which is generally associated with low Ca, P and Mo contents and high Al and eventually a high Mn content. Acidity may be responsible for impeding some major processes, especially N_2-fixation and nitrification.

The second remark refers to the climate. Just as frost does in temperate conditions, drought in tropical climates can act as a major limiting factor, which is responsible for a differential slow-down (Fig. 6) and ultimately a blockage of microbial activities, except in irrigated ecosystems. In West Africa we can distinguish three classical kinds of climates (Charreau, 1974):

- the desert climates which have very few tropical months (one or two), a large number of arid months (eight to ten), and one or two temperate months,

- the equatorial climates which have a large number of tropical months, one or two arid months, and no temperate months,
- the tropical climates which are characterized by the lack of temperate months and a variable number of tropical and arid months, but more than one or two arid months.

If we consider the tropical climates, a further distinction can be made on the basis of the proportion of arid and tropical months and we can distinguish two classes:

- dry climates, characterized by 2–4 1/2 humid months,
- wet-dry climates having 4 1/2–7 humid months.

Since tropical, dry or wet, climates exist in large areas of West Africa, the aridity factor is deemed to play a major role from both a microbial as well as an agronomic point of view. This should not be overlooked.

Flooded rice fields

In contrast with the situation in India and the far-eastern countries (see, for instance: IRRI, 1979), few studies have been devoted thus far to the nitrogen transformations occurring in rice fields of West Africa. However, some data are available as far as nitrogen fixation and denitrification are concerned.

N_2-fixation

Three groups of organisms are believed to be responsible for the nitrogen input to rice fields: bluegreen algae, heterotrophic N_2-fixing bacteria, and *Azolla*.

N_2-fixation by bluegreen algae

It is difficult to estimate the biomass of N_2-fixing bluegreen algae in rice fields, not only because such estimations are time-consuming, but also because large variations occur during the cultivation cycle. Such variations were carefully observed by Roger & Reynaud (1976), who showed that bluegreen algae make up only a low percentage of the total algae biomass up to the heading stage. But during the last growth phase, if the plant cover is dense enough, N_2-fixing algae could represent 13–99 % of the total algae biomass (Table 2), which itself is generally never higher than $6 \cdot 10^3$ kg (f.w.) ha^{-1} in acidic P-deficient paddy soils, which are most frequently encountered in Senegal.

Estimations of N_2-fixed by bluegreen algae in West Africa are few. Preliminary reports from Reynaud & Roger (1978) indicate that in this area the nitrogen input through bluegreen algae is between 1 and 30 kg ha^{-1} yr^{-1}. Low activities can be attributed to the effect of unfavourable climatic and/or edaphic factors. In the dry tropical conditions which prevail in Senegal, high light intensities reaching 70,000–80,000 lx are thought to be responsible for the relatively poor development of bluegreen algae, which are light sensitive (Roger & Reynaud, 1979a), whereas in equatorial conditions this limitation is not observed.

Temperature is not usually a limiting factor, except in the Sahelian zone during the dry season when a lower temperature at the beginning of the cultivation cycle inhibits bluegreen algae growth and favours eukaryotic algae (Roger & Reynaud, 1976). Other

Table 2. **Algal biomass in relation to rice development (40 rice soils studied) (Roger & Reynaud, 1978b)**

Stages of rice development	Dominant flora				N_2-fixing algae		
	Nature	% of total biomass			% of total biomass		
		Mean value	Max. value	Min. value	Mean value	Max. value	Min. value
Tillering	Diatoms, unicellular green algae	73	99	49	2	4	0.1
Panicle initiation	Filamentous green algae. Non-heterocystous bluegreen algae	89	93	86	3	9	0.1
Heading to maturity; weak plant cover	Filamentous green algae. Non-heterocystous bluegreen algae	70	91	62	8	14	0.2
Heading to maturity; dense plant cover	Bluegreen algae	71	99	16	38	99	13.0

major limiting factors in West Africa are related to soil characteristics, especially P deficiency and acidity. Biotic factors (predators and antagonists) may also influence the growth and activity of bluegreen algae, but their role has not yet been elucidated.

Heterotrophic N_2-fixation

Heterotrophic N_2-fixation occurs not only in the rhizosphere, but also in other soil micro-habitats, such as root litter, which provides heterotrophic N_2-fixing bacteria with favorable conditions for their activity (especially the presence of energy-yielding compounds and low pO_2 tension). Microorganisms involved have been shown to pertain to the usual genera that have been described elsewhere, i.e., *Spirillum, Clostridium, Enterobacter, Beijerinckia, Azotobacter, Desulfovibrio, Desulfotomaculum* (Rinaudo, 1974; Rinaudo *et al.*, 1977; Dommergues & Rinaudo, 1979).

Heterotrophic N_2-fixation in the rice rhizosphere is most difficult to investigate because of the interference of bluegreen algae and the occurrence of large variations during the rice growth cycle. According to Balandreau *et al.* (1974), N_2-(acetylene reducing activity)-fixation in a rice field in Ivory Coast (Lamto) was in the order of 72 kg ha^{-1} yr^{-1}, but considerably lower values have been reported by Rinaudo (pers. comm.), e.g., 0–20 kg ha^{-1} yr^{-1} in Senegal. These results must be cautiously interpreted and new *in situ* measurements are necessary along with long-term field experiments to reassess the quantitative significance of N_2-fixation in the rice rhizosphere.

One point is clear: the N_2-fixing system made up by the rice plant and the microorganisms associated with its rhizosphere is not a stable system in itself, since the composition of the rhizosphere populations is heterogeneous and changing. Moreover, this system is very sensitive to effects of soil factors which have already been mentioned as harmful to other systems (acidity, P deficiency, excess of inorganic nitrogen) and also to factors specific to the rhizosphere N_2-fixing system, especially an excess of O_2. No simple chemical or physical criterion can be used for predicting the N_2-fixing potential of a soil with planted rice. Thus, in a survey of 29 paddy fields from Senegal, Garcia *et al.* (1974) were unable to discover any significant correlation between N_2-fixing potential and the following soil characteristics: clay, loam, and sand content; C, N, S-SO_4^{2-}, or N-NO_3^- content. Laboratory experiments suggest that in some soils, such as newly reclaimed fields, the inadequacy of the N_2-fixing microflora could be held responsible for the low rhizosphere N_2-fixation.

Heterotrophic N_2-fixation occurring in microhabitats other than rhizospheres has been demonstrated by different authors, especially Matsuguchi (1979). This type of process has not yet been investigated in West Africa, but reports about the effects from ploughing under straw in rice fields in the Casamance (i.e., Beye, 1974) suggest that significant N_2-fixation could take place during the decomposition of straw in the soil, increasing the total soil nitrogen content and the crop yield.

N_2-fixation by *Azolla*

The *Azolla-Anabaena* association has been extensively studied for the last few years in India, in the Far East, and in the USA (IRRI, 1979). *Azolla* occurs in West Africa but, to the best of our knowledge, it has not yet been used in rice production as has been the case in China and Vietnam, for instance. *Azolla* grows well in the humid areas of West Africa, but in the semi-arid conditions which prevail in Senegal, its distribution seems to be mainly limited by desiccation and to a lesser extent by high light intensities, and by temperatures which are too high (Roger & Reynaud, 1979b).

Nitrification and denitrification

The surface layer of rice soils is known to be sufficiently aerobic to permit active nitrification. The nitrate produced in the aerobic layer readily diffuses to the underlying anaerobic layers, where it is rapidly denitrified (Focht, 1979). The nitrification potential of the surface layer of rice fields in West Africa has not been systematically studied, but in a recent survey, Garcia *et al.* (1974) found that the nitrification potential was moderately correlated with the soil pH and inversely correlated with salinity. To the best of our knowledge there has been no study published on the nitrifying microflora of West Africa.

Since denitrification depends primarily upon nitrate concentration, the results of Garcia *et al.* (1974) suggest that acidity and salinity might limit denitrification in acid and saline soils, which was actually verified *in situ*. Acid rice fields are far from being the exception in West Africa, and denitrification is presumed to be less important than in regions where neutral soils are more frequently found. However, laboratory studies indicate that denitrification may still occur in acidic conditions, nitrate being reduced to nitrite, which produces nitric oxide (NO) by a chemical reaction (Garcia, 1976). On the other hand, even in acidic or saline soils, denitrification can be enhanced by surface application of ammonium fertilizers (Mitsui, 1954). Moreover, denitrification is well known to be stimulated in a rice rhizosphere. This rhizosphere effect may be attributed to the development of anaerobic zones, the presence of roots exudates and large numbers of denitrifiers in the rhizosphere (Garcia, 1975; Raimbault *et al.*, 1977).

According to Gamble *et al.* (1977), *Pseudomonas fluorescens* biotype II and the "alcaligenes-like" group are the dominant denitrifiers. Many denitrifying strains of the *Bacillus* genus have, however, been isolated from rice soils in Senegal, using an enriched medium (Garcia, 1977b). Some of these organisms, which all tolerate high concentrations of nitrite during growth, can use nitric oxide as a respiratory substrate for growth (Garcia, 1977b; Pichinoty *et al.* (1978).

In order to decrease denitrification, deep placement of ammonium has invariably been shown to be superior to surface placement (Mitsui, 1954; Abichandani & Patnaik, 1955). This was confirmed in pot experiments with rice growing in a Senegalese soil by measuring N_2O reduction rates (Garcia, 1977a). The slow release nitrogen fertilizer, sulfur-coated urea (SCU), which appeared to be a promising nitrogen fertilizer for the tropical regions, was tested successfully in the same experiment. Deep placement of SCU appears to be a good way to reduce losses by denitrification. The extra cost of SCU (30 %) would be compensated by (1) saving nitrogen fertilizer and by (2) eliminating the different split applications which are necessary when using conventional fertilizers.

Mineralization of organic nitrogen

Mineralization rates in acid rice soils are surprisingly low as long as the soil is flooded (Fig. 1), but there is some presumptive evidence that this activity is restored when the water content decreases.

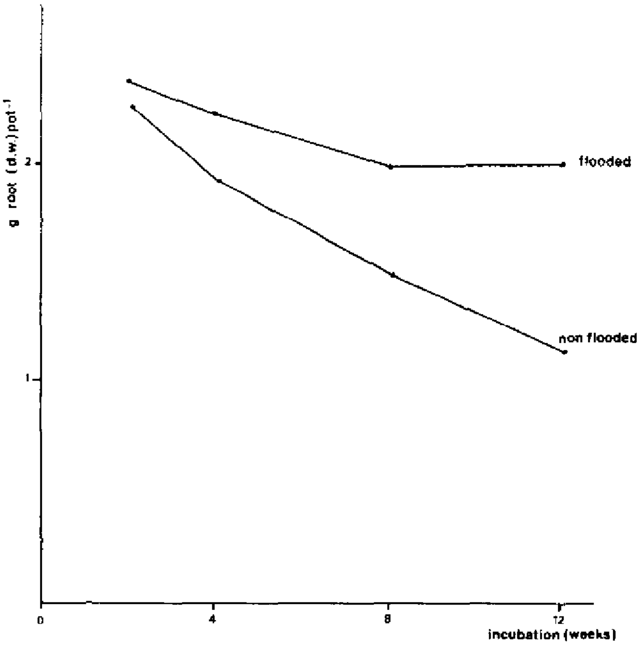

Figure 1. Time course of decomposition of rice roots introduced in flooded and rain-fed soil ("sol gris" from the Casamance) and incubated at 25°–28°C for 12 weeks. Root weight is expressed as g root (d.w.) per pot. Decomposition was much less in flooded than in rain-fed soil (Bernhard-Reversat, unpublished data).

N_2-fixation

N_2-fixation by *Rhizobium* associated with legumes

Legumes are largely responsible for the nitrogen input in tropical rain-fed agroecosystems. The amount of N_2 fixed by *Rhizobium* associated with the legumes varies widely (Hainnaux, 1979), however, not only according to the legume-*Rhizobium* association under study, but also according to environmental conditions, which can be a much more important cause of variation than is usually assumed. Therefore, our discussion of the microbiology of symbiotic N_2-fixation will be mainly devoted to the factors which limit this process (Table 3).

The soil *Rhizobium* population is inadequate (1) when specific *Rhizobium* are absent or sparse, (2) when indigenous *Rhizobium* are ineffective or partially effective in N_2-fixation. Response to inoculation can be expected when such a situation exists, which mainly occurs with introduced legumes. Thus at the International Institute of Tropical Agriculture at Ibadan, seed inoculation increased the N_2-fixation (acetylene reducing activity) and nitrogen content of soybean, but did not affect cowpea which is an indigenous legume (Table 4). It should be noted that populations of *Rhizobium* specific to indigenous legumes may be abnormally low in some cases, such as recently cleared forest soils and leached acid soils. Table 5 illustrates the latter situation where inoculation was found to increase N_2-fixation by groundnut in Senegal.

Table 3. Major factors limiting symbiotic N_2-fixation in West Africa; proposed means of controlling their effect

Limiting factor	Control
1. Moisture stress	– irrigation – search for drought registing cv of legumes; and drought resisting *Rhizobium* (survival) – stimulating VA-mycorrhizal infection
2. Nematodes [1]	– fumigation by nematicides – biological control
3. Soil acidity and toxicity	– liming – addition of organic matter (farmyard manure; green manure; compost)
4. Mineral deficiencies especially phosphorus deficiency	– addition of phosphorus – stimulating VA-mycorrhizal infection
5. Inadequacy of native *Rhizobium* populations and competetion between native and introduced strains	– inoculation

[1] Some pests and diseases may become serious in some circumstances

Table 4. Effects of seed inoculation on nitrogenase activity and nitrogen content of tops of cowpea and soybean in two soils (Ayanaba, 1977)

		Apomu soil		Egbeda soil	
Legume	Inoculant [1]	N(%)	C_2H_4 (μmole g^{-1} nod. h^{-1})	N(%)	C_2H_4 (μmole g^{-1} nod. h^{-1})
Cowpea	None	3.80	2.17	3.57	34.05
	EL	5.95	1.32	4.37	32.34
Soybean	None	2.60	11.64	3.93	0.00
	S	3.15	20.14	4.30	366.90
	Nitrogerm	3.20	17.24	4.40	10.28

[1] EL and S are inoculants of the Nitragin Co., USA. Nitrogerm inoculant is Australian.

Table 5. Estimation (A value) of N_2-fixed by field-grown groundnut at the Bambey Agronomic Research Center, Central Senegal (Ganry, 1975, 1976, unpublished data)

		kg N_2-fixed ha^{-1}	
Year	Rainfall(mm)	Inoculated	Non-inoculated
1974	458 [3]	52	56
1975	521 [1]	84	67
1976	403 [2]	26	16

[1] Satisfactory distribution within the rainy season

[2] Unfavorable distribution

[3] Intermediate distribution

Thus far, no characteristic failure of nodulation due to microbial antagonism has been reported in West Africa. Thus, groundnut chlorosis due to a decrease of nodulation which occurs frequently in Senegal, could not be related to the antagonism of actinomycetes, since the number of actinomycetes antagonistic to a *Rhizobium* cowpea strain was similar in sites where chlorosis occurred and in nearby sites where no chlorosis was seen (J.J. Panthier, pers. comm.). It is obvious that further research is necessary to improve our knowledge of the different categories of microbial antagonism, including interstrain competition. Plant pathogens, such as virus, insects, and nematodes, are known to be potential antagonists to symbiosis. Parasitic attacks by nematodes are probably responsible for the reduction of N_2-fixation and for low yields of groundnuts and soybeans in many semi-arid soils. Thus, a field experiment recently carried out in Central Senegal showed that soil fumigation with a nematicide (1,2-dibromo-3-chloropropane) not only reduced dramatically the nematode (*Scutellonema cavenessi*) population, but also markedly increased the N_2-fixing activity (acetylene reducing activity, Fig. 2); seed yields expressed

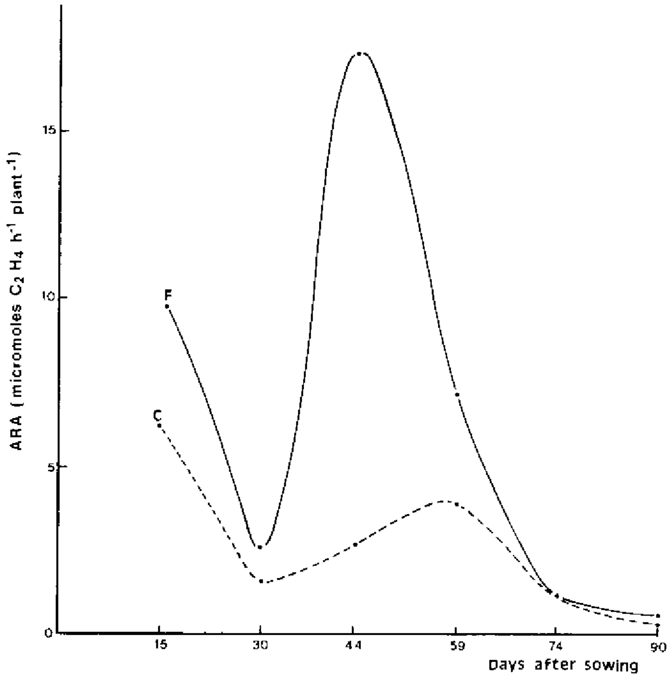

Figure 2. Influence of soil fumigation with 1,2-dibromo-3-chloropropane upon acetylene reducing activity (ARA) of field-grown groundnut. F: fumigated; C: control (non-fumigated) plot (Germani, unpublished data).

as kg N ha^{-1} were significantly increased (Germani *et al.*, 1978). Still unidentified biotic factors are probably responsible for the difference in N_2-fixing (C_2H_2) activity that are often observed *in situ*. Thus Dreyfus & Saint-Macary (unpublished data) found that soybeans growing in two adjacent plots, which did not differ in chemical soil properties and which had been similarly inoculated (10^9 *Rhizobium* per plant), exhibited large differences in acetylene reducing activity (Fig. 3).

High soil temperatures are often encountered in West African conditions during the dry season, but they seldom exceed 35°C during the rainy season. Such temperatures probably affect nodulation and N_2-fixation but, to the best of our knowledge, no specific field studies have been devoted to this problem.

By contrast, the influence of moisture stress on the *Rhizobium*-legume symbiosis has been given some attention at the Bambey Experimental Station in central Senegal over the last 3 or 4 years. N_2-fixation by groundnut (measured by the acetylene assay) was shown to be closely related to soil water content in 1976 and 1977 (Fig. 4). In 1977, nodulation was delayed by the low soil water content up to the 50th day, so that N_2-fixation started only after that date (Fig. 5). During the first 50 days the soil water content was high enough for the groundnut to grow, but too low for the infection process to take place.

Using the "A value method" (Fried & Middleboe, 1977), Ganry (1975, 1976, 1977)

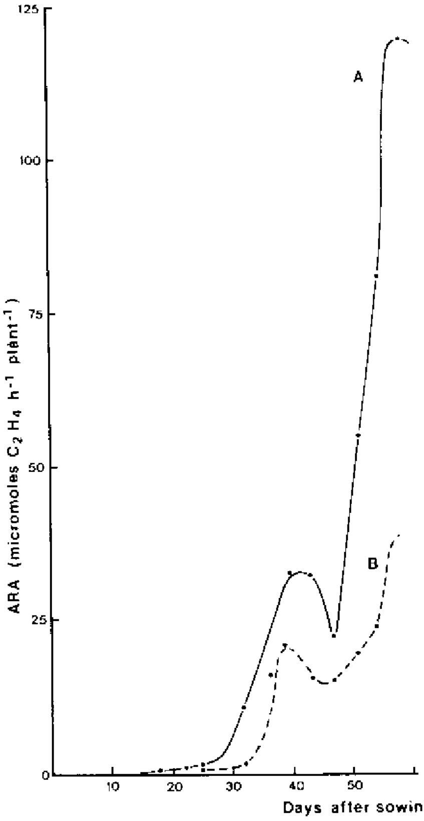

Figure 3. Acetylene reducing activity (ARA) of field grown soybean in two adjacent plots whose soil did not differ by any chemical or physical characteristic. Soybean had been massively inoculated (10^9 bacteria per plant) in both plots (Saint-Macary & Dreyfus, unpublished data).

found that N_2-fixation by field-grown groundnut at the Bambey Agronomic Research Center (central Senegal) depended largely on the rainfall (Table 5) and the distribution of rains within the rainy season. Thus, in 1976 the low overall rainfall (403 mm) and the occurrence of a period of relative aridity between August 15 and September 15 (the rainfall was only 65 mm, whereas the water requirement of the crop during this period was ca. 150 mm) caused a dramatic reduction in N_2-fixation (26 kg N_2 fixed ha^{-1}) in comparison with the satisfactory N_2-fixation (84 kg N_2 fixed ha^{-1}) that was recorded in 1975, when the rainfall was higher (521 mm) and precipitation well distributed. On the other hand, waterlogging, even if it is transitory, was noted to hinder nodulation and N_2-fixation of groundnut in the Casamance (south Senegal), where rainfall is higher than in central Senegal.

In conditions prevailing in West Africa, N_2-fixation by legumes is often restricted by unfavorable chemical characteristics, which have recently been reviewed by Kang *et al.* (1977). Soil acidity, which is known to inhibit nodulation by *Rhizobium*, is generally associated with Ca or P deficiency and Al or Mn toxicity. Therefore, the effect

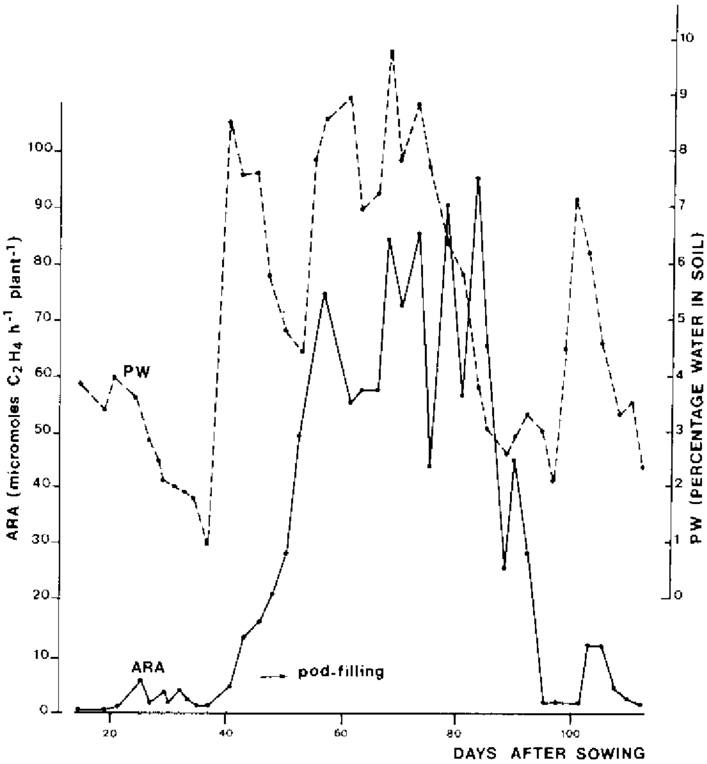

Figure 4. Variations of acetylene reducing activity (ARA per plant) of field-grown groundnut and of soil water content throughout the groundnut cycle (Ducerf, 1978).

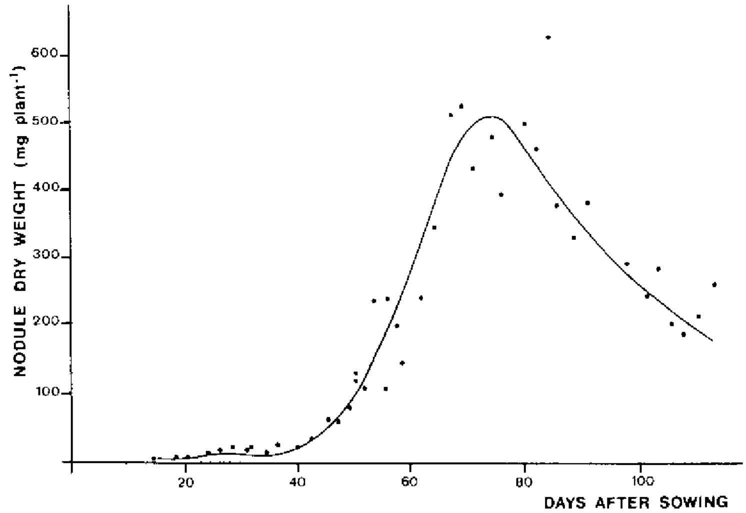

Figure 5. Time course of nodule weight of field-grown groundnut throughout the 1976 rainy season. For the first 45 days, the soil water content was high enough for the plant but too low for nodulation to occur (Ducerf, 1978).

Table 6. Effect of nitrogen application on N_2-fixation (estimated by A value method) by groundnut

Rates of application of nitrogen fertilizer (kg ha^{-1})	kg N_2-fixed ha^{-1}		
	Senegal[1]		Ghana [2]
	(1974)	(1975)	(1975)
15 at seeding	52.0	67.5	60.7
30 at seeding	56.0	75.4	69.3
30 split		67.2	38.2
60 at seeding	25.0	–	–

[1] Ganry (1976), trial carried out at Bambey Agronomic Research Center

[2] Kwakve & Afori (1977)

of limiting on N_2-fixation may be direct or indirect. Mn was reported to inhibit nodulation by Kang & Fox (1975) in Nigeria. Panthier (pers. comm.) hypothesized that excessive manganese uptake could be responsible for poor nodulation in soils of central Senegal (Thilmakha). By increasing pH through liming, exchangeable manganese is oxidized to manganic oxides, which are not assimilated by plants so that normal nodulation is restored. Phosphorus deficiency is well known in West Africa and upon the application of phosphorus in field trials increases in legume yield have been reported many times (e.g., Kang *et al.*, 1977).

By contrast, the beneficial role of sulfur is often overlooked. Some reports exist, however, such as that of Kang *et al.* (1977), indicating that sulfur application significantly stimulated nodulation of cowpea in a soil from West Nigeria.

Small additions of nitrogen fertilizer often, but not always, were shown to increase the yields of legumes and N_2-fixation. However, split application of 30 kg N ha^{-1} considerably reduced N_2-fixation of groundnut in Ghana (Table 6). Rates equal to or higher than 60 kg N ha^{-1} appeared to be detrimental to N_2-fixation in a sandy soil of central Senegal (Table 6).

Incorporating organic matter, particularly as farmyard manure, was reported to be generally most beneficial. The combination of liming, ploughing and farmyard manure application was reported to significantly increase groundnut yields, probably through increasing N_2-fixation, in central Senegal (Institut Sénégal de Recherches Agricoles, 1977).

At the present state of our knowledge, four major factors appear to limit symbiotic N_2-fixation in West Africa: moisture stress, nematode attacks, soil acidity and associated toxicity and the inadequacy of *Rhizobium* populations. Table 3 summarizes the means which are or could be recommended to control these limiting factors. We would like to stress here again that inoculation with even the best *Rhizobium* strain would be useless if just one of the other limiting factors were still operating.

Heterotrophic N_2-fixation

Nye & Greenland (1960), then Moore (1963) and Jaiyebo & Moore (1963) were the first investigators to draw attention to the possible importance of heterotrophic N_2-fixation in drained agroecosystems of West Africa. A recent review (Odu, 1977) has presented our current knowledge of this process for the area of Africa. It is well known that the main limiting factor for heterotrophic N_2-fixation is energy. Beside organic amendments, the two major sources of energy in the soil are (1) rhizosphere exudates and lysates, (2) and root litter.

Much experimental data has confirmed the role of living root systems as a source of energy for N_2-fixing bacteria, but this role has probably been over-estimated. There is increasing agreement that "root litter", or decaying root residues, may be a substantial source of energy for N_2-fixers, so that the contribution of "N_2-fixation in root litter" to the nitrogen input in the ecosystem could probably be more important that that resulting from "N_2-fixation on the living roots". Lysimeter measurements recently published (Ganry, 1977) show that nitrogen gains in a sandy acid soil of central Senegal (Dior soil), which had been enriched with chopped millet root (extrapolated rate: 15000 kg ha^{-1}), were as high as 88 kg ha^{-1} for a 4-month period.

Odu (1977) aptly drew attention to the strong influence of the water regime and specially to "the influence of alternating wet-and-dry cycles, with the attendant availability of carbon during flushes of decomposition accompanying the rewetting of dry soil, on N_2-fixation by free-living organisms". We do agree with his conclusion that it would be useful to assess the conditions that enhance heterotrophic fixation and to establish agronomic practices that would enhance such fixation. From our own experience, besides the control of the soil water regime, two factors should be dealt with in order to increase heterotrophic N_2-fixation: (1) acidity, which could be easily neutralized by liming, and (2) N_2-fixing micro-population, which could be achieved by proper inoculation methods.

Nitrification and denitrification

Nitrification is reportedly low in most West African soils, especially in acid soils (Ayanaba & Kang, 1976; Feller, 1977). In sandy soils of central Senegal, populations of nitrifiers are generally low (10^2 – 10^3 g^{-1} of soil) except in the rhizosphere of some plants (millet) where their numbers can be as high as 10^4 g^{-1} (Ganry, unpublished data). However, there is some indication that nitrification could be active in soils such as those from banana plantations or rain-fed maize or rice-crops (Chaballier, 1976) in the Ivory Coast, where large applications of ammonium fertilizer or urea seem to boost this activity.

It is well known that losses through denitrification are likely only when there is a large supply of both nitrate and energy-providing compounds in the soil. According to Greenland (1959), "high levels of nitrate usually exist for short periods following the dry season and it seems probable that at these times significant losses occur". Saturation or near saturation, conditions consecutive to heavy rains, obviously enhance the process, but in drained soils denitrification may also occur in anaerobic microsites (e.g., root debris), which are distributed in the soil profile. Recent lysimeter investigations on a typical sandy soil from Senegal (Dior Soil) indicate that losses through denitrification were ca. 30 % of the nitrogen fertilizer applied, whereas losses through leaching did not exceed 10 % (Ganry *et al.*, 1978).

Mineralization and immobilization of nitrogen

In the tropics, mineralization rates of organic nitrogen are generally high, because of favorable soil temperatures. This process is known to be enhanced in the rhizosphere (Blondel, 1971) and in sandy soils which occur most frequently in West Africa, the clay content being too low to protect the soil organic matter (humus and plant residues) against microbial attacks.

In arid conditions, it could be predicted that drought would stop mineralization. In fact, this process is somewhat slowed down but still persists after the rains have stopped, because many microorganisms are still active in the range of pF 4.2–5.2. Whereas nitrification is impeded when pF reaches 4.2, ammonification continues so that within the range of pF 4.2–5.2, the ammonium content increases (Fig. 6).

Consequently, the pool of organic matter in West African soils is usually very low (Charreau, 1974). On the other hand, immobilization of nitrogen in the form of humic compounds or microbial biomass is very limited. The microbial biomass is usually low (e.g., Table 1), so that amounts of nitrogen tied up in the soil microflora are negligible. But it seems possible to increase immobilization of nitrogen in the soil by increasing the input of plant residues. Thus, Ayanaba *et al.* (1976) showed that the heavy returns of organic matter from Guinea grass maintained and even increased both the total nitrogen and biomass in different Nigerian soils.

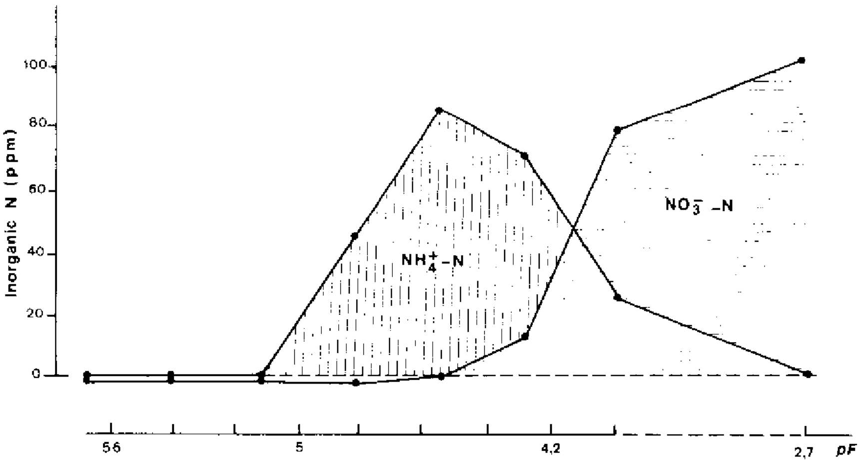

Figure 6. Influence of soil pF on the build-up of inorganic nitrogen after a 28-day incubation. Ammonification is favored by high pF (high water potential) whereas nitrification is favored by low pF (Dommergues, 1977).

Forest ecosystems

N_2-fixation

According to Greenland (1977), the humid tropical forest ecosystem of West Africa could accumulate 120 kg N_2 ha^{-1} yr^{-1} minus any gains from rainfall, dust, or collection from sub-soil sources. There has been much speculation about the source of the nitrogen accumulated.

In the semi-arid and arid zone different species of *Acacia* have been thought to contribute actively to N_2-fixation. Actually, although *Acacia albida* (Jung, 1967, 1969), or *Acacia senegal* (Bernhard-Reversat & Poupon, 1979) are nodulated when they are at the seedling stage at the laboratory or in nurseries, they seldom bear nodules as adults. This lack of nodules in the field was attributed by Bernhard-Reversat & Poupon (1979) to an active nitrate production in the soil. Drought may also be an important limiting factor of symbiotic fixation in forest ecosystems as it is in agroecosystems. *Casuarina equisetifolia*, a non-leguminous nodule-bearing tree, largely used for reforesting sandy soils on the coasts of West Africa, was reported to fix as much as 60 kg N ha^{-1} yr^{-1} in the Cap-Vert peninsula (Dommergues, 1963).

More investigations are obviously needed to obtain reliable data on the nitrogen input through non-symbiotic and symbiotic N_2-fixation in tropical forests.

Nitrification and denitrification

In contrast to the well-established concept that nitrification is slowed down in temperate forests, nitrification appears to be potentially active either in the humid forest such as the Banco and Yapo forests in the Ivory Coast (Bernhard-Reversat, 1974, 1975), in less humid conditions that prevail in the Casamance (Dommergues, 1956), or in the Sahelian savanna under *Acacia senegal* (Bernhard-Reversat, 1977). The nitrifying organisms which are involved in these acid soils have yet to be studied; investigations in that field should be initiated using the methodology proposed by Schmidt (1978).

Quantitative reports on denitrification in forests are lacking, but there is some presumptive evidence that losses through denitrification could occur rapidly, especially when soils are saturated (Moureaux, 1967; Bernhard-Reversat, 1975).

Mineralization of organic nitrogen

According to Bernhard-Reversat (1977), the mineralization rate in a Sahelian savanna in northern Senegal is considerable. She estimated that the amount of nitrogen mineralized under *Acacia senegal* and *Balanites aegyptiaca* during the period from January to November was 126 kg and 66 kg ha^{-1}, respectively. Such values compare well with data which have been reported for tropical humid forests of the Ivory Coast (Bernhard-Reversat, 1974).

Conclusion

For the last 5 years, qualitative and quantitative studies on biological N_2-fixation have been developed. But our knowledge of the ecology of this process is still inadequate and more investigations are urgently needed in order to elucidate vital problems such as that of the quantification of nitrogen fluxes attributable to biological N_2-fixation, competition between *Rhizobium*, interactions between *Rhizobium* and Vesicular-Arbuscular mycorrhizae, effects of aridity upon N_2-fixation.

Data related to nitrification, denitrification, humification and mineralization of nitrogen is still very scarce. Since it is not possible to initiate all the desirable investigations in these latter fields, we would like to suggest with Paul (1976) that, in the near future, the main effort be devoted to the evaluation of denitrification, together with other processes leading to losses of nitrogen (ammonia volatilization, leaching) in a number of typical ecosystems.

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Nitrogen Cycling in West African Ecosystems

THE NITROGEN CYCLE IN WEST AFRICA – AGRONOMIC CONSIDERATIONS

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Abstract

Far too little is known at present of the quantities to be attached to the terms of the nitrogen balance equation, and this is particularly true for cultivated land in West Africa. Although it is clear that agricultural development will cause a decline in the store of nitrogen in soil, and, at least for the forest region, in the vegetation, the manner in which the nitrogen is lost is not established. There is probably some increase in the quantity of nitrogen leached to groundwater, but this may not be particularly large and fertilisers may not add significantly to it. There is a substantial denitrification potential, but shortage of organic substrates may mean that in cultivated soils it is seldom if ever realized.

Nitrogen fixation by legumes is a potential source of substantial additions of nitrogen to the soil-plant store. In the tropics this potential is only starting to be developed.

Published nitrogen balance sheets for tropical regions (*e.g.*, Husz, in Frissel, 1978) are based on very limited data.

Much further information needs to be collected before any realistic balance sheets can be written for the movement of nitrogen in agricultural ecosystems in the tropics.

Introduction

The major processes involved in transfers of nitrogen between the different compartments of individual ecosystems are now well established. Detailed quantitative information regarding the amounts of nitrogen involved, and the rates at which it moves between different compartments, is, however, largely lacking. This is particularly true of tropical regions. The need to rectify this lack of information is the more important because the rates may be expected to be greater in the climatic conditions prevailing in the tropics.

For West African conditions, two major natural ecosystems exist – the forests, where a largely closed cycle operates under the mature forest, with substantial soil and plant stores of nitrogen and rapid rates of transfer between them, and significant though smaller rates of transfer with the 'outer' compartments of groundwaters and atmosphere; and the savanna zone, where the stores of nitrogen are much smaller, but the rates of transfer may be larger.

When the forest or savanna vegetation is removed to allow agriculture to be practised, the closed cycles are broken, and more open cycles introduced. In the forest zone the soil and plant store of nitrogen is likely to be much reduced. A smaller change is likely to

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occur in the savanna zone. At present the most widespread agricultural practice in West Africa is a natural fallow cultivation system (FAO/SIDA, 1974). Commonly this involves clearing of the existing vegetation, and cultivation of the soil for two to five years, after which the land is abandoned and the natural vegetation regenerates. The length of regeneration is usually three to a maximum of twenty years, so that only the earlier stages in the succession leading to mature forest or savanna woodland develop. With greater population pressure the length of the fallow period is falling in many areas, and efforts to introduce more intensive, continuous agriculture are increasing. In this paper evidence relating to the effects of agricultural practices on the nitrogen cycle in the forest and savanna zone are discussed. Apart from the loss of nitrogen contained in the existing vegetation, most of which is volatilised when the cut and felled vegetation is burnt, a decline in the amount of nitrogen stored in the soil normally accompanies agricultural development. This process, and the rate of mineralisation of organic nitrogen returned to the soil, are considered first, and then the limited information available on nitrogen losses from the soil by leaching, volatilisation and erosion.

Mineralisation of soil nitrogen during cultivation

The nitrogen level in the soil at any one time is the resultant of the rates of addition and loss. Given sufficient time, and reasonably constant addition and loss processes, an equilibrium is approached where the additions and losses are equal.

In static terms this may be written (Greenland, 1977)

Change in soil N, ΔN = Gains − Losses, or, at equilibrium when $\Delta N = 0$:

$$F + S + R + M + D - C - L - V - E = 0$$

where

ΔN = change in nitrogen content of a given mass of soil in unit time
F = total nitrogen converted from gaseous to combined form by the action of microorganisms
S = nitrogen returned to the given mass of (surface) soil from subsoil by plant roots or in upward movement of the soil solution
R = combined nitrogen added to soil mass in rainfall
M = nitrogen added to given mass of soil in fertilizers, manures and seeds introduced from outside the area
D = nitrogen added in dust
C = nitrogen removed from the given mass of soil by crops and standing vegetation
L = nitrogen lost from the given mass of soil in leachates
V = nitrogen lost from the given mass of soil by volatilisation
E = nitrogen removed from the given mass of soil by erosion.

Before equilibrium is attained, the soil nitrogen level will be changing. In cultivated soils, not growing legumes, F, S, R, D, E and probably V may be assumed to be small. Then $\Delta N = M - C - L$ and unless sufficient fertilizer N is added to balance the nitrogen lost in crop removals and by leaching, the amount of nitrogen in the soil will be declining. For natural fallow cultivation systems to be stable requires that the losses during cultivation do not exceed the increases under the natural vegetation during the fallow period (Nye & Greenland, 1960).

The equation suggests that by increasing the rate of fertilizer used, (increasing M), the decline should be prevented. While higher nitrogen levels are established under well fertilized crops, it is seldom possible to establish as high an equilibrium level of soil nitrogen, and hence organic matter. Continuing to add fertilizer increases the magnitude of the losses, L and C, so that M is not an independent variable.

Several examples of changes in soil nitrogen content following cultivation of soils in West Africa, initially under forest or savanna vegetation, have been published (Cunningham, 1963; Nye & Greenland, 1964; Jones & Wild, 1975). The data available have been discussed in terms of a simple first order reaction, in which the rate of change of N with time, dN/dt, is assumed to be the balance of a loss of a fixed proportion of the soil N, and a constant addition to it:

$$\frac{dN}{dt} = -k\,N + A\ .$$

Although this equation has been widely used (Bartholomew, 1977), it has also been criticised as an oversimplification because all the soil nitrogen does not mineralise at a uniform rate, the rates at which different fractions of soil N mineralise are not constant with time, and additions to the soil vary with time (Paul & van Veen, 1978). The major source of discrepancy appears to be the rapid mineralisation of part of the nitrogen which occurs when a soil is first cultivated after a long period under natural forest or grassland vegetation. This loss probably corresponds to the decomposition of relatively fresh plant material added to the soil during clearing operations (Greenland & Ford, 1964). Using ^{14}C labelled ryegrass and maize residues Jenkinson & Ayanaba (1977) found at Ibadan, Nigeria, that 80 % of the carbon in these materials placed in the surface layer of field soils was mineralised in one year. It is probable that the fresh residues in the soil would mineralise at a rate approaching this. The net nitrogen mineralisation rate is probably rather slower than the carbon, as a higher proportion of nitrogen is likely to be assimilated after mineralisation.

The bulk of the soil carbon and nitrogen, however, mineralises much more slowly than freshly added plant residues. In soils that have been cultivated for several years the rate of change is of the order of 4 % per annum (Jones & Wild, 1975; Bartholomew, 1977). This figure has to be compared with the much higher figures obtained if only the first two or three years of cultivation are considered (Bartholomew, 1977).

Changes in soil nitrogen for the first two years of cultivation after at least 40 years of forest regrowth, at Kade, Ghana, are compared in Fig. 1 with other data for West Africa given by Juo & Lal (1977) and other authors reported by Jones & Wild (1975). The data are given in terms of per cent of N by weight of soil, for the depth of soil shown. Presented in this way losses appear much greater for shallow soil depths, as is made clear by including data for both the 0–5 cm and 0–30 cm of the Kade example. The reasons for this are that the immediate surface layer loses N due to dilution with sub-surface soil of lower N content, and by erosion, as well as mineralisation and other loss processes. In addition, because the immediate surface layer normally becomes much more compact when used for agriculture than when under natural vegetation, sampling to a constant depth means that more of the sub-surface soil is included when the soil is sampled in later years, and so the change is further exaggerated.

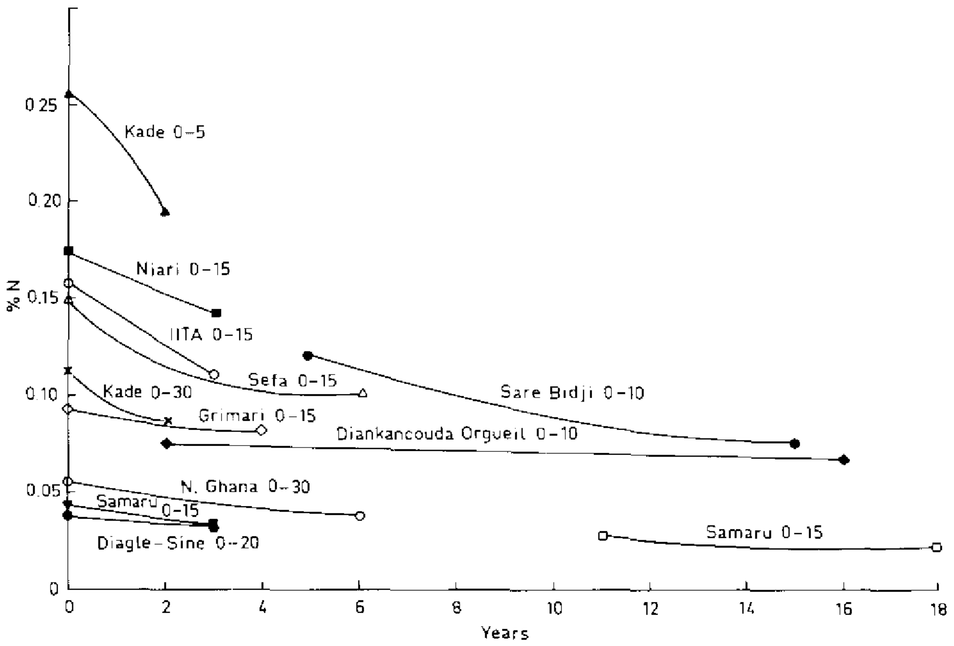

Figure 1. Nitrogen changes to soils after clearing from natural vegetation (Nye & Greenland, 1964; Jones & Wild, 1975; Juo & Lal, 1977).

Quantitative measurements of losses of nitrogen from the soil store should be based on repeated sampling, over many years, of a constant mass of soil, and should include surface, sub-surface and sub-soil.

The rate of mineralisation is affected by soil factors and agronomic practices. It is greater in lighter textured soils (Jones & Wild, 1975), and may be expected to be greater in less acid soils and in regions of higher temperature and intermittent rainfall, although good data relating to these points are not available. Agronomic practices affecting mineralisation rate include degree of exposure of the soil (and hence temperature and moisture regime) and direct and indirect effects of the crop on the microflora which are responsible for mineralisation.

The effect of crops on mineralisation rate (k) should be distinguished from their influence on the addition (A) of N to the soil. Nitrogen is of course removed in harvested parts of crops, but the total removed is very dependent on the way in which crop residues are used. After 3 years of continuous maize production at Ibadan, Juo & Lal (1977) found that with residues retained as mulch the soil nitrogen content only declined from 0.16 % to 0.15 %, whereas when the residues were removed as well as grain, it fell to 0.11 %. Addition of N fertilizer, or inclusion of legumes among the crops grown, will also tend to decrease the rate of decline.

The use of crop residues as mulches not only involves retention of the nitrogen they contain, but also provides organic substrates for nitrogen fixing microorganisms and a physical environment which is more uniformly moist and with less extreme temperatures, so that mineralisation is reduced. Cultivation of the soil generally leads to greater rates of oxidation of organic matter. This may be necessary in systems where nitrogen fertilizers are not used, and the soil store of nitrogen is low, so that as much mineralisation as possible needs to be induced if any crop is to be produced. Many sandy soils of the savanna regions of West Africa fall in this category. But if soils are managed on a conservative basis and the nitrogen requirements of the crops are met by fertilizers or manures, then suppression rather than promotion of mineralisation is desirable, and zero or minimum tillage techniques are more appropriate.

In spite of the range of factors affecting the mineralisation rate, most of the data from West Africa indicate that, apart from the first two years following clearing of forest, the rate of loss conforms reasonably well to an equation of the form $dN/dt = -kN + A$, with k values ranging from 2 to 6 % and with an average of about 4 % (Greenland & Nye, 1959; Jones & Wild, 1975; Bartholomew, 1977).

Leaching of nitrogen from cultivated land

A great deal of attention has been given in recent years to the extent to which nitrate is leached from agricultural land. In Europe and the United States interest has been largely concerned with the extent to which increasing use of nitrogen fertilizers is leading to pollution of water courses and reservoirs by nitrate (Stewart, 1975; MAFF, 1976).

In West Africa, food production is an immediate problem of major concern, and fertilizers are little used at present but offer the most immediate means to increase the production of food. Thus here the importance of leaching is not so much in relation to pollution, as to ensuring that the most efficient use is made of applied nitrogen. It is sometimes suggested that in the humid and sub-humid tropics the high rainfalls and intense leaching to which the soils are subjected must mean that fertilizers are inefficiently used. There appears to be little direct evidence to support this, and some evidence to negate it.

The best evidence comes from studies of the fate of ^{15}N-labelled fertilizers applied to lysimeters (Chabalier, 1975; Chabalier *et al.*, 1975). Other data come from lysimeter experiments where nitrogen was applied without a ^{15}N label (evidence reviewed by Jones & Wild, 1975; Greenland, 1959; Godefroy *et al.*, 1970), from studies of the movement of the NO_3^- ion in the soil profile (Wild, 1972; Bartholomew, 1977) and from determinations of the concentration of nitrate in streams and rivers draining cultivated catchments.

The studies of Chabalier *et al.* (1975) at Bouake, Ivory Coast, showed that over a two year period the labelled nitrogen fertilizer which drained below 80 cm from a ferrallitic soil under a rainfall of 1200 mm yr^{-1} did not exceed about 6 kg ha^{-1}, even when the high rate of 120 kg ha^{-1} of nitrogen was applied to crops of maize, non-irrigated rice and cotton. Studies at Bambey, Senegal (Tourte *et al.*, 1964; Blondel, 1971a) and at Legon, Ghana (Greenland, 1959) using lysimeters respectively 40 cm and 60 cm deep, showed leaching losses of N under crops not exceeding 15 kg ha^{-1} at Bambey and 30 kg ha^{-1} at Legon. Even when 300 kg of N was applied as ammonium sulphate to the Bambey lysimeters, only 9.9 kg ha^{-1} was recovered in the leachates. Rainfall at these sites is under 1000 mm yr^{-1}. As the lysimeters are shallow, it is probable that even these relatively small amounts of leached nitrate do not reach groundwaters, but remain in the sub-soil, to be utilised by deeper rooted crops or natural fallow vegetation, as discussed by Jones & Wild (1975) and Bartholomew (1977).

The studies by Blondel (1971b) and Wild (1972) of NO_3^- movement in the soil profile indicate that NO_3^- moves at a slower rate through the profile than water, presumably because most water movement occurs rapidly through relatively large channels in the soil, and diffusion equilibrium with electrolytes in the soil solution contained in finer pores is not established.

For areas of much greater rainfall very little information is available. Data from the Ivory Coast for nitrate leached under bananas (Godefroy *et al.*, 1970) suggest that, with rainfalls in excess of 1500 mm yr^{-1}, the losses may be substantially greater, but their results refer to very high rates of fertilizer application, and were not obtained using enclosed lysimeters. In the Alfisols and Ultisols of the forest zone with rainfalls between 1400 and 2400 mm yr^{-1}, mineralisation occurs rapidly in the soil, so that leaching is likely to be substantial, except insofar as it is offset by assimilation of NO_3 by plants, and possibly microorganisms, or by denitrification.

Where rainfalls exceed 2400 mm yr^{-1} highly acid soils occur, for instance in south-eastern Nigeria, Liberia and Sierra Leone. Nitrification may be slower in these soils (Ayanaba & Kang, 1976) and positive charges developed on the hydrous oxides at pH values close to 4 (Gallez *et al.*, 1976) may lead to significant retention of nitrate in the profile (van Raij & de Camargo, 1974). Thus, although the amount of water moving through soil profiles in these areas is very substantial, leaching losses of nitrogen may be rather less than anticipated from the rainfall.

In both forest and savanna areas there is ample evidence to show that leaching losses are more severe from soils devoid of vegetation, than when a crop or fallow vegetation is present. Thus, intercropping and relay cropping, which maintains vegetation on the soil for much of the year, is a desirable practice to minimise leaching of nitrate. Multiple cropping is of course the most widely practiced cultivation method in West Africa (Okigbo & Greenland, 1976).

Volatilisation of nitrogen from cultivated land

It has proved extremely difficult to quantify the volatilisation of nitrogen from cultivated land. The processes of conversion to ammonia gas, and nitrogen and nitrous oxide, and the circumstances in which significant losses are likely to arise by these mechanisms are well known, but little information is available on quantitative losses. Because most soils in West Africa are acid, losses as ammonia gas are unlikely to be common except in the driest areas, or in rice paddies. On the other hand, nitrogen has been shown to disappear rapidly from incubated samples when temporarily waterlogged (Greenland, 1962). Populations of denitrifying organisms are often high (Meiklejohn, 1962; Visser, 1966) and if adequate carbon substrate is available denitrification can proceed rapidly. However, lack of substrate may well restrict the losses from cultivated land (Greenland, 1962; Bremner, 1977). To quantify the losses from agricultural land by denitrification it is essential to study gases evolved from the soil (Burford & Stefanson, 1973) preferably supplementing field collection of evolved gases by use of ^{15}N labelled materials. Collection of a few samples from the field at IITA, Ibadan, by J.R. Burford, showed that nitrous oxide was present in the soil atmosphere. It was present in larger amounts in wetter sites, and so may be presumed to originate from denitrification, although Bremner & Blackmer (1978) have recently shown that small amounts can also be formed during nitrification of ammonium.

Nitrogen fixation in cultivated soils

Nitrogen fixation in cultivated soils other than those in which legumes are grown is generally small (Odu, 1977; Okafor, 1977). Although Moore (1966) provides some examples where non-symbiotic fixation may result in annual additions to cultivated soils in excess of 20 kg N ha^{-1}, these can probably be discounted as aberrant. In spite of the finding that active colonies of nitrogen-fixing organisms occur in the rhizosphere of some cereals, it is very unlikely that at present they contribute significantly to the nitrogen status of the soil (Döbereiner, 1977). In wetter areas, notably where rice is produced, nitrogen fixation by blue-green algae can become important (Fogg *et al.*, 1973).

Where legumes are included amongst the crops produced, substantial nitrogen fixation takes place. In West Africa, the most commonly grown legumes are cowpeas (*Vigna unguiculata*) and groundnuts (*Arachis hypogaea*). Many varieties of cowpea are used in different crop combinations (Okigbo, 1977). They are commonly nodulated by active, nitrogen fixing rhizobia (Ayanaba, 1977) which are found even in soils as acid as pH 4 in eastern Nigeria. Estimates of nitrogen fixation by cowpeas range from 70 to 240 kg ha^{-1} yr^{-1} (Nutman, 1971). Recent studies indicate that nodulated plants should normally yield better than those produced with nitrogen fertilizer (Dart *et al.*, 1977; Summerfield *et al.*, 1978). Information regarding nitrogen fixation associated with production of groundnuts is very inadequate (Obaton, 1977).

Too little is known at present regarding the fate of the fixed nitrogen. A large proportion will certainly be present in harvested parts of the legume, but much more needs to be determined about factors which control the amount of nitrogen made available to accompanying intercrops or succeeding crops (Whitney, 1977). Grain legumes may well be poorly suited to the role of nitrogen suppliers to the soil store or to accompanying crops. Thus, Juo & Lal (1977) observed that soil nitrogen declined substantially under continuous soybean production. Legumes used as groundcover or as fallows in rotation with other crops may be more valuable (Okigbo, 1977).

Erosion

Agronomic practices are always likely to lead to accelerated soil erosion. This is particularly true of West Africa. Lal (1976) has reported nitrogen losses from run-off plots under a range of conditions, and Jones & Wild (1975) reviewed other data for West Africa. The fate of nitrogen in eroded soil is not clear. Much of the eroded topsoil is dumped in river beds and stream courses. 'Sediment delivery ratios' are not known for West African conditions. For the United States they are often of the order of 25 %, *i.e.*, only a quarter of the eroded soil material actually leaves the catchment in which the erosion occurred. Thus, the influence of erosion on the nitrogen cycle may not be a simple removal of material out of the system.

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Nitrogen Cycling in West African Ecosystems

THE NITROGEN CYCLE – PEDOLOGICAL CONSIDERATIONS

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Abstract

The technological revolution brought about a considerable introduction into the soil of artificial nitrogen fertilizers and of bound nitrogen in industrial waste. The amount of nitrogen of industrial origin entering the soil can now compete with nitrogen coming into the soil through biological fixation. However, the distribution of artificially bound nitrogen in the soil varies widely in different regions of the Earth. These conditions give rise to a problem of nitrogen cycle disturbance during which mainly those links in the cycle that exist in the soil medium are broken. In the course of intensive agricultural practice the following links of the cycle undergo principal changes: (1) nitrogen fixation, by free-living and symbiotic microorganisms; (2) processes of mineralization and immobilization; (3) nitrification, and (4) denitrification.

Input of nitrogen mineral fertilizers in the soil causes a "nitrogen stress". Under this condition, the nitrogen fixation is reduced and the mineralization of soil organic matter is increased.

A number of long-term field experiments show that there is no accumulation of total nitrogen in the soil when mineral fertilizers are applied, although the immobilization of fertilizer nitrogen (experimental data with ^{15}N) in organic forms amounts to about a quarter of the nitrogen rate applied.

The accumulated mineral nitrogen, especially nitrates, can be relatively easily lost from the soil under certain moisture conditions due to leaching and/or denitrification.

Introduction

Nitrogen is one of the principal life-sustaining elements on Earth. For their well-being, people are largely dependent on the level of production of nitrogen-containing products. Foods and some industrial raw materials require for their production vast inputs of bound nitrogen, with soil nitrogen and that of fertilizers synthesized by Man as the major sources of the latter. Soil nitrogen remains, as previously, the chief source of nitrogen supply to agricultural plants.

Soil, as distinct from rock, is known to possess fertility. In turn, for the absolute majority of soils, their level of fertility is determined by the amount of organic matter and nitrogen present. It is, therefore, possible to state that soil is as fertile as it is rich in nitrogen. Soil nitrogen potential varies over a very wide range: In the humus horizons it may be anywhere from less than 0.1 %, as in desert and semidesert soils, to 2 % and more in soils rich in organic matter content, e.g., peat bogs (Stevenson, 1965; Kovda, 1973).

All in all, the Earth's soils contain 3 105 Tg (10^{12} g; million metric tons) of nitrogen (Söderlund & Svensson, 1976), a quantity negligibly small if viewed against nitrogen storage in rocks and the atmosphere (Stevenson, 1965).

Transformation of nitrogen in the soil

Soil is the basic medium where most of the processes binding molecular nitrogen into organic form take place, together with further transformation of forms into one another. Diagrams of the nitrogen cycle are given by many workers (Stevenson, 1965; Kovda, 1973, 1975; Söderlund & Svensson, 1976; Rosswall, 1976; Bolin & Arrhenius, 1977; Delwiche, 1977). Within the cycle (Fig. 1), the intensity with which the individual phases take place depends on soil properties and climatic conditions, such as temperature and moisture content. In tropical soils, the processes of nitrogen fixation, ammonification, nitrification and denitrification show up with much greater intensity than, say, in soils of the temperate zones or those of the forest-tundra and tundra. Bazilevich (1974) estimated the turnover time of litter nitrogen for different bioclimatic zones. The turnover time of litter nitrogen takes over 60 years for its mineralization in the polar zone, as against 1 to 12 years in the boreal and subboreal zones, and 2–4 months in the tropical and subtropical zones.

Climatic conditions, as well as the extent of soil cultivation, influence the qualitative and quantitative composition of soil nitrogenous compounds. Thus, semi-decomposed, or "canned" plant residues (tundra and peaty soils) featuring a wide carbon-to-nitrogen ratio are stored in larger quantities in cold and over-moistened soils. In contrast, mineralization processes reach their maximum limit in soils of warm latitudes, with adequate moisture and good aeration. Given certain conditions of the hydrothermal regime, there may well occur natural accumulation of nitrates with subsequent deposition of sodium nitrate (Chilean saltpeter).

Extensive evidence available in the literature makes it plain that the majority of soils contain organic nitrogen in their upper horizons which account for 90 % of the total quantity. Studies on profile distribution of nitrogen in the soil show that the amount of organic nitrogen declines with depth, except for soils with poorly pronounced differentia-

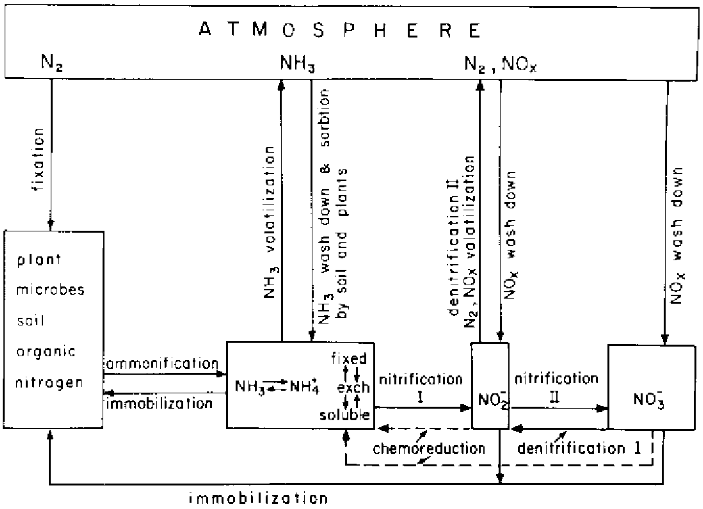

Figure 1. Nitrogen cycle in soil.

tion of genetic horizons. The amount of organic nitrogen correlates well with the content of organic carbon. The carbon-nitrogen ratio (C:N) in soils in the temperate zones is 10–11 (Kononova, 1963; Bremner, 1965). With depth, the C:N ratio is changed to 5 or less. This is explained by the fact that the soils contain fixed NH_4^+ which passes into the extract when total organic nitrogen is determined.

Composition of organic nitrogen forms is defined by analyses of acid hydrolyzates (6N HC1) by heating. Bremner (1965) suggested that aminoacids account for 20–40 % of hydrolyzed nitrogen, with the remaining 5–10 % in the form of hexosamines. Purines and pyrimidine never make up more than 1 % of the total nitrogen in topsoil horizons. Other organic nitrogen compounds, including choline, creatinine and allantonine, were recovered from soils but in very small quantities. As regards the form of non-hydrolyzable organic nitrogen, the nature of these compounds has not been fully elucidated. It is argued, nevertheless, that these may be lignin-ammonium or quinone-aminoacid complexes or, finally, condensed aminoacid products with hydrocarbons.

Inorganic nitrogen is found in soils in the form of ammonium (dissolved in soil water, exchangeable or fixed), nitrite and nitrate. The latter are present in soil in very low quantities, if at all. The amount of inorganic nitrogen makes up a minor proportion of the total soil nitrogen and is dependent on the influence of numerous factors. With normal soil conditions inorganic nitrogen is constantly produced from organic nitrogen due to mineralization. In turn, some part of the inorganic nitrogen is transformed into organically bound nitrogen.

The technical revolution has accelerated the use of artificial nitrogen fertilizers in an attempt to obtain increased food and fibre production in order to meet the demands of the globe's rapidly expanding population. Yet mineral nitrogen fertilizers are not the only source of bound nitrogen which enters the soil. Following combustion of fossil fuel (coal, oil and gas), nitrogen oxides are emitted in millions of tonnes into the atmosphere, from where they can later be partly washed away by rains and enter the soil. The quantities of industrially-produced nitrogen which reach the soil are of a similar magnitude as nitrogen entering via biological fixation; the figures cited by Söderlund & Svensson (1976) are 50–60 Tg for industrially bound nitrogen and 100–110 Tg for biological fixation on land. By 1990, the amount of industrial nitrogen fixation is expected to have exceeded the biological fixation (Söderlund & Svensson, 1976; Bolin & Arrhenius, 1977).

The quantity of industrially fixed nitrogen which is added to soils is about 0.07 % of the total soil nitrogen on Earth. Taken by itself, this amount is much too low for significant changes in the trend of transformation of soil nitrogen. However, the incoming flow of artificially bound nitrogen into soils is not evenly distributed among different regions of the world. For example, West European countries apply nitrogen fertilizers on occasions at 500 kg ha^{-1} yr^{-1} or more (grasses). Furthermore, in the majority of countries in Europe and North America, just as in some areas of the Soviet Union, nitrogen fertilizer application exceeds 100 kg ha^{-1} yr^{-1}. For many years these countries have applied nitrogen in quantities far in excess of the amount of nitrogen output with farm production. For the conditions in France, Herbert (1977) has found that on farms with no livestock, nitrogen fertilizer application over seven years exceeded nitrogen outputs with agricultural production by 240 kg ha^{-1}, or 34 kg ha^{-1} annually. On farms with livestock maintenance, which have extra nitrogen coming in with purchased forage, the surplus of inputs over outputs was 240 kg ha^{-1} yr^{-1}.

Therefore, in view of the intensification of farm production, problems arise due to disturbance of the normal nitrogen cycle, and particularly in those links which occur in the soil medium.

In the present paper an attempt is made to evaluate the status of that part of the nitrogen cycle which takes place in soil and is affected by intensive fluxes of nitrogen fertilizers.

Nitrogen fixation

Symbiotic nitrogen fixation is the most productive way in which nitrogen can be added to the soil at 73–865 kg ha^{-1} yr^{-1} (Hauck, 1971). Blue-green algae are capable of fixing up to 80 kg ha^{-1} yr^{-1} of nitrogen in rice paddies (Stewart *et al.*, 1975).

Nitrogen fixation by free-living microorganisms is viewed by many authors as being insignificant – hardly more than a few kilograms of nitrogen per hectare and year (Mishustin, 1956; Stewart, 1977). However, some indirect observations by Jenkinson (1977) give reason to believe that nitrogen fixation by free living organisms may reach impressive proportions in cultivated soils. The classic Broadbalk continuous wheat experiment over a period of more than 100 years revealed that in plots without any fertilizer, or without nitrogen fertilizer application (with P, K, Mg), there has been no change in nitrogen content in the topsoil over the past 115 years, whilst nitrogen uptake with crops during the same period amounted to 2,800–3,300 kg ha^{-1}. In fact, all soil nitrogen would have been taken up by wheat yields during 100 years if plants were exclusively dependent on the original stock of soil nitrogen. Jenkinson (1977) showed that in a plot given exclusively P, K, Mg, the biological nitrogen fixation over the period 1852–1967 was between 23 and 35 kg ha^{-1} yr^{-1}. Measurements of nitrogen-fixing activity by the acetylene method (Day *et al.*, 1975) demonstrated that nitrogen fixation could reach 28 kg ha^{-1} yr^{-1} in this trial.

With nitrogen entering the agricultural ecosystem in the form of mineral fertilizer, the intensity of nitrogen fixation alters. As a rule, the nitrogen-fixing capacity of symbiotic microorganisms decreases (Mishustin & Cherepkov, 1976; Nutman, 1976; Dart *et al.*, 1976). The latter authors showed that nitrogen fertilizer application to beans at the rates of 80 and 100 kg ha^{-1} suppressed nitrogen fixation completely.

There is also some decrease of nitrogen-fixing capacity in free-living microorganisms with nitrogen fertilizer application. In the Rothamsted experiment practically no accumulation of nitrogen was recorded in the plots given nitrogen fertilizer at 92–96 and 138–144 kg N ha^{-1} yr^{-1}, even though the yearly rate of nitrogen fertilizer exceeded nitrogen uptake by grain and straw by 8–31 kg ha^{-1} (Jenkinson, 1977).

Stewart *et al.* (1975) noted that blue-green algae can fix up to 30–50 kg N ha^{-1} yr^{-1}. With fertilizer application their nitrogen fixation activity becomes strongly inhibited, and especially so with application of ammonium fertilizers.

Mineralization and immobilization

Mineralization and immobilization processes proceed continuously and simultaneously in the soil. The processes are due to the activity of a broad range of microorganisms and fungi under both aerobic and anaerobic conditions.

Release of mineral nitrogen during microbiological decomposition of plant and animal residues or of soil organic matter is called mineralization. In the process the organic form of nitrogen gets transformed into the ammonium form (NH_4^+). In a normal soil environment, mineralization processes are accompanied by oxidization of ammonium to nitrate.

For their intensity both mineralization and immobilization depend on many factors, of which the important ones are temperature, moisture content and the type of organic matter (C:N ratio).

Bartholomew (1965) gives a review of studies concerned with nitrogen mineralization and immobilization in soils as affected by various conditions. There are a number of methods for evaluating the nitrogen supplying capacity of soil, which are bases in the determination of mineral nitrogen (NH_4^+ ; NO_3^-) released during incubation of soils at certain moisture and temperature conditions (Nömmik, 1965; Bremner, 1965; Gasser, 1969; Tinsley, 1969; Eagle, 1969; Stanford *et al.*, 1974; Kudeyarov *et al.*, 1975; Stanford, 1977).

The rates of mineralization and immobilization determine the intensity of other processes involved in the transformation of soil nitrogen compounds, such as nitrification and denitrification. Hence the methodology to evaluate the quantitative aspect of the processes of mineralization and immobilization appears to be extremely important.

Methods to define the potential nitrogen-mineralizing capacity of soils generally consist of determining the total sum of ammonium and nitrate nitrogen produced during a certain period of soil incubation under optimum conditions of temperature and humidity. Ammonium nitrogen as defined by these methods represents only soluble and exchangeable forms (Gasser, 1969; Stanford, 1977). It is a well-known fact, however, that ammonium nitrogen is found in soils not only in the soluble and exchangeable forms but also in fixed forms. The nature of fixed ammonium and its availability for plants and microorganisms is elucidated in Bremner (1965), Smirnov & Fruktova (1963), Peterburgsky & Korchagina (1964), Peterburgsky & Kudeyarov (1966), Mogilevkina (1970), Kudeyarov *et al.* (1975).

In our works (Egorova & Kudeyarov, 1974; Kudeyarov *et al.*, 1975; Bashkin & Kudeyarov, 1977), the fixed ammonium content in soil was shown to vary widely during the period of plant growth and soil incubation (Figs. 2–4).

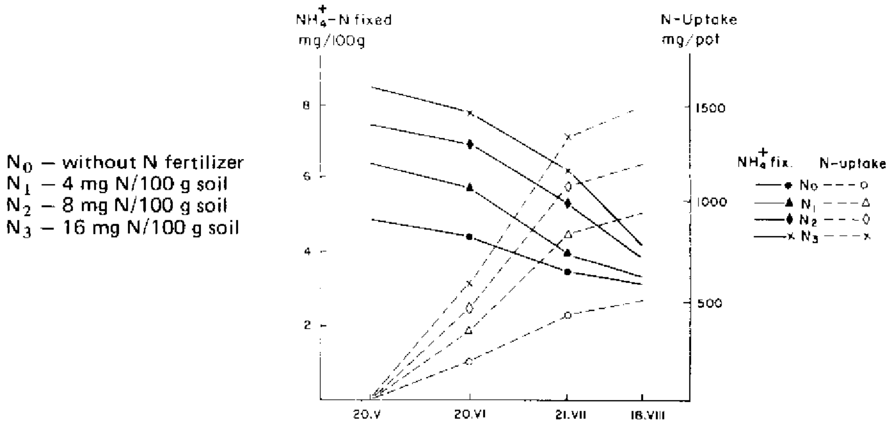

Figure 2. Dynamics of fixed NH_4^+ in sod-podzolic soil and N-uptake by corn (Kudeyarov *et al.*, 1971)

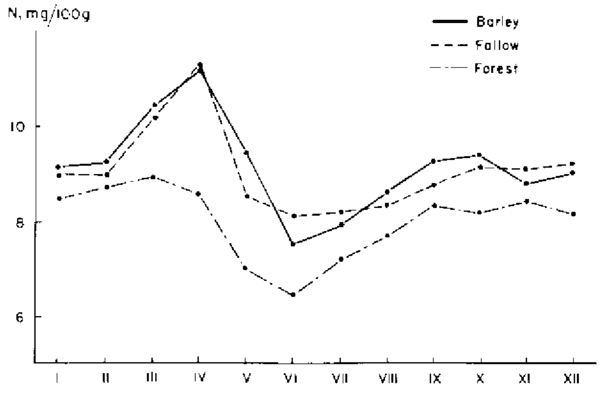

Figure 3. Dynamics of fixed NH_4^+ under field conditions (Bashkin & Kudeyarov, 1977).

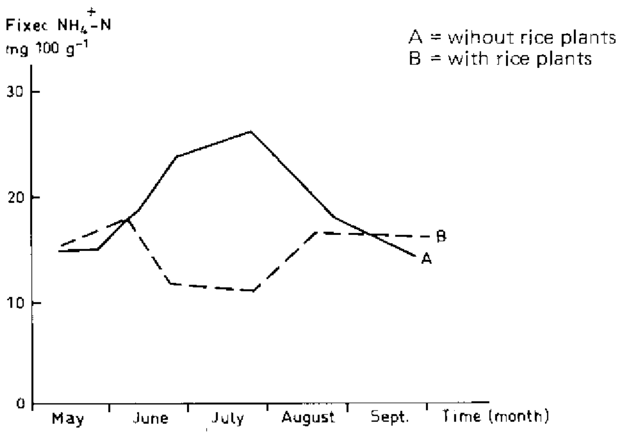

Figure 4. Dynamics of fixed NH_4^+ in paddy soil during vegetation period (no N fertilizers). (Unpublished data)

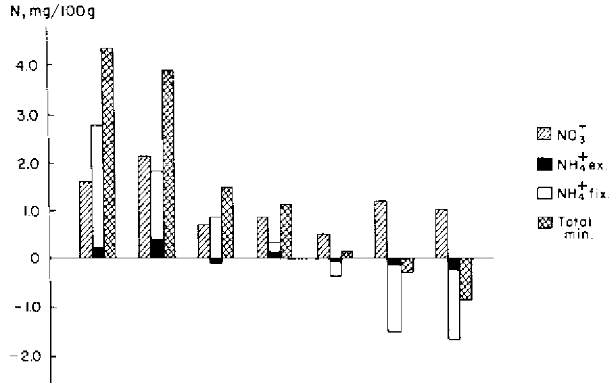

Figure 5. Changes of inorganic nitrogen content during 2-weeks incubation of different soils (Kudeyarov *et al.*, 1975).

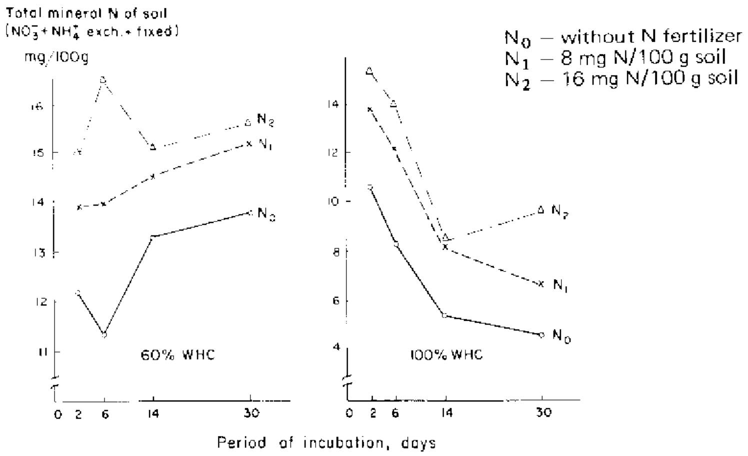

Figure 6. Effect of $(^{15}NH_4)_2SO_4$ on the mineralization of soil organic nitrogen (Egorova & Kudeyarov, 1974).

It was shown that intensity of mineralization can be almost completely determined by assessment not only of NO_3^- and exchangeable NH_4^+ but also of fixed NH_4^+. It should be expected that our ideas about the capabilities of soils to mobilize available nitrogen will broaden if fixed ammonium is taken into account (Fig. 5).

What is the status of mineralization of soil organic nitrogen with N fertilizer application? There is fairly extensive information about increased uptake of soil nitrogen by plants due to nitrogen fertilizer application. One of the likely explanations should be seen perhaps in the intensifying of mineralization processes when influenced by extra nitrogen introduced in fertilizer. In fact, with nitrogen fertilizer application, the C:N ratio tends to taper off in the decomposed organic material (Bartholomew, 1965), which in turn gives new vigour to the mineralization processes. Thus, following introduction of trace nitrogen fertilizer (in nitrate and ammonium forms) into various soils, an increased mineralization of soil nitrogen could be recorded already a few days later (Fig. 6). However, there is another explanation of this. Laura (1975) suggested that introduction of NH_4^+ fertilizers into soil causes a proton to pass from the NH_4^+ ion to the amino group which, as soon as it gains the proton, becomes capable of forming a NH_3-R-NH_2 complex.

In this context, the effectiveness of nitrogen fertilizers should be seen as a combined impact of two factors: a direct effect of the nitrogen fertilizer itself as an immediate source of nitrogen supply to plants, and an indirect effect which shows up in a surge of mineralization processes and release of extra quantities of soil nitrogen in plant-assimilable form.

The nitrogen "stress" caused by mineral nitrogen fertilizer application into soil affects the overall status of the nitrogen cycle. Accumulation of mineral nitrogen, especially in the nitrate form, sets the stage for a comparatively easy withdrawal of excessive nitrate quantities from the system. Under certain moisture conditions, nitrates can be leached from soil and find their way into different water bodies and, given inadequate oxygen supply, may also denitrify and escape into the atmosphere in the form of nitrogen oxides and molecular nitrogen. As a result, nitrogen fertilizer application fails to cause organic

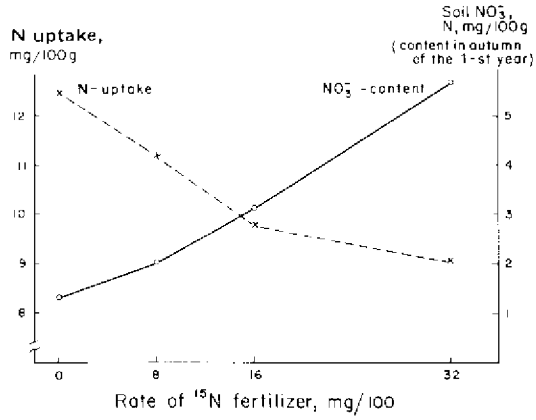

Figure 7. Effect of nitrogen fertilizer on the uptake of soil N by wheat on the 2nd year after application (microfield experiment).

nitrogen to accumulate in soils and even inversely, the organic nitrogen may well decrease. The foregoing can be illustrated with a few examples.

In micro-field experiments carried out with ^{15}N-enriched nitrogen fertilizers on a grey forest soil, it was found that uptake of soil nitrogen by crops in plots fertilized with NPK exceeded the uptake in the PK plots by 15–20 %. Besides, following harvesting, the mineral nitrogen content (mostly NO_3^-) of soil origin was much higher in the NPK than in the PK plots. A second crop which was sown without nitrogen fertilizer had to utilize residual fertilizer nitrogen and soil nitrogen. Utilization of the residual fertilizer nitrogen was fairly low, less than 4 % of the quantity of fertilizer nitrogen introduced in the first year. Meanwhile, the uptake of soil nitrogen fell off in proportion to the increasing quantity of nitrogen applied in the first year of the experiment (Fig. 7). This can be explained as follows: in the first year of the trial organic nitrogen was subject to enhanced mobilization due to the introduction of N-fertilizers. As a result, the first crop utilized this extra nitrogen. The non-utilized nitrate nitrogen was lost during the winter or in the next early-spring period. In the following spring, the nitrate content was very low in all experimental plots and differed little or not at all from plot to plot.

With steady and regular application of mineral nitrogen fertilizers, even though the amount introduced exceeded nitrogen uptake by crops, there is no accumulation of organic nitrogen in soil. In this context, one feels tempted to mention once again the Broadbalk experiment at Rothamsted. Application of ammonium sulphate at the rate of 144 kg N ha^{-1} yr^{-1} during 155 years caused soil nitrogen content to decrease by 380 kg ha^{-1} in the 0–23 cm layer even though input of nitrogen exceeded the output by more than 300 kg ha^{-1} (Jenkinson, 1977).

In the USSR, long-term field trials carried out on sod-podzolic soil revealed also that regular introduction of mineral nitrogen fertilizers failed to increase organic carbon and nitrogen contents in the soil (Koshelkov *et al.*, 1960). Meit *et al.* (1977) determined for US conditions organic nitrogen losses from soil during 50–55 years not only in plots without nitrogen application but also in those treated with nitrogen fertilizer.

Mineral nitrogen of the soil, or applied fertilizer, is immobilized in organic matter by

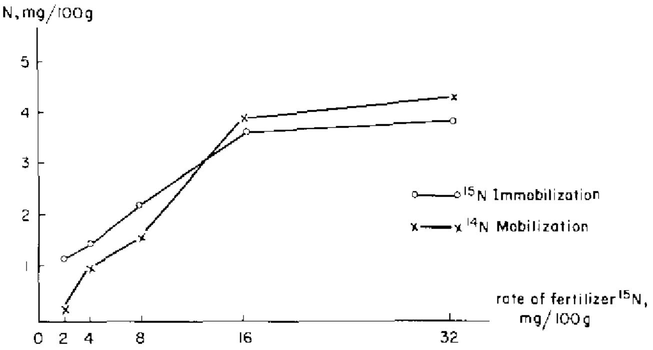

Figure 8. Immobilization of fertilizer ^{15}N and mobilization of soil ^{14}N (Pot experiment, gray forest soil) (Egorova & Kudeyarov, 1975).

microorganisms. The quantity of immobilized N depends on many factors but primarily on the presence of available organic compounds and their C:N ratio (Bartholomew, 1965). Studies with ^{15}N show that fertilizer nitrogen is immobilized in all soils at more or less the same rate. When straw or fresh harvest residues with low nitrogen content are incorporated in soil, the mineral nitrogen is immobilized into organic matter very rapidly. According to numerous literature data (see a selected bibliography on ^{15}N compiled by Hauck & Bystrom (1970)) the immobilization of fertilizer N constitutes 10–30 % of the applied rate when fresh organic material is not applied.

In some experiments a correlation was observed between the rate of additionally mineralized soil organic N caused by application of ^{15}N fertilizer and the amount of immobilized ^{15}N (Fig. 8). Smirnov (1977) showed that in non-limed sod-podzolic soil the intensity of immobilization of fertilizer ^{15}N exceeded the mineralization of soil N, but in limed soil the situation was reversed.

According to Bartholomew (1965), turnover rates of organic N in arable soils are as high as 10 % per year, but usually about 2 to 5 %. Jenkinson & Johnston (1977) calculated the turnover time of organic N in soil of the Hoosfield continuous barley experi- (U.K.) running since 1852. In the soil of plots receiving farmyard manure (FYM) annually since 1852 the turnover time of organic N was 32 years. But in soil of plots receiving FYM annually between 1852 and 1871, and none since, the turnover time is now 87 years. The variation of the turnover may be explained by the C and N contents in the soil of these plots. Jenkinson & Johnston (1977) calculated also the equilibrium levels for organic carbon and total nitrogen in Hoosfield. Nitrogen values for unmanured plots, manured between 1852 and 1871, and manured since 1852, are 2.99; 2.98 and 7.62 t ha^{-1}, respectively, which were reached after more than 100 years.

Thus, soil can accumulate nitrogen provided it receives a balanced quantity of C and N in the bound form – in the form of organic compounds exhibiting a structure similar to the soil organic matter. Regular introduction of FYM or prolonged growth of perennial grasses with legume components is crucial for the well-balanced inflow of carbon and nitrogen above all, and consequently, a prerequisite for the accumulation of nitrogen and carbon is that they are in a relatively stable state of being bound with each other.

Denitrification

Most of the atmospheric nitrogen would now be in a fixed form in the ocean and in sedimentary rocks if nitrogen was not returned to the atmosphere through denitrification. Denitrification is a process caused by microorganisms at low oxygen contents. In the general nitrogen cycle, denitrification involves of NO_3^- into nitrogen molecular gas (N_2). Normally denitrification takes place in soil when it is saturated or nearly saturated with water. Such microzones are often present in all soils. The presence of available carbon for the activity of denitrifiers is also necessary.

Söderlund & Svensson (1976) estimated that terrestrial denitrification amounts to 108–160 Tg N yr^{-1}. Studies with ^{15}N show the gaseous losses of fertilizer nitrogen to vary between 0 and 50 % of that applied, although many workers feel that 10 to 15 % is an average value (Hauck, 1971; Smirnov, 1977). The composition of nitrogenous gases volatilized from soil depends on many factors. Gilliam *et al.* (1978) showed that the N_2 : N_2O ratio of the total nitrogenous gases volatilized from soil varied between 100:1 and 1.4. It is recognized there are many uncertainties in prediction of the proportion of N_2 and N_2O released during denitrification processes.

Concluding remarks

All processes of nitrogen transformations in the soil are harmoniously interdependent. It is therefore possible to assume that soil presents a self-regulating buffer system of a kind in which the inputs and outputs of mineral nitrogen are kept in a relative equilibrium. But this equilibrium may change due to the type of agricultural management, and fertilization in particular. Overuse of mineral nitrogen fertilizers provokes not only losses of soluble fertilizer nitrogen due to leaching or denitrification of nitrates, but also "extra" mineralization of soil organic matter and inhibition of biological nitrogen fixation. The latter cannot be ignored as this source of bound nitrogen is the cheapest one in farming.

In order to prevent undesirable after-effects of nitrogen fertilizer application in agricultural practice, it should always be remembered that there are ways to prevent fertilizer residues from losses, e.g., there is a well-known, but only occasionally used, method of incorporation of straw or harvest residues in the soil. Chemicals for controlling nitrification and denitrification processes and slow release nitrogen fertilizers can be recommended as well.

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Nitrogen Cycling in West African Ecosystems

PRODUCTIVITY OF SAHELIAN RANGELANDS IN RELATION TO THE AVAILABILITY OF NITROGEN AND PHOSPHORUS FROM THE SOIL

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Abstract

Annual productivity of natural rangelands with annual grasses in the Sahel is not restricted by the actual precipitation, but by the low fertility of the soils. Deficiences of the elements nitrogen and phosphorus are predominant. Which of these two limits productivity most in a particular case can be determined from their ratio in plant tissue.

Productivity and nitrogen uptake by the vegetation of natural pastures were studied in sets of fertilization experiments on different soil types. On the basis of their results a static model is developed to predict N-uptake and productivity of rangelands. Inputs for this model are the natural fertility of the soil, fertilization and its recovery, and the duration of the phase of vegetative growth. Little attention is paid to losses of N that may occur in the seed filling period and afterwards. Recovery of fertilizer N was generally good. Very locally, denitrification and/or leaching may occur. Low availability of P was found to limit N-absorption, and thus plant yield, on some overgrazed soils.

Introduction

Natural grasslands of the Sahel are rangelands of a very poor quality, except for the brief period that they carry fresh, young plants. An important aspect of the low nutritive value of these pastures is the low protein content of only 3–6 % in the dry vegetation. Most of the biomass consists of annual grasses. In some areas, perennial grasses make up a considerable part of the biomass of natural pastures. Their quality often exceeds that of annual grasses. Trees maintain still higher levels of protein in their leaves, and so do many leguminous plants. Although consumption of these species can improve the animal diet considerably, the bulk intake of cattle, sheep and goats consists of annual grasses. This paper deals particularly with these annuals.

Mature annual grasses in the Sahel are poor in protein because of the low natural fertility of the soils. In the southern part of the Sahel (400–600 mm annual precipitation) the natural vegetation would grow up to 3 to 5 times more biomass with a higher protein content if the availability of plant nutrients, particularly of nitrogen and phosphorus, were higher. This would not require more water than the normal precipitation, as will be shown below. This observation agrees with similar findings in semi-arid lands of the of the United States (Power, 1970), of Israel (Van Keulen, 1975) and of Australia (Date, 1973). Only at very low levels of annual precipitation, water availability limits the annual herbage production. In Israel, this level is about 150 mm yr^{-1}. Some of our experiments suggest that this level is about 150–200 mm yr^{-1} in the Sahel.

Nitrogen is much more a mobile element in the soil-plant system than P is. However, the soil-plant system is an open system for N: 1–20 % of the N in the vegetation and in soil organic material enters and/or leaves the system annually. Some of the fluxes of N may be influenced or manipulated. It is therefore of special interest for the management of semi arid grasslands to be well informed about the elements of the N-cycle, and to understand the dynamics of the combined processes. The central question in this paper will thus be in what quantitative manner plant production depends on N-uptake from the soil, and how N-uptake relates to the natural fertility of the soil and to fertilization. On the basis of results of field experiments, a model is proposed that can be applied outside the area where our experiments were performed. The main field observations required for application of this model are the amount of N contained by the vegetation at flowering on pastures that were not fertilized, and the duration of the growing season.

The annual gain or loss of P from the system is negligible, although local accumulation or exhaustion may occur over a sequence of years. The P available for uptake by plants is a small and variable percentage of the total P in the soil. Considerations of the dynamics of P-availability must therefore concentrate on transformations within the system. Some of these are of a biological nature, some are of a chemical nature. The last section of this paper deals with some of its aspects. Because plants need P and N in a certain ratio, one should not consider the N-cycle and P-cycle independently, particularly not on poor soils.

This paper is an interim report of a study aiming at the determination of the relative importance of various processes in the N-cycle in Sahelian grasslands. A final report (PPS, in prep.) will be available in 1980. The study is carried out in the framework of the research project "Production Primaire au Sahel" (PPS) on a ranch near Niono (14°N, 5°W) in Mali. The annual precipitation in Niono amounts to 570 mm ± 20 %. The area consists of sandy dunes, clayey depressions and loamy plains. During the years of experimentation, the ranch was covered by a closed vegetation of annual grasses with very few leguminous plants, and by a fairly open tree and shrub vegetation. Anatomical analysis showed that the grass species had all the arrangement of sheath bundle cells typical of plants with the C-4 type of photosynthesis. They will be referred to as C-4 grasses, in contrast to C-3 grasses that lack this arrangement. The composition of the vegetation had changed considerably as a result of drought in preceding years (Breman & Cissé, 1977). Grazing on the ranch is partially controlled and at a low intensity since 1960.

Primary productivity and nitrogen availability

Methods of analysis

The relation between N-uptake and production was analysed by van Keulen (1977) and van Keulen & van Heemst (1980) for a number of agricultural crops, using data from fertilization experiments in which economic yield and total nitrogen uptake at maturity were available. Their method of analysis is illustrated in Fig. 1, using data from a pot experiment, reported by Colman & Lazenby (1970). In the upper half of the graph,

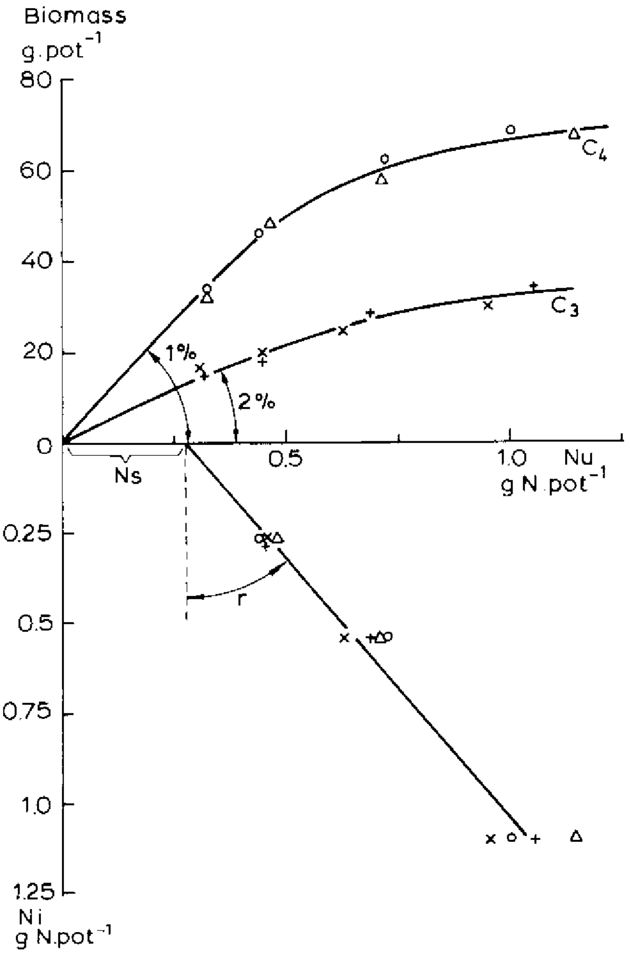

Figure 1. Results of a growth experiment in pots with different levels of fertilization with ammonium nitrate at 25–35°C, with 2 C-3 grasses (Phalaris (x) and Lolium (+)) and 2 C-4 grasses (Digitaris -o- and Paspalum -Δ). The upper part shows the above-ground dry matter versus the N that it contains (Nu), the lower part Nu versus the N-supplied as fertilizer (Ni). Experiment by Colman & Lasenby (1970).

the relation between above-ground biomass and nitrogen uptake is given, while the lower half contains the relation between fertilizer application and uptake. The data are averages of four cutting regimes, and thus of plants of different ages. In the upper half it is shown that in N-limiting conditions, the amount of biomass produced is proportional to the amount of N taken up, indicating that growth continues until a minimum concentration in the tissue is reached (Nmin). At higher levels of availability the N-concentration in the tissue is above the minimum level and yield increases less than proportional to the amount of N absorbed. When N is abundantly available, the tissue may reach a maximum

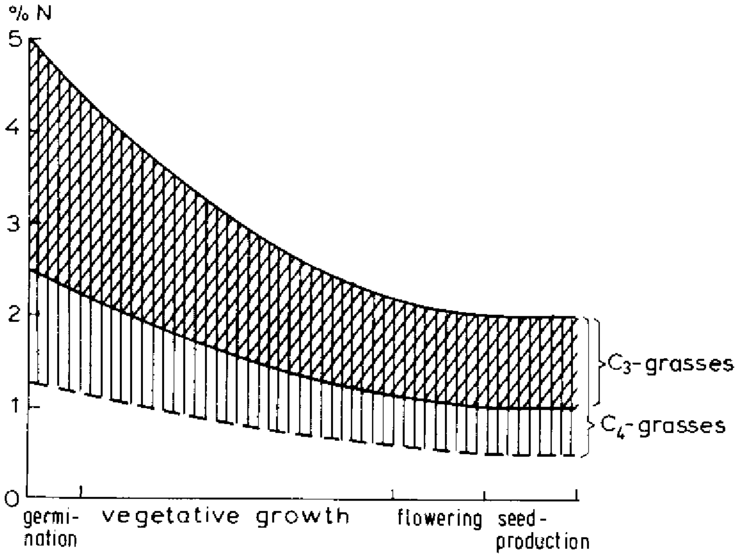

Figure 2. Maximum and minimum N concentrations of total above-ground biomass in C-4 and C-3 grasses as a function of their development stage.

level, above which no more nitrogen can be taken up (Nmax). The values of Nmin and Nmax vary with the age of the plant, being about 2.5 times higher in very young tissue than in mature issue. At any moment during development, the minimum concentrations are about half the maximum values in most C-3 grasses and cereals. The results presented in Fig. 1, as well as other observations, suggest that the maximum level in the tissue of C-4 grasses and cereals is similar to that of the C-3 grasses, but that their minimum value may be as low as a quarter of the maximum. When it is assumed that these observations point to general physiological characteristics of the two groups, the range of possible N-concentrations in the tissue of C-3 and C-4 grasses can be estimated. A schematic representation of these values, as related to development stage is given in Fig. 2. Comparison of N-concentrations in C-3 and C-4 grasses given by Brown (1978) support the hypothesis presented here. The data on uptake refer to total N in the plant tissue, regardless of the form in which it is present. It should be realized that especially under heavy fertilizer application up to 10 % of the total N may be in the form of nitrate, which is not part of the structural tissue. A distinction has not been made, however, since only a very limited number of observations on NO_3-content are available, while moreover, the standard error in the basic experimental data is considerable (10–20 %).

The lower half of Fig. 1, relating application and uptake, is characterized by the slope of the line, representing the fraction of the fertilizer nitrogen recovered in the above-ground biomass (r) and the intercept with the x-axis, representing the availability of soil N without fertilization (Ns). The graphical procedure illustrated in Fig. 1, which permits discrimination between uptake of applied nitrogen and the subsequent conversion into plant material will be applied to the experimental results obtained.

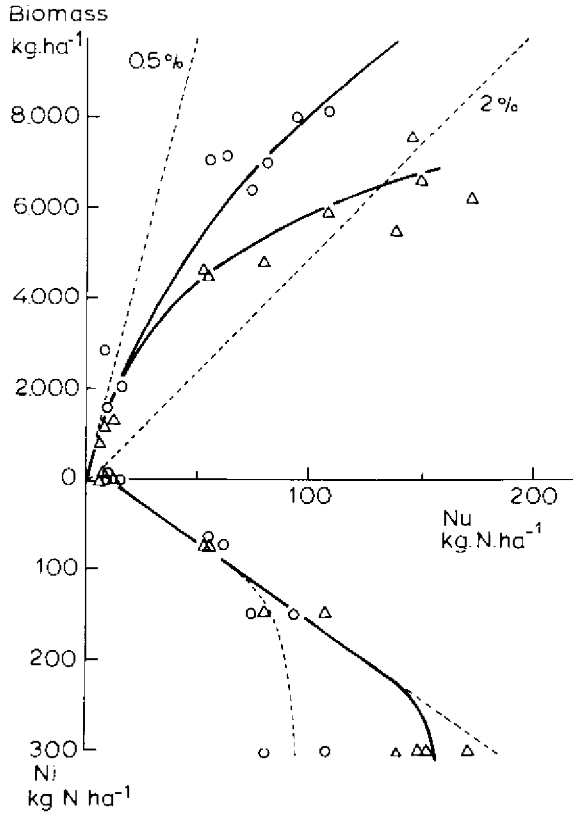

Figure 3. Fertilization with urea on a clayey soil, strongly dominated by the C-4 grasses *Diheteropogon hagerupii* and *Loudetia togoensis*. The lines representing the minimum and maximum N-concentrations at flowering are shown. The triangles correspond with the harvest on 31/8/77 just before flowering, the circles with the harvest on 14/9/77 during flowering and seed production.

Experimental procedure

Five experiments were performed on small fields on soil types that predominate on the ranch and in the Sahel: a clayey, a sandy and a loamy soil, an overgrazed sandy soil and a heavy clay soil. The latter becomes briefly flooded in the growing season. For details about the plant species on these soils, see the legends of Fig. 3–7. Except for a control plot, 100 kg P ha^{-1} (as triple superphosphate) was always given to avoid P-shortage. Preceding experiments showed that after such a P-dressing, N was the only element limiting plant production. No other mineral deficiencies occurred. Urea was applied broadcast at rates of 0, 75, 150 or 300 kg N ha^{-1} shortly before the growing season. On the overgrazed soil where the legume *Zornia* grew, seedlings were eliminated and the annual grass *Schoenefeldia* was sown. The surface of the heavy clay soil was slightly tilled manually, but the natural vegetation was allowed to develop. On the overgrazed sandy soil and on the heavy clay soil, a second group of experiments was performed with nitrate instead of urea. Nitrate was worked into the top 3 cm.

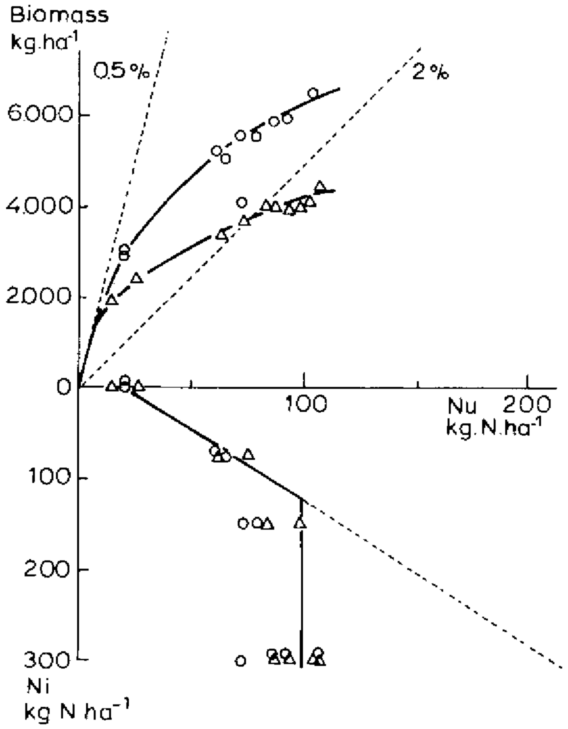

Figure 4. Fertilization with urea on a sandy soil, strongly dominated by the C-4 grass *Schoenefeldia gracilis*. The triangles correspond with the harvest on 27/8/77 when the vegetation was in a late vegetative stage, the circles with the harvest on 10/9/77 when all plants flowered.

Yields were determined by duplicate harvests of 10 m^2 subplots, approximately at the onset of flowering, and again 15 days later. Plant samples were analysed for N, P and ash at the Centre National de Recherche Zootechnique in Sotuba, Mali.

Results

The marked response to fertilizer application depicted in Figs. 3–7, proves that soil fertility rather than moisture availability limited plant productivity, as was already anticipated in the introduction.

The shape of the curve relating production to N-uptake in these figures is similar to that of Fig. 1, and to those reported by van Keulen & van Heemst (1979). The initial slope of the yield-uptake curves, representing the minimum N-concentrations at flowering, are similar in all but one graph and conform to those of Fig. 2. The results presented in Fig. 5 suggest a minimum N-concentration of about 0.75 %, which is attributed to the fact that the vegetation was a mixture of C-3 dicotyledons and C-4 grasses. The experiment on the heavy clay soil (Fig. 7) was harvested a little before flowering, so that the maximum concentration of N is slightly higher than 2 %.

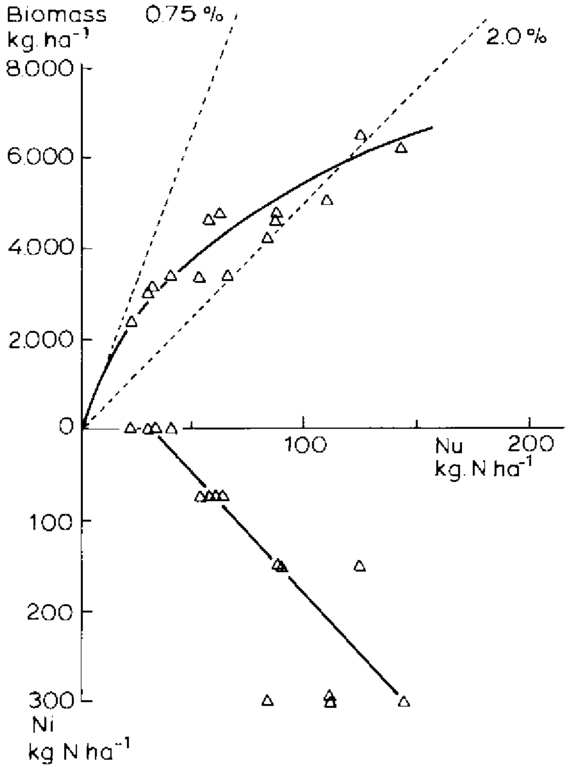

Figure 5. Fertilization with urea on a loamy soil, dominated by the C-4 grass *Dactylotenium aegyptium* and the C-3 dicotyledons *Borreria spp* and *Blepharis linearifolia*. All data are obtained from the harvest on 21/0/77, when all plants were flowering and/or producing seeds.

The total N-uptake and the biomass produced at the highest fertilization levels vary considerably in different experiments. This is attributed to differences in the duration of the vegetative period, as will be discussed below. Comparison of the results of the first and of the second harvest of the same treatment shows that biomass increases after flowering, whereas the total N-uptake remains constant or diminishes, thus leading to an upward shift of the uptake-yield curve.

The lower halves of Figs. 3–7 show the availability of N without fertilization (Ns) and the recovery fractions (r). Ns varies from 10 to 35 kg N ha^{-1} yr^{-1} in these experiments. Such values are not characteristic for the soil types, but are strongly influenced by differences in long term exploitation between the sites. The values of Ns are quite low when compared to those found by van Keulen & van Heemst (1980) in their survey, but are normal for sahelian pastures. Mineralization is the most important process that makes N and P available for plant growth on unfertilized soils. Use of radioactive tracers in rice fertilization studies showed that the amount of N provided by mineralization is independent of the level of fertilization (FAO, 1970). This is supposed to be similar in sa-

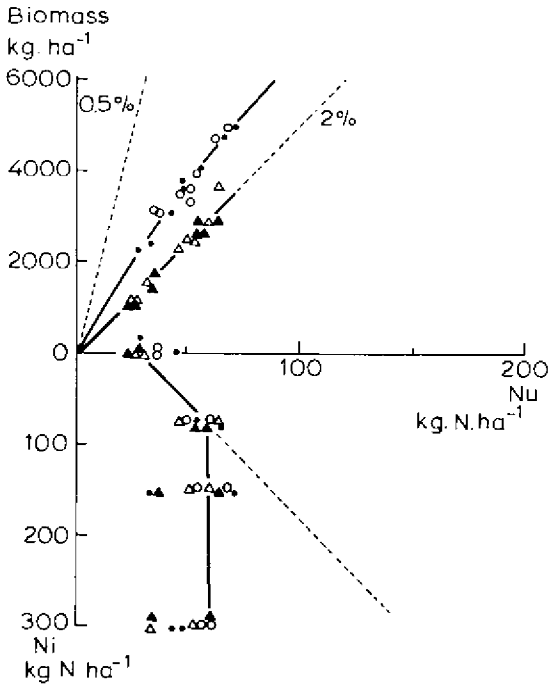

Figure 6. Results of an experiment on a sandy soil that used to be occupied by *Zornia glochidiata*, but that was sown to the C-4 grass *Schoenefeldia gracilis*. The open symbols represent the plots fertilized with nitrate, the closed symbols those fertilized with urea. The triangles indicate the harvests of 5/9/78, the circles the harvests of 20/9/78.

helian soils, although no direct evidence supports this assumption. The N in precipitation and N_2-fixation contribute also to the availability of N on unfertilized soils. The relative importance of the latter process is probably affected by application of N, but its contribution was not substantial in the experiments described. Hence, it seems reasonable to assume that the amount of N available to the plants without fertilization will also be available when fertilizers are applied. The proportionality between supply of N and its absorption by the vegetation therefore reflects a constant recovery fraction. The value of r was between 0.40 and 0.65 in these experiments for the first year after fertilizer application. These values are in the middle of the range reported by van Keulen & van Heemst (1980).

Because the vegetation at flowering contains 2 % N at most, there is a limit to how much N can be absorbed. The recovery fraction is thus only a constant up to a certain rate of fertilization. This is shown clearly in Figs. 4 and 6. The recovery fraction is similar for both the early and the late harvests, or seems to decrease in time, particularly at high levels of productivity.

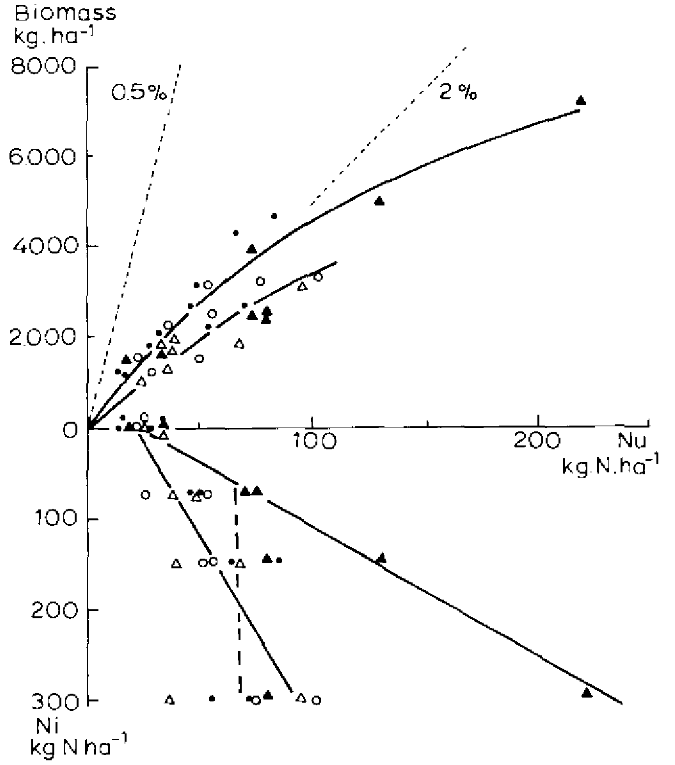

Figure 7. Results of an experiment on a heavy clay soil, dominated by the C-4 grass *Echinogloa colona*. The open symbols represent plots fertilized with nitrate, the closed symbols those fertilized with urea. The triangles indicate the harvests on 28/8/78, the circles the harvests on 9/9/78 when most plants flowered.

Interpretation of experimental results

For the prediction of herbage yields in response to treatments, it is useful to be able to construct graphs like those of Figs. 3–7 for a particular situation, with only a minimum of experimental information to be collected in the field. The results of the experiments presented will be analysed below to this end. We will concentrate on four aspects:

1. the amount of biomass at flowering and at maturity under conditions where nitrogen is non-limiting;
2. the N-concentration at flowering in conditions of N-deficiency and of ample N-supply;
3. the natural fertility of the soil;
4. the recovery fraction.

The amount of N in the above-ground parts of the vegetation attains a maximum around flowering. This is shown in Fig. 8, which presents results of one of many similar experiments (PPS, in prep.). This phenomenon was found at all levels of herbage produc-

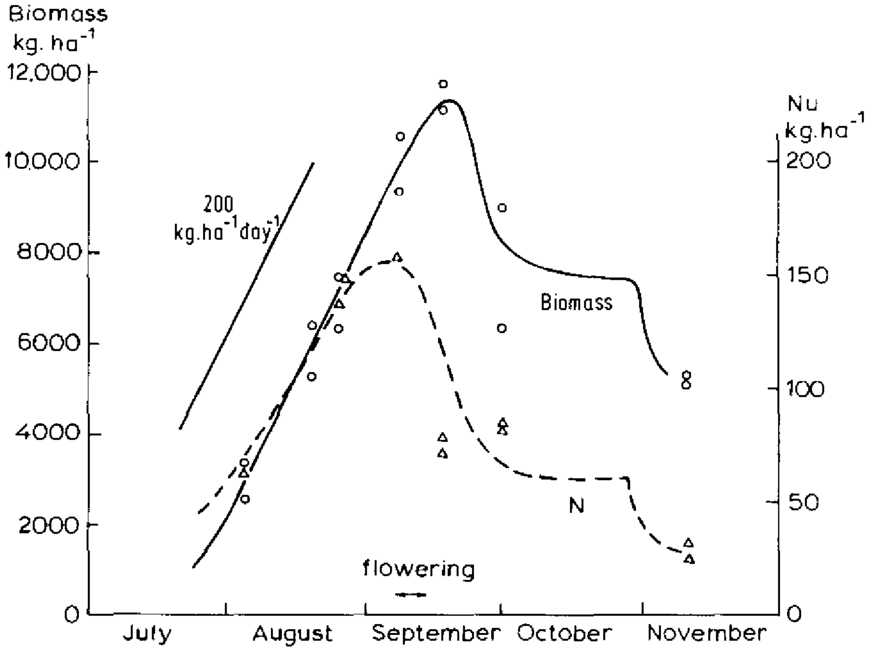

Figure 8. Primary productivity and N-uptake of a natural vegetation, strongly dominated by the C-4 grasses *Diheteropogon hagerupii* and *Loudetia togoensis* on a clayey soil in Niono in 1976. Each data point represents one harvest. The vegetation grew for almost 50 days at a rate of 200 kg^{-1} day^{-1}. Heavy and exceptionally late rains caused extra losses of biomass and of N in October.

tion. The observation that the amount of N in the vegetation does not increase after flowering is most valuable, because it provides a clue for the calculation of N-uptake: when nitrogen is non-limiting, the concentration of N at flowering is 2 % (cf. Fig. 2), and the amount of N taken up can be related directly to the amount of biomass present at that moment. The latter quantity is a function of the rate of growth and the duration of the period of vegetative growth. The natural vegetation of annual grasses grows at rates of about 220 and about 150 kg dry matter ha^{-1} day^{-1} on clayey and sandy soils, respectively, under optimum conditions of plant nutrients and soil moisture. This was found in field experiments with periodic harvests in conditions which were identical to those at the highest fertilization level of the experiments of Figs. 3–7. Results of one series of periodic harvests are given in Fig. 8; results of other experiments are summarized in Table 1. A sudden acceleration of the growth rate, following a drastic change in the weather, marks the beginning of a period of vigorous, vegetative growth, which ends at flowering. The duration of this period, indicated in Table 1, is only slightly longer with heavy fertilization than without it, so that in practice, the period of vigorous, vegetative growth can be established in unfertilized pastures. Alternatively, the date of growth acceleration can be derived from the actual precipitation pattern, accounting for local run off and

Table 1. The duration of the period of vigourous vegetative growth, the amount of biomass at flowering and the amount at maturity in some experiments on fertilized, natural pastures in Niono, Mali. Annual grasses dominated strongly the vegetation in all cases. Fertilization was 300 kg N ha^{-1} (as urea), 100 kg P ha^{-1} (as triple superphospate) plus 225 kg K_2SO_4 ha^{-1}. Biomass data are averages; the standard error of the average is about 10 %.

Description of the site			Results		
Soil type	Year	Run off/run on	Vigorous vegetative growth (days)	Biomass at flowering (kg dry matter ha^{-1})	Biomass at maturity (kg dry matter ha^{-1})
Clayey soil	1976	none	45	10.000	11.500
" "	1977	"	30	6.750	8.500
" "	1978	"	35	7.500	9.500
Vertisol	1978	run on	25	3.500	5.000
Loamy soil	1977	none	25	5.000	6.500
Sandy Soil	1976	run off	30	5.000	6.000
" "	1977	none	40	4.750	6.000
" "	1978	run off	20	3.250	5.000

run on. The date of flowering of most Sahel grasses is partially controlled by daylength (PPS, in prep.) and may be estimated when observations are lacking. The values of Table 1 shows that the amount of biomass at flowering is clearly related to the number of growing days. The lower maximum growth rates at the sandy soils are probably due to a lower availability of soil water.

In the experiments described, the vegetation was usually strongly dominated by one species. If two or more species are present, that differ considerably in their dates of flowering, the analysis of the data may be more complex, but not necessarily so. If the species are thoroughly mixed, the longer living species may finally dominate the vegetation and thus determine its herbage production. If both species are in monospecific patches, the analysis can be done for both species separately.

After flowering, the vegetation grows for another 10–20 days until the plants mature. The growth rate drops to zero over that period, so that on the average it is half of that during the vegetative phase.

For the time being, the amount of N available to the vegetation from unfertilized soil cannot be predicted from basic data. It needs to be determined in the field by harvesting vegetation on unfertilized plots at flowering. As mineralization proceeds only when the soil is humid, a relation between Ns and the length of the period that the top soil is wet is to be expected. There are indications of such a relationship in sahelian soils, as in the Negev (Harpaz, 1975), and they will be discussed in a later report (PPS, in prep.). It means that Ns needs to be determined in an average year, or adjusted when determined in relatively wet or dry years.

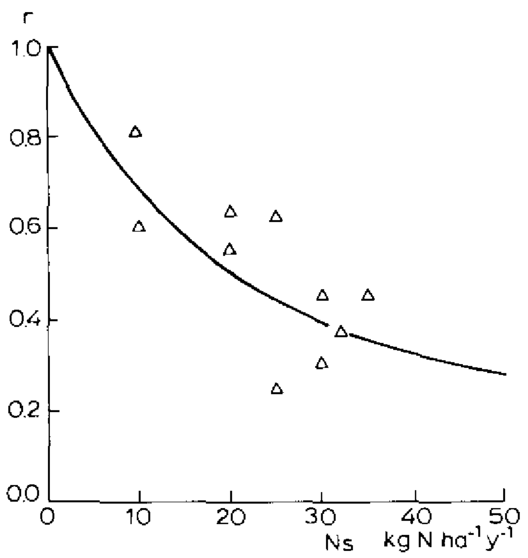

Figure 9. The fraction (r) of N applied as fertilizer recovered in above-ground biomass versus the fertility of soils without fertilization (Ns).

Experimental determinations of the recovery fraction of the N applied requires careful field experimentation, since there is not yet a good theoretical basis to calculate the value of r for particular conditions. However, when plotting r versus Ns from Figs. 3–7 and some other PPS data, a relation between Ns and r seems to exist (Fig. 9). The data points suggest that r is inversely related to Ns. This relation could provide an estimate of r when only Ns has been determined. Although this relation is supported by only a few data points, there is an additional argument, based on competition for available N in the soil between plants and soil microorganisms. If plants would be grown on pure and sterile sand to which nutrient solution is added, the recovery of N would be complete and the 'natural fertility' zero. But in soil with some organic matter, decomposition makes inorganic N available for uptake by microorganisms and by plants. Microorganisms will absorb part of this N because the soil organic matter has often a high C/N ratio (20–35) and its decomposition does then not provide sufficient N for microbial growth. The more microorganisms are active, the higher the 'natural fertility' of the soil, but also the stronger their competitive power for N. This suggestion would support an inverse relation between r and Ns. It also implies that recovery of fertilizer N in sahelian pastures will be quite high in the long run since the fertilizer N fixed by soil organic matter will be released in due course when the organic matter decomposes.

It is not yet known over what range of soil fertilities this relation is valid nor is investigated whether it changes at higher or lower rainfall levels. For British soils, Brockman *et al.* (1971) found a positive correlation between r and Ns. Such a relation can be expected whenever fixation of fertilizer N by soil organic matter is relatively unimportant, compared to denitrification and leaching.

A limited number of observations suggests that the size of the root system of a mature vegetation of annual grasses is 700–1400 kg dry matter ha^{-1} and is only to a limited

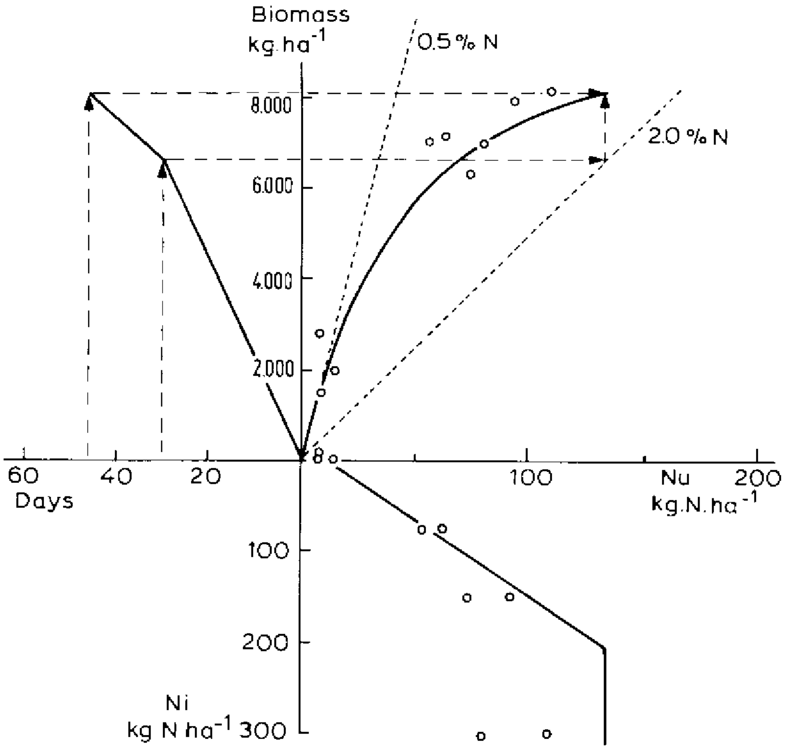

Figure 10. A graphical presentation of the procedure explained in the text to calculate productivity and N-uptake by annual pastures at various levels of fertilization. The procedure is here applied for the conditions of the experiment of Fig. 3. The results of this experiment, second harvest, are included for comparison.

extent dependent on the amount of above-ground biomass. Also the N-concentration of the roots is quite constant: 1.1 to 1.2 %. Hence, there is always about 10 kg N ha^{-1} contained in the root system, at least in our experiments. This is quite an appreciable proportion of the total N absorbed under N-deficient conditions, but since this quantity seems too invariable, it does not affect the above considerations.

A simulation model

Based on the evidence presented above, a static simulation model is developed. It enables one to calculate the biomass present at the end of the growing season for pastures in the southern part of the Sahel, and the amount of N that it contains. Its application is restricted to vegetations of annual grasses, and to situations where P-deficiency is not severe. For each situation in which the model is used, the duration of the period of vigorous, vegetative growth, the amount of N in the vegetation at flowering on an unfertilized field, and the rate of fertilization need to be specified. The minimum and maximum concentration of N at flowering are supposed not to vary with conditions. The value of the recovery fraction may be based on its relation to Ns (cf. Fig. 9), or it may be determined experimentally in case of doubt about the validity of this relation for the specific case. The model is presented graphically in Fig. 10.

The amount of biomass at flowering is calculated first for a situation with an ample supply of plant nutrients. It is found by multiplying the growth rate of 220 or 150 kg dry matter ha^{-1} day^{-1} on clayey or sandy soils respectively, by the length of the period of vigorous, vegetative growth. In the example of Fig. 10, this period is 30 days. The N-concentration at flowering is 2 %. During seed fill, the biomass increases at about half the preceding rate, without further uptake of N. In Fig. 10, this lasts for 15 days. The biomass of the mature vegetation and the N contained in it, are thus calculated for a condition with abundant nutrients. The curvilinear relation between the productivity and the N taken up by the vegetation at lower levels of N-availability can now be approximated by drawing a line through the origin at a slope equal to the minimum concentration of N at maturity, and approaching the uptake-yield point determined for optimum conditions.

Plotting the relation between the supply of N by fertilization and its uptake is very straightforward once Ns and r are known.

This simple, static model is not very accurate. However, it takes into account essential growth processes, and thus improves our understanding of the system. It may also improve considerably our factual knowledge of productivity and N-uptake, as may be concluded from the reasonable agreement between predicted and measured productivity (Fig. 10).

Other conclusions from the experiments

The total amount of N in the biomass often drops after flowering, though not always (Figs. 3–8). The magnitude of such losses is positively correlated with the rainfall after flowering and with the amount of N in the vegetation. Various processes have been suggested to explain this phenomenon, but further analyses are needed before general conclusions can be drawn. It is clear, however, that for the determination of the actual uptake of N by the vegetation, harvest should be around flowering, particularly if productivity is high, and lodging of herbage occurs before the end of the rainy period. This situation occurred in the experiments of Figs. 3, 7 and 8, where rotting became very intensive.

In one experiment (Fig. 7) a value of r (0.21) was found well below the one expected (0.44) on the basis of Fig. 9 and its value of Ns (25). This was the case on the heavy clay soil, fertilized with nitrate which was flooded for some time. The low recovery is ascribed to denitrification and/or leaching. On the basis of Fig. 7, one cannot discriminate between the two. When the recovery of urea is used as a standard, one or both processes seem to have caused the loss of just over half the N supplied. Since urea is usually nitrified within a relatively short time, the large difference between urea and nitrate fertilization was unexpected. It seems as if nitrification was slow in this experiment. We have no indication why, and further research will be conducted on this point. Incubation experiments are being executed to ascertain the potential for denitrification during flooding in heavy soils from a few sites in the Sahel.

It seems contradictory to assume the occurrence of denitrification and/or leaching and still to find a relatively high value of Ns, since exhaustion of soil N would make Ns very low. It is suggested that Ns can remain fairly high because most of the N is already absorbed by the plants before flooding occurs in these N-deficient conditions. Only when more N is present than can be absorbed before flooding, *i.e.*, in some of our experimental conditions, denitrification and/or leaching could occur. Also here the recovery fraction is constant only up to a certain level of fertilizer application and declining at increasing rates. On the basis of such considerations, it is expected that denitrification and leaching may only rarely and very locally be of importance in natural vegetation of the Sahel because soils are generally very poor. When intensive fertilization is practised, one or both processes can become important locally.

Whenever severe deficiency of soil water during the main growth period or of available P occurs, the above approach to productivity and N-uptake is no longer valid. How P-deficiency influences productivity is the topic of the next section.

Primary productivity and availability of phosphorus

The P/N ratio

Annual productivity is more limited to the low availability of N than by that of P on many soils in the Sahel. For instance, in the experiments cited above, the amount of herbage produced and the amount of N taken up on the control plot without P was the same or only slightly below that on the fields with only P-fertilizer. A situation will now be presented where P limited productivity severely. It presents a fine example of fertilization with P only, which has the same effect as that usually caused by supply of P and N together. Before the results of experiments are interpreted, the rational of the relation between N and P concentrations in plants will be discussed.

N and P are functionally closely linked. Both are parts of essential components of functioning cells: the N in enzymes and P in compounds that provide energy for many enzymatic reactions. Moreover, the biochemical maintenance of cell proteins requires the presence of nucleic acids, which contain P. It may thus be expected that the ratio between N and P is of particular importance. The hypothesis is put forward that the ratio of total P over total organic N may be used to determine whether N or P limited plant productivity in a particular case, provided that no other deficiencies occur. This hypothesis is based on experimental work by Dijkshoorn (pers. comm.), who varied the nutrient supply to some plant species over a wide range and found that the P/N ratio (in g P g^{-1} organic N) in vegetative tissue did reflect such variations, but only within certain limits (Table 2).

Table 2. The range of P/N ratios found in four plant species (Dijkshoorn, pers. comm.)

Species	P/N minimal	P/N maximal
Lolium perenne (C-3 grass)	0.045	0.18
Schoenefeldia gracilis (C-4 grass)	0.029	0.12
Helianthus annuus (C-3 dicot.)	0.041	0.16
Cassia tora (C-3 dicot)	0.060	0.24

Accumulation of the element which is not in short supply to values beyond the P/N range indicated, is apparently avoided. The differences between the species are not very large (with the possible exception of *Cassia*), and part of the variation may be due to experimental errors. *Cassia tora* not being an important species, the minimum and maximum value of the P/N ratio is used in this paper will be the average of the first three species. Old, and well fertilized plants show sometimes a P/N ratio that considerably exceeds 0.15. Still we suggest, as a first approximation, that if the P/N ratio of an annual plant is 0.038 g P g^{-1} organic N, one must conclude that this plant is very P-deficient. Fertilization with P will then be most effective, while fertilization with N will not enhance productivity. If the P/N ratio equals 0.15, P-fertilization will have no effect, while N-fertilization will be most effective. When the P/N ratio is close to one of these boundaries, growth will be severely retarded, but it is not always halted: the plant can still grow by dilution of P and N simultaneously, maintaining the P/N ratio at a constant value, until the minimum value of N (cf. Fig. 2) or that of P is reached. (The absolute minimum value of P in flowering C-4 grasses is probably about 0.05 % P.) A common situation in the Sahel is that the P/N ratio of plant tissue is not extremely high or low, but that P- and N-uptake proceed slowly because their availability is low. Fertilization with one element increases its uptake, and makes the other element the limiting factor. The limiting element becomes then diluted to a lower concentration than it would have been without fertilization, so that application of either element stimulates the herbage production. Results of such experiments are presented elsewhere (PPS, in prep.).

When collecting plant samples for determination of its P/N ratio, one should be aware that this ratio often changes during the growing season, particularly in plants grown on poor soils: N is more available to a small root system than P because of the higher mobility of nitrate (van Keulen *et al.*, 1975). Young plants are thus more susceptible to P-shortage than old plants. To characterize quickly the P-status of the soil relative to N, it may thus be useful to determine the P/N ratio of quite young plants. This idea is supported by other PPS-data (unpublished), showing that the productivity of a vegetation, with young grass plants, only a few cm high, having a P/N ratio of less than 0.06, was stimulated more by P-fertilization than that of vegetations with young plants having higher P/N ratios.

Nitrogen uptake and availability of phosphorus

Large areas of the Sahel are covered with a vegetation of almost pure stands of *Zornia glochidiata*, an annual N-fixing legume. This vegetation occurs especially where overgrazing has taken place or takes place, or where land has been cultivated for some time. A sandy soil on the ranch, for many years covered with such a vegetation, was fertilized with P and its effect on productivity of some grass and legume species was studied. The experiment of Fig. 5 was performed on a run-off area of the same soil type. *Zornia* seedlings were removed, and by sowing, pure stands were obtained of the annual C-4 grasses *Cenchrus biflorus*, and *Schoenefeldia gracilis*, and of the annual legumes *Cassia mimosoides, Alysicarpus ovalifolius, Zornia glochidiata* (all N_2-fixing) and *Cassia tora* (not N_2-fixing). Subplots of 1 m^2 were harvested at the full flowering stage.

Upon addition of P, the uptake of P, the uptake of N and dry matter yields of grasses and legumes increased considerably (Fig. 11), the responses being similar in different species. The P/N ratio ranges from 0.049 in plants on non-fertilized plots to 0.140 in plants on the soil fertilized with P. This suggests that plants grown on the unfertilized soil had taken up the maximum amount of N per unit of P absorbed, and that the plants on

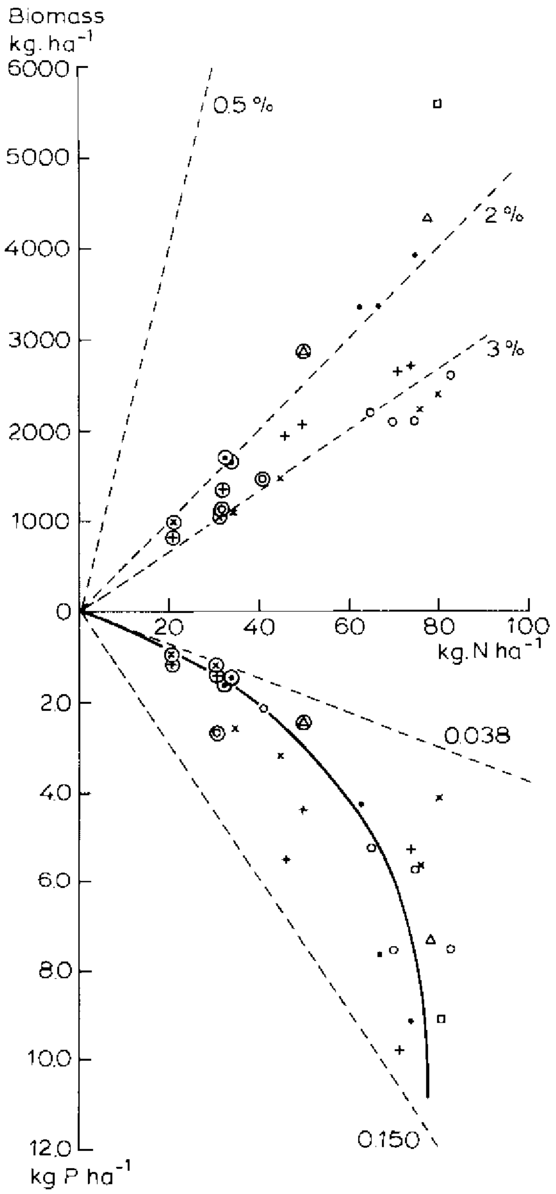

Figure 11. The relation of dry matter production, N-uptake and P-uptake of some annual grasses and legumes on an overgrazed sandy soil. Each point represents one harvest at a fully flowered stage. Symbols: Δ *Cenchrus* (sown 19/7, harvested 7/9), □ *Schoenefeldia* (19/7-7/9), ○ *Alysicarpus* (20/6-24/8), x *Cassia mimosoides* (20/6-24/8), +*Zornia* (20/6-24/8) and ● *Cassia tora* (20/6-24/8). The encircled symbols represent non-fertilized plots.

the fertilized plots contained the maximum amount of P per unit of N. This implies also that without fertilization, much available N was probably left in the soil, which with P-fertilization was absorbed by the plants. About 20 kg NO_3 ha^{-1} was indeed found in the top 20 cm at the end of the rainy season on a plot nearby. The possibility exists that P-fertilization stimulated mineralization, but this phenomenon is extremely rare. The total amounts of N absorbed by grasses and by legumes capable of N_2-fixation were not significantly different. Fixation of N_2, if any, did thus not increase the total amount of N in the vegetation, irrespective of P-fertilization. This is not surprising, as their N-concentrations are at a maximum level.

Although the amounts of P in vegetations on the unfertilized plots were small, they are not smaller than those on surrounding sandy soils, where P-fertilization had little effect on the yield. The P-response was thus not primarily due to an extremely low availability of P in the unfertilized soil, but to a deficiency of P relative to N.

Another situation in which plant productivity was completely limited by P-availability was found by a colleague (Cissé, pers. comm.), who studied regeneration of loamy soils that are barren due to overgrazing. He found that such soils near Niono released about 40 kg N ha^{-1} after tillage (to enable rain to infiltrate) and sowing C-4 grasses (*Schoenefeldia gracilis* and *Digitaria exilis*). The P/N ratios of these plants were about 0.038 at an early stage, indicating severe P-deficiency. P-fertilization (30 kg P ha^{-1}) increased N-uptake to 100–150 kg N ha^{-1}, and P/N to 0.078. The availability of N in the soil was even so high that additional fertilization with N gave almost no response. Harvests the following year, without further fertilization, showed that N-uptake decreased only little on the unfertilized plot, but was down to 20 kg N ha^{-1} on the field that received P previously. The P/N ratio was adequate in all cases. On the plot that received fertilizer, all available N had apparently been taken up by the vegetation in the first year of the experiment. These experiments show that P-fertilization may be quite advantageous for one year, and provides possibilities for complete regeneration of a vegetation. But it also shows that when overgrazing of the restored area is resumed, the soil has lost a considerable portion of its N-stock, and will be in a worse condition than it was before. A description of experiments and results concerning regeneration of heavily overgrazed soils is in preparation (Cissé, in prep.).

It is not surprising to find that the tilled, barren soil contained such a large amount of available N. Mineralization will take place whenever these soils become moist even though this period will be brief because of very considerable run off. Since no plants are present to absorb the N released, it will accumulate. Hence the soil shows a fallow effect after reclamation. It is, however, not obvious why P is relatively unavailable, since mineralization releases both P and N. As a possible explanation it is suggested that, as a result of overgrazing, insufficient plants are present to absorb the N and P released by decomposition of the soil organic matter. Available N and P accumulate as a result. When the soil dries out at the end of the rainy season, N and P precipitate. N becomes readily available when the soil is moistened the next year, but this may not be so for P, since its precipitation can occur in highly insoluble forms. If this suggestion is correct, under-exploitation of the available nutrients by over-exploitation of the vegetation would lead to fixation of P by the soil, and to accumulation of available N. The latter process is sometimes reinforced by N_2-fixation by legumes. The strong P-deficiency is then the resultant of these processes.

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Nitrogen Cycling in West African Ecosystems

LE CYCLE DE L'AZOTE DANS LES AGRO-SYSTEMES DE L'AFRIQUE DE L'OUEST

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Abstract

The nitrogen cycle comprises all the transformations that this element is subject to in the biosphere. Most of these transformations are carried out by microorganisms and their agricultural importance is considerable in that they regulate the nitrogen balance in the soil and the nitrogen available to the plants in a mineral form.

In an agroecosystem where the objective is to produce, the nitrogen cycle is influenced by management practices. African agriculture is characterized by cropping systems, which have a very varied intensification in their management, and the importance and frequency of the influence on the nitrogen cycle are very variable.

An evaluation is made of the different components of this cycle: the importance of different pools and determination of the annual fluxes are evaluated based on literature data for systems in a crop rotation.

Introduction

Le cycle de l'azote concerne l'ensemble des transformations subies par cet élément dans la biosphère. La plupart sont d'origine microbienne et leur importance agricole est considérable dans la mesure où elles régissent le bilan de l'azote dans le sol et conditionnent la mise à la disposition des plantes des formes minérales.

Dans un agrosystème dont l'objectif est de produire, ce cycle subit la pression des techniques culturales exercées par l'homme dans le cadre des systèmes de cultures qu'il met en place. L'agriculture africaine se caratérisant par la juxtaposition de systèmes de cultures présentant des niveaux d'intensification très divers, l'importance et l'incidence de ces pressions sont très variables. Par ailleurs, si la mise en valeur agricole du milieu se traduit par la rupture des équilibres naturels originels, l'installation de cultures pérennes arbustives semble permettre le plus souvent le rétablissement d'un équilibre stable du fait de la faible fréquence des interventions. Avec les cultures annuelles, l'évolution peut être fort différente. En effet, l'intensification et les diverses interventions culturales qu'elle implique, résultant plus de choix devenus nécessaires au niveau de la planification que d'une progressive évolution de la pratique agricole, peut se traduire par la dégradation rapide des qualités d'un milieu généralement considéré comme fragile compte-tenu de l'agressivité des facteurs climatiques et de la rapidité des cycles biologiques.

Une évaluation moyenne des principales composantes du cycle de l'azote: importance des différents pools et mesure des fluxes annuels, sera dégagée des données bibliographiques pour d'une part les systèmes traditionnels et d'autre part les systémes améliorés, essentiellement ceux constitués de cultures entrant en rotation.

L'agriculture traditionelle

Les systèmes mis en place dans le cadre de cette pratique vont de l'agriculture itinérante sur brûlis à une agriculture alternant périodes de culture à périodes de jachère plus ou moins longues selon la pression démographique locale. L'importance relative de ces deux périodes peut être illustrée par le coefficient d'utilisation des sols tel qu'il est définit par Allan (1965) qui est de l'ordre de 2 à 6.

L'alimentation azotée des plantes

La cycle interne de l'azote: Dans ces systèmes, le taux d'azote total du sol tend vers un équilibre dont la valeur est déterminée par le rapport entre pertes survenant essentiellement lors de la phase de culture et gains qui prédominent en phase de jachère.

Les apports d'engrais sont nuls et l'alimentation azotée des plantes est dépendante du cycle de minéralisation des réserves organiques du sol. Celles-ci sont très variables selon les zones écologiques: de 0,051 % en moyenne (variation de 0,008 à 0,290 %) pour les sols de savanes (Jones, 1973) elles atteignent des taux doubles ou triples en zone forestière. Ainsi, les teneurs observées en basse Côte-d'Ivoire par Bernhard-Reversat (1976) varient de 0,95 à 2,94 %. Sous jachère au Ghana, Nye (1958) note des taux variant de 0,033 à 0,303 % et des variations de stock dans les 25 premiers centimètres allant de 800 à 6400 kg ha^{-1}.

Ces réserves sont minéralisées à des taux annuels variant entre 2 et 5 % (Charreau & Fauck, 1970). Dans ces conditions les quantités moyennes d'azote mises annuellement à la disposition des plantes se situent entre 50 kg ha^{-1} en zone de savane et 150 kg ha^{-1} en zone forestière.

La dynamique de cette minéralisation étudiée au Senegal par Blondel (1971 b à d) montre qu'après une phase d'inactivité en saison sèche, les phénomènes microbiens sont stimulés par les premières pluies et se traduisent par des flux de minéralisation important atteignant sur un profil de 1 mètre respectivement 157 et 55 kg ha^{-1} à Sefa et Bambey avec dans ce cas une variabilité inter-annuelle de 24 à 100 kg. Ces fluxs intervenant dans un délai de 3 à 6 semaines après le début des pluies sont susceptibles d'entrainement en profondeur et de ce fait plus ou moins bien utilisés par les plantes selon le calage du cycle cultural par rapport au cycle pluviométrique. Ainsi, une pluie de 20 mm est susceptible de diminuer de moitié le stock de 35 kg libéré dans les conditions de Bambey dans les 20 premiers centimètres du sol. Cette dynamique impliquant des semis précoces n'est cependant pas caractéristique de toutes les zones de savane (Wild, 1972b) et peut être plus progressive (Wild, 1972a).

Les apports météoriques: Nye (1961) au Ghana chiffre les apports par les eaux de pluie à 23,6 kg ha^{-1} an^{-1} dont 11 proviendraient du pluviolessivage de la végétation. En basse Côte d'Ivoire, Roose (1977) les estime à 23,7 kg ha^{-1} an^{-1}. La variabilité observée semble dépendre de la proximité de la mer comme l'illustre le Tableau 1.

Tableau 1. Apports d'azote par les eaux de pluies
(1) d'après Thornton (1965); (2) d'après Jones & Bromfield (1970)

Distance de la mer (Km)	15	130	218	400
Apports kg ha^{-1} an^{-1}	47,1 (1)	40,1 (1)	21,7 (1)	4 à 5 (2)

L'évaluation moyenne serait tant en zone tempérée qu'en zone tropicale de l'ordre de 10 kg ha^{-1} an^{-1} (Eriksson, 1952).

La fixation biologique: Cette fixation peut-être symbiotique ou non, mais quoi qu'il en soit, on dispose de peu de données quantitatives quant à son importance réelle au champ surtout en milieu traditionnel.

Aussi, en ce qui concerne les cultures de légumineuses est-il préférable d'estimer que la fixation par voie symbiotique de l'azote atmosphérique permet de satisfaire aux besoins de la culture sans modifier le stock d'azote du sol (Jones & Wild, 1975) bien que des variations importantes soient souvent observées mais le plus souvent en culture améliorée.

C'est ainsi qu'après culture d'arachide Jones (1974) note sur les céréales des augmentations de rendement équivalent à un apport de 30 kg ha^{-1}.

Les pertes liées à la culture

Les immobilisations et exportations par les plantes: La productivité des systèmes traditionnels est généralement faible et dépend essentiellement de la proximité du défrichement.

Les immobilisations moyennes annuelles par les cultures entrant en rotation varient de 20 à 40 kg ha^{-1} (Tableau 2). Les exportations par les produits marchands représentent une quantité moyenne de 10 à 35 kg.

Tableau 2. Immobilisations et exportations moyennes en culture traditionelle.
(1) d'après FAO 1970–1972 in "Memento d'Agronomie. Ministère de la Coopération – Paris 1974).
(2) Calculées d'après (1) et des données du Tableau 4.

Cultures	Rendements moyens en Afrique de l'Ouest (1) (kg ha^{-1}) (1)	Immobilisations (kg ha^{-1}) (2)	Exportations (kg ha^{-1}) (2)
Riz	1030 (paddy)	25	13
Maïs	778 (grains)	22	12
Mil	659 (panicules)	26	12
Sorgho	806 (panicules)	28	13
Igname	9500 (30 % MS)	40	35
Manioc	7700 (30 % MS)	32	21
Banane pl.	8500 (30 % MS)	–	17
Arachide	720 (gousses)	34	25
Coton	683 (graine)	37	15

Tableau 3. Exportations par les produits marchands en Afrique de l'Ouest. (1) d'après les données de FAO – 1971 (Production Yearbook Vol. 25)

	Exportations de N (kg ha^{-1}) (produits marchands)	
	Totales	sans légumineuses
Dahomey	13	11
Ghana	13	12
Guinée	16	15
Côte d'ivoire	13	12
Niger	10	9
Nigeria	18	15
Sénégal	21	13
Haute-Volta	12	11
Moyenne	14	12

Tableau 4. Teneur en azote (% de la matière sèche) de quelques cultures.

	Céréales		autres cultures		
	Grains	Pailles	Arachide:		
Riz	1,0 à 1,5	0,5 à 1,2		gousses	1,8 à 5,0
Maïs	1,6 à 1,9	0,6 à 1,0		fannes	0,8 à 2,0
Sogho	1,4 à 2,0	0,30 à 0,60	Igname		1,20 à 2,0
Mil	1,8 à 2,5	0,60 à 0,95	Manioc		0,48 à 0,55

Les estimations prenant en compte l'importance respective des différentes cultures dans les assolements (Tableau 3) sont inférieures et se situent entre 10 et 20 kg ha^{-1} an^{-1} ou 10 et 15 kg ha^{-1} an^{-1} selon que l'on prend en compte ou non les cultures de légumineuses.

Les évaluations de Nye & Greenland (1960) sont notablement supérieures et chiffrent les exportations à respectivement 35 et 23 kg ha^{-1} an^{-1} en zone forestière et en zone de savane. Toutefois, ces estimations restent délicates dans la mesure où la pratique des cultures associées est fréquente. Quoi qu'il en soit, ces quantités utilisées par les cultures, comparées à celles libérées à partir des réserves du sol, laissant supposer l'existence de pertes nettes non négligeables essentiellement en zone forestière.

Evolution du sol sous culture: La mise en culture qui supprime la source principale de matières organiques constituée par les restitutions issues de couvert végétal originel se traduit au niveau de l'azote par des pertes dans le sol variant de 25 à 78 kg ha^{-1} an^{-1} 3 à 4 ans après défrichement (Martin, 1970; Jones, 1971; Fauck *et al.*, 1969) dans les 15 premiers centimètres. Elles peuvent être beaucoup plus importantes l'année suivant de défrichement et Fauck (1956) observe des pertes de 187 kg ha^{-1} à Sefa.

En moyennes ces pertes peuvent être estimées à 4 % par an. Elles sont le fait, d'une part de l'érosion et du ruissellement et d'autre part, de la lixiviation.

Les pertes en terre par érosion citées par Jones & Wild (1975) passant en revue les résultats concernant la zone de savane varient de 0 à 21 t ha^{-1} an^{-1} selon les techniques culturales et pour des pentes inférieures à 4 %. Les résultats moyens obtenus par Roose (1967) à Sefa sont de 9,3 t ha^{-1} an^{-1}. Ils sont voisins de ceux cités par Kowal (1970) à Samaru. Selon cet auteur les pertes moyennes en azote attribuables à l'érosion sont de 6,3 kg ha^{-1} an^{-1} et de 7,4 kg pour le ruissellement. En zone forestière, les pertes, compte-tenu des teneurs plus élevées en matière organique sont plus élevées. C'est ainsi que Roose (1973, 1977) sur pente de 7 % cite des pertes en terre de 32 t ha^{-1} se traduisant par une perte en azote de 98,3 kg ha^{-1}. Sous sol nu elles atteignent 259 kg ha^{-1} alors qu'elles ne sont que de 3,5 kg sous forêt naturelle.

En ce qui concerne la lixiviation, faible sous cultures non fertilisées: de 2 à 7 kg ha^{-1} an^{-1}, elle peut atteindre 50 kg ha^{-1} sous sol nu (Vidal & Fauche, 1962) à Sefa.

La phase jachère

Outre la protection du sol, la jachère permet une fixation nette annuelle au niveau de la végétation de l'ordre de 95 kg ha^{-1} sous forêt et de 35 kg ha^{-1} en savane (Nye & Greenland, 1960). Selon ces auteurs, compte-tenu du traitement par brûlis de cette jachère, les gains moyens annuels au niveau du sol sont respectivement de 35 et 10 kg ha^{-1} an^{-1}.

Ils ont pour origine d'une part le recyclage en surface, par le biais des restitutions, d'éléments puisés en profondeur et d'autre part les fixations biologiques.

Le recyclage de l'azote provenant des formes fixées en profondeur $N\text{-}NH_4$ est invoqué par Jaiyebo (1967) sans toutefois être chiffré. Quant aux fixations biologiques, Balandreau & Villemin (1973) ont pu mesurer en savane de Côte d'Ivoire une fixation non symbiotique de l'ordre de 10 kg ha^{-1} an^{-1}. En ce qui concerne la fixation symbiotique, Dancette & Poulain (1969) mentionnent des accroissements de rendements équivalents à des apports de 20 kg ha^{-1} sous *Acacia albida*. Son importance en général dépend de la composition floristique de la végétation et plus particulièrement de la part des légumineuses. En culture pure de *Centrosema pubescens* Moore (1963) note des gains nets dans le système sol-plante variant de 112 à 224 kg ha^{-1} des grains analogues étant obtenus sous graminées (Moore, 1962).

Conclusion

Les termes du bilan azoté d'un système sol-plante en culture traditionelle ont, exceptées les immobilisations et exportations, fait l'objet de peu de mesures en conditions réelles. Par ailleurs, beaucoup d'entre eux variant en fonction des conditions locales, il est difficile de donner des estimations moyennes.

On peut cependant noter que la productivité, bien que faible, de ces systèmes n'est entretenue que sous réserve d'un rapport temps de jachère/temps de culture assez élevé, variable selon les zones écologiques, mais supérieure à 3 en zone de savane et à 5 en zone forestière. Cette jachère permet de thésauriser les apports extérieurs: apports météoriques et fixation biologique; tandis qu'en phase de culture prédominent les pertes par érosion et lixiviation.

Les systèmes améliorés

Dans ces systèmes, l'augmentation de la productivité relève de l'amélioration d'un ensemble de facteurs agissant plus ou moins directement sur le cycle de l'azote en particulier:

- choix de variétés répondant aux engrais et densités de semis;
- applications de techniques culturales aptes à assurer une bonne alimentation minérale du couvert végétal;
- calage correct du cycle cultural par rapport au cycle climatique;
- utilisation rationnelle des engrais (modalifés des apports et nature).

En outre, l'introduction de la mécanisation peut permettre une meilleure restitution des résidus de culture et l'enfouissement de la matière verte produite par la sole de régénération quand elle existe.

Toutefois, l'enterdépendance de ces facteurs fait que les rendements observés traduisent une série complexe d'inter-actions et ceci amène à considérer différents niveaux d'intensification selon que ces facteurs sont pris en compte globalement ou partiellement.

L'alimentation azotée des plantes

Elle est assurée d'une part par la minéralisation nette des réserves du sol et d'autre part par les apports d'engrais destinés à ajuster l'offre lors des périodes de forte demande.

L'élaboration d'un plan de fumure nécessite donc la connaissance des exigences des cultures compte-tenu des objectifs de production fixés. Il doit également être raisonné en fonction du système de culture pratiqué comportant ou non des légumineuses entrant en rotation et incluant ou non une sole de régénération, celle-ci pouvant être productive au cas où une prairie est substituée à la jachère classique.

Cycle interne de l'azote: Ce cycle réglé par l'activité microbiologique est étroitement dépendant des conditions pédoclimatiques et a pour support le stock de matières organiques du sol intervenant par la valeur de leur rapport C/N. C'est ainsi que les réponses aux engrais azotés sont faibles en zone forestière immédiatement après défriche tandis que l'azote est le premier facteur limitant en zone de savane (Djokoto & Stephens, 1961 a,b).

La résultante des processus de minéralisation et réorganisation fixe la disponibilité du sol en azote minéral. Selon Chabalier (1976) travaillant sur des sols de Côte d'Ivoire où la minéralisation annuelle n'excèdent pas 120 kg ha^{-1}, on observe après des apports d'engrais de 100 kg ha^{-1} des pics de minéralisation équivalant à une fourniture de 300 kg d'azote. Par ailleurs, cet auteur par des études en laboratoire a pu préciser les paramètres cinétiques des transformation de l'azote dans le sol.

Les vitesses de minéralisation mesurées sont de l'ordre de 0,8 à 0,5 ppm par jour mais variables en fonction du pH dont la baisse se traduit par une action inhibitrice et de la nature des matières organiques incorporées au sol. C'est ainsi que des apports répétés de compost, bien qu'augmentant le coefficient de minéralisation de 3,7 à 5,4 % provoquent un ralentissement de la nitrification. Dans ces mêmes expériences, l'emploi d'engrais marqué a permi de montrer que le "turn over" de l'azote était très rapide: 25 % de l'azote minéral apporté est réorganisé en 12 jours tandis que le taux de renouvellement est de 46 %.

Cette réorganisation peut affecter 30 à 70 % de l'engrais apporté et concerne principalement les formes labiles. Les résultats mentionnés par Blondel (1971 b) illustrent également l'existence d'un cycle minéralisation – immobilisation. Les immobilisations affecteraient des quantités de l'ordre de 66 kg/ha représentant le tiers des apports. Toutefois la présence de plantes cultivées maintiendrait durant cette phase une certaine activité minéralisatrice variable selon les plantes qui interviendraient par leur activité rhizosphérique (Blondel, 1971 e).

Ces possibilités de réorganisation temporaire d'une fraction des engrais constituent dans des sols où la lixiviation des nitrates est rapide, un facteur de conservation intéressant à considérer.

Les fixations biologiques: En ce qui concerne les capacités de fixation des légumineuses Agboola & Fayemi (1972) les estiment à respectivement 450, 350, 324 kg ha^{-1} pour *Calopogonium mucunoides, Vigna sinensis* et *Phaseolus areus* cultivées en sol fertiles. Ces plantes seraient aptes à assurer leur propre alimentation azotée, et procureraient au sol des gains que Fauck (1956) a pu chiffrer à 250 kg ha^{-1} pour une culture d'arachide. Toutefois, selon Jones & Wild (1975), ce chiffre est suspect. En effet, d'autres auteurs (Martin, 1970) constate une diminution du stock d'azote total après culture d'arachide. Cependant, sous culture fourragère de légumineuse *(Stylosanthes gracilis)*, Hainnaux *et al.* (1978) chiffrent des gains nets dans le système sol-plante variant en moyenne de 50 à 150 kg ha^{-1} an^{-1} selon que ces plantes reçoivent ou non une fertilisation d'appoint autre qu'azotée.

Sous cultures de riz et de maïs Chabalier (1976) estime qu'il est peu vraisemblable qu'elles dépassent 30 unités.

Les apports d'engrais azotés: Ils sont très variables selon le niveau d'intensification. Les doses les plus fréquemment vulgarisées pour les cultures entrant en rotation dépassent rarement 25 à 50 kg ha^{-1}.

Ils visent essentiellement à l'optimisation économique du rapport outputs/inputs et ne sont pas toujours compatibles avec les nécessités agronomiques (Poulain, 1977). Dans les systèmes faiblement améliorés les apports sont par ailleurs préférentiellement réservés d'une part aux cultures de rente (coton) et ensuite aux céréales.

Toutefois, l'étude des courbes de résponse montre que sous réserve d'application d'un ensemble de techniques culturales adaptées et les autres facteurs limitant ayant été éliminés, les doses peuvent être notablement augmentées et se situer de 60 à 150 kg ha^{-1} pour les céréales. Ils peuvent atteindre 750 kg ha^{-1} an^{-1} pour les cultures fourragères mais restent faibles sous cultures de légumineuses. Toutefois, il est à noter que l'apport de hautes doses effectué le plus souvent sous forme de sulfate d'amonium provoque des chutes notable du pH.

Ces apports destinés à compenser globalement les pertes dues à la culture doivent aussi permettre la satisfaction des besoins instantanés des plantes qui peuvent varier de 1,5 à 5 kg ha^{-1} jour^{-1} selon les plantes (Blondel, 1971 f).

Le coefficient d'utilisation des engrais est plus élevés aux faibles doses que pour des apports élevés et varie de 33 à 25 % pour le riz de 60 à 35 % pour la maïs lorsque les apports passent respectivement de 60 à 120 unités et de 100 à 200 unités. Les taux pour des cultures fourragères n'excèdent pas 50 % (Hainnaux *et al.*, 1978) sont améliorés par le fractionnement (Roose & Talineau, 1974). L'engrais non utilisé par la culture peut l'être par les cultures suivantes, les quantités ainsi mises en jeu sont de l'ordre de 20 % des apports (Chabalier, 1976).

Les immobilisations

Elles sont fonction des apports et des niveaux de production qu'ils permettent comme le montrent les courbes de résponse, mais aussi des variétés plus ou moins bien adaptées. C'est ainsi que pour des apports moyens sur céréales Poulain (1967) indique que sur les variétés traditionelles cultivées l'accroissement de production affecte plus les pailles (+124 %) que les grains (+33 %). Sur cotonnier, pour un rendement de 770 kg ha^{-1} de coton-graine les résidues aériens représentent 69 % du poids total, ce taux n'est plus que de 48 % pour une production de 2150 kg ha^{-1} (Deat & Sement, 1974).

Les types de sols et les caractéristiques climatiques induisent également une forte variabilité. Dupont de Dinechin (1967a) note sur sorgho des gains de rendement variant de 624 à 1131 kg ha^{-1} selon les années, que les doses apportées soient faibles (22 kg ha^{-1}) ou fortes (100 kg ha^{-1}), les variations entre points d'essais s'échelonnant de 0 à 785 kg ha^{-1}.

Cette importante variabilité est illustrée dans les Tableaux 5 et 6. Les Tableaux 7 et 8 donnent des estimations moyennes de ces immobilisations et exportations pour différents niveaux de fertilisation azotée et en l'absence de tout autre facteur limitant. Les rendements correspondant aux fertilisation faibles à moyenne sont voisins des objectifs de production envisagés actuellement dans le cadre des opérations de développement mises en place. Ceux correspondant à la forte fertilisation sont relatifs aux résultats obtenus en stations expérimentales.

Compte-tenu des assolements et de la succession des cultures pratiquées, le Tableau 9 donne le niveau moyen des immobilisations et exportations selon que les restitutions sont totales ou partielles. En effet, dans la pratique agricole habituelle, les restitutions sont,

Tableau 5. Immobilisation d'azote par quelques cultures améliorées

Plante	Rendement (kg ha^{-1})	Azote immobilisé (kg ha^{-1}) dans la plante	dans le grain	Engrais (kg ha^{-1})
Mil P C 28 (Bambey) (1)	1930	79	31	75
Mil P C 11 (Bambey) (1)	2200	92	32	75
Mil local (Sefa) (1)	3130	132	45	50
Riz 63–83 (Sefa) (1)	3360	84	42	100
Sorgho 51–69 (Nioro) (1)	4060	134	72	100
Riz T (N) (Sefa) (1)	4240	74	50	100
Maïs Z M 10 (Sefa) 1967 (1)	4466	121	75	200
Maïs Z M 10 (Sefa) 1969 (1)	5440	138	98	200
Sorgho S 29 (Saria) (2)	2882	84	48	100
Maïs local (Faroho-Ba) (2)	3418	49	32	75
Maïs local (Faroho-Ba) (2)	3979	57	37	150

(1) : d'après Blondel (1971 b)

(2) : d'après Dupont de Dinechin (1967 a & b)

Tableau 6. Reponse à la fertilisation azotée de quelques cultures

Riz Senegal (Siband 1970)		Sorgho Haute-Volta (Chaminade 1970) Sols à concrétions		Mais Haute-Volta (Dupont de Dinechin 1967 a & b)	
Apports (kg ha^{-1})	Rendements (kg ha^{-1})	Apports (kg ha^{-1})	Rendements (kg ha^{-1})	Apports (kg ha^{-1})	Rendements (kg ha^{-1})
0	2610	0	1150	0	716
37,5	4620	25	1460	25	1549
75	5420	50	1610	50	2656
112	5800	75	1740	75	3456
				150	3979
Côte d'Ivoire (Chaminade) +		**Haute-Volta (Chaminade) + Sol gravelleux**			
0	2300	0	420		
20	2740	25	520		
40	3080	50	710		
80	3960	75	800		

Tableau 7. Exportations en azote (kg ha^{-1}) par tonne de produits marchands

Culture	Exportation par les produits marchands (kg ha^{-1})	
Riz	12	(0 à 15)
Mais	15	(10 à 19)
Sorgho	16	(14 à 22)
Mil	20	(18 à 25)
Arachide	50	(30 à 55)
Coton	28	(25 à 32)
Igname	4	(3 à 6)
Manioc	3	(2 à 4)

pour certaines cultures, faibles. Pour le manioc, les bois qui immobilisent environ 30 % de l'azote ne sont pas restitués et servent à la préparation des boutures. En ce qui concerne le coton, les tiges sont pour des raisons techniques (difficultés d'enfouissement) ou phytosanitaires, brûlées. Quant aux fanes d'arachide, elles servent dans de nombreuses régions à l'affouragement du bétail. De plus, cette culture ne reçoit en général qu'une faible fertilisation azotée.

Ainsi, dans la plupart des systèmes pratiqués, les restitutions proviennent essentiellement des pailles de céréales. Elles constituent comme l'ont noté de nombreux auteurs et en particulier (Poulain (1977) une pratique nécessaire à l'entretien de la fertilité.

La variabilité observée tient aussi d'une part à la possibilité d'effectuer un ou deux

Tableau 8. Immobilisations et exportations moyennes en fonction des niveaux de fertilisation

Niveau de fertilisation azotée (kg ha^{-1})	Rendements (kg ha^{-1})			Immobilisation par la plante (kg ha^{-1})			Exportation par les produits marchands (kg ha^{-1})		
	8 – 15	25 – 50	75 – 150	8 – 15	25 – 50	75 – 150	8 – 15	25 – 50	75 – 150
Riz	1300	2800	3500	40	70	85	20	34	45
Maïs	1500	3500	5000	45	80	115	25	52	75
Mil	1100	1700	2000	50	70	95	20	30	40
Sorgho	1300	2500	3000	45	75	90	20	38	45
Arachide	2200	–	–	130	–	–	88	–	–
Coton	900	1500	1900	70	90	100	25	42	55
Igname	15000	30000	–	75	140	–	70	110	–
Manioc	15000	30000	50000	80	150	200	50	90	130

Tableau 9. Immobilisations et exportations moyennes annuelles (kg ha^{-1})

Apports kg/ha	Immobilisations (kg ha^{-1})	Exportations (kg ha^{-1})	
		Restitutions totales	Restitutions partielles
8 – 15	85 (60 à 105)	50 (25 – 65)	65 (40 – 90)
25 – 50	110 (85 à 130)	70 (40 – 85)	85 (60 – 105)
75 – 150	125 (95 à 150)	80 (60 – 105)	95 (75 – 115)

cycles culturaux par année et d'autre part à la proportion des céréales par rapport aux autres cultures, essentiellement les légumineuses et les plantes à tubercules. En ce qui concerne la balance (apports-exportations), il appararaît qu'elle ne devient positive que pour des apports élevés qui correspondent à l'efficience moyenne la plus faible des engrais, et à condition de restituer le maximum de résidus de cultures.

Les bilans minéraux sous culture

Les pertes par lixiviation mesurées à Bambey en cases lysimétriques (Blondel, 1971a) varient en fonction de la dose et de la nature des apports (Tableau 11). Elles sont aussi fonction du couvert végétal comme l'illustrent les résultats de Tourte *et al.* (1964) selon lesquels elles passent de 45, 6 kg ha^{-1} sous sol nu à 14, 9 kg ha^{-1} sous culture d'arachide et à 4 kg sous jachère. Sous culture de céréales, elles se situent entre 40 et 45 kg ha^{-1} pour des apports variant de 83 à 140 kg ha^{-1}.

Selon, Chabalier (1976), seulement 1 à 5 % des pertes, sur un total variant de 30 à 70 % des apports, proviendraient directement des engrais, la reste résulterait de la minéralisation.

Jones (1975) par des études au champ sur maïs les estime à 25 % des apports en zone de savane. Sous cultures fourragères, graminéennes Hannaux *et al.* (1978) observent des pertes annuelles variant de 560 kg ha^{-1} sous *Cyonodon aethiopicus* à 170 kg ha^{-1} sour *Panicum maximum* pour des apports de 750 kg ha^{-1} an^{-1}. Le fractionnement de ces apports sous *Panicum* réduiraient ces pertes des 2/3 (Roose & Talineau, 1973). D'autre part, en culture bananière intensive, les pertes par ruissellement et drainage atteindraient 210 kg ha^{-1} an^{-1} pour des apports de 380 kg (Roose & Godefroy, 1977; Godefroy *et al.*, 1975).

Quant aux pertes par dénitrification, Chabalier (1976) a pu expérimentalement en préciser l'importance et les évalue entre 25 et 75 kg ha^{-1}. C'est ainsi que pour des cultures céréalières conduites avec restitution des pailles, il calcule pour le système sol-plante des bilans dont le déficit varie de 25 à 190 kg d'azote. Tourte *et al.* (1964) pour une succes-

Tableau 10. Balance entre gains et pertes en azote à Sefa, pour une succession de 5 cultures

Culture	Traitement des résidus	Apports kg/ha	Exportations kg/ha
Jachère	enfouis	40	0
Maïs	enfouis	120	95
Riz	exportés	69	86
Arachide	exportés	10	0
Mil	brûlés	69	120
Total		308	301
Pertes par lixiviation		–	150
Moyenne annuelle		61	90

Tableau 11. Bilan de l'azote en sol sableux au Sénégal. (Blondel 1971 a)

	N ($NO3^{-}$)		N ($NH4^{+}$)		
Azote apporté (kg ha^{-1})	300	600	300	600	0
Azote mobilisé par la culture (kg ha^{-1})	110,6	294,9	220,0	262,8	9,4
Azote lixivé (kg ha^{-1})	64,9	108,6	9,9	17,9	3,9

sion jachère-arachide-céréale-arachide situent le déficit entre 48 et 96 kg ha^{-1} an^{-1} sans prendre en compte le rôle bénéfique éventuel de l'arachide. Si l'on suppose une auto-suffisance de cette culture, le déficit est ramené à 40 kg ha^{-1} an^{-1}.

Charreau & Fauck (1970) ont calculé un déficit de l'ordre de 30 kg ha^{-1} dans le cadre d'une rotation de cinq ans à Sefa (Tableau 10). Ces déficits le plus souvent constatés du bilan minéral expliquent les diminutions des réserves azotées du sol observées sous cultures continues (Fauck *et al.*, 1969; Jones, 1071; Siband, 1972).

Conclusion

Si la culture continue semble possible sous réserve d'une utilisation rationelle des engrais et d'une restitution de l'ensemble des résidus de récolte, elle reste l'apanage des stations expérimentales où l'ensemble des techniques culturales peuvent être appliquées dans des conditions d'efficacité maximum. Les apports d'engrais minéraux tout en augmentant considérablement la productivité des systèmes sol-plante ne permettent pas, le plus souvent, du fait de l'importance des pertes par érosion, drainage et volatisation, d'équilibrer le bilan en azote.

Aussi, tant qu'un seuil minimal de technicité n'aura pas été atteint, l'introduction d'une sole fourragère à base de légumineuses peut constituer une solution efficace à l'entretien d'un équilibre azoté satisfaisant au niveau des rotations culturales. De même, la restitution des résidus de culture constitue un impératif au maintien du bilan humique des systèmes intensifiés (Talineau *et al.*, 1976).

Conclusion générale

La mise en cultures puis leur intensification se traduit au niveau du cycle de l'azote par une ouverture de plus en plus importante. Si la productivité ne peut être en l'état actuel des connaissances améliorée et maintenue que par des apports d'engrais, ceux-ci ont pour conséquence une augmentation souvent importante des pertes.

Ainsi, même les apports à doses faibles ou moyennes, vulgarisées plus en fonction de critères "économiques" que de critères agronomiques restent insuffisants pour équilibrer le bilan azote. Ils risquent par ailleurs, du fait des effets cumulatifs, d'engendrer à terme des déséquilibres affectant des éléments autres que l'azote. Tourte (1971) ont illustré ces problèmes au Sénégal et montré qu'un bilan positif ne peut être obtenu que par l'intensification simultanée d'un ensemble de techniques culturales qui outre l'utilisation des engrais à des doses moyennes à élevées comportent l'enfouissement d'une jachère et la restitution des résidus de culture.

Dans ces conditions, l'adaptation de l'ensemble des techniques culturales d'une part, et le choix judicieux des systèmes de culture d'autre part, constituent des éléments essentiels du contrôle de ce cycle.

Une autre voie possible d'amélioration semble être l'introduction dans les rotations, d'une sole fourragère productive constituée de légumineuses. D'autre part, étant donné l'accroissement notable des pertes d'engrais aux fortes doses d'apport, et compte tenu de la diminution de leur efficience, l'amélioration génétique et la sélection de variétés aptes à utiliser par voie de fixation symbiotique ou non l'azote atmosphérique, constituent des voies à approfondir.

Enfin, il est nécéssaire pour rationaliser la gestion du stock d'azote du sol de mieux connaitre les mécanismes qui règlent le cycle interne de cet azote et leur déterminisme.

Quoi qu'il en soit, les données disponibles sont en l'état actuel des connaissances insuffisantes pour évaluer de façon exhaustive et fiable tous les termes du bilan azoté d'une succession culturale au champ. La détermination des valeurs moyennes à partir d'expérimentations particulières et adaptées à la mesure de chacun d'entre eux pris isolément élimine les interactions possibles et peut présenter un risque d'erreur important.

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Nitrogen Cycling in West African Ecosystems

FARMING SYSTEMS OF WEST AFRICA IN RELATION TO NITROGEN CYCLING

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Abstract

An overview of farming systems in West Africa is given. Considerations include the influence of the physical environment. The developments of different farming systems are discussed. The nitrogen cycles of regional farming systems are considered as is the management impact of the nitrogen cycle.

The physical environment

In this paper, West Africa is considered to be the region which extends from between Capes Blanco and Verde in the north to Mount Cameroun in the south. It is bounded by the Atlantic Ocean to the south and the Sahara Desert to the north. This corresponds to an area between latitudes 4.5° and 18° N and between longitudes 15° E and W. It is approximately 3,500 km long and 1,900 km wide with an area of about 6.5×10^6 km^2. Topographically much of West Africa consists of plains ranging from 150 to 450 m above sea level with lowland areas below 150 m consisting of the narrow coastal belt and lower valleys of major rivers flowing into the Atlantic from the Senegal River in the north to the River Niger and Cross River in the south. Much of the hinterland consists of a plateau of above 500 m which rises by a series of steps from the coastal plains. On the plateau there are scattered hills and mountains of over 900 m such as the Futa Jallon, Mount Loma, Guinea Highlands, Nimba mountains, Tibesti mountains, Jos Plateau, Adamawa mountains and Mount Cameroun which attains the highest altitude of 1380 m (Fig. 1). The plains are dissected into a mosaic of watersheds and valleys of two river systems, consisting of those flowing from the edge of the plateau directly to the sea and others which flow inland and then like the Niger turn southwards and empty into the Atlantic. The land mass itself is made up of crystalline igneous and metamorphic rocks of the Basement Complex, older sandstones in parts of Ghana, Mali and Guinea and younger sedimentary rocks in the extreme west and northern margins of the region, the valleys of the Niger and Benue rivers and coastal plains of Nigeria. There are small areas of volcanic rocks near Dakar, Jos Plateau and Adamawa mountains in Nigeria, Mount Cameroun, Air and Tibesti mountains in Niger and Chad (Pugh & Perry, 1960; Morgan & Pugh, 1969).

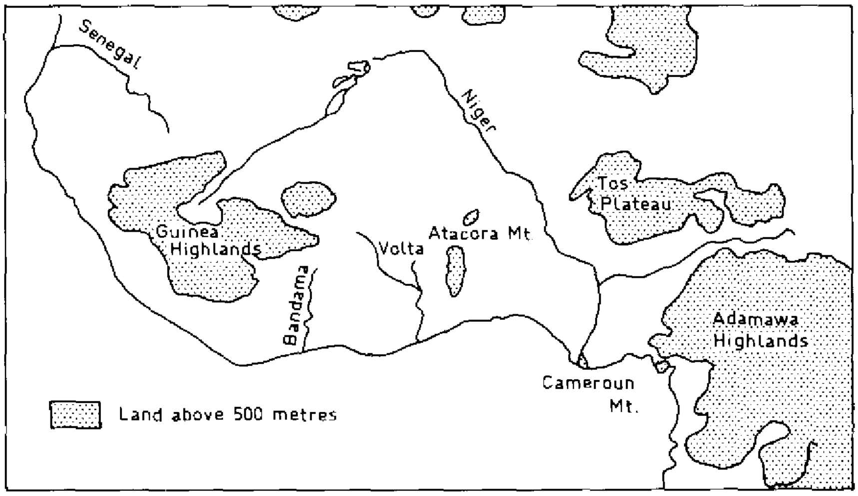


Figure 1. West Africa showing main topographic features.

Climate

The climate of West Africa varies from wet in coastal areas to dry or desert in the northern area close to the Sahara (Fig. 2). In the humid and subhumid areas of *Af* and *Am* climates of Koppen and Thornthwaite (Trewartha, 1968; Hare, 1973) prevail. There is in general high uniform insolation and temperatures with annual means of 25–27°C in areas of not more than 1000 m altitude near the equator with the average coldest monthly temperature not exceeding 18°C. In the savanna and semi-arid areas of the *B* climates, insolation is also usually high and the mean monthly maximum temperatures range from 27–35°C in August and March, respectively, while the minimum monthly means range from 14–22°C in December/January and April, respectively. The two dominant wind systems of the region – the northerly dry harmattan from the Sahara and southwesterly monsoon of humid oceanic air meet at the Intertropical Convergence Zone. The annual north to south movements of this zone result in a very short rainy season of less than 2 1/2 months close to the Sahara and a longer rainy season of 10 to 12 months in the coastal areas. The coastal areas are noted for their high atmospheric humidity and heavy rainfall during all or most of the months of the year. The mean annual rainfall ranges from that of a single peak of up to 4000 mm and no dry season in areas of *Af* climate, to the two peak rainfall areas of below 1500 m with *Am* climate. In areas of *B* climates, mean annual rainfall varies from slightly above 1000 mm to less than 400 mm in the extreme north (see Fig. 3). The characteristics of the bioclimatic zones of West Africa are summarized in Table 1.

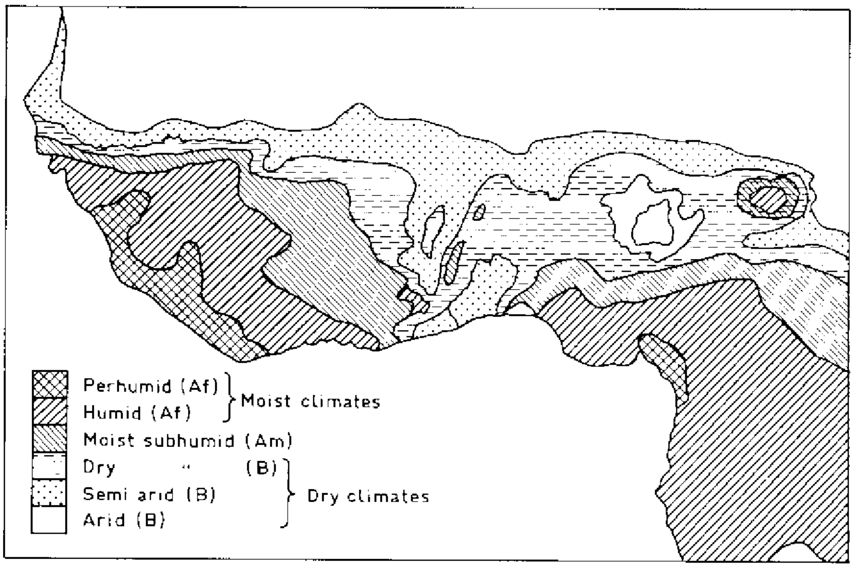


Figure 2. Climatic zones of West Africa (after Thornthwaite & Johnson, 1958).

Table 1. Bioclimatic regions of West Africa

1. **Guinean climatic region proper (perhumid and humid)**

   Subequatorial climate
   Rainfall two peaks or one
   Rainy season 7–12 months
   Dry season driest month with 50 mm
   Temperature (mean) about 21°C
   High relative humidity throughout year
   Woody fallows

2. **West Guinean region (humid – most subhumid)**

   One rainy season of 7–9 months
   Dry season more pronounced
   High relative humidity

3. **Guinean–Sudanic transition (dry subhumid)**

   A. Southern Sub-Guinean
   Two rainy seasons 7–9 months
   Slight variation in temperature and dry season

   B. Northern Sub-Sudanic
   Single rainy season 5–7 months
   Minimum temperatures in dry season
   Zone of Tsetse infestation

4. **Sudanic Tsetse free zone (dry subhumid)**

   Tropical dry climate
   Rainy season 2 1/2–5 months
   Pronounced dry season

5. **Sahelian (semi-arid)**

   Low rainfall
   Rainy season $<$2 1/2 months
   Irrigation necessary for crop production except for millet

6. **Saharan (arid)**

   Total annual rainfall $<$25 mm
   Occasional rainfall in rainstorms

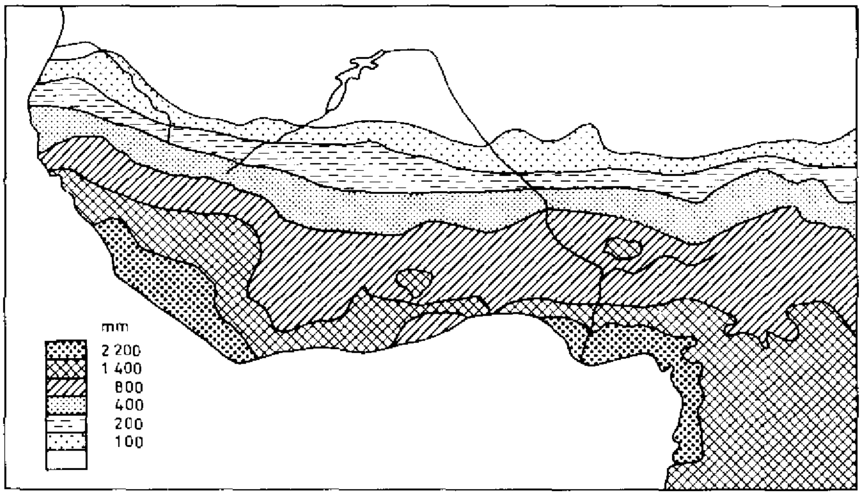


Figure 3. West Africa: Mean annual rainfall (adapted from Morgan & Pugh, 1969; Best & Vlij, 1977).

Vegetation

The vegetation zones run parallel to those of rainfall and temperature from the coast inland. The coastal areas are mangrove swamps. Next to these and further inland, areas of *Af* climate support broadleaved evergreen climax vegetation of tropical rainforest followed by areas of *Am* climate with a mixture of evergreens and deciduous trees (Fig. 3). Further inland are parallel zones of forest/savanna mosaic, Guinea savanna, Sudan savanna and Sahel Savanna vegetation zones. Mountainous vegetation is found in areas of over 1000 m in elevation (Fig. 1).

Soils

As a result of interaction of parent material, topography, vegetation and organisms through time, soils of West Africa consist mainly of Alfisols, Oxisols and Ultisols (Donahue, 1970; NAS 1972; Sanchez, 1976) (Fig. 4).

In Nigeria, for example, there are (1) upland well-drained Alfisols of low to medium native fertility derived from the Basement Complex rocks associated with relatively more fertile but poorly drained valley bottom and hydromorphic soils (Entisols and Mollisols), (2) upland well-drained Ultisols of low native fertility derived from Cretaceous sandstones and Pleistocene coastal sandy sediments with more fertile valley bottom soils (Entisols) and (3) the acid sulphate problem soils (Sulfaquents) of the coastal mangrove swamps. Aridisols predominate in the areas bordering the Sahara desert.

As compared to the soils of the temperature regions, these soils are characterised by (a) deeper and more intensely weathered pedons with few remaining weatherable minerals, (b) lower percentage of silicon, (c) higher percentage of iron and aluminium especially in the form of amorphous oxides, (d) higher percentage of kaolinite and smaller percentage of montmorillonite, (e) lower cation exchange capacity, (f) lower

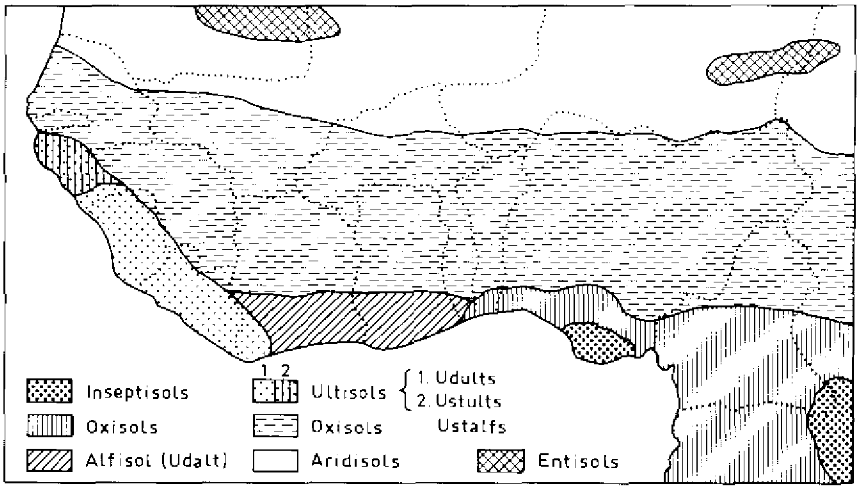


Figure 4. Major soils of West Africa (NAS, 1972).

buffer capacity, (g) lower available water capacity, (h) a lateritic (plinthite) layer in some soils that hardens by crystallization of the iron in continuous exposure to cycles of wetting and drying as would occur under continuous cropping, (i) less accumulation of leaf litter as a result of more rapid decomposition and (j) low reserves of total available nutrients (Donahue, 1970). Consequently, although these soils possess good structural characteristics, they are inherently infertile and processes of degradation are intense and active throughout the year. Fertility is maintained in the surface horizons under forest or good vegetation cover but rapid losses in fertility and soil erosion occur with the removal of vegetation, especially on sloping land.

Countries and peoples

In West Africa, as defined above, there are 18 countries with a population of over 120 million people of diverse religious, linguistic and cultural groupings, and different colonial history and background. They are characterized by (a) their having gained independence within the last two decades, (b) they belong to the developing countries of the world, (c) over 70–80 % of the population are engaged in agriculture, (d) agricultural economy is predominantly in the hands of smallholders, (e) traditional agriculture is mainly for subsistence but is by necessity increasingly becoming also partly commercial, (f) low agricultural productivity, (g) commercial agriculture is mainly export-oriented with narrow regional specialization except for countries such as Ivory Coast, (h) until recently cash or export crops have been given high priority at the expense of food crops, (i) high rates of population growth with over 40 % of population less than 15 years old, (j) land and labour resources under-utilized, (k) increasing gap between the rich and the poor, (l) increasing food import bills and (m) preoccupation with nation-building and economic development.

It is against this background that the farming systems of the region and nitrogen cycling associated with them are reviewed below.

Farming systems of West Africa: Their development, characteristics, complexity and problems

Farming systems: What they are and the need to study and understand them

A farming, farm, or agricultural system consists of an enterprise or business in which sets of inputs and resources are uniquely orchestrated by the farmer in such a way as to achieve, with varying degrees of success, one or more objectives in a given environmental setting (Table 2). In the tropical West African context, the farm may be an enterprise or activity of one or more individuals, usually a family unit. Varying numbers of people in the family participate for part or most of the time in farm work. The farming systems of West Africa are often complex because of the range of objectives that they are expected to satisfy. Each of these complex farming systems consists of one or more subsystems each of which is differentiated from others in terms of physico-chemical (soils, water, climate, nutrients), biological (crop plant, animal, pests), socio-economic (labour, markets, preference, religion), technological (tools, machines, practices) and managerial (knowledge, decision-making) elements involved in the agricultural production process. Consequently, a given farm system or subsystem is location specific in terms of sets of these elements that are involved in relation to the objectives to be satisfied.

It is necessary to study and classify farm systems if we are to be able to operate them, repair them, improve them or otherwise modify them, and model or construct more efficient new ones as may be necessary (Spedding, 1975). There is no currently accepted

Table 2. Objectives of agricultural production or farming systems*

	Major products		Objectives
1.	Human food	(a) plant origin	(a) Feeding local population
		(b) animal origin	(b) Export or substitution for imports
2.	Animal feed	(a) plant origin	(a) Feeding local animals
		(b) animal origin	(b) Export for farm animals and pets
3.	Raw materials for industry		(a) Industrial food production
		(a) plant origin	(b) Industrial feed production
		(b) animal origin	(c) Processing, manufacture of clothing, furnishings, etc.
4.	Waste products and manures**		
		(a) plant origin	(a) animal feed
		(b) animal origin	(b) plant food (organic manures)
5.	Recreational or Aesthetic Facility		(a) Farm zoos
			(b) Ornamentals for landscaping
			(c) Other amenities provision
6.	Money		(a) Profit
			(b) Return on investment

* Source: Adapted from Spedding (1975) based on Bunting (1971)

** Not included in the original.

typology for the classification of farm systems but the classification of existing farming systems shown in Table 3, which is of relevance to the topic of concern in this paper, is based on those of Whittlesey (1936), Allan (1965), Benneh (1972), Greenland (1974), Ruthenberg (1974), Spedding (1975), and Okigbo & Greenland (1976).

Development of farming systems of West Africa

The existing farming systems of tropical West Africa may be regarded as the culmination of several centuries or thousands of years (perhaps over 4000 years) of trial and error, diffusion of ideas and transfer of materials and practices developed elsewhere (Okigbo, 1978). The historical background to the existing farming systems in West Africa have been reviewed by Portères (1962), Wrigley (1960), Coursey (1976), Morgan & Pugh (1969), Shaw (1968, 1972, 1976), Purseglove (1976), Harris (1976), Harlan (1976) and Havinden (1975). Only a brief review relevant to the discussion in this paper will be presented. The report of Harlan *et al.* (1976), based on all available evidence (archaeological, botanical, anthropological, etc.), concluded that 'traditional African agriculture is a mosaic of crops, traditions and techniques which does not reveal a center, a nuclear area or single point of origin'. Portères (1962) and Harris (1976) have advanced the concept of African agriculture originating as two complexes – a seed agricultural complex characteristic of the savanna and a vegecultural complex peculiar to the forest regions and in-

Table 3. Classification of farming systems in Africa*

A. Traditional and transitional systems	B. Modern farming and their local adaptation
1(a) Nomadic Herding*** (b) Shifting cultivation (Phase I) $L > 10$**	1. Mixed farming
2. Bush fallowing or land rotation (Shifting cultivation; Phase II) $L = 5 - 10$)	2. Livestock ranching***
3. Rudimentary sedentary agriculture (Shifting cultivation; Phase III) $L = 2 - 4$)	3. Intensive livestock production (poultry, pigs, dairying)
4. Compound farming and intensive subsistence agriculture (Shifting cultivation; Phase IV) $L < 2$)	4. Large scale farms and plantations (a) Large scale food and arable crop farms based on natural rainfall. (b) Irrigation projects involving crop production. (c) Large scale tree crop plantations
5. Terrace farming and floodland agriculture	5. Specialized horticulture (a) Market gardening (b) Truck gardening and fruit plantations (c) Commercial fruit and vegetable production for processing
6. Mediterranean agriculture (traditional)***	6. Mediterranean agriculture (modern)***

* Adapted from Whittlesey, 1936; Morgan and Pugh, 1969; Floyd, 1969; Laut, 1971; Benneh, 1972; Greenland, 1974.

** $L = C+F/C$ where C = Cropping period, F = Fallow period, L = Land use factor

*** Of little or no relevance to the humid tropics proper.

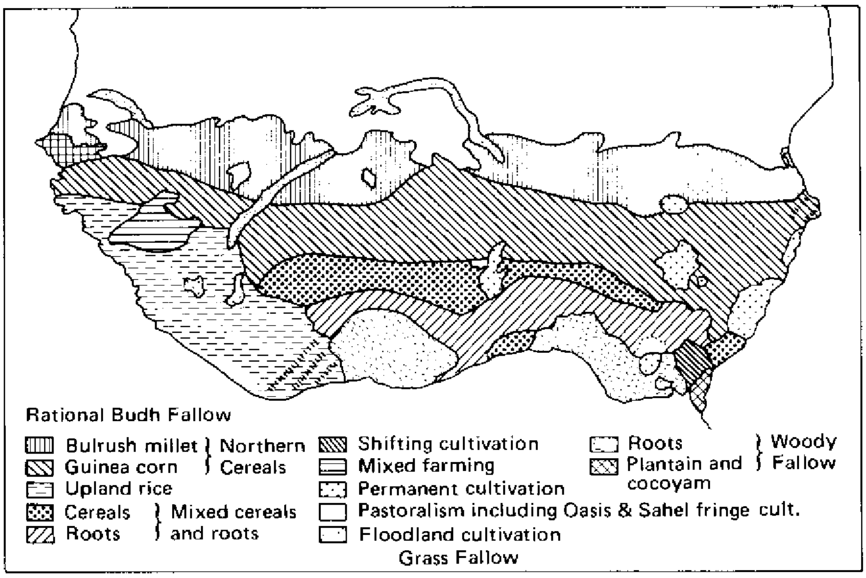


Figure 5a. Farming systems and crop dominance of West Africa (after Morgan & Pugh, 1969)

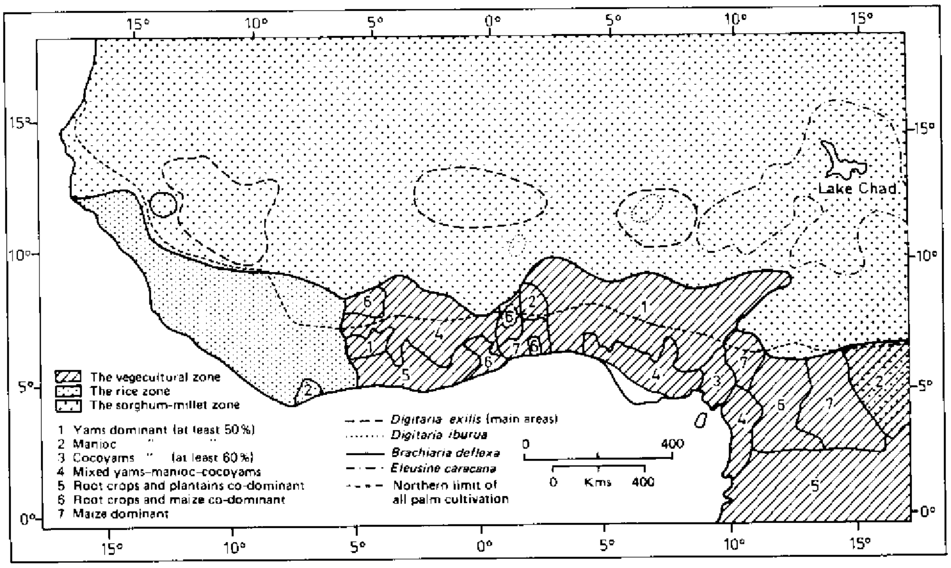


Figure 5b. West Africa: traditional crop zones and subareas of crop dominance (Harris, 1976).

volving the growing of roots, tubers and cuttings in gardens rather than seeds in fields. While there is no agreement among proponents of diffusion and those of independent origin, it would appear that after thousands of years of hunting and gathering and experimentation with plants and animals, there were domesticated, perhaps over 4,000 years ago, (a) African yams (*Dioscorea* spp.) oil palm and other crops east of the Bandama river, (b) African rice (*Oryza glaberrima*) west of the Bandama river but originating in the middle Niger basin and (c) further inland in the Sudan and Sahel savannas sorghum (*Sorghum bicolor*) and millets (*Pennisetum* spp. and *Digitaria* spp.) (Fig. 5a and b).

In each crop dominance area other minor crops including fruits and vegetables were also domesticated. The production of these crops was part of an early slash and burn shifting agriculture and in the case of rice, a hydraulic system of production followed by upland rice culture. At about the first millenium A.D. came Asian crops such as water yam (*Dioscorea alata*), bananas and plantains (*Musa* spp.), cocoyam (*Colocasia* sp.), citrus fruits (*Citrus* sp.), etc. Following these, after the discovery of America in 1492, were maize (*Zea mays*), cassava (*Manihot esculenta*), papaya (*Carica papaya*), groundnuts (*Arachis hypogaea*), lima beans (*Phaseolus lunatus*), and more recently cocoa (*Theobroma cacao*). Many of these were not only cultivated as indigenous yams or other crops but were grafted into the existing farming systems. Associated with those crops is the rearing of animals, with the larger animals such as cattle and horses restricted to the savanna areas where tsetse flies are absent and where nomadic herding developed early and is still widespread today. In more humid tsetse infested areas, varying numbers of small livestock such as sheep, goats, pigs and poultry are kept.

It is obvious that the farming systems in West Africa have not remained static. Significant changes have occurred as a result of (1) European colonization which followed the trade in spices, forest products, ivory, slaves, etc., (2) rapid population growth resulting from advances in medicine and sanitation and necessitating increased production of food and intensification of production, (3) development of markets for perennial crops, (4) expansion of cassava production due to its adaptation to marginal soils and ability to grow in the dry season, (5) increasing commercialization of food crop production, (6) development of railways, road systems, with new settlements and markets along them, (7) increased demand and production of vegetables for urban centres and local processing plants and (8) efforts made to introduce production systems used in developed countries, all of which have resulted in development of new farming systems and adaptation of exotic crops and techniques to local conditions. Consequently, the existing farming systems may be regarded as consisting of traditional, transitional and 'modern farming' systems (Table 3). It is necessary that in relation to nutrient cycling due consideration be given not only to the classification based on intensity of cropping (Table 3) but also to the various crop dominance regions (Fig. 5).

General characteristics of farming systems of West Africa

As presented in Fig. 5, the various crop dominance regions of West Africa consist of an eastern root crops/plantain, cocoyam dominant region, a cereal dominant region in the Accra plains (coastal savanna) and west of the Bandama river in Ivory Coast, a rice dominant area where also maize and cassava are becoming increasingly important. North of the root crops and rice zones is a 'middle belt' of mixed cereal and root crops followed by

Table 4. Areas (acres) under important crops in Nigeria in relation to the system of production in 1970/71

Crops	Acreage Sole	Acreage Mixed	Percentage Mixed
Yams	503.7	733.2	59.2
Cassava	307.2	112.6	26.8
Cocoyam	27.4	173.9	86.4
Rice	103.9	143.3	58.0
Maize	355.2	1092.8	75.5
Melon	25.9	334.3	92.8
Cowpeas	39.0	3777.1	99.0
Groundnut	19.8	419.7	95.5
Cotton	130.2	524.5	80.1
Guinea corn	1152.0	4557.0	79.8
Soya-bean	48.2	51.8	51.8
Benniseed	36.8	41.3	52.9
Millet	510.9	4411.1	89.6

Source: Okigbo, B.N. (1978)

sorghum and millet dominant zones. A common feature of the cropping systems of tropical Africa is the widespread practice of intercropping, the extent of which is shown in Table 4 summed over states and ecological zones in Nigeria. Most farmers in the more humid areas of West Africa keep small livestock (goats, sheep, pigs, poultry) in association with crop production. It is only in the tsetse-free areas and the savannas that there are nomads who specialize in livestock production in addition to mixed farmers who keep large animals for work and other purposes in addition to crop production.

A simplistic model of traditional farming systems would consist of a concentric pattern of fields on which are practised various methods of fertility maintenance or fallows, clearance systems, production of varying numbers of species of crops and cropping patterns and sequences according to prevailing practices, customs and needs of the farmer (Fig. 6). Below is a review of the general characteristics of traditional farming systems of tropical Africa according to Okigbo & Greenland (1976):

(a) Farm sizes are small and in southern Nigeria over 80 % of the farms are only 2 ha or less (Table 5). Large-scale tree crop plantations or monocultures are in countries such as Ivory Coast and Cameroun but smallholder tree crop plantations predominate in Ghana and Nigeria. Farm sizes in the savanna are slightly larger than in the humid areas.

(b) Farming is based on simple tools and predominant use of human labour in the humid areas since cattle are almost absent where tsetse flies and trypanosomiasis are endemic. Increasing use of animals for work is being made in savanna areas where mixed farming has been successfully introduced.

(c) There is diversity of farming systems ranging from 'true shifting cultivation' and nomadic herding where settlement is moved to permanent cultivation. Although true 'shifting cultivation' where settlement is moved is claimed to be restricted to

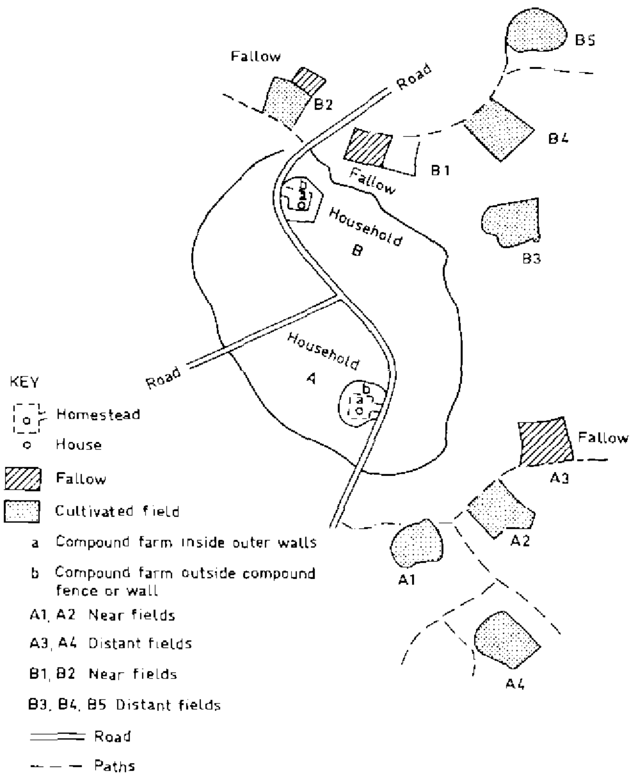


Figure 6. Schematic diagram of compound forms in relation to associated field systems in traditional farming systems of the humid tropics of West Africa (Okigbo & Greenland, 1976).

Table 5. Percentage of total land area farmed by size of household farms in Nigeria and in Bendel (humid tropics region) and Northwestern State (Savanna and Sahel) region in 1970/71

Size of household	Nigeria Percentage of total area on farm	Bendel State Percentage of total area on farm	Northwestern State*
Under 0.01	3	6	1
0.01–0.019	6	13	3
0.01–0.039	15	26	9
0.04–0.9	31	40	25
1.0 –1.9	27	11	43
2.0 –3.9	15	4	18
4.0 –5.9	3	–	1
6.0 –7.9	–	–	–
8.0 +	–	–	–

Source: Agricultural Statistic Unit (1972) Nigeria Rural Economic Surveys: Consolidated Results of Crop Estimation Surveys 1968/69, 1969/70 and 1970/71. Lagos: Federal Office of Statistics.

*Northwestern state = present Sokoto and Niger states.

parts of Ivory Coast and the Cameroun Republic (Morgan, 1969; Grigg, 1974), it is very likely that long term fallows, where temporary settlement is built on or close to distant farms, have replaced it.

(d) The centre of activity from where roads or paths radiate to all field systems is the compound farm or homestead garden on which permanent cultivation occurs. Permanent cultivation occurs in the terrace agriculture on steep hill slopes such as in parts of the Guinea Highlands, Jos Plateau, Mandara Mountains and at Maku in the Anambra State of Nigeria. Permanent cultivation is also a feature of the overcrowded high population density areas of southeastern Nigeria in parts of Anambra, Imo and Cross River States and the Kano close settled zone in northern Nigeria.

(e) The compound farm, which is the most widespread feature of agriculture of the region, is the most intensive farming system in which the largest number (up to 60 species of crops in the more humid areas and about half as much in the savanna) are grown for food, fibre, condiments, or spices, masticants, drugs, dyes, structural materials, animal feed, demarcation of boundaries, firewood, ornaments, shade and protection of homestead, religious and social functions and various other uses. Its development is related to (i) the division of labour between the sexes in which women, responsible for cooking, grow as many vegetables, condiments and spices in the compound as they can to enhance regular harvesting, minimize storage problems and purchasing from the local market and (ii) use of the compound for growing various useful plants which are fast disappearing from the forest due to frequent clearing or exotic and choice useful plants introduced from neighbouring compound farms and distant places. Soil fertility for permanent cultivation is usually maintained with household and kitchen refuse, ashes, farm residues, animal pen manure, human waste, etc. Annual staples, vegetables and other food plants are grown among perennial trees and shrubs. Some crop plants on compound farms occupy characteristic locations in rows, patches and complex intercropping mixtures producing a multi-stored structure approximating a tropical forest ecosystem in areas of sufficient rainfall.

(f) Next to the compound farm and on its periphery are 1–2 year or short term fallow rotations in which tree crops are cultivated or protected in mixtures with annual staples and other crop plants, but the agroecosystem rarely attains the complexity of the compound farm. In savanna areas protected trees such as *Parkia* spp., *Baobab*, and *Butyrospernum paradoxum* are dotted about the farm. In southern Nigeria, oil palms, oil bean (*Pentaclethra macophylla*) and *Dialium guineense* may occupy similar locations on the farms.

(g) On the other field systems farther away from the homestead are practised the second most widespread farming system consisting of bush fallows of short or long duration depending on population pressure and characterized by (i) the length of fallow decreasing with increasing population pressure and distance from the compound farm, (ii) dominant crop species consisting mainly of staple food crops and some vegetable crops with some protected or wild useful plants scattered about the farm, (iii) use of natural fallows of *Acacia* spp. and other plants in savanna areas or in the humid tropics dominant species such as *Alchornea cordifolia*, in association with abundant species including *Harunga madagascariensis*, *Dialum guineense* and

Cnetis ferruginea, Uvaria chamae, Monodora tenuifolia, Napoleona vogelli, etc. (iv) purposely planted fallows of *Acioa barteri* and *Anthonata macrophylla* in densely populated areas of southeastern Nigeria where fallows are of only 4 -8 years duration, and *Glyricidia sepium* in Oyo and Ondo States, (v) heavy pruning of trees and shrubs to stumps of 1.5 -2.5 m and clearing by the conventional slash and burn techniques and (vi) use of the short stumps for staking of climbing or twining crops such as yams, lima beans, and pumpkins and hanging or desiccating of hard-to-kill weeds such as *Commelina* spp.

(h) Preplanting cultivations may be on the flat with minimum cultivation, holes, mounds, beds or ridges of various sizes.

(i) Intercropping of various kinds (mixed, row, patch and relay patterns) and their sequences is common in all field systems but row intercropping is restricted to situations where animals or tractors are used for ploughing. Multiple cropping involving sole crop sequences is rare except in vegetable gardening. Cropping is continued for 3–5 years as long as fertility of the land can support and weeds do not take over.

(j) Growing of crops in pure culture (sole cropping) is most common in cash crops such as cotton and groundnuts in the savanna or cocoa, rubber and oil palm in more humid areas. Classical rotational sequences of sole crops are rare but there is a definite order of certain crops in the sequence during the cropping phase. For example, nitrophiles or important staples such as yams, maize and associated vegetables in intercropping systems are planted first after bush clearing, while others such as cassava, which is adapted to marginal soils, are often the last in the sequence just before the land reverts to fallow. Sometimes one cassava crop may precede another cassava crop.

(k) Most cropping patterns in upland areas depend on the prevailing rainfall regime unless there is supplementary irrigation.

(l) Traditional cropping systems take advantage of local topographic features - toposequences, microrelief, termite hills and other related relief peculiarities. Unfortunately, except for sugarcane and vegetable crops production, especially close to urban centres, not much advantage has been taken of the highly fertile hydromorphic soils as is the practice in the rice culture of southeast Asia. Depressions and temporarily flooded valley bottom soils in savanna areas close to towns and villages are often used for horticultural crops and off-season vegetables. Not only do some crops such as pineapples, bananas, plantains, mangoes, roselle, neem, cowpeas and citrus often occupy well-defined positions on the compound farm and other fields but some heliophytes such as cocoyams are grown in the shade of cocoa or other tree crops.

(m) In the savanna areas nomadic cattle herders who usually move north or south with the rains and related pastural conditions sometimes coral animals on farmers' fields and their animals feed on crop residues in lieu of droppings the animals leave behind to enrich the soil. On almost all farms, small numbers of small livestock (chicken, goats, sheep and pigs) may be kept restricted in pens in the compound all the year, restricted only during cropping season, on free range or tethered to graze in fields not far from the homestead. Livestock are important as (i) sources of meat or milk, (ii) thrifty scavengers converting farm, pasture, compound and kitchen waste into food, (iii) sources of manure for maintaining soil fertility and adequate levels of soil organic matter and (iv) a sort of savings which yield cash in emergencies and sometimes, according to Uchendu (1965), livestock tenancy is important in spreading risks among relatives and friends.

Traditional farming systems of West Africa can be extremely complex. A typical farm may operate a compound farm, several field systems of arable food or export crops and other patchy farms, gardens or fields sited at certain peculiar topographic locations. Women may in addition maintain patches and gardens of vegetables, dye plants, fibre plants, tomato and pepper (*Capsicum* spp.). Sometimes they raise seedlings for sale in the local market. Even in the humid areas where tsetse flies are endemic, almost every small farm is a mixed farm, since animals are also kept and special shrubs or trees are grown on the compound or distant fields as browse plants for goats or sheep while also serving as boundary plants, fence posts, stakes for crops, sources of wood for tool handles, drug plants and miscellaneous purposes (Table 6). One farm family thus operates more than one of the farming systems listed in Table 3 and individual members may still be involved in different non-farm activities.

Nitrogen cycling in traditional farming systems of West Africa

In general, nutrient cycling is essential not only for maintaining agricultural productivity but also for support of vital life processes in the biosphere since all living organisms require 30–40 of the 90 elements that occur in nature and of these nitrogen is one of the most important (Simmons, 1974; Bormann & Likens, 1967). Nutrient cycles involving solution, gaseous, and solid phases in which nutrients occur are interrelated in such a way that there are feedback mechanisms which ensure compensatory movements in one direction of a given phase in response to changes of another phase in a specific direction (Bormann & Likens, 1967). Nutrient levels in the biosphere are results of dynamic processes among various forms of a given nutrient in interaction with various environmental factors (temperature, moisture, acidity, etc.). Determination of the level of a given nutrient depends on knowledge of their sources, uptake and losses by which the construction of a biogeochemical budget of the nutrient is possible. A generalized nutrient cycle is presented in Fig. 7 and components of a nutrient budget in field or forest ecosystems are shown in Table 7. Most nutrients in the ecosystem are located in the (a) atmosphere as atoms and/or molecules in gaseous or particulate form below and above the ground, (b) nutrient pool in the soil in the form of ions adsorbed on clay or humus complex, or even dissolved in solution, (c) rock and soil minerals incorporated in primary and secondary minerals that enter the system including more readily decomposable minerals that are in equilibrium with available nutrients, and (d) inorganic materials (biota or organic debris) including all ions incorporated into living organisms or their remains (Bormann & Likens, 1967). Thus, the degree to which a nutrient circulates in the ecosystem depends partly on its physical state and is very closely linked with the hydrologic cycle. Within the ecosystem there is usually an internal cycle resulting from uptake of nutrients by plants, release of nutrients by plants through direct leaching, release of nutrients

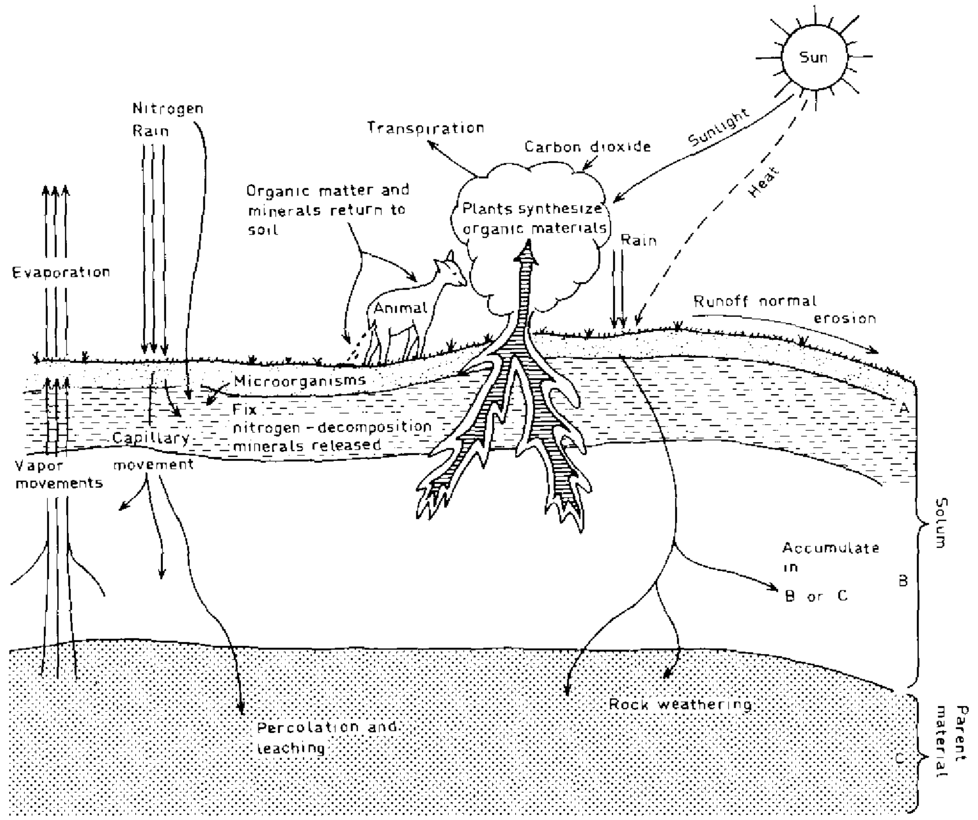


Figure 7. Diagram showing how (1) plants take nutrients from air, soil and water and synthesize various organic materials (including plant and animal food) under the power of sunlight in the green parts of the plant and (2) how water moves up and down through the soil, through the plant, and off the surface (Kellog, 1975).

from organic matter by biological decomposition and equilibrium reactions that convert insoluble chemical forms in the soil or rock compartment to soluble forms in the available nutrient compartment and vice versa (Bormann & Likens, 1967). Nutrients may, however, enter the ecosystem from the outside and also through physical, biological and chemical weathering of rocks and soil minerals in the system. This applies to all nutrients including nitrogen, and under natural conditions of a forest ecosystem there is more or less a closed system where losses are less or in balance with inputs. Under farm conditions where the agroecosystem is more or less an artificial and greatly modified environment, an open system exists and losses through erosion, harvest of produce, burning, etc., may result in a net negative balance in the biogeochemical cycle. Nutrients may be brought into the system from outside.

Details of the nitrogen cycle have been dealt with in other papers and only pertinent aspects will be mentioned here. According to Bolt & Bruggenwert (1976) nitrogen in agricultural areas may be present in or pass through the ecosystem in a number of forms consisting of (a) constituents of leaves, stems, roots and other parts of the crop, (b) soil

Table 6. Main sources of inputs and outputs necessary in construction of a biogeochemical budget of a nutrient in field or forest*

Inputs	Losses (Outputs)
1. **Geological Inputs**	1. **Geologic Output**
a) Dissolved or particulate matter carried in water, colluvial action or both.	a) Dissolved or particulate matter in moving water, colluvial material or both.
2. **Meteoric Inputs** – of atmospheric origin	2. **Meteoric**
a) Gaseous material	a) Diffusion or transport of gaseous or particulate matter carried by wind or water (erosion).
b) Material dissolved or particulate matter in precipitation.	
c) Dust and other wind-borne material.	
d) Chemicals in gaseous form fixed by biological activity in ecosystem.	
3. **Biologic Input** – result of animal activity	3. **Biologic**
a) Decomposition of material originally gathered from somewhere, e.g., fecal matter.	a) Nutrient loss by activity of organisms including man.
b) Fertilizers intentionally applied to crops by man; or animal feed.	

* Source: Bormann and Likens (1969).

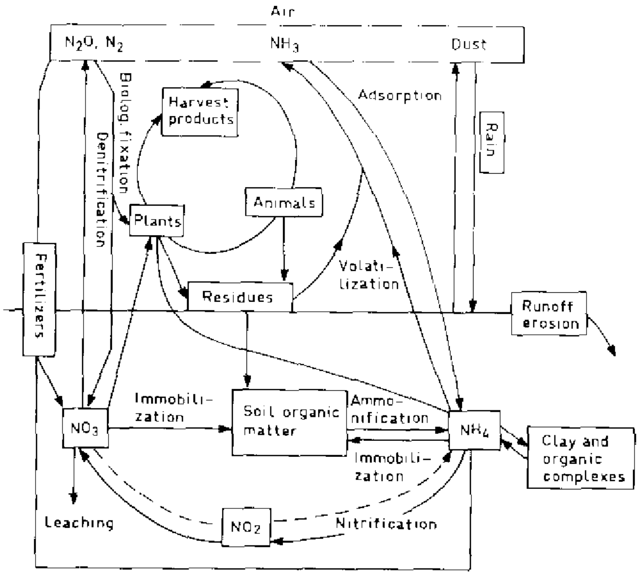


Figure 8. Nitrogen cycle in agriculture (Stanford, 1977).

constituents in either organic or inorganic nitrogen forms, (c) immobilized nitrogen in microbial tissue resulting from decay of plant or organic residues, and (d) N_2 or N_2O returned to the atmosphere following denitrification, especially under anaerobic conditions. Some nitrogen is present in rain-water and some plants are associated with bacteria or some algae which fix nitrogen. Nitrogen may also inadvertently be supplied to the ecosystem through industrial pollution and waste disposal (De Haan & Zwerman, 1976). Within the ecosystem available nitrogen may be immobilized in different parts of the plant, microbial tissues and plant residues. It may, however, be mineralized by its conversion from organic to inorganic forms through uptake by plants or microorganisms (De Haan & Zwerman, 1976). Of nonmicrobial nature is the fixation of nitrogen in clay lattices or humus complexes. The nitrogen cycle in agriculture is presented in Fig. 8. There is usually a relationship between the carbon, other nutrients and nitrogen in the system such that there is a tendency to develop a C:N:P:S ratio with the C:N ratio in the system approximating that in the cell tissue (Bolt & Bruggenwert, 1976). Consequently, since the ratio is about 100 for the soil organic fraction, addition of organic material to the soil may result in mineralization when the ratio is smaller than 10 or immobilization when it is larger. The nitrogen in the soil is present mainly as ammonium and nitrate nitrogen, which are readily available to plants and as more labile nitrites, nitrous oxide, nitric oxide and as hydrooxylamine and nitramide which are unstable (Bolt & Bruggenwert, 1976). It is also known that most of the nitrogen in most surface soils consist of organically bound nitrogen, which may amount to above 90 % of the total nitrogen in the top soil. With the above background, it is in order to review the nitrogen cycle in relation to farming systems since this involves those aspects of crop and animal production practices which in various farming systems may result in favourable or adverse balance of the nitrogen in the system and in relation to the total nitrogen in the environment of which a given agroecosystem is a part. An efficient farming system should involve resource use and manipulations of the environment that ensures that the nitrogen cycle in the system results in a budget that favours maintenance of good yield on a sustained basis without serious losses or excess nitrogen in the environment.

Operations or practices in farming systems and their implications in the nitrogen cycle

In all farming systems practised in tropical West Africa (Table 3), the usual farm practices and operations affect the nitrogen budget irrespective of whether the farming system involves only crops or animals or varying degrees of association of both. These operations include:

1. Land development and preparation
2. Cultivations
3. Cropping patterns
4. Miscellaneous cultural practices such as weeding, mulching, fertilizer application, etc.
5. Pest, weed and disease control
6. Harvesting and grazing
7. Processing and utilization.

All traditional and transitional farming systems involve (a) bush clearing through slash and burn techniques and (b) land preparation, tillage and harvesting with such simple tools as matchet, axe, hoe, and digging sticks, (c) cropping patterns involving simultaneous and/or relay intercropping systems without systematized rotations of sole crops, and (d) cropping periods under which nitrients which have been brought up to the surface or immobilized during the bush fallow period, are made available for one or more years of cropping before reverting to fallow again. Since all farm practices are related to the objectives of the farmer and the resources at his disposal, the farm system in any given location is associated with different crop plants and/or animals in addition to residue and environmental management which determine the overall amount of nitrogen that is lost through processes such as erosion, burning and volatilization, flooding, crop residue management, etc.

Land development and preparation: The widespread slash and burn technique used in land preparation for crop production in traditional farming systems and burning of natural ranges by nomads is usually aimed at achieving one or more of the following objectives, (a) reducing the amount of plant residues on farm land, (b) obtaining uniform fresh luxuriant grazing for livestock, (c) killing of pest and disease organisms, (d) controlling weeds and (e) releasing nutrients for crops or pastures. But the burning of vegetation results in some loss of nitrogen and destruction of soil organic matter in which some residual nitrogen or nitrogen leached into the soil may be held in addition to destruction of soil microflora and other organisms which may be active in the mineralization of nitrogen or its storage through immobilization. Nye & Greenland (1960) reported estimates of the amount of nitrogen lost by burning in forest and savanna vegetation in relation to the rate of humus increase and carbon nitrogen ratio. The more intensive the burn, the higher the temperature attained, the more the nitrogen lost, the greater the damage to soil structure, fauna and flora, and the deeper the penetration of the adverse effect produced in the soil. Moreover, the more frequent the burn the thinner the vegetation cover that can be established and the higher the erosion hazard, resulting in more losses of nitrogen, most of which is in the surface soil. High soil temperature would also be detrimental to nitrogen-fixing bacteria either in the wild or in planted legumes. Regulated burning, which is often recommended, may be used to attain a desirable mixture of grasses and broadleaved plants in such a way as to enhance a more stable ecosystem of high plant diversity index. A more favourable nitrogen budget may be attained under such a system. Where animals are grazed, burning destroys the droppings and may also kill organisms, which are active in the mixing of the dung with the soil and enhancing the residual effect of nitrogen in the dung. Nye & Greenland (1960) also reported nutrient release, heating and change in pH of the soil as a result of burning, which may produce adverse or beneficial effects on the nitrogen level in the ecosystem depending on the circumstances. There is no doubt that light regulated burning at the appropriate time may be more beneficial in nitrogen recycling than intense and haphazard burning. Traditional land clearing methods which result in a lot of stumps being left to regenerate in the field usually result in less erosion hazard with a beneficial effect on nitrogen balance than the total clearing and stumping of modern farming systems.

Cultivations: Cultivations are carried out in order to prepare a good seed bed, enhance water infiltration, control weeds and bury weeds and pests, etc. Cultivations which expose the soil to greater erosion hazard will result in a more adverse nitrogen balance. Where organic residues are buried they may decompose faster in a tropical environment resulting in a more rapid loss of nitrogen by erosion and leaching. Cultivations may change soil structure and develop hard pans that adversely affect root development and are thus detrimental to the nitrogen balance in the agroecosystems since they create conditions that do not enhance plant growth. In traditional farming systems, cultivation with hoes does not usually cause as much formation of hard pans and increases in soil bulk density as does heavy machinery. Also, exposure of weed seeds during cultivation may result in excessive weed growth and competition between crops and weeds for the limited nitrogen available.

Cropping patterns: When carried out with compatible crops traditional intercropping systems always keep the soil more covered and can reduce erosion and nitrogen loss as compared to sole row crop patterns. Where a legume is included in both the combinations or sequences, nitrogen fixation is enhanced and fertility may be maintained. Individual crop species, whether grown in pure culture or intercrops, remove nitrogen and other nutrients from the soil to different extents (Table 7) and also leave different amounts of residues after harvest. The cropping pattern may interact with cultivations in determining the extent of erosion and nitrogen loss (Table 7). Traditional cropping patterns and production practices are based on relatively unimproved land races of staple food crops. Modern cropping systems sometimes call for crop improvement through development of photoperiod insensitive short and early maturing cereals as a means of significantly increasing productivity. While this has obvious advantages, it may run counter to the uses of the crop in traditional cropping systems and even adversely and indirectly affect the nitrogen balance. An example of this in savanna areas is photosensitive tall and late-maturing sorghum which not only does not produce culms that can be utilized in staking but

Table 7. Amounts of nitrogen removed in harvest of important staples or food crops*

Crop		Yield (kg/ha)	Nitrogen (kg/ha)
1.	Maize (grain only)	1,100	17.1
2.	Rice (paddy)	1,100	13.6
3.	Groundnuts (kernels)	550	28.5
	(shells)	220	2.2
	Total	-	30.7
4.	Cassava (fresh tubers 30 % dry matter)	11,000	25.0
5.	Yam (fresh tubers 30 % dry matter)	11,000	38.6
6.	Bananas (fruits 30 % dry matter)	11,000	30.7

* Source: Nye & Greenland (1960).

produces very limited amounts of residues which can be used to increase soil organic matter or as mulch. Moreover, in the savanna areas, the crop may not produce enough residues for feeding animals whose droppings may constitute a good source of manure and nitrogen. In zero tillage rotations, crops that produce very little residue are not effective in combating erosion and maintaining good levels of soil organic matter and nitrogen.

Cultural practices: In traditional farming systems, very little or no fertilizers are usually applied and often this is limited to cash crops. The traditional method of using planted or natural fallows to replenish soil fertility and nitrogen is only effective when the duration of the fallow is up to five years or more, but under increasing population pressure the fallow period may be reduced to the extent that it is ineffective in restoring fertility through nutrient recycling. Natural fallows, while providing reasonable soil cover, may not be as effective in nitrogen replenishment unless action is taken to ensure that the vegetation contains a high proportion of leguminous shrubs that are effective in nitrogen fixation. Moreover, in highly leached sandy soils, fallow shrubs or trees with deep root systems may be more effective in nitrogen and overall nutrient recycling since the roots can tap nutrients from deep down the profile. The bringing up to the surface of nutrients other than nitrogen is useful in ensuring adequate utilization of nitrogen. It is, therefore, very important that since frequent cropping reduces soil fertility and yield, fertilizer application should be regarded as imperative, but various ways should be found to reduce the amount and cost of fertilizer used. In this regard there is need to study the nitrogen-fixing potentials of plants which constitute dominant species in natural and planted fallows in traditional farming systems so as to ensure maximum benefits from the use of fallow crops that are efficient in nitrogen fixation and nutrient recycling. Where fertility is reduced by constant cropping, the level of soil organic matter is also reduced and the poor growth of cultivated crops and even fallow plants may result in greater erosion hazard where aggressive weed species fail to take over. The method, amount and time of fertilizer application may be detrimental to crops in relation to nitrogen fixation and utilization. Use of organic residues and animal manures as on compound farms is more widespread in traditional farming than the use of fertilizers. This usually increases the amount of nitrogen in the soil in addition to creating more favourable soil conditions for plant growth, especially in sandy soils. The only disadvantage is that organic manures are more bulky and cumbersome to handle.

Weeding is another widespread cultural practice which exposes the soil to greater erosion hazard and more nitrogen loss. At the same time, weeds left on the soil surface may act as mulch and also reduce soil erosion, temperatures and nitrogen loss. Various other cultural practices such as staking, plant population, etc., may have adverse or beneficial effects on the nitrogen balance and this should be borne in mind in the development of technology for small farmers.

Pest, disease and weed control practices

Weed, disease and pest control in traditional farming systems does not involve the use of costly chemicals, some of which may have adverse effects on soil organisms, nitrogen fixation or organic matter decomposition. Similarly, since chemicals are not used, the mechanization involved in their application is avoided and thus the adverse effects on soil structure and increased risk of erosion hazard do not arise.

Harvesting: Harvesting generally results in removal of a lot of nutrients immobilized in the crop, the extent depending on the crop, plant population, variety, part of crop used and the fertility of the land on which the crop is grown in addition to the intensity of cropping. For example, although legumes fix nitrogen, they have more nitrogen stored in their seeds than cereals. Moreover, where leaves, seeds, and stems are harvested, more nitrogen is removed and consequently, soil fertility is more drastically reduced. Where harvesting involves carrying away or burning of crop residues, an adverse nitrogen balance usually results.

Grazing may be regarded as a form of harvesting and overgrazing results in a serious depletion of nitrogen. Consequently, suitable frequency of grazing and/or height of cutting may be determined for various mixtures and sole crop pastures. Use of suitable mixtures and regulated grazing is one way of achieving not only increased productivity but effectively providing adequate cover against erosion. Moreover, grazing animals should not be allowed to accumulate droppings on pastures which may be detrimental to the growth of the pasture. Where animals are penned, protection of farmyard manure – preferably mixed with bedding and sheltered from the rain and sun – is a suitable way of conserving nitrogen. Traditional farming systems often do not involve such large numbers of animals as to result in animal waste disposal problems. Where large numbers of animals are kept, the association of some crop production with rearing of animals is one way of ensuring that the manure is put to good and effective use with minimum hazard to the environment.

Processing and utilization

Processing and utilization of crops or animal products often results in by-products, some of which are rich in nitrogen and other nutrients. When these by-products are not properly handled or disposed of they may cause pollution in the environment but may also, when turned into animal feed or compost, result in efficient conservation and utilization of nitrogen. Mixed farming constitutes a system that ensures the adequate utilization of by-products of crops or animal processing in the form of organic manures or animal feeds.

On the basis of the above considerations, the probable changes in nitrogen regime and balance likely to occur in the farming system of tropical Africa are briefly summarized below.

Survey of farming systems and associated nitrogen changes

As presented in Table 3 farming systems of tropical Africa are classified into (1) traditional and transitional farming systems and (2) modern farming systems and their local adaptations. The former represent indigenous agricultural systems in addition to changes they are or have been undergoing due to various socio-economic pressures. The latter represent attempts to transplant agricultural systems of temperate countries to the tropics.

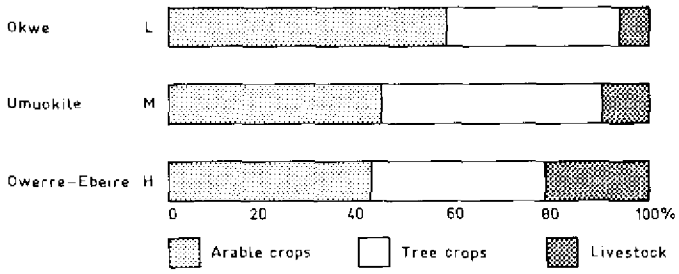
Traditional and transitional systems

Shifting cultivation phase I (including Nomadic Herding): Fallows under this system are of sufficiently long duration to enhance effective nitrogen and nutrient recycling and decomposition of enough organic matter needed to maintain soil fertility. Provided that the cropping period is not very long, crops may be grown for two years without fertilizer application. However, the burning during clearing may lead to serious nitrogen losses. In nomadic herding, nitrogen cycling is effective as long as overgrazing and erosion are avoided. At certain stages of pasture growth the nitrogen content of the very succulent fodder may have adverse effects on animals. The overall nitrogen balance will depend on how scientifically sound the soil management and other animal and crop production practices are carried out in relation to the nitrogen cycle. For example, the amount of organic matter and number of years of fallow will depend on the rainfall and temperature of the area. These should be taken into account when designing suitable farming systems for a given location.

Bush fallow or land rotation: General practices under this system are the same on outlying fields as under shifting cultivation, except on the associated compound farms which are under reduced periods of fallow. On compound farms, fertility is maintained with household refuse, human and animal manures, kitchen refuse and compost. Favourable nitrogen balance is attained by gathering nutrients from a wide area around the homestead. The effectiveness of this depends on the soil fertility and the human and animal population density in the area. However, the high crop diversity index of the compound farm agroecosystem which approaches a forest condition in more humid areas, results in more stable ecological conditions. The nitrogen budget here should approach that of the forest except for the fact that more materials may be removed in harvested produce as compared to the forest. The effects of harvesting will depend on the crops in the mixture, their management and amount and part of plants involved. Burning on compound farms and intense grazing by livestock may produce negative or adverse effects on the nitrogen balance. In savanna areas, not enough organic refuse and animal waste are available for maintaining adequate levels of soil organic matter and fertility even on compound farms. Tree crops and shrubs around the homestead and those used in fallows in outlying fields could be selected and managed to enhance nitrogen fixation and organic matter accumulation.

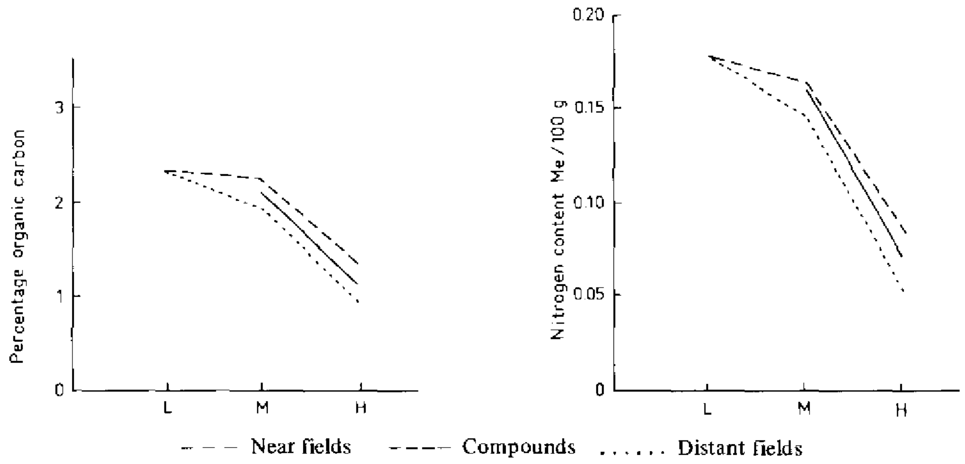
Rudimentary sedentary agriculture: The situation here is similar to that on compound farms except that with high population pressure and shortening of period of fallow, there is greater danger of nitrogen deficits than in the more extensive bush fallow systems with longer periods of fallow.

Compound farming and intensive subsistence agriculture: As in the compound farm system, fertility here is maintained with animal manure and organic manure from various sources. The intensity of cropping is very high and since these are found in areas of high population density, the bush fallows of surrounding areas may have deteriorated to mere weeds and dominated by herbaceous species which do not supply enough crop residues and browse plants for animal feeding. There is danger in such areas of rapid soil degradation and erosion. In the compound farm and adjacent fields dominant weed species in the humid tropics are mostly perennial weeds, which may be effective in nutrient cycling. Since these weeds are usually deep rooted, they may not compete seriously with crops for nitrogen. Under very rapid soil degradation and population pressure these farming systems result in agroecosystems on which the erosion hazard is very high. Fertilizers, compost, night soil, etc., may have to be resorted to on a big scale if farming is to be continued and fertility maintained. Studies of these farming systems in the densely populated areas of southeastern Nigeria indicate that as population densities increased, the importance of tree crops and animals increases while that of arable crops declined (Fig. 9). Moreover, the organic carbon and nitrogen content of the soil decreased as population density increased although fertility on the compound farms was maintained at the expense of distant fields (Fig. 10).



L = Low population density, M = Medium population density, H = High population density

Figure 9. Relative importance of arable crops, tree crops and livestock as sources of gross returns in three villages in southeastern Nigeria (Lagemann, 1977).



L = Low population density, M = Medium population density, H = High population density

Figure 10. Organic carbon and nitrogen contents in relation to population density in compound farms and farms at varying distance from homestead (Lagemann, 1977).

Terrace farming and floodland agriculture: Terrace farming is a very intensive system of agricultural production developed in some areas on defensive hillsides during the slave trade period. High value crops are usually grown on such farms close to urban centres. On floodland farms along the big rivers, farmers constantly risk losing crops as a result of sudden annual floods which make harvesting difficult or impossible. Very early planting and harvesting are imperative. Some of these farming systems are currently threatened by large hydroelectric power schemes, where siltation above the dams is gradually reducing the amount of silt and fertility deposited each year. In Nigeria, it is on these farms that the best yam crops are grown. In valley bottom soils and poorly drained areas large mounds have to be made for crops such as yams and cassava to avoid high water tables causing anaerobic conditions resulting in loss of nitrogen, lack of oxygen and death of crops other than rice. Where the water level is controlled, good rice crops are displacing yams. These are soils of high potential for two or more crops of rice each year followed by dry season vegetables. In many areas, for example, Oyo State, these soils are somewhat inefficiency utilized for the production of sugar-cane. In some locations, they have become highly polluted and are of no use in agriculture. There is a possibility that the nitrogen cycle and budget can be favourably altered creating conditions that enhance the use of nitrogen-fixing algae and other aquatic plants, thereby reducing the amount of nitrogen applied to rice. Investments in drainage and water control may enhance adequate nitrogen supplies for a range of crops other than rice.

Modern farming systems and their local adaptations

This group of farming systems is outside the interest of this paper but presents a different problem in nitrogen cycling. They involve more intense farming systems, mechanization and increased use of fertilizers. The problems associated with them are similar to those of developed countries, but their solution requires higher priorities in research, since existing practices which constitute their solutions in developed temperate countries are not directly applicable to the tropics.

Conclusions and recommendations

This review of nitrogen cycling in traditional farming systems has been more descriptive than quantitative, since only fragmentary data on the nutrient cycles of only individual crops on farms or experiment stations are available. It is increasingly recognized that certain practices in traditional agriculture favour a positive balance in the nitrogen budget, but no study of the role of these practices in each total system based on interdisciplinary systems approach has been carried out. Moreover, no effort has been directed towards developing appropriate methods to effectively replace or modify already identified practices in traditional agriculture that result in nitrogen losses or limit efficient conservation and utilization of nitrogen. It is recommended that:

1. Special long term experiments be started to study the nitrogen-fixing and nutrient cycling potentialities of various plants that are dominant in traditional natural or planted fallows.

2. While nitrogen fixation constitutes a way of reducing the cost of fertilizers, its use or realization in farming systems of smallholders in the tropics has been minimal, consequently, efforts should be made to attain this with leguminous crops currently being grown/or by discovering legumes that are more highly efficient in nitrogen fixation than those currently being grown.
3. Special interdisciplinary research efforts should be devoted to the study of intercrop and mixed farming agroecosystems of the tropics as alternatives to the modern sole crop and intensive livestock agroecosystems now being introduced into West Africa as a basis for developing new more efficient systems. These should take advantage of existing known practices in both groups of farming systems that have been identified as efficient in the conservation and utilization of nitrogen.

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Nitrogen Cycling in West African Ecosystems

NITROGEN CYCLING IN A SEMI-ARID REGION OF TROPICAL AUSTRALIA

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Abstract

In the markedly monsoonal rainfall region of Katherine, Australia, with an annual precipitation of 902 mm, there is no evidence of major gains or losses of gaseous nitrogen.

The introduction of legumes can add as much as 163 kg ha^{-1} of nitrogen to the soil-plant system, but this nitrogen will only contribute to the soil nitrogen status when the legume plant nitrogen is returned directly or indirectly (via animals) to the soil.

Rainwater contributes little, if any, nitrogen to the soil/plant system. In the native vegetation, termites, grass bush fires and litter decomposition dominate the recycling of the total 16 kg ha^{-1} yr^{-1} of litter nitrogen.

The rate of mineralization of soil organic nitrogen is on average 5.5 % per annum and is affected by total amount of annual rainfall, soil type and land history. The fate of the mineralized nitrogen, virtually all in the nitrate form, depends on the depth of the soil profile and the effective rooting depth of the crop. On average, non-leguminous crops can recover 45 % of this nitrogen per annum.

Equations are given to predict plant nitrogen yield and soil organic nitrogen changes as an aid to calculating rates of nitrogen cycling under different cropping conditions in the Katherine region.

Location and environment

This paper restricts itself to the semi-arid region of northwest Australia in a monsoonal climate of 902 mm annual rainfall, nearly all of which falls between the summer months of November and April. During the growing season dry spells of 2–3 weeks are not uncommon, while the winter is reliably dry. The main climatic variables for Katherine (14.3°S) are given in Fig. 1, where they are compared with those of Kano, Nigeria. The similarity of the two climates is remarkably high, and underlines the relevance of the Katherine results to some parts of the West African ecosystems.

Most of the nitrogen studies were carried out at Katherine on a well-draining lateritic red earth (Tippera clay loam) and the remainder on a sandy soil (Blain sand). The main characteristics of these two soils are given in Table 1.

Agricultural activities are restricted to extensive beef cattle grazing of native pastures and some introduced pastures. Large-scale commercial growing of sorghum has been attempted several times, but has mainly failed owing to poor management associated with unrealistically high yield aims (Fisher *et al.*, 1978).

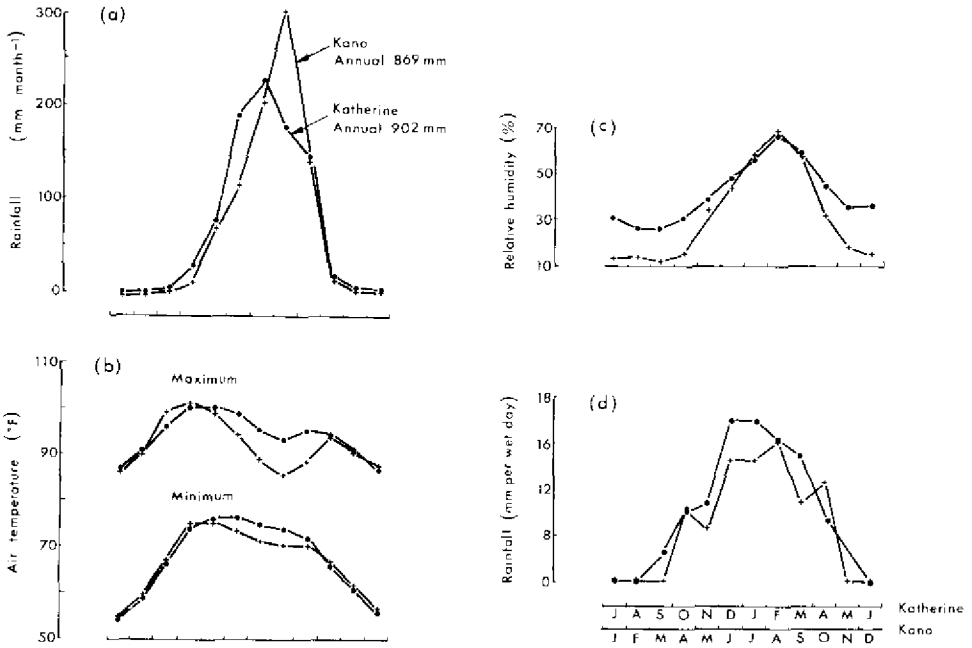

Figure 1. Comparison of Katherine and Kano climates (a) rainfall, (b) air temperature, (c) relative humidity, and (d) rainfall per wet day (Sources: Anon., 1958; Norman, 1966; Slatyer, 1954, 1960).

Table 1. Characteristics of the topsoil of the two main soil types

	Clay (%)	Organic N (%)	pH	Avail.moist.range (%)*
Tippera clay loam	25	0.067	6.5	4.9–6.1
Blain sand	6	0.035	8.7	5.0–2.0

*Field capacity minus -15 bars at 10 and 100 cm respectively.

Nitrogen accession via rainfall

Wetselaar & Hutton (1963) analyzed rainwater at Katherine on samples that were uncontamined by dryfall. Average nitrate concentration in successive rainfall events decreased as the wet season progressed (Fig. 2a) and decreased in time within a single event (Fig. 2b). There were high and positive correlations between nitrate and chloride, potassium and magnesium, and chloride and degree of terrestrial contamination (determined as insoluble silica). The ratio between the several ions in the rainwater resembled that of the soil of the area rather than that of the nearest coastal sea water 300 km north of Katherine. There was no obvious correlation (R = + 0.027) between nitrate and incidence of lightning. It was concluded therefore that most of the mineral nitrogen in the rainwater

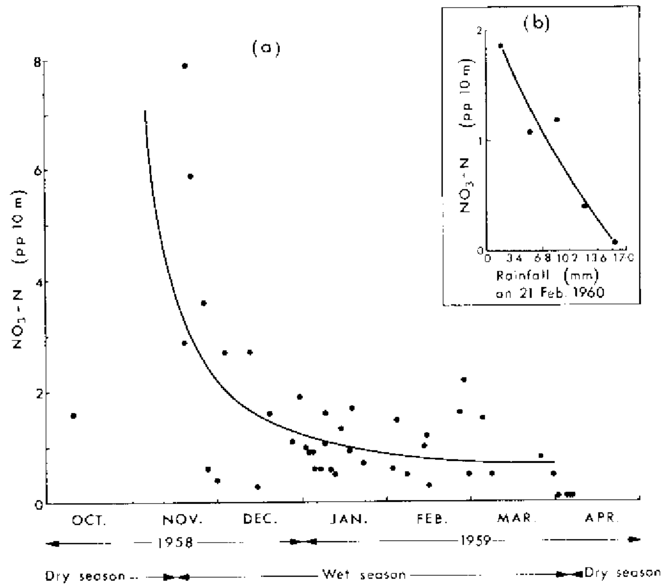

Figure 2. Nitrate nitrogen concentrations in rainwater at Katherine (a) average for each shower (1958–59), and (b) changes during one shower.

(total about 1 kg ha^{-1} yr^{-1}) is part of a terrestrial cycle and therefore cannot be regarded as true accession.

Nitrogen cycling in the native vegetation

The native vegetation of the Katherine region is a savannah woodland (Christian & Stewart, 1953). The tree flora is dominated by eucalyptus and the ground flora by graminaceous species (mainly *Sorghum plumosum, Themeda australis* and *Chrysopogon fallax)* (Arndt & Norman, 1959).

The trees shed an average of 770 kg ha^{-1} yr^{-1} of litter (dry matter of leaves and twigs) with a mean nitrogen content of 1.05 % (Wetselaar, unpublished). Annual dry matter production of the native pasture under undisturbed conditions is about 1500 kg ha^{-1} of dry matter containing 8 kg ha^{-1} of nitrogen (Norman, 1966). Thus, the total annual turnover is 16 kg N ha^{-1} contained in 2270 kg ha^{-1} of dry matter.

The mechanisms involved in this turnover are believed to be the following:

(i) The native herbivorous fauna (mainly kangaroos and wallabies) is likely to have a minor influence at a population density equivalent to 1 kg ha^{-1} of liveweight (Lee & Wood, 1971).

(ii) According to Lee & Wood (1971) the population density of termites can be extremely high, equivalent to 700 kg ha^{-1} of liveweight. A dry matter consumption rate of 11.6 g m^{-2} yr^{-1} per 3 g of termites (see Lee & Wood, 1971, p. 132) is equivalent to a total consumption of 2700 kg ha^{-1} yr^{-1} of plant dry matter, which is close to the total litter production of 2270 kg ha^{-1} yr^{-1}. Some of the excretion products of termites are incorporated in mounds within which relatively closed cycles can develop (Lee & Wood, 1971). The nitrogen economy of termite mounds is not well known, but Meiklejohn (1965) found in Rhodesia a 30-fold increase in denitrifying organisms in the mound compared with the adjacent soil, and nitrogen fixation by termites has been established (Breznak *et al.*, 1973; French *et al.*, 1976).

(iii) Fire is a natural feature of the environment and of frequent occurrence. Burning of natural pasture results in a loss of 93–94 % of pasture nitrogen above ground (Norman & Wetselaar, 1960a) and similar losses can be expected from tree litter.

(iv) Decomposition of plant material, even with a low nitrogen content, occurs rapidly during the wet season (Wetselaar & Norman, 1960), but it is not known whether gaseous losses are involved in this process.

(v) Over a 4-week period at the end of the wet season a loss of about 60 % of the total above-ground plant nitrogen yield of the native pasture has been observed by Norman (1966). It was assumed that this was due to a translocation of nitrogen to basal organs and roots (seed and leaf fall could be largely excluded), but leaching of the leaves and/or release as ammonia (Farquhar *et al.*, 1979) might also have been involved. Translocation and leaching would protect the pasture from subsequent losses by dry season burning.

(vi) Leaching of nitrogeneous compounds from trees is likely to occur via throughfall and stem flow. In the absence of actual measurements no estimate can be given for this part of the nitrogen cycling, but it can be assumed that no losses are involved from the ecosystem.

(vii) Fixation of nitrogen in the native pasture could be via nitrogenase activity in the rhizosphere of grasses or via native legumes. Weier (1978) found a fixation rate for *Sorghum plumosum* of 136 g of nitrogen ha^{-1} day^{-1}, but extrapolation of this laboratory result to the field situation must be treated with caution. Native legumes are sparse in the unburned pasture but become more prominent following disturbance (Arndt & Norman, 1959). Hence some compensation might occur following a fire.

The presence of non-symbiotic nitrogen-fixing organisms has been established for undisturbed soil (Y. Tchan, unpublished), but their actual contribution has not been assessed. Gas phase transfers of ammonia to and from the soil and plant leaves may take place. Uptake of ammonia from the atmosphere has been established for many plant species (Hutchinson *et al.*, 1972; Porter *et al.*, 1972; Meyer, 1973; Aneja, 1977). The ambient partial pressure of the ammonia in the region is likely to be extremely low, especially during the wet season and the early part of the dry season, in view of the absence of human activity and it is more likely that ammonia is released rather than taken up by the plant communities (Farquhar *et al.*, 1979). However, towards the end of the dry season, when bush fires are predominant, the ammonia concentration in the atmosphere might be high enough for uptake to take place.

Naturally the significance of each of the mechanisms described above will depend on the interactions between them. For instance, fire in the dry season reduces the dry matter production of the pasture in the following wet season by about 50 % (Arndt & Norman, 1959). This in turn would reduce the litter available to termites and the return of litter-nitrogen to the soil while on the other hand the native legume population could increase.

The current interference by man is mainly extensive beef cattle grazing and prescribed burning. The mean stocking rate is about 2 beast km^{-2}, equivalent to about 10 kg ha^{-1} liveweight. Compared with a possible maximum of 700 kg ha^{-1} of termites, grazing cattle will have little effect on the cycling of nitrogen in the native pasture system. Further interference of the natural cycle is due to the introduction of pasture legumes such as Townsville stylo (*Stylosanthes humilis*) together with additions of phosphate fertilizer. The effect of such practices will be discussed later.

Nitrogen cycling in bare fallow soils

Clearing of bush land involves bulldozing and windrowing of trees followed by burning. After cultivation and following the onset of the wet season, mineralization of soil organic nitrogen takes place. This process is strongly dependent on soil water potential and temperature. Ammonification continues down to -50 bars, while nitrification ceases at -30 bars (Wetselaar, 1968). The maximum rates of ammonification and nitrification occur at 50°C and 37°C respectively (Myers, 1975). At the end of the wet season, when the water potential of the soil surface layer reaches -30 bars, nitrification ceases. Immediately thereafter a redistribution of nitrate takes place within the top 30 cm of the soil profile *via* an upward flow of nitrate in the soil solution, resulting in high nitrate concentration near the soil surface (Wetselaar, 1961a, b).

During the wet season the rates of ammonification and nitrification in the topsoil show strong diurnal fluctuations in response to temperature and water potential fluctuations. Therefore a description of the mineralization process on an hourly basis is complex, but has been achieved by Myers (1975). Whilst some temporary ammonium accumulation can occur during brief periods when the water potential is between -30 and -50 bars (Wetselaar, 1962b), his model predicts that under most circumstances ammonium will not accumulate in the topsoil during the wet season but will be oxidized to nitrate.

The mineralization coefficient, M_c (Wetselaar, 1967a), represents the percentage of the topsoil organic nitrogen that has been mineralized per wet season. For Tippera clay loam $M_c = 5.5$ and is independent of the number of years of cultivation, whereas on the sandy Blain soil the coefficient decreases from 12.5 during the first year after clearing to 5.0 after 4 years of cultivation. For the clay loam M_c is affected by the total amount of rainfall per season, i.e., in seasons with higher rainfall a greater nitrogen availability can be expected (Wetselaar, 1967a).

Nearly all this mineralized nitrogen is in the nitrate form and is subject to leaching (Fig. 3), denitrification and immobilization. Denitrification losses and immobilization are virtually absent under bare fallow conditions (Wetselaar, 1962b, 1967a); leaching is the dominant factor (Wetselaar, 1962a, b). Within one season the rate of movement of the mean depth of accumulation of nitrate is 1 cm of soil depth per 1 cm of rainfall in Tippera clay loam and 2.12 cm per 1 cm in Blain sand. Thus after an average season of 902 mm of rainfall any nitrate present in the topsoil at the beginning of that season will move down 1.8 m in a clay loam with a peak of accumulation at 0.90 m. Even after 5 years such nitrate can be fully recovered (Wetselaar, 1962b), implying absence of denitrification losses.

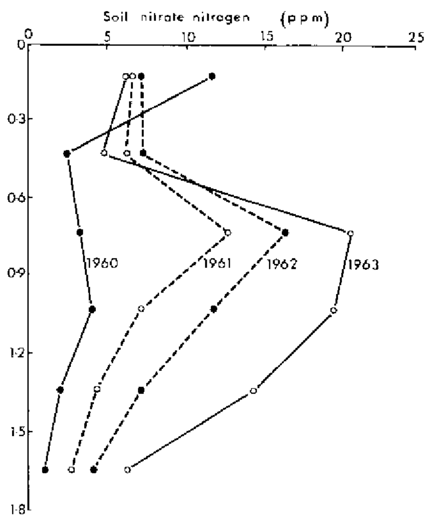

Figure 3. Soil nitrate concentration at different depths of bare fallowed Tippera clay loam, after 1, 2, 3 and 4 wet seasons.

The continuous mineralization of organic nitrogen in a bare fallow soil is accompanied by a concomitant reduction in soil organic nitrogen content, since virtually no nitrogen-fixing organisms could be found in the topsoil of cultivated Tippera clay loam (Y. Tchan, pers. comm.) and nitrogen in the rainwater cannot be regarded as an accession. It follows that a reduction in the total nitrogen content of the whole soil profile will depend largely on the depth of that profile. It can be calculated from Wetselaar's (1962a, b) results that, for no loss to occur, this depth should be at least double the mean depth of nitrate accumulation during one wet season. Consequently, soil depth can be a major factor in the preservation of the nitrogen status of a soil in a semi-arid region.

Nitrogen cycling under cropping conditions

At the Research Station at Katherine many cropping systems have been investigated intensively for 30 years. The following discussion of nitrogen cycling in such systems is confined to situations where phosphate is not a limiting factor.

For any monoculture or cropping system the rate of nitrogen turnover depends largely on the rate of soil organic nitrogen mineralization, the effective rooting depth of the crops, the amount of nitrogen fixed from the air, the extent of removal of plant products or their return to the soil and gaseous nitrogen losses. These factors are discussed below.

Rate of mineralization of topsoil organic nitrogen

The effects of soil water content and soil temperature have been discussed earlier for a bare fallow soil, and these are likely to apply also to cropping conditions. With an average

Table 2. Mineralization coefficient of Tippera clay loam after different crops

After	M_c (%)
All-grass pastures	1.3
Cowpea	3.5
Peanuts	5.4
Guar	6.6
Townsville stylo	7.0

M_c value of 5.5, 86 kg ha^{-1} yr^{-1} is made available to a crop on Tippera clay loam, but this amount varies widely with land history (Table 2) and to some extent with rainfall.

Effective rooting depth and soil nitrogen recovery

After bare fallowing, nitrate accumulates at depth (Fig. 3), and in this situation there is a marked variation between crops such as pearl millet and grain sorghum in the rate of subsoil nitrate extraction (Fig. 4) (Wetselaar & Norman, 1960). In the case represented by Fig. 4 millet and sorghum yielded respectively 203 and 105 kg ha^{-1} following the bare fallow, compared with 90 and 86 kg ha^{-1} following a Townsville stylo pasture with little nitrate in the subsoil. Clearly, crops differ in their ability to extract nitrate that has accumulated in the subsoil, and this characteristic is of major significance in the cycling of nitrogen.

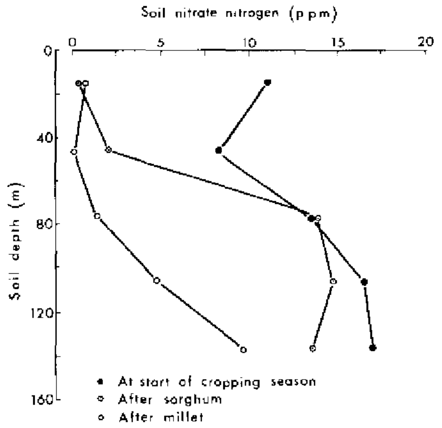

Figure 4. Soil nitrate concentrations in Tippera clay loam at start of cropping season, and at end of same season after sorghum and millet.

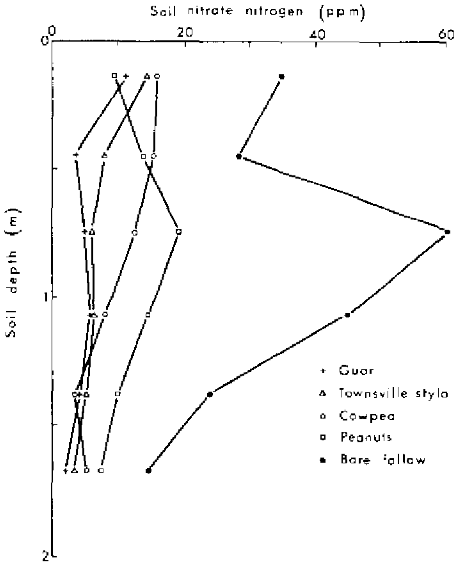

Figure 5. Soil nitrate concentrations in Tippera clay loam after 3 years of different legumes.

Table 3. Plant nitrogen yields as percentage of total available soil nitrogen (nitrate in profile at start of season plus organic soil nitrogen mineralized during wet season) of non-leguminous crops following legumes

After	Millet	Sorghum	Sudan grass	Cotton	Weighted mean
Guar	42.7	43.1	56.8	43.1	46.4
Townsville stylo	37.9	47.4	42.6	42.6	42.6
Cowpea	54.0	47.3	56.0	48.7	51.3
Peanuts	35.4	41.9	50.2	38.6	41.4
Weighted mean	41.8	44.9	51.6	42.8	45.0
Bare fallow	46.2	19.9	25.3	25.6	

Under continuous cropping there is less nitrate accumulation in the subsoil than under bare fallowing; the quantity appears to be higher after peanuts than after other legumes (Fig. 5). The mean recovery by non-legume crops of accumulated nitrate plus the nitrate made available during the growing season is about 45 %, Sudan grass being more efficient than millet, grain sorghum and cotton (Table 3).

In cropping systems without bare fallowing, some prediction of crop nitrogen yield can be made according to

$$N_y = 0.45\,(n_p + 0.01\,M_cN_i)$$

where N_y = above-ground crop nitrogen yield (kg ha^{-1}), n_p = amount of nitrate nitrogen in the soil profile at start of season (kg ha^{-1}), M_c = mineralization coefficient, and N_i = total amount of organic nitrogen in the topsoil at start of season (kg ha^{-1}).

Non-symbiotic and symbiotic nitrogen fixation

Weier (1978) investigated nitrogenase activity in intact cores of native and introduced grass species from northern Australia. Relatively high rates of fixation were associated with 7 species out of 16, but there was significant site x species interaction. The maximum rate found was 346 g ha^{-1} day^{-1} of nitrogen for *Rhynchelytrum repens*. Grasses growing on heavier soil tended to have higher fixation rates. At present these results cannot be translated into the realities of the Katherine region, and it is not known whether such fixation also occurs when the grasses are grown in association with a legume.

A carefully executed nitrogen balance field study, growing annual legumes for 3 consecutive years at Katherine on Tippera clay loam (Wetselaar, 1967b) (Table 4 and Fig. 6), indicates the following: Townsville stylo, guar, cowpea and peanuts effectively fix nitrogen. Cowpea and peanuts fixed less in the 2nd and 3rd year than in the 1st year, probably owing to an increase in available soil nitrogen over time. Cowpea had a short growing period, which implied a short bare fallowing effect in late wet season, while for peanuts the wide row spacing (90 cm) allowed some mineralization and leaching of nitrate from the inter-row soil. Hence, any favourable effects of these legumes on following non-

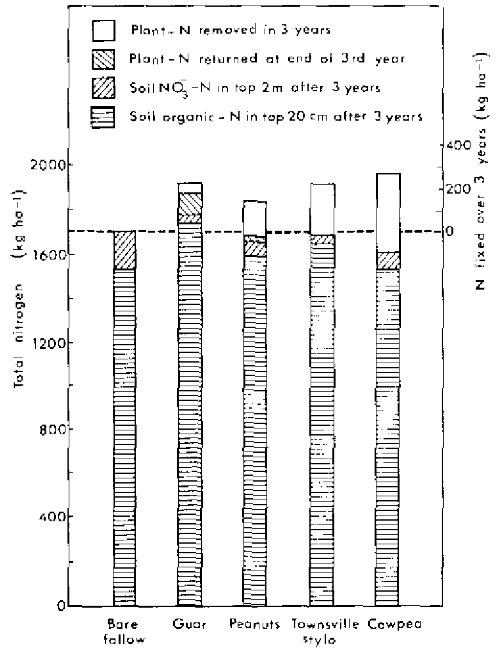

Figure 6. Nitrogen balance after 3 years of legumes or bare fallow.

Table 4. Amount of nitrogen (kg ha^{-1}) effectively added to the soil/plant system by four legumes after 1 and 3 years at Katherine

	Townsville stylo	Guar	Cowpea	Peanuts
Year 1+2+3	220	220	269	124
Year 1	34	41	136	72
Year 2+3	186	179	133	52
Mean for years 2+3	93	89.5	66.5	26

legumes could be due to the high residual soil nitrate status, rather than to nitrogen added by fixation. Only with guar was topsoil organic nitrogen status maintained.

Removal and return of plant products

Experiments at Katherine have clearly demonstrated that whenever above-ground material is not returned to the soil, its organic nitrogen content decreases. For non-leguminous crops without nitrogenase activity in the rhizophere this decrease will be equivalent to the amount of plant nitrogen removed plus the difference of any nitrate nitrogen in the soil profile at the end and beginning of the growing season, assuming no gaseous gains or losses.

Table 5. Topsoil organic nitrogen content and amount of plant nitrogen removed and returned to the soil after 3 years of legumes

	Soil org. N (kg ha^{-1})	Plant-N removed (kg ha^{-1})	Plant-N returned (kg ha^{-1})
Guar	1720	50	202
Peanuts	1580	168	56
Townsville stylo	1640	230	34
Cowpea	1510	364	0
At zero time	1700	–	–

For legumes, some compensation due to fixation occurs, but this depends on the proportion of plant tops removed or returned (Table 5). Consequently, the positive effects on the nitrogen status of a soil ascribed to introduced legume crops is largely a myth unless the greater part of the plant material is returned to the soil. Such return occurs when a grass/legume pasture is grazed, via litter fall and via animal waste products. Wetselaar *et al.* (1974), incorporating ^{15}N-labelled pasture litter with the top 0.5 cm of the local soil, found that after two years 15–26 % (depending on the C/N ratio of the litter) of the litter nitrogen had been taken up by the mixed pasture. All litter-nitrogen could be accounted for in the plant/soil system.

No measurements are available on the amount of nitrogen that is returned and possibly lost via animal waste products. In the first 3 years after establishment, the topsoil of a grazed Townsville stylo/grass pasture gained on average 106 kg ha^{-1} yr^{-1} of organic nitrogen (Wetselaar, 1967b). In older grazed pastures no nitrogen change could be detected (Myers, 1976).

Gaseous losses and additions

No ammonia volatilization losses could be detected when ammonium sulphate was applied to the soil surface of Tippera clay loam (Wetselaar, 1962b; Myers, 1978). In addition, under bare fallow conditions, nitrogen from applications of ammonium sulphate and sodium nitrate could be fully recovered as nitrate in the soil profile at the end of a wet season (Wetselaar, 1962b, 1967a), suggesting no losses due to denitrification. This could be due mainly to the good drainage characteristics of the soil and the depth of its profile. Whether the absence of such losses also applies to cropping conditions is not known, but is under investigation (R.J.K. Myers, pers. comm.).

As has been mentioned earlier, no losses could be detected when ^{15}N-labelled pasture litter was lightly incorporated with the soil surface of Tippera clay loam, again suggesting that gaseous nitrogen losses do not appear to be of significance with this soil type.

Ammonia uptake from the air by leaves and soil has been discussed above, but this process is unlikely to be of any consequence in view of the low air-ammonia concentration in the region, as reflected in the very low ammonia levels in the rainwater (Wetselaar & Hutton, 1963), except perhaps during periods of bush fires. Farquhar *et al.* (1979) have found ammonia release to occur from senescing leaves of maize, and the observed reduction in nitrogen yield of tops at the late stage of growth of many annual crops (e.g., Norman & Wetselaar, 1960b) may be due to loss by this pathway.

For non-leguminous cropping systems the change in the organic nitrogen status of the topsoil can be represented by the 'apparent' decomposition constant, K_c (Greenland & Nye, 1959), according to

$$K_c = 1/t \ln (N_i/N)$$

where N_i = initial organic nitrogen content, and N = that content after t years. With the plant nitrogen yield being equal to $0.45(n_p + 0.01\ M_cN_i)$:

$$K_c = 1/t \ln (N_i/(N_i - 0.0045\ a\ (n_p + 0.01\ M_cN_i)))$$

where a = per cent of plant nitrogen removed.

Assuming a topsoil nitrogen content of 1700 kg ha^{-1}, with 50 kg ha^{-1} of nitrate nitrogen in the soil profile, a mineralization coefficient of 4.8 and all plant material being removed at end of season, then K_c = 0.0354. After 2 years peanuts followed by 3 years of pearl millet K_c values of 0.0144 and 0.0356 were obtained for Tippera clay loam and Blain sand, respectively (Wetselaar, 1967a).

Nitrogen fertilizers

In the nitrogen cycle the apparent recovery of fertilizer nitrogen by plant tops is an important component. Studies of nitrogen recovery have been restricted mainly to grain sorghum which recovered 14 to 74 % of the applied nitrogen (Myers, 1978). This wide variation is a reflection of the variability of rainfall amount and distribution within and between seasons. For instance, Wetselaar (1962b) found that during a season with 280 mm of rainfall above the mean, one-quarter of the 100 kg ha^{-1} of nitrogen applied to sorghum as ammonium sulphate was found in the 60–120 cm soil profile as nitrate not taken up by the crop at the end of the season. In contrast, in a season with below average rainfall, 44 % of an application of 80 kg ha^{-1} of nitrogen in the same form to the same crop was unnitrified in the surface soil at the end of the season.

The major effects of the variable climatic conditions on the soil water regime and thus on the subsequent fate of the applied nitrogen has been described in detail by Myers (1978), and he explains why on average the highest recoveries will be obtained by banding the fertilizer at depth when it is applied at sowing. His work confirms the earlier conclusion of Wetselaar *et al.* (1972) that banding inhibits nitrification owing to the high concentration effect on nitrifying organisms. In addition, with deep banding as opposed to surface application, fluctuations in soil water content at the fertilizer site are less, and root development around the band is stimulated (Passioura & Wetselaar, 1972).

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Nitrogen Cycling in West African Ecosystems

A SURVEY OF NITROGEN LEVELS IN THE MAJOR SOILS OF GHANA

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Abstract

Nitrogen content of the surface soil and profile distribution of nitrogen were studied in major soil groups selected from various ecological zones of Ghana. Organic carbon content and C/N ratios in the soils were also studied. Soil groups studied included, forest Oxysols, forest Ochrosols, savanna Ochrosols, forest acid Gleisols, savanna acid Gleisols, ground-water Laterites, tropical Black Earths and tropical Grey Earths. Nitrogen levels in the surface soils range from 0.024 % in savanna Ochrosols to a maximum of 0.507 % in forest Ochrosols. In all soils studied the highest concentration of nitrogen was within the 0–5 cm layer of the surface soil. Nitrogen levels dropped sharply in the forest soils and gradually in the savanna soils below this layer. Nitrogen content of the soils was found to be related to kind of vegetation, climate and soil factors. Nitrogen increased with rainfall, reaching a maximum of about 0.5 % in the 1270–1780 mm rainfall belt. Where annual rainfall exceeded 1780 mm nitrogen levels declined slightly. Soils under forest were higher in nitrogen than soils under savanna vegetation. Soils with coarse surface textures were lower in nitrogen than soils with fine surface textures. Soil acidity and mineralogy of parent material appeared to have influenced the nitrogen status of the soils. In all cases, soils under cultivation showed a decline in nitrogen.

Introduction

Environmental and pedogenic factors are known to influence nitrogen levels in soils. Jenny (1930, 1931) observed that variation in nitrogen content of soils was influenced by rainfall and temperature. He noted that organic matter and nitrogen increase as effective moisture becomes greater and nitrogen decreases with increasing temperature. For a fall of 10°C in mean annual temperature the average nitrogen content of the soil increases 2 to 3 times in relation to its organic matter content. Nitrogen levels in soils are closely related to the kind of vegetative cover.

In Ghana, findings by several workers showed that soils under forest are higher in nitrogen than soils under savanna grass (Nye, 1951; Nye & Greenland, 1960; Brammer, 1962; Asiama, 1976). This was attributed to greater accumulation of litter under forest than under savanna grass. Jenny (1950) attributed the high content of organic matter and nitrogen in certain tropical soils to the luxuriant vegetation of legumes and non-legumes and to relatively slow decomposition of humus in such soils. Nitrogen levels are highest under climax vegetation and decrease as the fallow period is reduced (Charter, 1953; Nye & Greenland, 1960). Continuous cultivation has a reducing effect on the nitrogen content of surface soils (Chang, 1950). Differences in nitrogen levels of soils can be partly attributed to pedogenic factors. Anderson & Byers (1934) reported a close correlation between carbon-nitrogen ratio and soil types. Soils derived from basic igneous rocks were reported to contain twice as much nitrogen as in granitic soils of the same locality.

The purpose of this study is to investigate the levels of nitrogen in the major soil groups of Ghana and the effect of environmental and pedogenic factors on nitrogen status of the soils. The content of organic carbon determines the release of nitrogen in soils. Therefore in this study carbon contents of the soils were considered in relation to nitrogen levels.

Climate and vegetation

The mean annual rainfall and annual mean monthly temperatures are given on the map showing the various ecological zones of Ghana (Fig. 1). The rain forest zone is characterized by a mean annual rainfall of 1778–2159 mm distributed in two main wet seasons. Temperatures are uniformly high throughout the year. The annual mean monthly temperature is 25–26°C. The natural vegetation is evergreen forest with three main indicator species: *Cynometra ananta, Lophira alata* and *Tarrietia utilis* (Taylor, 1952; Mooney,

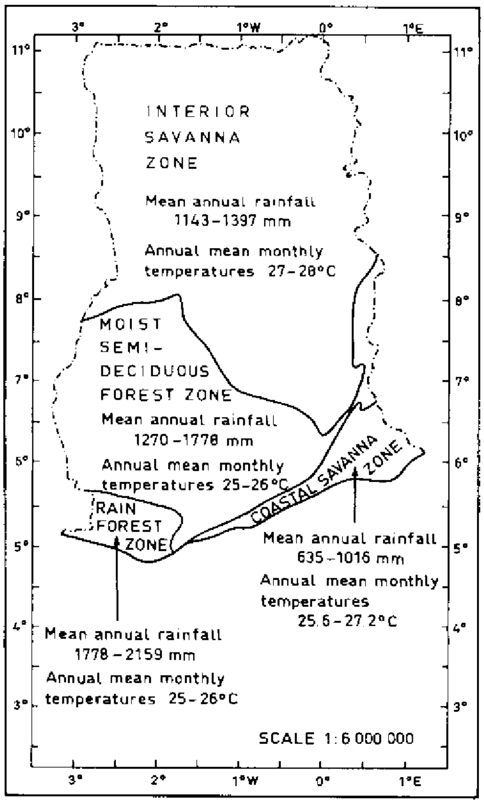

Figure 1. Ecological zones of Ghana.

1959). According to Ahn (1960) the forest in this zone is less high and the total weight of vegetation less than in the moist semi-deciduous forest.

The moist semi-deciduous forest zone has a bimodal distribution of rain with mean annual rainfall of 1270–1778 mm. Annual mean monthly temperatures are in the same order as for the rain forest. In this zone, dry seasons are more pronounced than in the rain forest. The moist semi-deciduous forest is characterized by two very frequent species, *Celtis mildbraedii* and *Triplochiton scleroxylon* (Taylor, 1952). *Antiaris-Chlorophora* association occupies the drier northern fringe of the forest (Mooney, 1959).

The interior savanna zone has a mean annual rainfall of about 1143–1397 mm. All the rain falls in one season. The annual mean monthly temperature is in the order of 27–28°C, a few degrees higher than in the forest zones. The vegetation is tall grass savanna with scattered trees.

The coastal savanna zone has a bimodal distribution of rainfall with an annual mean of 635–1120 mm. Temperatures are uniformly high. The annual average monthly temperature is about 25–27°C. The vegetation is characterized by short and medium grass with widely scattered small clumps of thicket confined to termite-mounds. Thicket vegetation occurs over Red Earths while short grass dominates the Black Earth and Grey Earth areas (Brammer, 1962).

Little original vegetation is left in the zones described above owing to cultivation and timber extraction. The following are descriptions of some vegetation units listed in Table 3:

Broken forest: This unit occurs on unfarmed land. It consists of the climax forest vegetation, which has been disturbed by the extraction of timber in patches.

Secondary forest: occurs on fallow land ranging in age from about 8 to 20 years. The unit consists of two strata. The lower stratum is characterized by light-demanding trees such as *Albizzia* spp. and the upper stratum by species such as *Triplochiton scleroxylon* and others commonly found in the climax vegetation.

Forest thicket occurs on fallow land ranging in age from 3 to 7 years. The unit consists of shrubs, woody climbers and coppice shoots forming an entangled mass.

Forb-regrowth consists of herbaceous plants and relics of food crops on fallow land of not more than 3 years old.

Materials and methods

Soils

The soil samples studied were collected from soil profile pits from the various ecological zones of Ghana (Fig. 1). The soil groups studied were classified in the system in use in Ghana (Brammer, 1962) and correlated with the USDA (Soil Survey Staff, 1970) and the FAO/UNESCO (1970) Systems (Table 1). The nine great soil groups covered were distributed as follows: forest Oxysol from the rain forest; forest Ochrosol and forest acid Gleisol from the moist semi-deciduous forest; savanna Ochrosol, savanna acid Gleisol and ground-water laterite from the interior savanna zone and savanna Ochrosol, tropical Black Earth and tropical Grey Earth from the coastal savanna zone. The soil groups and their representative soil profiles were fully described by Brammer (1962).

Table 1. Approximate correlation of the soil groups studied in the new U.S. soil taxonomy and FAO/UNESCO soil classification system

Charter's System (Brammer, 1962)	USDA System (Soil Survey Staff, 1970)	FAO System (FAO/UNESCO, 1970)
1. Forest Oxysol	Paleudult	Humic Nitosol, Dystric Nitosols
2. Forest Ochrosol	Typic Paleudult, Rhodic Paleudult	Orthic Acrisol, Dystric Nitosol, Eutric Nitosols
3. Forest Acid Gleisol	Tropaquept	Eutric and Dystric Cleysols
4. Savanna Ochrosol (Interior)	Paleustult	Orthic Acrisol, Dystric Nitosols
5. Savanna Ochrosol (Coastal)	Paleustalf	Eutric Nitosols, Orthic Acrisols
6. Savanna Acid Gleisol	Tropaquept	Dystric Cleysols
7. Ground-water Laterite	Eutropept	Luvic Arenosols, Ferric Luvisols
8. Tropical Black Earth	Typic Chromustert, Typic Pellustert	Pellic Vertisols, Chromic Vertisols
9. Tropical Grey Earth	Natrustalf	Dystric Planosol, Gleyic Solonetz

Table 2. Percent nitrogen distribution in representative soil profiles of the major soil groups

	Soil Groups								
Depth (cm)	Forest Oxysol (% N)	Forest Ochrosol (% N)	Forest Acid Gleisol (% N)	Interior Savanna Ochrosol (% N)	Savanna Acid Gleisol (% N)	Ground-water Laterite (% N)	Coastal savanna Ochrosol (% N)	Tropical Black Earth (% N)	Tropical Grey Earth (% N)
0– 5	0.325	0.490	0.154	0.068	0.032	0.058	0.024	0.065	0.030
5– 20	0.110	0.191	0.053	0.042	0.029	0.036	0.021	0.040	0.029
20– 50	0.065	0.056	0.018	0.036	0.025	0.023	0.024	0.024	0.022
50–100	0.036	0.045	0.014	0.035	0.014	0.021	0.021	0.022	0.004
100–150	0.022	0.021	0.014	0.028	0.012	0.018	0.015	0.012	0.003
150–200	–	0.018	–	0.019	0.008	0.016	0.009	0.001	0.001

Analytical methods

Particle size analysis was made by the pipette method (Kilmer & Alexander, 1949) and the textural classes determined on the triangular scale. The pH was measured in water (1:1) using a Cambridge pH meter. Organic carbon was determined by the Walkley-Black wet combustion method (Piper, 1950) and nitrogen was determined by Kjehldahl digestion and ammonia distillation (SCS. USDA, 1972).

Results and discussion

Most of the nitrogen present in the soils was concentrated in the 0–5 cm surface layer (Table 2). This supports the findings of others (Ahn, 1961; Brammer, 1967; Asamoa, 1968; Adu, 1969; Smith, 1962). In the lower surface soil (5–20 cm) nitrogen declined rather sharply in the forest soils by about 60–70 % and gradually in the savanna soils. In the upper subsoil (20–50 cm) the decline in nitrogen content was about 80–90 % in the forest soils and 20–70 % in the savanna soils. The distribution of nitrogen in the subsoil was gradual with depth in all soils. The sharp decline in the lower surface and upper subsoil layers of the forest soils was probably due to greater leaching under the forest climate and to more effective recycling of nitrogen by forest plants (Nye & Greenland, 1960).

For any given soil group studied, the nitrogen content of the surface soil was closely related to the organic carbon content (Table 3). The higher the organic carbon content the higher the nitrogen content. Comparing similar soils, forest soils (Ochrocol and Oxysol groups) contained more nitrogen than savanna soils (Ochrosols). The average percentages of N in these related groups of soils varied as follows: coastal savanna Ochrosol 0.024 %; interior savanna Ochrosol 0.05 %; forest Oxysol 0.306 % and forest Ochrosol 0.507 %. This showed that nitrogen levels increased with rainfall up to a maximum of 0.507 % N in the forest Ochrosol belt with 1270–1780 mm rainfall. In the forest Oxysol belt where rainfall exceeded 1780 mm there was a decrease in nitrogen level to about 0.306 %. The increase in nitrogen with rainfall may be attributed to indirect influence of rainfall in promoting luxuriant vegetative growth. The slight fall in nitrogen within the rain forest may be partly explained by greater leaching of nitrogen under the rain forest conditions. Unfavourable soil conditions such as high acidity and the nature of forest species in this zone may also account for the decline in nitrogen. Temperature differences are very slight over the four zones (Fig. 1). However, the slightly higher temperatures in the savanna zones lead to relatively faster rates of decomposition of humus in the savanna soils (Jenny, 1950). Furthermore, annual fires in the savanna grassland reduced the organic carbon content of the soils and hence their nitrogen content (Nye & Greenland, 1960). The main effect of vegetation on the nitrogen content of the soils was in the organic matter it furnished. Soils under savanna grass with less litter were therefore lower in nitrogen than similar soils under forest (Nye, 1951; Nye & Greenland, 1960; de Endredy, 1954).

Well drained soils generally contained higher nitrogen levels than the associated poorly drained soils. The well drained loamy forest Ochrosols under forb-regrowth contained 0.380 % N compared with the 0.265 % N in the poorly drained associated loamy forest acid Gleisol under forb-regrowth (Table 3). However, it should be noted that the poorly drained savanna Ochrosol of the interior zone contained twice as much nitrogen as the

Table 3. Carbon and nitrogen contents, pH and C/N ratios of surface samples (0–5 cm depth) of major soils from different ecological zones of Ghana

Ecological zone	Great soil group	Vegetation or crop	No. of soil profiles	Texture of surface soil	pH	Average % C	% N	Range in % N	Average C/N ratio
1. Rain forest	Forest Oxysols	Broken forest	11	Silty clay loam	4.3	4.50	0.306	0.166–0.500	14.7
		Rubber	5	” ” ”	4.5	3.57	0.304	0.254–0.373	11.7
2. Most semi-deciduous forest	Forest Ochrosols	Broken forest	12	Clay loam	6.0	5.60	0.507	0.291–0.753	11.0
		Secondary forest	5	” ”	5.8	3.65	0.340	0.163–0.607	10.7
		Forest thicket	5	” ”	5.8	4.98	0.435	0.262–0.633	11.4
		Forb regrowth	5	” ”	5.6	4.08	0.380	0.341–0.463	10.7
		Plantain/Cocoyam Young cocoa	5	” ”	5.4	3.22	0.318	0.282–0.412	10.1
		Cocoa	25	” ”	6.1	3.91	0.337	0.109–0.714	9.5
		Cocoa	5	Sandy loam	6.2	1.74	0.158	0.109–0.176	11.0
	Forest acid Gleisols	Forb regrowth	8	Loamy sand	5.5	1.39	0.115	0.086–0.152	12.1
		Forb regrowth	5	Loam	6.0	2.36	0.265	0.154–0.387	9.0
3. Interior savanna	Savanna Ochrosol	Tall grass	10	Loamy sand	6.5	0.74	0.050	0.026–0.109	14.8
	Savanna acid Gleisols	Regrowth swamp grass	5	Clay loam	6.2	1.31	0.101	0.039–0.189	13.0
	Ground-water Laterites	Regrowth tall grass	6	Sandy loam	6.3	0.93	0.064	0.034–0.112	14.5
4. Coastal savanna	Tropical Black earths	Short grass	5	Clay	6.8	0.98	0.084	0.055–0.106	11.7
	Tropical Grey earths	Short grass	5	Loamy sand	6.3	0.40	0.027	0.021–0.032	16.7
	Savanna Ochrosols	Medium grass	5	Loamy sand	6.3	0.37	0.024	0.018–0.030	15.4

associated well drained savanna Ochrosol (Table 3). This may be attributed to the difference in surface texture of the two soils. Fine textured soils generally contain more nitrogen than coarse textured soils, other conditions being equal. The savanna acid Gleisol had a clay loam surface texture whereas the savanna Ochrosol had a loamy sand surface texture. Savanna acid Gleisol retained more moisture in the prolonged dry season than the sandy Ochrosol and this could favourably influence the activity of soil microorganisms, thereby contributing to the higher nitrogen status of the soil. Another example of the effect of surface soil texture could be seen in the forest Ochrosols under cocoa (Table 2). The soils with clay loam texture contained 0.337 % N whereas those with sandy loam texture contained 0.158 % N. Also under short grass savanna the tropical Black Earth with a clay surface texture contained 0.084 % N compared with 0.027 % of the tropical Grey Earth with a loamy sand surface texture. In this case there is an added effect of kind of parent material. The tropical black earth was developed over basic gneiss rich in basic minerals (Ca and Mg), whereas the tropical Grey Earth over acidic gneiss is less rich in basic minerals. The presence of calcium, inducing neutral soil conditions, promotes faster mineralisation of nitrogen than under acid conditions where calcium is deficient (Alexander, 1965). The effect of cultivation or length of fallow on nitrogen level could be seen in the differences in nitrogen content of the Forest-Ochrosols under various kinds of vegetation or crop (Table 3). The data showed a trend of decreasing nitrogen with reduction in length of fallow. The highest nitrogen was under broken forest (0.507 %) followed by forest thicket (0.435 %) and the least amount of nitrogen was in the soils under a newly established farm of plantain, cocoyam and young cocoa (0.318 %). Nitrogen levels were also reduced under mature cocoa trees. These findings support the works of others (Nye, 1951; Charter, 155a, 1955b).

Carbon: nitrogen ratios were highest in the savanna soils, about 14.3 on the average. The forest Ochrosols were lowest with a ratio of 10.6 and the forest Oxysols were intermediate with a ratio of about 13.2.

Conclusions

Differences in nitrogen levels of the soil groups studied appeared to be related to differences in rainfall, temperature, kind of vegetation and length of fallow period in cultivated areas. Soils with coarse textured surface soils were lower in nitrogen status than soils with finer textured surface soils. Soil drainage condition, mineralogy of soil parent material and to some extent soil acidity appeared to have influenced nitrogen levels in the soils. The decline in nitrogen level with cultivation needs to be further investigated under various farming or cropping systems. The trends indicated in this study suggest that carefully controlled experiments will be necessary for investigating the effect of soil factors on nitrogen levels in different soil types.

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NITROGEN PROFILE IN A KAOLINITIC ALFISOL UNDER FALLOW AND CONTINUOUS CULTIVATION

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Abstract

A long-term field experiment was established at Ibadan, Nigeria to study effects of fallow and continuous cultivation on the soil physical and chemical properties with special reference to soil nitrogen and organic matter. Continuous cultivation after four years with maize, soybean, and cassava resulted in rapid decline of the initial levels of soil total N and organic C. Planted fallow species such as Guinea grass (*Panicum maximum*), pigeon pea (*Cajanus cajan*), and leucaena (*Leucaena leucocephyla*) with periodic return of plant residue were able to maintain relatively high levels of total N in the soil. Profile studies of total N up to one meter depth showed that total N in the fallow and cropping plots was mostly concentrated within the 0–15 cm surface layer.

Vertical distribution of nitrate measured at the end of the rainy season showed that NO_3-N content in the subsoil horizons under fallow was very low throughout the one-meter profile, whereas in the cropped plots, substantial accumulation of NO_3-N was found below the depth of 45 cm in the one-metre profile.

Weekly determinations of NO_3-N and NH_4-N in the surface soils (0–15 cm) indicated considerable seasonal fluctuations both in the fallow and cultivated plots. Nitrate level in the surface soils remained high during the first part of rainy season, indicating a flush in nitrogen mineralization at the onset of rainy season.

Introduction

A long-term field experiment was established at the International Institute of Tropical Agriculture (IITA) in 1972. Its main objectives are as follow: i) to investigate the extent of decline of soil fertility of a forest Alfisol under continuous cultivation, with particular reference to soil nitrogen and organic matter; ii) to study the effectiveness of planted fallow species in maintaining soil physical and chemical conditions of the soil in comparison with natural bush or forest fallow.

The result from the first three years of the experiment have been reported by Juo & Lal (1977). They showed that continuous cultivation with maize (stover removed) and soybean (stover returned) for three years resulted in 30 to 40 % decline of the initial soil total nitrogen. However, returning maize stover as surface mulch was able to maintain total N and organic matter in the surface soil at levels comparable to that of bush fallow. They concluded that in order to maintain favourable levels of soil organic matter and total N, frequent and periodic return of large quantities of plant residues (i.e., maize, guinea grass) are required.

This paper reports on the vertical distribution of soil nitrogen and seasonal variations of inorganic nitrogen in the surface soils under different cropping and fallow treatments.

Experimental

The experimental site was cleared from secondary forest in 1971 at the end of the rainy season. Clearing was done manually without burning to ensure minimum disturbance of the surface soil. The plots were planted in March 1972 with three fallow species and three crop species. The fallow treatments consisted of tree-type pigeon pea (*Cajanus cajan*), Guinea grass (*Panicum maximum*), leucaena (*Leucaena leucocephyla*) and bush regrowth. The cropping treatments included continuous soybean (*Glycine max*) with residue (stover) returned at soil surface after harvest, continuous maize (*Zea mays*) with stover return as surface mulch, and maize and cassava inter-cropped with maize residue returned. All cropped plots were under minimum tillage. Plots (10 x 10 m) were laid out according to a randomized complete block design with three replications. Two crops of maize and soybean were planted each year in the mono-cropping plots. One crop of maize was planted in the maize/cassava inter-cropped plots.

All cropped plots received recommended rates of chemical fertilizers, and plant protection. Each crop of maize received 150 kg ha^{-1} of N as urea, 26 kg ha^{-1} of P as single super, 25 kg ha^{-1} of K as KCl and 1 kg ha^{-1} of Zn as Zn-chelate. The P and K rates for each group of soybean were the same as those for maize but only 50 kg ha^{-1} of N was applied at the time of planting. Nitrogen application for maize was split into two, 1/3 at planting (broadcasted) and 2/3 at 4 weeks after emergence (banded).

The fallow plots received no chemical fertilizers, no tillage and no plant protection with the exception of pigeon pea, which was sprayed periodically with insecticide during flowering and pod-forming stages.

Pigeon pea and leucaena were ratooned once a year at the onset of the rainy season and Guinea grass was cut three or four times each year at flowering stage. All plant residues were returned to the respective plots as surface mulch. Pigeon pea plants were replanted every 2 to 3 years when necessary.

Profile samples at 15 cm depth interval were taken at the end of the rainy season in November 1975 (4th year since the beginning of experiment). Due to high gravel concentration (quartzite) in the upper B horizon of the profile (common characteristic of upland soils in the area), sampling was done by digging a 3 m long and 1 m deep pit at one side of each plot. Soil samples were taken across the length at the inner side of the pit.

The moist samples were passed through a 2 mm sieve and soil moisture content and NO_3-N were determined immediately. Nitrate was extracted by 1N KCl for 30 minutes at 1:5 soil to solution ratio and determined colorimetrically by the brucine method.

Air-dried profile samples (passed 2 mm sieve) were analyzed for total N by Kjeldahl digestion and colorimetric determination on a Technicon Autoanalyzer. Organic C was measured by the dichromate-sulphuric acid oxidation method.

To monitor the seasonal changes in inorganic N (NO_3-N and NH_4-N) in surface soils (0–15 cm), weekly samples were taken from all plots during 1976. A composite sample of 20 random cores was taken from each plot. The samples were extracted immediately with 1N KCl for 30 minutes at 1:5 soil to solution ratio for NO_3-N and NH_4-N analysis. A subsample was taken at the same time for soil moisture content. The NH_4-N content in the KCl extracts was measured colorimetrically on a Technicon Autoanalyzer.

Results

Soil at the experimental site is classified as Oxic Paleustalf (Moormann *et al.*, 1974). Under secondary forest, the surface soil has a pH value around 6.5 and remains fairly constant with depth up to 150 cm. The surface soil contains about 4.5 meq, 0.7 meq and 0.3 meq of exchangeable Ca, Mg and K per 100 g of soil, respectively. Clay content in the surface soil is about 17 % and increases with depth (55 % at 100 cm depth). The clay fraction contains predominantly kaolinite with small amounts of goethite, hematite and mica. The total N content in the surface soil under forest fallow ranges from 0.15 to 0.25 %, which varies considerably with sampling sites and also with the time of the year when the samples were taken (A.S.R. Juo, unpublished data).

Crop performance, nutrient cycling and effects on soil physical and chemical properties were reported in a previous publication (Juo & Lal, 1977). The present paper deals mainly with aspects of soil nitrogen.

Vertical distribution

Vertical distributions of total N in the 105 cm profiles taken from the fallow and cultivated plots are shown in Fig. 1. Using the bush fallow plot as a reference, it is seen that continuous cultivation resulted in the loss of total N from the surface soil, whereas it has little effect on the subsoil horizons which contain very low levels of total N under both fallow and cultivation.

Planted fallow of Guinea grass and pigeon pea maintains a reasonably high level of total N in the surface soil and it is considerably higher than the soil under bush fallow. As no nitrogen fertilizer was added to the fallow plots, the gain in total N must be coming mainly from biological fixation of atmospheric nitrogen through symbiotic (pigeon pea)

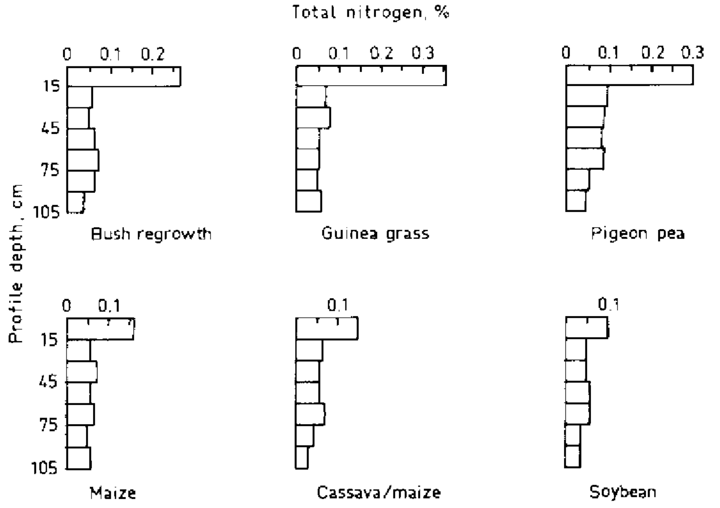

Figure 1. Profile distribution of soil total N after four years of fallow and continuous cultivation.

and non-symbiotic (Guinea grass) processes. The high levels of total N soil organic matter in the Guinea grass plot are attributed to the frequent plant residue addition as surface mulch (3 or 4 cuttings and total of 16 t ha^{-1} yr^{-1}). The tree-type pigeon peas were ratooned once a year. A large number of plants died after 2 years and they were replanted at the beginning of the rainy season. Therefore, the decomposed roots might account for the slightly higher levels of total N and organic C (A.S.R. Juo, unpublished data) in the subsoil as compared with the bush and grass plots.

The vertical distribution of organic C follows a similar pattern as that of total N; the C/N ratio in the surface soils in all plots ranging from 12 in the Guinea grass plot to 8 in the pigeon pea and leucaena plots.

It is important to note that total N and soil organic matter are mainly concentrated in the surface layer (0–15 cm) followed by a sharp decrease in the subsequent layers of the profile. This phenomenon, together with the kaolinitic clay mineralogy and the low CEC value in the subsoils suggest that loss of surface soil by erosion due to inadequate soil and crop management would result in a drastic change in the soil fertility status of this soil.

Vertical distribution of NO_3-N of selected plots at the end of the rainy season in 1975 are shown in Fig. 2. Profiles under natural bush, Guinea grass and leucaena fallow contain negligible NO_3-N in the subsoil down to 105 cm. It is reasonable to assume that most of the inorganic N mineralized in the surface soil is taken up by the plant and, hence, leaching losses under such circumstances are negligible (Greenland, 1975). The substantial amount

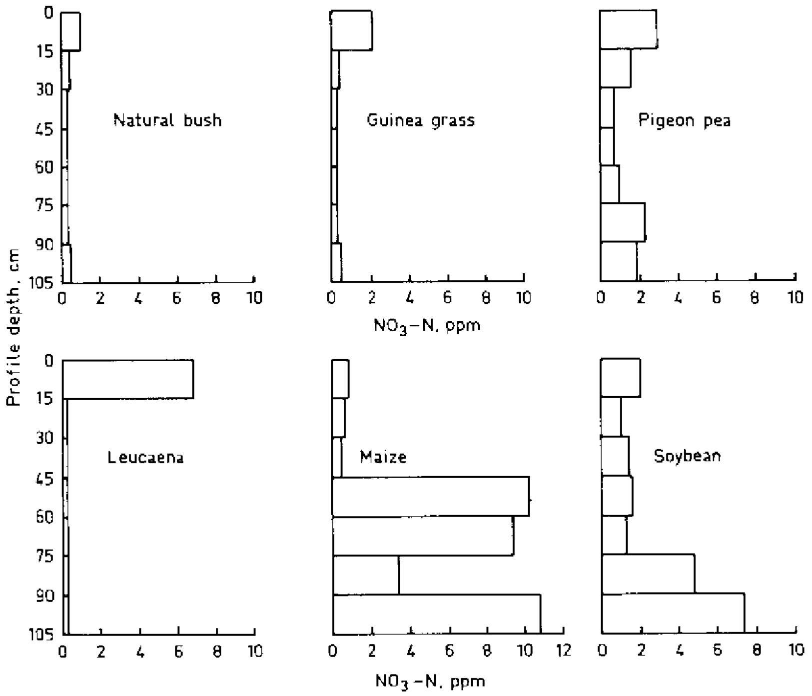

Figure 2. Vertical distribution of NO_3-N in fallow and cultivated plots sampled at the end of the season.

of NO_3-N in the surface soil under leucaena is apparently due to frequent litterfall followed up by subsequent rapid mineralization of the fresh plant materials with low C/N ratio. The pigeon pea plot gives measurable amounts of NO_3-N in the subsoil horizon; indicating some downward movement of nitrate.

In contrast to the fallow plots, the cropped plot showed substantial downward movement of NO_3-N. The second season maize (residue removed) plot received 50 kg ha^{-1} N at planting and 100 kg ha^{-1} N as urea 4 weeks after planting. In other words, the second N application was made about 5 weeks before the soil sampling date. Therefore, it is reasonable to assume that the nitrate found in the subsoils is from leaching of fertilizer because little mineralization from organic N occurs during the end of the rainy season, particularly in this low organic matter plot (maize stover removed). Leaching of nitrate in the soybean plot is also expected during the later stage of growth. At the time of soil sampling, the crop was matured and hence little uptake is expected. A major portion of the NO_3-N found in the subsoil should have come from the soybean nodules, as the soybean plot received 50 kg ha^{-1} N as urea at the time of planting in September. If there was any leaching of fertilizer N in the soybean plot, it would probably move far beyond the one metre depth.

The pH profile of soils under different cropping and fallow treatments is given in Table 1. Cultivation after 4 years resulted in a decrease in soil pH throughout the depth measured. The pH drop is particularly pronounced in the subsoils in the maize plots where the stover was removed after each harvest. This coincides with the high nitrate concentration in the lower horizons of the profile shown in Fig. 2.

It is interesting to note the slightly higher pH values of the subsoil horizons in the pigeon pea plot as compared with the bush plot. Pigeon pea fallow apparently has the advantage of exploiting Ca and Mg through its deep root systems. Hence it is capable of raising the exchangeable base status in subsoil (A.S.R. Juo, unpublished data). Such plant species could be an important fallow crop in the acid soil regions.

Decreases in exchangeable bases (Ca, Mg, K) and CEC in the profiles under cultivation were also observed, particularly in the low organic matter plots (i.e., maize with residue removed). The loss of exchangeable Ca, Mg and K may be partially attributed to the accompanying movement with nitrate. The decrease in CEC in the cultivated profile is due to the drop in soil pH as the soil contains predominantly pH-dependent charges.

Table 1. Soil pH (in water, 1:1) of profile samples under fallow and cultivation

Depth cm	Natural bush	Guinea grass	Pigeon pea	Maize + residue	Maize – residue	Soybean
0–15	6.7	6.9	5.6	6.1	6.1	5.9
15–30	7.0	6.9	6.6	6.5	6.2	5.9
30–45	6.8	6.7	6.9	6.2	6.1	5.9
45–60	6.7	6.7	7.0	6.0	5.9	6.0
60–75	6.5	6.6	7.1	5.9	5.5	6.0
75–90	6.5	6.5	7.0	6.1	5.6	6.0
90–105	6.4	6.5	7.0	6.3	5.4	6.0

Seasonal fluctuations of inorganic N

Nitrate and ammonium nitrogen in the fallow and cropped plots were monitored weekly during the period between November 1975 and December 1976. Selected results are given in Figs. 3 and 4. The nitrate data from the fallow plots fluctuate considerably throughout the period measured (Fig. 3). The monthly data were means of 4 weekly determinations of 3 replicated plots. The nitrate peaks generally coincide with the rainfall pattern (Fig. 4). The highest nitrate level in the surface soil occurred during the months of May and June. The pigeon pea plot maintained a relatively high level of NO_3-N throughout the first rainy season. The patterns of NH_4-N fluctuation in the bush and grass plots are similar to those of NO_3-N but the amounts of NH_4-N during the peak season are generally smaller.

The nitrate levels in the bush and Guinea grass plots were low and showed little fluctuation during the second rainy season. The NH_4-N levels during the same period were slightly higher than NO_3-N, whereas in the pigeon pea plot, the NO_3-N levels during

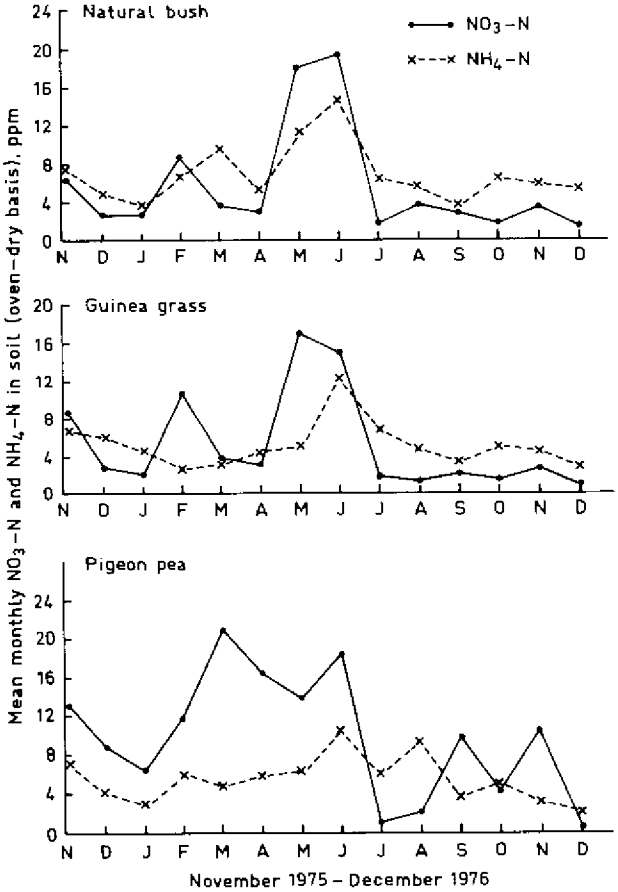

Figure 3. Mean monthly contents (oven-dry basis) of NO_3-N and NH_4-N in surface soil (0–15 cm) under natural bush, Guinea grass and pigeon pea fallow.

the second rainy season were considerably higher than in the bush and grass plots.

Seasonal fluctuations in NO_3-N of soils in the tropical regions have been reported by several workers (Birch, 1958; Semb & Robinson, 1969; Greenland, 1958). As a prolonged dry season is prevalent in many humid and subhumid tropical regions, dessication of the soil followed by wetting tends to cause a surge of microbial activity and of nitrogen mineralization (Birch, 1958). This flush in N mineralization at the onset of the rainy season is an important factor for soil-available nitrogen management in the tropics (Bartholomew, 1975; Nye & Greenland, 1960).

In the cultivated plot (maize with residue returned), the two large nitrate peaks reflect the two applications of N fertilizer (urea) during the two growing seasons (Fig. 4). The much lower levels of NH_4-N present indicate the rapid rate of nitrification in the soil (Kang & Ayanaba, 1976).

The rainfall and evaporation data (Fig. 4) were obtained by Lawson (1975, 1976). The total rainfall during 1976 amounted to 1012 mm, which was about 20 % below the average of 20-year rainfall data from the nearby University of Ibadan.

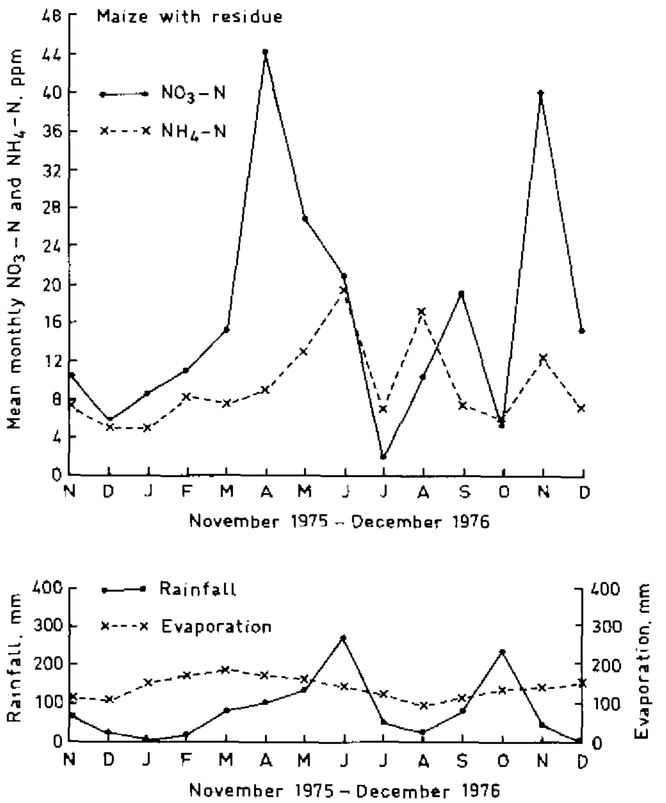

Figure 4. Mean monthly contents (oven-dry basis) of NO_3-N and NH_4-N in surface soil (0–15 cm) under maize cultivation (stover returned) and rainfall and evaporation data (from Lawson, 1975, 1976) during the period of measurement.

General discussion and conclusions

Loss of total soil nitrogen due to cultivation is a worldwide concern. In temperate regions, long-term trends of soil total N and organic C losses are relatively low and depend upon management practices. Meints *et al.* (1977) reported a 5 to 20 % decline of initial soil total N in Mollisols and Alfisols in the midwestern United States over a period of 36 years. In England, Jenkinson & Rayner (1977) reported a loss of approximately 45 % of soil organic C over a 100-year period.

In view of the rapid turnover of plant and soil organic materials under tropical conditions (Jenkinson & Ayanaba, 1977), the rate of soil N losses is expected to be rapid, particularly when soil erosion of the cultivated field is not prevented. From the same experimental plots, Juo & Lal (1977) showed a decline of 30 to 40 % of the initial soil total N from the Alfisol under secondary forest after three years of cultivation with maize (stover removed) and soybean (stover returned). However, periodic additions of plant residue as surface mulch such as maize stover and Guinea grass were able to maintain soil organic matter and total N levels comparable to forest fallow.

Profile data given in the present paper further demonstrate the importance of fallow in the maintenance of soil fertility. The total N values in the surface soil of the profile (Fig. 1) were considerably higher than the surface soil data given by Greenland (1975) and Juo & Lal (1977) from the same plots sampled one or two years earlier. This difference may be due mainly to the method of soil sampling. The profile pits were dug in a relatively small but uniform area within each plot, whereas the surface soil samples (20 cores per plot) are randomly taken from the entire plot.

Under the traditional shifting cultivation systems, soil fertility of the cultivated land is restored by building up soil N and soil organic matter levels through bush or forest fallow (Laudelout, 1958; Nye & Greenland, 1960; Bartholomew, 1975). The question remains whether such a system can be replaced by a shorter fallow period with more effective fallow species, or by continuous cropping with adequate chemical fertilization and crop rotation.

Results from the present study indicate that chemical fertilization and conventional rotation with grain legumes such as soybean and cowpea with insufficient amounts of crop residue return are incapable of maintaining the initial soil fertility level of the forest soil. As the maintenance of soil organic matter and subsoil structure are the key factors to soil productivity of the kaolinitic Alfisols (Jaiyebo & Moore, 1964; Juo & Lal, 1977), returning the soil to a fallow period after 3 to 4 years of arable cultivation becomes inevitable. Planted fallow such as tree-type pigeon pea or Guinea grass or other leguminous shrubs may be a better choice than natural bush fallow. Soil fertility restoration by fallow is particularly important on soils cropped with yam and cassava, where surface disturbance cannot be avoided.

The savanna and drier forest zones with annual rainfall between 800–1600 mm comprise the major grain-producing area of West Africa. Nitrate leaching in these regions cannot be over-emphasized. Work on nitrate leaching in northern Nigeria under bare fallow showed that nitrate formed from soil organic matter persisted in the top 120 cm of the soil profile throughout most of rainy season (Wild, 1971). Results from the present study conducted in the drier forest zone, showed a considerable accumulation of NO_3-N at the lower horizons of the 105 cm deep profile under cultivation at the end of the rainy season. Little NO_3-N was detected in the subsoil in the fallow plots. These results, together with the data on seasonal nitrate fluctuations, suggest that loss of inorganic nitrogen in these regions could be minimized by adequate crop and soil management practices.

Field data on nitrate leaching in the high rainfall region of west Africa are unavailable. Speculations from rainfall, soil permeability and small lysimeter studies suggest that leaching losses may become a limiting factor for crop production.

The argument for utilizing subsoil NO_3-N by Jones (1975) and Bartholomew (1975) is plausible but it requires experimental verification. A majority of the upland soils in the humid and sub-humid tropics are deep and well-drained. If there is any appreciable amount of NO_3-N in the subsoil horizons, it is probably located far beyond the reach of young fallow plants during the early stages of growth.

Acknowledgements

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Nitrogen Cycling in West African Ecosystems

NITROGEN FIXATION BY BLUE-GREEN ALGAL SOIL CRUSTS IN NIGERIAN SAVANNA*

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Abstract

Blue-green algae, many of which are known to be nitrogen fixers, occur on the surface of the soil as crusts. Crusts are masses of algal filaments that grow on top of each other. These blue-green algal crusts were collected from all of the savanna zones of Nigeria in order to estimate the quantitative role they may play in the nitrogen economy of savanna ecosystems. Algae of the genus *Scytonema*, which are nitrogen fixers, were dominant in all the crust samples collected.

Using the acetylene reduction assay, it was found that the crust samples fixed nitrogen 24 h after rewetting and were affected by pH, temperature, light and moisture variations.

If sufficient light were available for near maximum photosynthesis, with an algal cover of the soil surface of about 30 % and mean to maximum-fixation during 70 % of the rainy season of 180 days of 10-hour day-length, from 3.3 to 9.2 kg ha^{-1} yr^{-1} of nitrogen would be fixed. This amount would replace much of the nitrogen lost from the grass standing crop as a result of annual burning of the savanna.

Introduction

For the past three years a study has been carried out to investigate the stocks and flows of nitrogen in some chosen savanna ecosystems in Nigeria. The study involves evaluating input, cycling and output of nitrogen in these ecosystems.

Blue-green algae are known to fix nitrogen (see for example Fogg *et al.*, 1973) and are therefore considered as sources of nitrogen input. Most attention has been paid to their role in rice paddies where – free-living (Singh, 1961, 1972) and in symbiotic association with the water fern, *Azolla* (Moore, 1969) – they contribute substantial amounts of nitrogen to the ecosystem. The blue-green algae are also common components of the microbial flora of the soil in many parts of the world.

In Nigeria, blue-green algae also occurs as crusts 1 to 5 mm thick on the surface of soil that is exposed and not too sandy. These crusts are composed of intertwining filaments of blue-green algae which usually dry up in the dry season and begin to grow again with the coming of the rains or when wetted. They are very resistant to drought and quite resistant to fire.

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* Part of this material, in different form, was presented at the Symposium on "The potentials for nitrogen fixation in the tropics", Rio de Janeiro, Brazil, 18–25 July, 1977: "Nitrogen fixation by soil algae of temperate and tropical soils' '. (Stewart, W.D.P., Sampaio, M.J., Isichei, A.O. & Sylvester-Bradley, R.).

No work on surface crust blue-green algae has been reported from Nigeria or other tropical regions, excepting the preliminary report at the Brazilian symposium which includes some of the present work (Stewart *et al.*, 1977). Jones (1977) has investigated the effects of environmental factors on *Nostoc* mats in southern Africa, a sub-tropical-Mediterranean region. This study is concerned with finding out whether surface crust blue-green algae in Nigerian savanna fix nitrogen, and elucidating the environmental factors that affect their fixing ability. It must, however, be emphasized that the present work is of a preliminary nature and is concerned with only the general aspects of nitrogen fixation by the blue-green algal crusts of this specific region and the factors that may affect their quantitative contribution of nitrogen to the savanna ecosystem.

Materials and methods

Crust samples were collected from all the savanna zones and from some parts of the forest and sub-montane zones of Nigeria (Fig. 1). The samples were collected by scooping the crusts from the soil surface with a spoon. The crusts were sealed in envelopes and notes made of the area and the nature of the soil. The samples were later air dried. Each sampling was divided into two portions: one packed for later study of the effects of environmental factors at the laboratories of Professor W.D.P. Stewart in Dundee, and the other sent to Professor K. Anagnostides of Athens University for culturing and identification. The cover was estimated by laying random quadrats of a string grid and recording the number of grid intersections above the algal crusts (Isichei, in preparation).

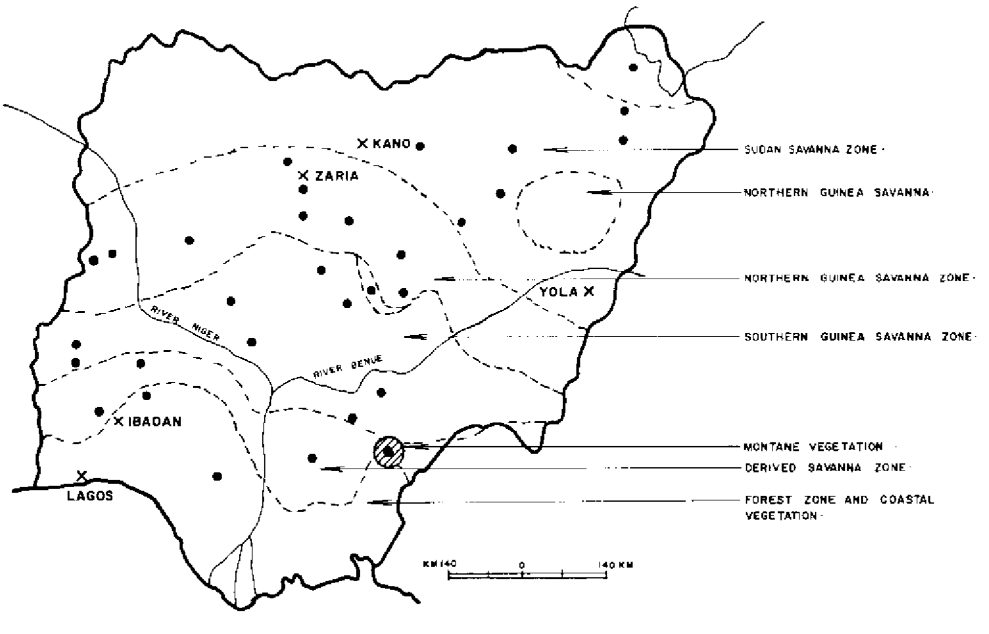

Figure 1. Nigeria: Dots indicate areas where algal crust samples were collected.

Before the effects of environmental factors were studied, the samples were wetted with a nitrogen-free medium, 'BG–11' (Stanier *et al.*, 1971) and incubated at 3000 lux and 27°C. The wetted samples were first tested for nitrogenase activity using the acetylene reduction assay (Renaut *et al.*, 1975). Since crust effectiveness in N-fixation will be expressed per unit area, tests were carried out using 1 cm^2 circular crusts sampled by using a metal corer 1 cm^2 in area to cut out samples from the crust collections.

The incubated samples were used to test the effects of the following environmental variables: (1) moisture; (2) pH; (3) light intensity; (4) temperature. The first reaction to moisture of the dry crusts would be water uptake. This would be manifested by increase in weight on immersing the crusts in water and decrease in weight when the immersed sample is exposed to air. The crusts were therefore immersed in water, brought out immediately and the weight monitored continuously by suspending them from a hand spring balance ('Pesola', Switzerland, 5 g). This was repeated for several crust samples.

Relative humidity is a measure of available moisture in the atmosphere, to which the crusts are exposed. Incubated samples were subjected to different relative humidities at room temperature (20°C). The different humidities (RH) were achieved by use of saturated salt and sugar solutions (Winston & Bates, 1960), as shown below:

Solution	**Approximate RH at 20°C**	**Solution**	**Approximate RH at 20°C**
Water	100.0 %	Sodium chloride	77.5 %
Potassium sulphate	97.5 %	Glucose	55.0 %
Potassium sodium tartarate	87.0 %	Air in the laboratory	40.0 %
		Silica gel	20.0 %

When these solutions are kept in closed containers for some time, the air above them is assumed to have the stated relative humidities. The solutions were placed in tightly closed bottles and crust samples were put into the bottles in open 5 cm^3 vials. The bottles were left closed for at least 24 h before acetylene reduction assay was carried out. The level of acetylene reduction in each sample was tested immediately before each experiment. After 24 h the level of acetylene reduction was expressed as a proportion of the original value.

To test the effect of pH, the crust samples were kept at pH levels of 4 to 10 for 24 h. The pH buffers used were prepared from nitrogen-free universal buffer (Teorell & Stenhagen, 1938). The samples were incubated for acetylene reduction assay for 60 minutes. The pH buffers were fresh so that there was no change in pH of greater than 0.2 pH units during the experimental period.

Tests for acetylene reduction by a particular sample were carried out at various light intensities. Light intensity was varied by moving the crust sample away from a projector light source. At each point the light intensity was measured using a light meter (Corning-EEL Lightmaster 18/335b). The range of intensity used was from 200 to 34,000 lux. Each sample was left at each light intensity for an hour before being subjected to a 60-minute acetylene reduction assay.

Temperature effects were tested by putting a sample in a closed vial and leaving it in a water bath at the required temperature for one hour before assay.

Results

It was found that all crust samples were dominated by *Scytonema myochrous* (Dillw.) Ag. ex Born. et Flah., which has well developed heterocysts. Small quantities of non-heterocystous *Oscillatoriaceae* and occasional *Tolypothrix* and/or *Nostoc* species were also found. It can thus be stated that the crusts from all Nigerian locations contain mostly potentially nitrogen-fixing blue-green algae. The mean values of acetylene reduced are given in Table 1.

The crusts were found to absorb water very fast (to double their weight in a few minutes, Fig. 2) but to lose it slowly. Dry crusts start reducing acetylene within 24 h of wetting, and activity increases exponentially after this time until at least 72 h (Fig. 3).

Table 2 illustrates the effect of various relative humidities on acetylene reduction. The maximal reduction occurs at a relative humidity of 75 %. At humidities as low as 40 % no reduction takes place. No activity occurred at the relative humidity where potassium sodium tartarate was used. It was suspected that this salt was toxic to the algae.

The blue-green algae present in the crusts have a wide pH tolerance with an optimum near pH 8 but with good activity at pH 5 and pH 10 (Fig. 4).

The crust samples showed little activity at 5°C, but activity increased with increasing temperature up to 40°C. Activity stopped above this temperature (Fig. 5).

No clear-cut trend in nitrogenase activity was observed with variations in light intensity; the crusts did not reach saturation even at 34,000 lux, the point at which the experiment was stopped.

Table 1. **Acetylene reduction by algal soil crust samples from various habitats in Nigeria.**

Location (Zone according to Keay, 1959)	Mean rate of C_2H_2 reduction (nmoles cm $^{-2}$h^{-1})	Maximum rate of C_2H_2 reduction (nmoles cm $^{-2}$h^{-1})
Sahel savanna	2.0	10.0
Sudan savanna	6.6	25.2
Northern Guinea savanna	5.7	29.7
Southern Guinea savanna	9.2	23.7
Derived savanna	10.6	24.5
Forest	11.2	76.4
Mean of Sudan, Guinea and derived savanna zones	8.2	25.8

Table 2. **The effect of various relative humidities on acetylene reduction by algal crusts from Nigeria.**

Relative humidity (%)	% Relative C_2H_2 reduction in comparison with reduction at almost 100 % RH
97.5	118
75	149
55	58
40	0

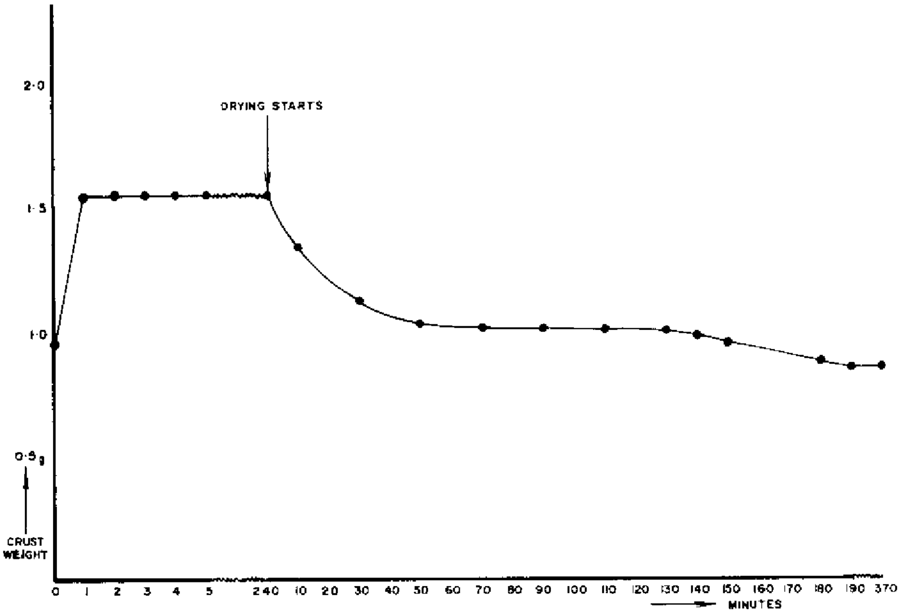

Figure 2. Water uptake and loss by algal crust sample at 20°C and 40 % relative humidity.

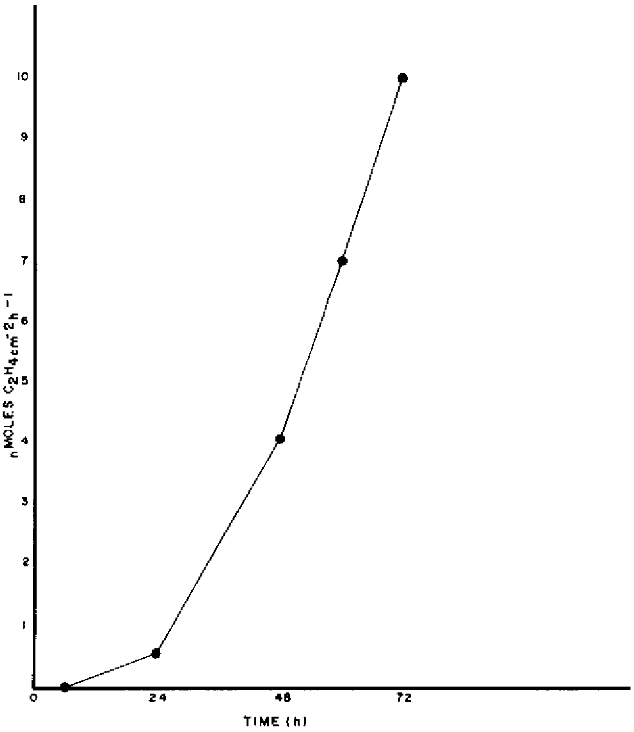

Figure 3. Time course of acetylene reduction by crust sample after rewetting.

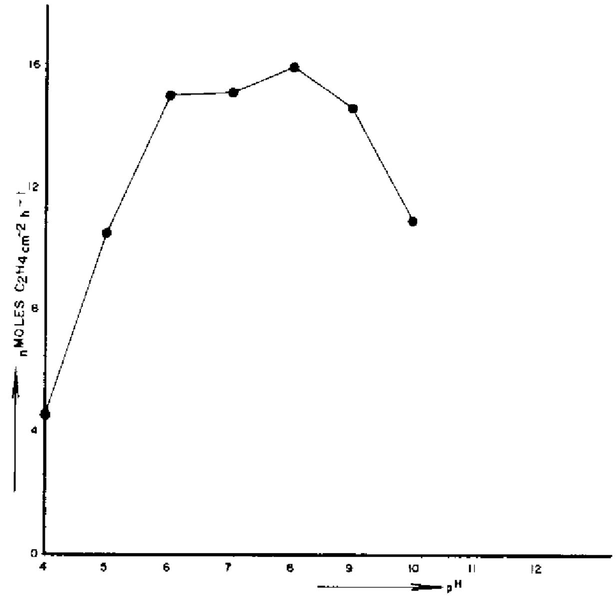

Figure 4. The effect of pH on acetylene reduction by blue-green algal crust.

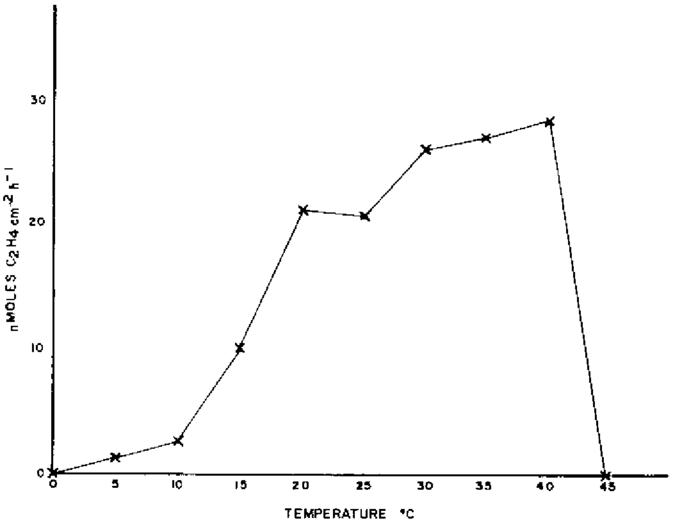

Figure 5. The effect of temperature changes on acetylene reduction in blue-green algal crust samples.

Discussion

The algal crusts are able to survive drought and are fairly resistant to fire because of the extensive mucilaginous sheaths of the filaments, but the sheaths do not impede water absorption. In fact, the slow rate at which water is lost once absorbed make the sheaths a necessary tool for survival and for active growth in the savanna where water is limiting for a major part of the year.

Atmospheric humidity varies tremendously with distance above soil surface, and the usually expressed values of relative humidity may not coincide with the situation at ground level. One can certainly assume that during the rainy season, when water is available for growth, humidity will be high enough for nitrogenase activity most of the time. Some activity may also occur during part of the dry season.

The response of the algae to temperature is not unexpected, because soil surface temperatures in the savanna are often high (see Jones & Wild, 1975). It is interesting, however, that there was nitrogenase activity at low temperatures unknown in Nigeria. This is an example of the physiological versatility for which blue-green algae are noted.

The crusts showed activity under a wide pH range. The algae must possess an efficient pH buffering mechanism, because *in vitro* the nitrogenase enzyme of Cyanophytes is susceptible to pH change out of the 7.0 to 7.5 range (Stewart *et al.*, 1977).

The algae were not light-saturated under the prevailing experimental conditions, probably because their dark pigmented sheaths served as a light screen; if this should be so in nature, it would be a disadvantage, because light intensity is lowest in the rainy season when there is enough moisture for growth. Stewart (pers. com.) believes that the algae adapt to the prevailing light intensity in their growth area by varying their pigmentation. Jones (1977) also found that *Nostoc* mats, depending on the amount of radiation received during the day, may fix nitrogen at night. This claim cannot be evaluated without more thorough work on the nitrogenase activity of blue-green algae and their use of stored photosynthates in the fixation reaction.

The relevance of studying the effects of environmental factors is to see how these factors affect the contribution made by soil crust algae to the nitrogen economy of the savanna ecosystem. Mean values of nitrogenase activity for the various savanna zones are given in Table 1. A maximum mean value of 25.8 moles C_2H_4 cm^{-2} crust h^{-1} was produced by the crust samples from the derived, Guinea and Sudan savanna zones; the corresponding mean value was 8.0 kg N ha^{-1} yr^{-1}. Nitrogen fixation at these levels of activity would represent between 3.3 and 9.2 kg ha^{-1} yr^{-1} of nitrogen. (The ratio of 3:1 of ethylene produced to nitrogen is assumed. In making these estimates, it was also assumed that fixation occurred for 70 % of the time of a rainy season 180 days in length with 10 daily hours of sunlight and 30 % cover of the soil surface by the crusts.)

The actual amount of nitrogen fixed may, however, be smaller or larger. Moisture may not necessarily be available all the time during the rainy season and may very occasionally be available during the dry season. Light, the role of which is not yet clearly understood, may also be limiting. On the other hand, 30 % cover may be an underestimate of algal cover in many locations (Isichei, unpublished data). Also, cover varies considerably over the year and one can reasonably assume that a thicker crust may fix more nitrogen than a thin one. Generally, it can be expected that field conditions vary more widely than is assumed in the laboratory.

With all this in mind, one can say with certainty that the blue-green algae may replace some of the nitrogen lost in the annual fires on the savanna (Isichei & Sanford, 1979). This goes a long way in explaining how production can be maintained year after year in West African grasslands. In this connection, it is perhaps worth mentioning that Stewart *et al.* (1977) found that growing crusts release ammonia and/or amino acids when dried and later rewetted. This clearly indicates that fixed nitrogen in blue-green algae is not necessarily leached into the soil only at the death of the blue-green algae. E.A. Obot (unpublished) also found the dry matter production of maize seedlings grown in nitrogen-free medium to be significantly greater when algal crusts grew on the pot surface.

Acknowledgements

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Nitrogen Cycling in West African Ecosystems

FIXATION D'AZOTE PAR LES LEGUMINEUSES SPONTANEES AU MALI*

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Abstract

Several strains of *Rhizobium* were isolated from 13 species of native legumes growing in the region of Bamako (Mali). The nitrogen-fixing capacity of these strains inoculated to *Vigna sinensis* seedlings (in jars) confirmed the large variation of this group of rhizobia (cow-pea).

Measurements of nitrogen-fixing capacity *in situ* and of dry matter production, with and without inorganic fertilizers (P, Ca, Mo) support the hypotheses of an important contribution of these native legumes to the nitrogen content of the soil and to the productivity of the Sahel-Sudan ecosystems, at least during the favourable wet season.

Introduction

Les sols de la zone sahélo-soudanienne sont en général carencés en azote et souvent en phosphore. Dans certains cas, il s'agit de sols légèrement acides, et, en pH acide, la disponibilité du molybdène est affectée, de sorte que la carence en cet oligo-élément est très souvent associée à la carence en phosphore. Les légumineuses ne réagissent pas de façon uniforme à la présence de ces éléments (variations spécifiques) et il existe, à cet égard, peu de données relatives aux légumineuses spontanées des pâturages sahélo-soudaniens, qui peuvent cependant participer de façon très efficace à l'augmentation de la teneur en azote des sols et donc à l'accroissement de la productivité de ces écosystèmes.

Nous avons isolé et identifié les souches de *Rhizobium* de plusieurs espèces de légumineuses spontanées des pâturages de la région de Bamako (Mali). L'activité nitrogénasique de ces souches a été mesurée en pots sur des plantules de *Vigna sinensis*. Nous avons suivi la variation *in situ* de cette activité nitrogénasique au cours d'un cycle de végétation chez un certain nombre d'espèces, en présence ou en l'absence d'éléments minéraux (P, Ca, Mo); la production de ces espèces a été également déterminée dans les mêmes conditions d'un écosystème sahélien.

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* Outre ces recherches portant sur la fixation d'azote par les légumineuses spontanées au Mali, des travaux sont effectués au Laboratoire de l'Ecole Normale Supérieure dans les domaines suivants:
- taxonomie des cyanobactéries du Mali et catalogue des algues d'eau douce du Mali (K. Traore);
- cycle de l'azote des rizières du Mali et étude du rôle des cyanobactéries (T. Traore);
- fixation d'azote par les légumineuses cultivées, arachide et *Vigna* (M. Lahbib).

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Méthodes d'étude

Les *Rhizobium* ont été isolés des nodosités de germinations en pot sur sol d'origine ou de plantules récoltées *in situ* durant la saison humide.

Les nodosités sont écrasées après avoir été soigneusement lavées et stérilisées par passages successifs de 5 minutes dans une solution aqueuse à 3 % de $HgCl_2$ et dans de l'éthanol à 95 %, puis rincées à l'eau distillée. Le broyat dilué est étalé en boîte de Pétri sur milieu gélosé au mannitol et extrait de levure (milieu YEMA; Vincent, 1970); l'incubation se fait à 30°C. Les colonies de *Rhizobium*, reconnaissables à leur aspect gommeux et translucide, sont purifiées par repiquage sur milieu YEMA à l'actidione (2,5 ml/l de solution alcoolique à 1,2 %) et au rose Bengale (10 ml/l de solution aqueuse à 0,33 %). Les souches purifiées sont maintenues en tube à essai sur milieu gélosé YEMA incliné.

La vérification de la nature des bactéries isolées à partir des nodosités a été faite par réinoculation à des plantules des légumineuses d'origine obtenues en environnement stérile. Seules les souches nodulantes ont été conservées. Les plantules proviennent de la germination de graines scarifiées au papier de verre, puis stérilisées dans des bains successifs de 5 minutes dans une solution aqueuse à 3 o/oo de $HgCl_2$ et dans de l'éthanol à 95 %, et, après rinçage, mises à germer en boîte de Pétri sur milieu "Nutrient agar" à 8 o/oo et incubées à 30°C. Les germinations non contaminées ont ensuite été plantées dans des "Leonardjars" confectionnées selon la technique de Burton *et al.* (1972) et contenant un mélange de vermiculite et de sable, le dispositif ayant été préalablement stérilisé pendant 2 heures à 120°C. Après 3 jours, les plantules ont été inoculées avec 10 ml d'une culture de *Rhizobium* âgée de 10 jours et obtenue sur milieu YEMA liquide en agitateur thermostaté à 30°C. Le dispositif est placé à la lumière et les plantules arrosées une fois par semaine avec 10 ml de milieu minéral de Thornton. Après 30 jours, les jeunes plants sont déterrés et le système radical observé.

Le dénombrement des *Rhizobium* libres dans le sol a été fait selon la technique indirecte mise au point par Vincent (1958, 1962), Brockwell (1963) et Date (1968). Elle consiste à inoculer des plantules de *Desmodium asperum* (choisi pour sa germination rapide) par des suspensions-dilutions de sol de en 5, raison de 4 répétitions par dilution. Le nombre le plus probable de germes est déterminé en utilisant les tables de Brockwell.

La mesure du pouvoir fixateur d'azote des souches isolées et de l'activité nitrogénasique *in situ* de quelques légumineuses a été faite par la méthode de réduction de l'acétylène en éthylène (Hardy *et al.*, 1973) à la suite de la découverte par Dilworth (1966) de cette propriété de la nitrogénase. Deux dispositifs ont été utilisés:

- le cylindre de Balandreau & Dommergues (1973) modifié: il est fait d'une seule pièce en chlorure de polyvinyle, la partie supérieure étant un disque d'altuglass percé en son centre d'un septum en caoutchouc; le dispositif coiffe la plante *in situ* et de l'acétylène est injecté à travers le septum à raison de 10 % du volume total;
- le flacon à sérum dans lequel toute la plante déterrée, ou seulement son système radical, est introduit, après on y injecte un volume d'acétylène égal à 10 % du volume total.

Un prélèvement de 10 ml de l'atmosphère du cylindre ou du flacon est effectué immédiatement après injection de l'acétylène, un deuxième prélèvement étant fait après une incubation de 30 minutes et ce à l'aide d'une seringue ou d'un tube "vacutainer". Les échantillons gazeux ramenés au laboratoire sont analysés dans un chromatographe en phase gazeuse PERKIN ELMER 990 équipé d'une colonne au "Sphérosyl" de 2 m de long et 2 mm de diamètre.

L'activité nitrogénasique est exprimée en nanomoles d'éthylène/g de nodosités sèches/heure.

Les doses des éléments minéraux dans les expériences de fertilisation ont été les suivantes:

- 100 kg P ha^{-1} (sous forme de "super triple phosphate");
- 150 kg N ha^{-1} (sous forme d'urée);
- 150 kg Ca ha^{-1} (sous forme de carbonate de calcium);
- 5 kg Mo ha^{-1} (sous forme de molybdate de sodium).

Les activés nitrogénasiques mesurées au cours de la période de végétation, avec ou sans apport d'éléments minéraux, sont exprimées en millimoles d'éthylène ha^{-1} $heure^{-1}$. La production des plantes est exprimée en kg de matière sèche ha^{-1}.

Résultats

Identification et efficience des souches de *Rhizobium*

De nombreuses souches ont été isolées et 21 seulement ont été retenues et mises en culture. Elles ont été ensuite inoculées à des plantules de *Vigna sinensis* phase de végétation et leurs activités nitrogénasiques ont été mesurées (Tableau 1).

Dénombrement des *Rhizobium* dans le sol

Le dénombrement a été fait dans des échantillons de sol prélevés à une profondeur de 0 à 10 cm:

Date du prélèvement	Nombre le plus probable de *Rhizobium*/g de sol
30 avril 1975 (après 20 mm de pluie)	10 à 68
30 juin 1975 (après 123 mm de pluie)	31 à 208

Ces sols paraissent très pauvres en *Rhizobium*, mais leur nombre peut augmenter d'une saison à l'autre. En avril, la température moyenne enregistrée est de 31°C, mais elle atteint quelquefois des valeurs extrêmes de 40 à 42°C, qui sont léthales pour les *Rhizobium*. Outre la température, l'humidité du sol joue un rôle important dans survie des *Rhizobium*. Selon des chercheurs australiens, cette survie durant l'été et l'automne varie, en Australie, suivant les souches; des températures comprises entre 41°C et 62°C (à 14 heures), à la surface de sol et à l'ombre, sont léthales pour la plupart des *Rhizobium*. Cette opinion est partagée par Vincent (1970). *Rh. trifolii* est sensible à des températures de l'ordre de 40°C dans le sol humide. On a émis l'hypothèse que les *Rhizobium* pouvaient migrer dans les horizons édaphiques plus profonds, à quelques centimètres, et induire la formation de nodosités sous le collet des plantes. On pense que les particules argileuses du sol jouent un rôle important dans la survie des *Rhizobium*.

Il est très probable que dans les sols du Mali, en région sahélo-soudanienne, les températures très élevées des horizons édaphiques superficiels expliquent dans une large mesure la rareté de ces bactéries après la saison pluvieuse.

Tableau 1. Activité nitrogénasique des plantules de Vigna sinensis inoculées et ayant formé des nodosités

Désignation de la souche	Localité	Activité nitrogénasique (nMC_2H_4 g^{-1} h^{-1})	Remarques*
Aes. ind. 3	Sotuba	36 536	M
Aly. rug. 1	Lido	5 022	L
Crot. ret. 1	Sotuba	51 118	Ef
Crot. ret. 3	Sotuba	103 412	H
Des. asp. 4	Sotuba	87 537	Ef
Des. asp. 12	Sotuba	80 516	Ef
Ind. ast. 7	Sotuba	143 548	H
Ind. ast. 8	Sotuba	136 314	H
Ind. num. 5 B	Sotuba	8 875	L
Ind. num. 9	Sotuba	48 450	M
Pso. pal. 1	Lido	9 239	L
Pso. pal. 4	Lido	0	O
Ses. lept. 2	Lido	50 244	Ef
Ses. lept. 3	Lido	37 028	M
Ses. pac. 2	Lido	118 784	H
Vig. rac. 2	Sotuba	45 875	M
Vig. rac. 5	Sotuba	55 706	Ef
Vig. ret. 2	Sotuba	40 960	M
Vig. ret. 9	Sotuba	5 026	L
Vig. sin. A 2	Sotuba	3 662	L
Vig. sin. A 4	Sotuba	378	L

* H, hautement efficiente (15 000 à 100 000 nMC_2H_4 g^{-1} h^{-1})
Ef, efficiente (100 000 à 50 000 nMC_2H_4 g^{-1} h^{-1})
M, moyennement efficiente (50 000 à 10 000 nMC_2H_4 g^{-1} h^{-1})
L, légèrement efficiente ($<$10 000 nMC_2H_4 g^{-1} h^{-1}).

Mesures *in situ* de l'activité nitrogénasique de quelques légumineuses spontanées

Les mesures d'activité nitrogénasique ont concerné cinq espèces parmi les légumineuses spontanées croissant dans les pâturages naturels du Centre national de recherches zootechniques de Sotuba, près de Bamako. Ces mesures de fixation *in situ* ont été effectuées entre les mois de juin et d'octobre 1975, à divers stades du développement des plantes, en utilisant la méthode de réduction de C_2H_2 en C_2H_4. Deux protocoles expérimentaux ont été utilisés. La méthode du cylindre a servi uniquement à la mesure de l'activité nitrogénasique *in situ* durant le cycle nycthéméral complet de *Indigofera nummulariifolia* (5 septembre 1975: période de fructification optimale de la plante), afin de déterminer les périodes de fixation maximale d'azote atmosphérique (Fig. 1). Les autres mesures *in situ* ont été faites pour quatre espèces de légumineuses spontanées ainsi que pour *I. nummulariifolia*, à l'aide de la technique du flacon, entre 11 h et 13 h, deux fois par mois pour chaque espèce, de juin à octobre 1975, afin de suivre cette fixation en fonction de l'évolution du cycle végétatif et reproducteur des plantes. Nous avions vérifié dans le cas de

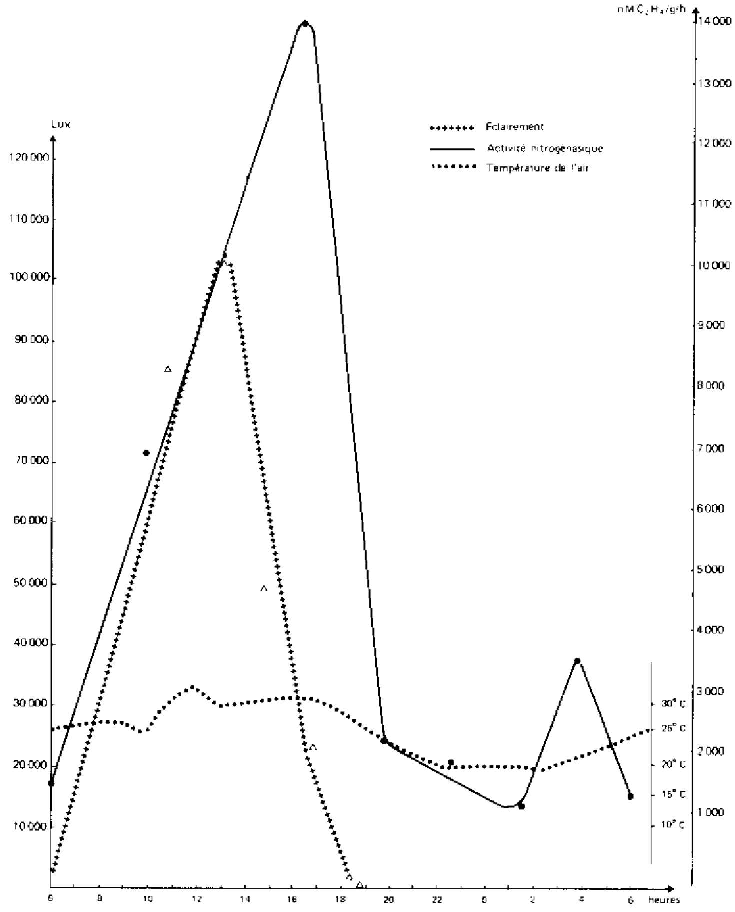

Figure 1. Activité nitrogénasique au cours du cycle nycthéméral complet de *Indigofera nummulariifolia.*

I. nummulariifolia que la réduction de C_2H_2 en C_2H_4 était linéaire pendant 30 min.; les mesures pouvaient donc être faites à des intervalles de 30 min. pendant deux heures (entre 11 h et 13 h), durant lesquelles les nodosités demeurent dans un état physiologique satisfaisant.

Pour chaque mesure au temps T_0, T_{30}, T_{60}, T_{90} et T_{120}, on prélevait 10 systèmes radicaux de 10 plantes de la même espèce qu'on introduisait dans 10 flacons à sérum. Les résultats, exprimés en nanomoles de C_2H_4 g^{-1} de nodosités sèches heure^{-1} (nmol. C_2H_4 g^{-1} h^{-1}), représentent la moyenne de ces 10 mesures.

L'étude du cycle nycthéméral (Fig. 1) a consisté à suivre l'activité nitrogénasique *in situ* pendant 24 heures, de 6 h à 6 h. Des études faites sur le soja indiquent que cette activité présente un seul maximum diurne (Mague & Burris, 1972), tandis qu'avec l'arachide on note deux maximums, l'un de jour et le second de nuit (Balandreau *et al.*, 1974). Nos propres mesures, faites le 5 septembre 1975 sur *Indigo nummulariifolia*, sont en faveur de l'existence de deux maximums. Parallèlement à cette activité nitrogénasique, nous avons effectué des mesures d'éclairement et de température de l'air. La courbe de variation de l'activité nitrogénasique est étroitement liée à la photosynthèse (Bergersen, 1980; Balandreau & Villemin, 1973; Sloger *et al.*, 1974), on enregistre vers 13 h le maximum d'éclairement et de température de l'air, mais seulement 3 heures plus tard, vers 16 h, le maximum de l'activité nitrogénasique; la courbe traduit ensuite la diminution d'intensité du phénomène, le minimum se situant vers 01 h; on enregistre à 04 h le second maximum. Balandreau & Villemin (1973) ont estimé qu'un délai de 3 heures était nécessaire pour la migration des photosynthétats des feuilles aux racines et que le premier maximum d'activité nitrogénasique s'expliquait par l'exsorption au niveau des racines des glucides nouvellement synthétisés; que le second maximum nocturne était lié à l'exsorption dans la rhizosphère de produits d'hydrolyse des réserves amylacées accumulées pendant la phase diurne. Entre l'arrêt (19–20 h) et le début de cette hydrolyse, un arrêt de formation des glucides migrants pourrait expliquer la dépression d'activité nitrogénasique enregistrée entre 0 h et 01 h.

L'évolution de l'activité nitrogénasique durant le cycle végétatif a été suivie chez *Vigna racemosa, Vigna reticulata, Zornia glochidiata, Desmodium asperum* et *Indigofera nummulariifolia*. Chez toutes ces espèces, l'activité augmente régulièrement avec la croissance de la plante et le maximum s'observe à la floraison; puis l'activité décroît régulièrement, pour s'annuler vers la fin du cycle. Les activités maximales ont été les suivantes:

Vigna racemosa	25 309	nanomoles d'éthylène g^{-1} h^{-1}
Vigna reticulata	25 000	–"–
Zornia glochidiata	20 000	–"–
Desmodium asperum	25 000	–"–
Indigofera nummulariifolia	30 000	–"–

Influence de l'apport d'éléments minéraux sur l'activité nitrogénasique

Ces expériences ont été effectuées en zone sahélienne (isohyète 600 mm) et les espèces étudiées furent *Zornia glochidiata* et *Indigofera astragalina*, qui sont parmi les légumineuses les plus répandues dans les pâturages de la zone. Les sols choisis ont les caractéristiques suivantes:

	profondeur cm	pH (eau)	pH (KCl)	C (%)	N (%)	C/N
sol sableux	5–15	6,1	5,3	0,56	0,017	33
	20–60	5,5	4,0	0,26	0,010	26
sol argileux	5–20	5,2	3,9	0,40	0,020	20
	25–60	5,3	3,6	0,28	0,018	16

Le Tableau 2 récapitule les mesures de l'activité nitrogénasique et de la production de *Zornia glochidiata*.

La Fig. 2 montre que la production de la plante croît en même temps que l'activité nitrogénasique et que ces deux activités sont maximales au début de mois de septembre, au commencement de la floraison.

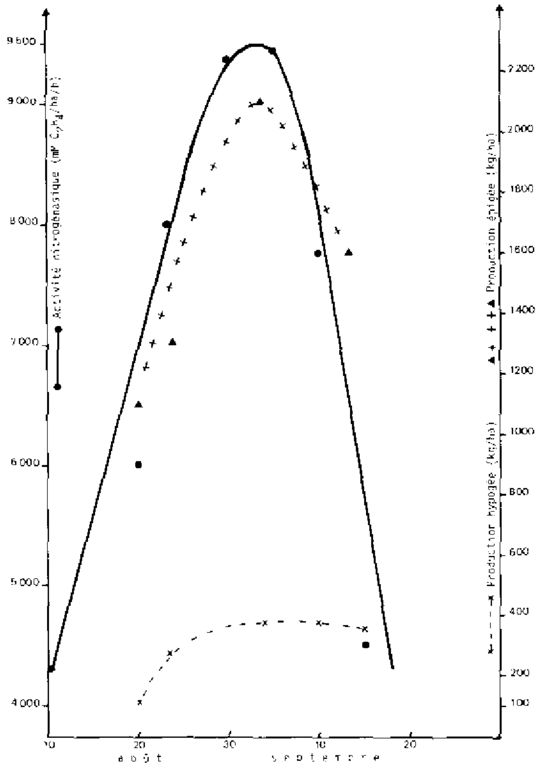

Figure 2. Activité nitrogénasique et production de *Zornia glochidiata* (sans apport d'éléments minéraux) pendant un cycle végétatif (août–septembre 1977).

Le Tableau 3 récapitule les mesures de production de *Indigofera astragalina* dans les deux types de sol.

L'apport d'éléments minéraux a stimulé la production, et l'augmentation est de l'ordre de 70 % par rapport au témoin, pour les traitements P et P+Mo. La combinaison P+N correspond à une augmentation de 120 %, l'apport d'azote ayant pour effet un doublement de la production.

En sol argileux, où la légumineuse pousse en mélange avec des graminées (*Loudetia togoensis*), l'augmentation de la production est de 70 % (P + Ca, P + Mo) et de 95 % (P). On peut noter que la part revenant à la légumineuse, bien que faible, augmente dans les mêmes conditions. En présence d'azote combiné (traitements N et N+P), la production globale augmente, mais la part de *Indigofera astragalina* est moindre, ce qui pourrait s'expliquer par la concurrence avec la graminée.

Les résultats de ces investigations soulignent le rôle que pourraient jouer les *Rhizobium* et les légumineuses spontanées dans les écosystèmes naturels de la zone sahélo-soudanienne, où les sols sont souvent carencés en azote et où les papilionacées peuvent parfois représenter jusqu'à 80 % du couvert végétal. Les mesures de production faites en 1976, entre les isohyètes 400 et 800 mm, sur 30 postes d'observation, avaient donné des

Tableau 2. Activité nitrogénasique (millimoles d'éthylène ha^{-1} h^{-1}) et production (kg matière sèche ha^{-1}) de Zornia glochidiata sur sol sableux, avec et sans apport d'éléments minéraux (août-septembre 1977).

	Témoin	Apport de P	Apport de P+Ca
Activité nitrogénasique moyenne	7 125	8 400	12 750
Azote fixé (estimation: kg ha^{-1})	64	76	115
Production:			
épigée	2 030	2 600	3 600
hypogée	370	470	612
totale	2 400	3 070	4 212

Tableau 3. Production (kg de matière sèche ha^{-1}) de *Indigofera astragalina* (août-septembre 1977).

	Témoin	Apport de P	Apport de P+Ca	Apport de P+Mo	Apport de P+N	Apport de N
Sol sableux	3 755	6 350	-	6 170	8 350	7 500
Sol argileux (en mélange avec des graminées)						
production totale	3 200	6 200	5 400	5 500	10 750	2 400
production de la légumineuse	32	1 250	2 230	2 600	1 075	480

valeurs comprises entre 900 et 3 300 kg de matière sèche à l'hectare, la contribution des légumineuses variant entre 36 et 1 700 kg respectivement. Une sélection de légumineuses appropriées et de *Rhizobium* efficients pourrait sérieusement contribuer à la fertilisation des sols et à l'accroissement de la productivité de ces écosystèmes.

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Nitrogen Cycling in West African Ecosystems

PREMIERS RESULTATS CONCERNANT L'INOCULATION DU SOJA AU SENEGAL

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Abstract

Soya bean inoculation has received more attention during recent years in the subtropical zones. Nevertheless, the development of this crop is limited in Africa for many reasons relating to the specificity of soya bean regarding *Rhizobium japonicum*.

In Senegal, spontaneous nodulation is poor. Inoculation with specific strains of *Rhizobium* is necessary to induce nodulation and N_2 fixation capable of matching the nitrogen requirement of soya bean.

Four years of field experiments confirm the need of soya bean inoculation in Senegal. The best technique of inoculation combines:

- use of the strain G_3 (31. 1B 138 Beltsville)
- soil incorporation of the inoculant.

INTRODUCTION

Le soja, *Glycine max* (L) Merrill, plante originaire d' Asie a été adapté depuis 75 ans aux régions tempérées chaudes des Etats-Unis et d'Europe méditerranéenne. Actuellement un nouvel effort de sélection est en cours pour adapter cette plante aux régions subtropicales (Floride, Brésil, Nigéria, Sénégal, Côte d'Ivoire, ...). Un vaste programme de coopération international pour le testage des variétés, l'ISVEX, a été mis en place par l'International Soybean Program (INTSOY) de l'Université de l'Illinois aux USA, qui a permis de préciser les cultivars les plus producteurs en zone intertropicale (Whigham, 1975).

Au Sénégal par ailleurs l'IRAT puis l'ISRA ont entrepris un programme de sélection qui donne des résultats très encourageants (Durovray, 1976).

Le développement de la culture reste cependant modeste en Afrique car de nombreux problèmes techniques restent à résoudre: techniques culturales, techniques de récolte, de conservation, et d'utilisation dans l'alimentation humaine.

L'un de ces problèmes réside dans la spécificité du soja vis-à-vis des *Rhizobium japonicum* et dans la nécessité d'inoculer des souches de cette bactérie fixatrice d'azote. Au Sénégal, de même qu'en Côte d'Ivoire, au Zaïre (Bonnier, 1960), ou à Madagascar (Denarié, 1968), le soja semé sans inoculation porte souvent quelques nodosités mais en nombre toujours trop faible pour satisfaire les besoins azotés de la culture.

L'inoculation est donc indispensable au développement de la culture si l'on veut éviter l'utilisation des engrais azotés pour répondre aux exigences de la culture. Cet article résume les travaux entrepris au Sénégal depuis 1971 dans ce domaine par la recherche agronomique.

Principaux résultats et discussions

Les premiers tests d'inoculation ont été menés en 1971 dans les zones centre-nord (Bambey) et centre-sud (Nioro-du-Rip). L'effet de l'inoculation a été très net (Tableau 1), mais les variétés utilisées n'étant pas adaptées aux conditions climatiques locales, le rendement n'a pu être mesuré. Les essais de soja n'ont pas été poursuivis dans cette zone (pluviométrie annuelle de 650 à 900 mm) trop sèche pour les variétés actuellement disponibles.

A partir de 1972, les essais de soja ont été menés dans la région sud du Sénégal (pluviométrie annuelle 1100 à 1500 mm), zone plus adéquate pour cette culture du point de vue climatique. En 1972 et 1973, l'inoculation a été effectuée par enrobage des graines, depuis 1975 par pulvérisation d'un inoculum liquide sur le sol et enfouissement par un binage.

Les expérimentations réalisées en 1977 n'ont pas donné de résultats interprétables du fait de la sécheresse.

Tableau 1. Etude de l'inoculation du soja à Bambey et Nioro-du-Rip – Var. Gedult (d'après Oulie, 1971)

		Témoin	Apport azote 18 kg N ha^{-1}	Inoculation (1)		C.V. %	Test F (2)
				G3	G 11		
NIORO DU RIP	Nombre de nodosités par plante	7,2 a	7,5 a	36,6 a	30,2 b	17,6	H S
	Poids sec nodosités (mg $plante^{-1}$)	69,4 a	78,5 a	300,8 b	256,0 b	24,2	H S
BAMBEY	Nombre de nodosités par plante	2,7 a	3,8 a	32,1 c	24,6 b	47,0	H S
	Poids sec nodosités (mg $plante^{-1}$)	70,0 a	85,0 a	388,4 b	285,0 b	37,4	H S

(1) Inoculation des graines

(2) Les résultats portant la même lettre ne sont pas significativement différents au seuil $p = 0{,}01$

Les résultats obtenus en 1972, 1973 et 1975 sont reportés dans les Tableaux 2–4; dans ces tableaux on peut remarquer que les coefficients de variation correspondant aux variables nombre et poids de nodosités sont souvent très élevés. Ceci peut être attribué au fait que la distribution statistique des données n'est pas normale. Dans le cas présent des essais de transformation de type $\sqrt{x}$, $\sqrt{x} + o$, $\log (x + xo)$, on relève que les distributions peuvent suivre une loi de Poisson ou une log normale qui rejoint les observations de Roger *et al.* (1977) concernant l'activité nitrogénasique.

Tableau 2. Etude de l'inoculation du soja à Séfa en 1972 – Var. Gedult – (d'après Corriau, 1973)

	Témoin	Fumier	Inoculation (1)	Fumier+ Inoculation (1)	C.V. %	Test F (2)
% de levée	43,8 ab	50.7 b	36,4 a	40,1 a	8,9	H S
Nombre de nodosités plante^{-1}	0,3	0,2	25,6	53,6	80,5	–
Poids graines (g plante^{-1})	13,4 a	17,7 ab	16,6 ab	23,5 b	29,8	S
Rendements graines (kg ha^{-1})	993	1568	983	1547	32,5	N S

(1) Inoculation des graines, souche G3

(2) Les résultats portant la même lettre ne sont pas significativement différents à p = 0,01 (H S)
p = 0,05 (S.)

Tableau 3. Etude de l'inoculation et de la fumure organique sur le soja à Séfa (1973) – Var. Gedult.

	Témoin	Fumier	Inoculation (1)	Fumier + Inoculation (1)	C.V. %	Test F (2)
Nombre de pieds ha^{-1} – au 10 e jour après le semis	453.000 a	429.000 a	316.000 b	329.000 b	4,6	H S
Poids grains (g plante^{-1})	6,94 a	9,16 a	12,68 b	14,18 b	18,2	H S
Rendements graines (kg ha^{-1})	2016 a	2574 ab	2541 ab	2829 b	16,3	S
Poids sec nodosités au 60 e jour (mg plante^{-1})	57 c	76 c	294 a	204 b	29,0	H S
Nombre de nodosités au 60 e jour plante^{-1}	4,8 c	3,9 c	25,0 a	19,7 b	21,0	H S

(1) Inoculation des graines par la souche G3

(2) Les résultats portant la même lettre ne sont pas significativement différents à p = 0,01 (H.S.)
p = 0,05 (S.)

En 1975, la pluviométrie excédentaire en début de culture a eu un effet dépressif sur les rendements.

Ces trois essais mettent en lumière:

- l'effet dépressif de l'inoculation par enrobage des graines sur le taux de levée du soja;
- l'effet positif de l'inoculation sur les rendements qui est d'ailleurs d'autant plus net que ce problème de fonte de semis est résolu par l'inoculation du sol;
- le rôle prépondérant de la matière organique, ce qui correspond aux résultats obtenus par ailleurs sur arachide (Wey & Obaton, 1978);
- le bon comportement de la souche G_3 (3.I.1B 138) dans les conditions pédoclimatiques du Sénégal où elle s'avère plus efficiente que les souches autochtones isolées et multipliées par le laboratoire.

Tableau 4. Comparaison des souches de Rhizobium sur le soja (1975): var. Jupiter

	Témoin non inoculé	Souche G3	Souches locales (1)				C.V. %	Test F (2)
			Souche SA	Souche SB	Souche OP	Mélange de souches		
Nombre de pieds par ha	356.000	373.000	369.000	379.000	372.000	359.000	5,1	N S
Pourcentage de levée	79,1	83,0	82,0	84,4	82,8	60,0	–	–
Taux d'azote dans les fouilles au 60 e jour	2,41 a	4,23 b	3,22 a	2,61 a	3,01 a	2,80 a	10,8	H–S
Poids frais de nodosités en mg par plante	236	1971	1750	633	615	363	59	–
Rendement en graines (kg ha^{-1})	685 a	1583 c	1087 b	682 a	685 a	704 a	23	H S
Taux d'azote dans les graines	5,58	6,69 b	5,71 a	5,44 a	5,61 a	5,55 a	6,8	H S
Azote exporté par les graines (kg ha^{-1})	38,5	105,9	62,1	37,2	38,4	39,1	–	–
Nombre de nodosités par plante au 60 e jour	2,5	41,4	16,6	12,1	10,2	6,5	73,0	–

(1) Inoculation liquide de sol

(2) Les résultats portant la même lettre ne sont pas significativement différents au seuil de P = 0,01 (H.S.) et P = 0,05 (S)

Conclusion

Ces premiers résultats confirment l'intérêt de l'inoculation pour améliorer la nutrition azotée de la plante et pour accroître les rendements. La meilleure technique d'inoculation semble reposer actuellement sur:

- l'utilisation de la souche G_3 ou d'une souche similaire.
- l'apport d'un inoculum au sol de préférence à l'enrobage des semences. Cette expérimentation met aussi en évidence l'importance des techniques culturales et des conditions climatiques pour la réussite de la culture du soja et l'efficacité de l'inoculation.

Les recherches en cours visent d'ailleurs la mise au point de ces techniques culturales et la définition des zones favorables à la culture des variétés de soja créées au Sénégal comme la 44-A-73.

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PRESENCE ET DISTRIBUTION DE *RHIZOBIUM JAPONICUM* ET DE *RHIZOBIUM* COWPEA DANS LES SOLS DE CÔTE D'IVOIRE

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Abstract

During June, July and August 1977, we conducted nodulation experiments in Ivory Coast. The natural presences of rhizobia of soya (*Glycine max* (L.) Merrill.) and of cowpea (*Vigna unguiculata* (L.) in different types of soils were evidenced in the 27 testing points throughout the country. We recorded 21 positive tests on soya and 27 on vigna. Fourteen strains of *R. japonicum* and 15 of *R. cowpea* were isolated. An efficiency study of these different strains is presently underway. A count of viable *R. japonicum* and of *R. cowpea* in the soil samples was also done.

Matériel et techniques

Réalisation des parcelles

Des graines de soja (var. Bossier) et de niébé (var. Vita 3) désinfectées au chlorure mercurique à 2,5 % (Bonnier, 1969) ont été semées sur des parcelles de deux mètres sur trois dans des sols n'ayant jamais porté de cultures de soja ou de niébé.

Quarante-cinq jours après le semis, les racines des plantes ont été observées pour constater la présence ou l'absence de nodosités (Tableau 1).

Deux parcelles, dont une pour le soja et l'autre pour le niébé ont été réalisées pour chaque essai.

Prélèvement des échantillons de sols

A chaque point d'essai, cinq prélèvements sont effectués à la bêche sur une profondeur de dix à quinze centimètres et dans un rayon de 500 mètres. Les cinq échantillons ainsi prélevés sont soigneusement mélangés et un seul échantillon de 300 grammes environ est retenu à partir du mélange.

Les outils sont flambés à l'alcool après chaque échantillonnage.

Dénombrement des Rhizobium

Le dénombrement des *Rhizobium* s'est effectué suivant la méthode Gibson (Vincent, 1970).

Trente grammes de sol sont mis en suspension dans 100 ml d'eau distillée stérile. Après une agitation de quinze minutes sur un agitateur vibreur, la suspension est diluée de dix en dix dans des tubes de 9 ml d'eau distillée.

Des plantules de quatre à cinq jours de Bossier et de Vita 3 cultivées sur de la vermiculite stérile sont placées dans des tubes de Gibson (Vincent, 1970) de manière à ce que la radicelle soit en contact avec la gélose. Ces tubes sont inoculés avec chaque dilution à raison de cinq tubes par dilution. Ils sont ensuite placés dans une salle de culture où la température est maintenue à 20°C (jour de 13 h., à 7000 lux). Les plantes reçoivent régulièrement une solution nutritive (Vincent, 1970). L'observation se fait après trente jours de culture. Les plantes portant des nodules permettent de constituer le nombre le plus probable et à l'aide de la table de MacCrady, on calcule le nombre de *Rhizobium* par gramme de poids terre sèche.

Parallèlement, des déterminations de poids sec et de pH sont effectuées sur le même échantillon de sol.

Résultats et discussion

Les essais de nodulation ont été effectués en 27 points. Les résultats sont consignés dans le Tableau 1. D'après ces résultats, 21 essais positifs ont été enregistrés avec le soja et 27 avec le niébé. D'une manière générale et contrairement au soja, nous avons observé une nodulation normale sur le niébé avec plusieurs nodules par plante dans certains cas.

Tous les sols dépourvus de *Rhizobium* d'après le test de nodulation le sont également après dénombrement sur plantes (Tableau 2). Par contre, certains sols où nous avons observé des nodules ne contiennent pas de *Rhizobium* après l'analyse au laboratoire (Tableau 2). Cette anomalie, certes due au nombre très faible de *Rhizobium* dans certains échantillons et à l'imprécision de la méthode utilisée, paraît plus accentuée avec le soja qu'avec le niébé. Par ailleurs, aucune influence notable de l'acidité des sols n'a été observée et les échantillons provenant de sols marécageux (1) ne présentaient aucune différence avec les sols bien drainés, quant au nombre de *Rhizobium* Tableau 2).

La présence des *Rhizobium* est liée à celle des nodules. Mais, inversement, l'absence de ceux-ci n'implique pas nécessairement que le sol soit exempt de *Rhizobium*. En effet, comme le pense Bonnier (1969), le phénomène d'adaptation pourrait jouer un rôle dans le processus de la formation des nodules pour une légumineuse introduite nouvellement dans un sol.

Conclusion

Cette première approche de l'écologie des *Rhizobium* dans les sols de Côte d'Ivoire nous a permis de mettre en évidence la présence de souches capables de noduler le soja et le niébé. L'étude de l'efficience de ces souches révèlera leur importance. D'ores et déjà, un problème de compétition entre ces souches locales et celles éventuellement apportées par l'inoculation est à envisager.

Tableau 1. Présence de nodules. (+): Présence de nodules, (–): Absence de nodules

Points d'Essais	Nodules	
	Soja	Niébé
Abidjan	–	+
Agboville	+	+
Aboisso	+	+
Zatta	+	+
Bozi 1	+	+
Daloa	–	+
Séguéla	+	+
Touba	+	+
Tiémé	+	+
Kolia	+	+
Korhogo	+	+
Solomougu	+	+
Niakaramandougou	+	+
Bouaké	+	+
Bouna	+	+
Kakpin	+	+
Bondoukou	+	+
Groumania	+	+
Ouellé	+	+
Niablé	+	+
Grand-Lahou	–	+
Gagnoa	–	+
Soubré	+	+
Sassandra	–	+
Grabo	+	+
Zagné	+	+
Danané	–	+

Tableau 2. Nombre de *Rhizobium* par gramme de terre sèche sur soja et niébé

		Nombre de *Rhizobium* par gramme de terre sèche	
Origine des échantillons	**pH**	**Soja**	**Niébé**
Agboville	4,2	0	219
Séguéla	5,6	2	8
Ouellé	4,1	0	97
Zatta	6,9	0	185
Korhogo (1)	3,2	2	549
Groumania	7,4	0	881
Yokoboué (Grand-Lahou)	3,3	0	370
Aboisso	4,4	0	4443
Badikaha	4,9	0	1475
Bouna	6,7	0	290
Kolia	5,8	0	35
Niablé	6,0	0	18
Agboville (1)	4,7	0	61
Bouaké	5,5	0	113
Daloa	6,7	0	7
Bozi 1 (1)	6,7	3	8
Grabo	4,1	0	2
Aboisso (1)	4,6	0	2
Bozi 1	5,7	0	3
Zagné (1)	4,4	0	0
Gagnoa (1)	5,0	0	1
Danané (1)	3,7	0	0
Poundiou	4,6	2	1
Kakpin	4,7	17	2
Touba	4,8	4	92
Tabou (1)	3,9	0	1
Solomougou	4,3	17	61
Korhogo (1)	5,4	1	419
Bondoukou	5,6	3	319
Gagnoa	5,8	0	572
Grand-Lahou	5,8	0	101
Solomougou (1)	4,8	0	17
Soubré	5,6	0	3
Ouellé (1)	5,6	0	6
Danané	5,1	0	63
Sassandra	5,8	0	2
Tiémé	5,2	0	48
Korhogo	5,2	5	22
Zagné	3,7	0	9
Soubré (1)	4,8	0	9
Abidjan	5,6	0	305

(1) sols marécageux

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A DEFICIENCY OF THE SYMBIOTIC NITROGEN FIXATION IN A DRY TROPICAL AGROSYSTEM – THE NITROGEN CHLOROSIS OF GROUNDNUT (*ARACHIS HYPOGAEA*) IN SENEGAL

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Abstract

Various types of chlorosis on groundnut occur in Senegal. One that spreads over Northern Senegal is described here, and identified as a nitrogen chlorosis due to a deficiency of nitrogen fixation resulting from poor nodulation.

This chlorosis arises in acid soils, where there may be aluminum and manganese toxicity. No micronutrient deficiency has been found so far. Biotic factors, among which the inadequacy of the *Rhizobium* population and the attacks of nematodes, may be responsible while the existing antagonism of actinomycetes towards *Rhizobium* would not interfere.

Liming and, above all, organic matter application have proved to be means of control of the chlorosis.

Introduction

In Senegal, different types of chlorosis of groundnut have been observed. They generally show up in well-defined areas often known as "yellow patches" (Bouhot, 1978).

A first type of chlorosis is related to a high soil pH. It occurs:

- at sites of burning where houses were located years ago (Germani, 1975) or where the crop residues (straw) were burnt before the rainy season
- at the place of termite mounds recently leveled
- in soils where irrigation with water containing large amounts of basic cations increased pH well above 8.0.

A second type of chlorosis may occur in areas where waterlogging prevented diffusion of oxygen in the soil, thus inhibiting nodulation and nitrogen fixation. This type of chlorosis has been observed in Casamance in shallow depressions which favor waterlogging.

A third type of chlorosis which will be described here, occurs in acid soil. It was observed in the regions of Louga, Thies and Diourbel and in the northern part of Sine Saloum, which are characterized by an irregular rainfall of 300 to 700 mm during three months from July to October and usually a groundnut-millet rotation sometimes accompanied by a one- or two-year fallow.

Symptoms of the chlorosis occurring in acid soils

Symptoms of this chlorosis are described from observations made during the rainy season at Thilmakha (region of Thies), where the average rainfall is 500 mm. The soil is a Dior soil (Table 1).

Table 1. Physico-chemical characteristics of the Dior soil

Organic matter %	Clay+ silt %	Sand %	C %	N %	C/N	Exchange-able bases (meq.)	pH (water 1/2.5)
0.3	3.3	96.4	2	0.18	11	0.70	5.5

Yellow patches made up of chlorotic groundnuts were compared with non-chlorotic adjacent areas which were used as controls (Fig. 1).

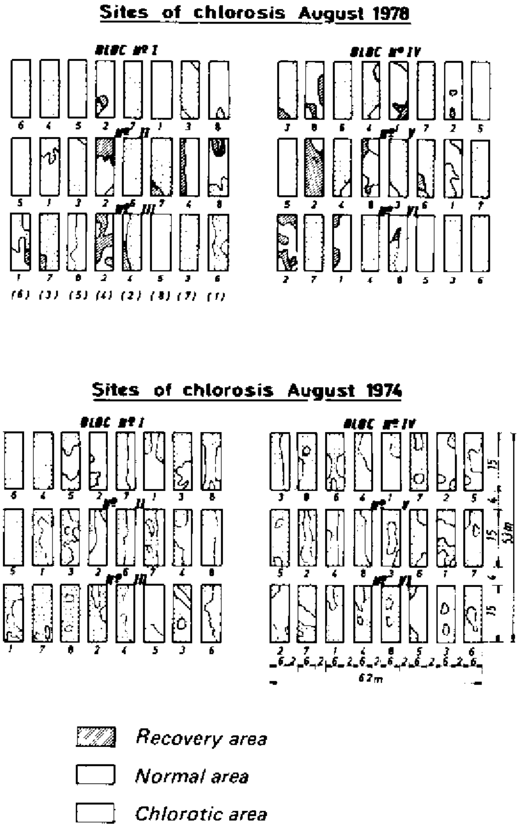


Figure 1. Extension of chlorosis in the Thilmakha field trial.

Faint yellowing of leaves is first seen between the 20th and the 30th day after sowing. The plant growth and emergence of new leaves are slowed down. The severity of this type of chlorosis is variable:

(1) The plant may turn yellow and remain dwarf. It wilts and consequently dies after the 60th day.

(2) The plant may be less affected by the chlorosis. It turns yellow, but keeps growing slowly (Fig. 2).

(3) Faintly yellowish plants may recover after the 30th day (Fig. 1) (such a recovery was also observed in greenhouse experiments after the 55th day). New green leaves emerge and normal growth rate is rapidly restored.

The total number of flowers produced by the chlorotic plants is lower than that produced by the non-chlorotic ones, and the rate is slower (Fig. 3). The number of nuts in the chlorotic plants is 40 % less than in the non-chlorotic ones.

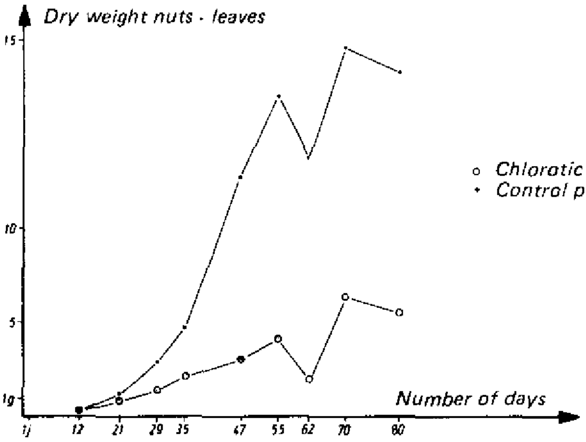


Figure 2. Dry weight of the plants. Thilmakha 1978.

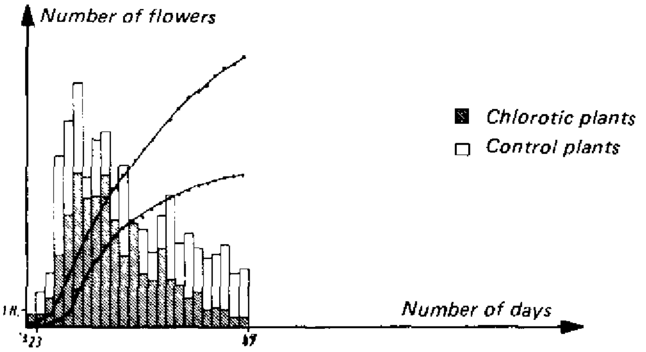
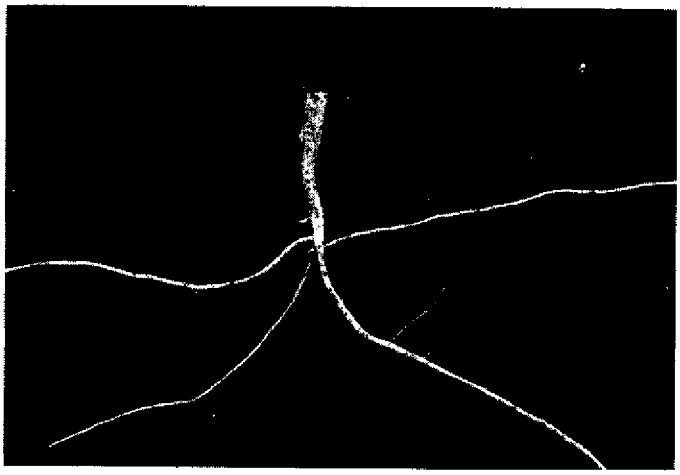
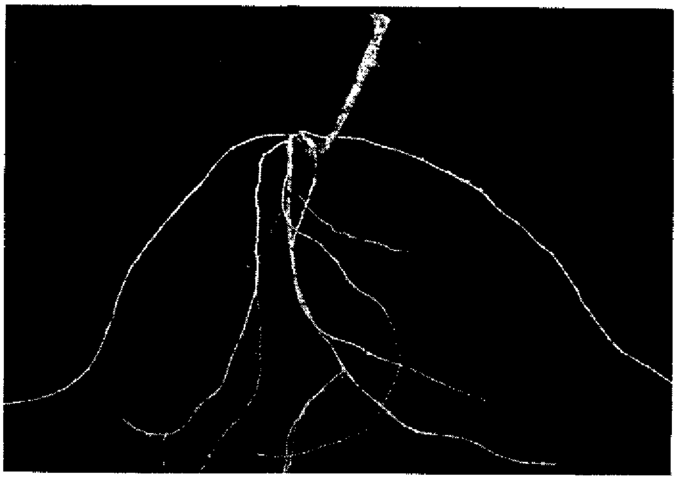


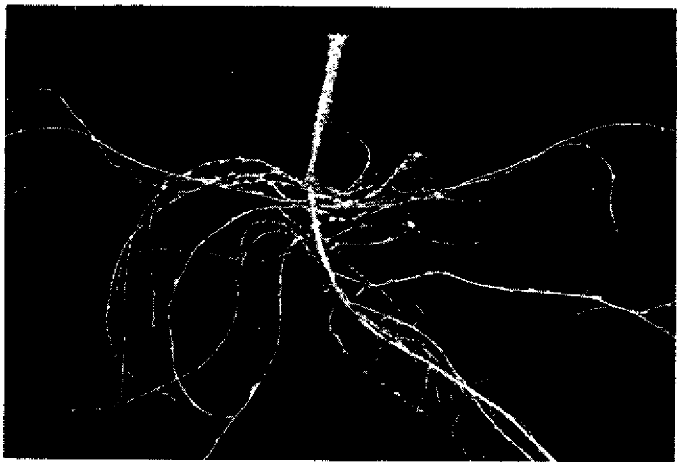
Figure 3. Flowering (daily cumulative). Thilmakha 1978.



Type I – Chlorotic plant



Type II – Chlorotic plant



Type III – Non-chlorotic plant

Figure 4. Arachis roots 56 days after sowing.

The root system of chlorotic plants is more or less atrophied. Two kinds of atrophied root systems were observed:

(1) Root systems made of the tap root with only one or two lateral roots, no radicles (Fig. 4). Type I.

(2) Root systems with many lateral roots but only a few radicles. Type II.

There were very few nodules on the roots of chlorotic plants. While the number of nodules grew steadily until the 70th day on non-chlorotic plants, it stayed at a low level after the 30th day on the chlorotic plants (Fig. 5); on the 70th day, the average number of nodules (mean of 20 plants) was 130 on the non-chlorotic plants and 10 only on the chlorotic ones. Moreover, a great number of brown protrusions were found on chlorotic plant roots (Fig. 6). The exact nature of these 0.5 mm long cone-shaped protrusions, which contain bacteria, is still obscure.

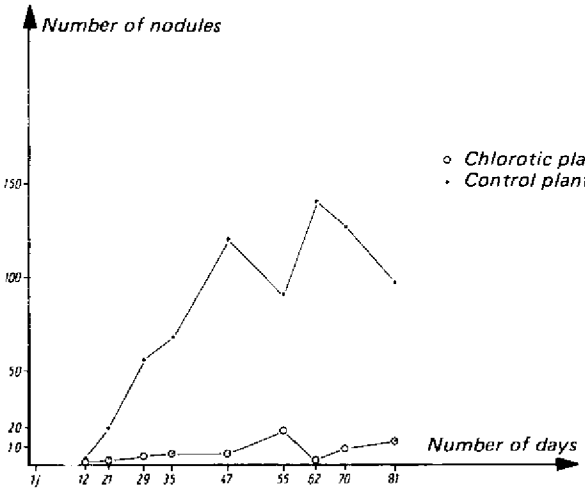


Figure 5. Number of nodules per plant. Thilmakha 1978.

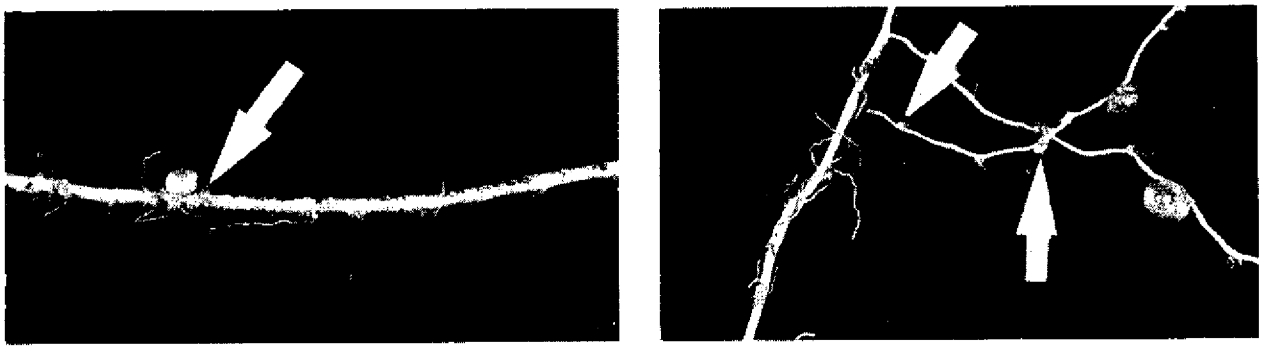


Figure 6. Protusions on lateral roots.

Introduction of the chlorosis by a nitrogen deficiency

By applying 100 kg N ha^{-1} as ammonium nitrate to field-grown groundnuts, Blondel (1970) obtained a satisfactory recovery of chlorotic plants. Under greenhouse conditions, the chlorosis was reproduced on soil from Thilmakha. Urea application (equivalent to 100 kg ha^{-1} nitrogen) eliminated the chlorosis symptoms. Therefore, the chlorosis studied here appears to result from a nitrogen deficiency. This conclusion was confirmed by nodule counts (Fig. 5) and by acetylene-reducing activity expressed per plant, which was significantly lower in chlorotic plants than in non-chlorotic plants (Fig. 7). Moreover, the specific acetylene-reducing activity of nodules from chlorotic plants was generally lower than that of nodules from non-chlorotic ones (Table 2). It may be attributed either to infection by less-efficient strains or to decrease of the photosynthetic activity which caused a reduction in the energy supply of the nodules of chlorotic plants.

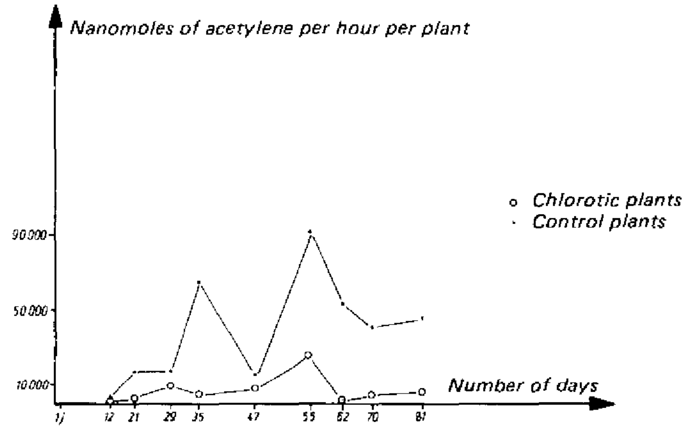


Figure 7. Reduction of acetylene per plant. Thilmakha 1978.

Table 2. Specific acetylene-reducing activity (micromoles acetylene mg^{-1} nodules dry weight $hour^{-1}$). Thilmakha 1978. Average of 20 plants

Number of days after sowing	35	47	55	62	70	81
Chlorotic plants	192	626	267	232	119	166
Non-chlorotic plants	721	121[1]	509	317	406	306

[1] This level of activity is due to a 15-day drought which affected the well-developed non-chlorotic plants much more than the chlorotic ones.

Cause of the decrease of nitrogen fixation in chlorotic plants

Groundnut is affected more by chlorosis when the rainfall is inadequate or when the seeding is delayed. However, as chlorosis is reproduced on soil samples under greenhouse conditions, the soil itself seems to be mainly responsible for this deficiency. The different soil characteristics that have been thought to cause the decrease of nitrogen fixation by groundnut are as follows:

The mineral status of the soil

The soils in which the chlorosis is mostly observed are of the Dior-type tropical ferruginous and deep soils. They are mainly sand (96 %) with only 3 % to 4 % of clay and 0.3 % of organic matter. They progressively become acid under cultivation with specific intensive agricultural practices (Poulain, 1968; Charreau, 1971).

Soil acidity

Blondel (1970) first noticed that in the case of yellow dwarf plants of groundnut, the pH (water pH 1/2.5) was below 5.0. Later, Pieri (1976) showed that there was only a loose relation between water pH and the chlorosis of groundnut, around the values of 5.0 (measured by the water pH 1/2.5 method) and this pH varies widely in the soil profile. Measures of pH made on rhizosphere soils (Thilmakha, 1978) showed that, in most cases, the pH of the chlorotic-plant rhizosphere stays between 4.7 and 5.2, but some values as high as 5.7 were also found. Besides, the pH of the non-chlorotic plant rhizosphere was as low as 5.4 to 5.0.

Aluminum toxicity

According to Pieri (1976) a better approach of the noxious effects of soil acidity would be to measure the saturation of the absorbing complex with exchangeable aluminum. In an experimental study in a glasshouse, he showed that aluminum is toxic to the nodulation when the rate of saturation of the absorbing complex is more than 30 %, and to the plant itself when it is more than 50 %, in the case of the 57422 variety of groundnut. Exchangeable aluminum appears in the Dior soils when the measure of water pH is well below 5.5. But the pH KCl which measures the exchange acidity is then more suitable.

Manganese toxicity

Mineral analysis of the aerial vegetation reveals a higher proportion of manganese in the chlorotic plants (777 ppm), in comparison to non-chlorotic plants (267 ppm), at the 21st day after sowing (Thilmakha 1978; Panthier, pers. com.). The manganese would be toxic to the groundnut when the proportion in the leaves is more than 600 ppm (Prevot *et al.*, 1955).

The microelement nutrition

The chlorosis is observed when mineral fertilizers were applied: 150 kg ha^{-1} of NPK (8: 18: 27) (containing also sulfur) on groundnut and 150 kg ha^{-1} of NPK (14:7:7) on millet in rotation. But some micronutrients are necessary for the nodulation of groundnut, among them molybdenum, boron, cobalt, iron, copper and zinc. A significant effect on molybdenum was obtained in field trials (Martin & Fourrier, 1965), but there were no chlorotic plants in the control plots.

In Thilmakha, foliar spreading of a complete micronutrient solution for legumes has no effect on the chlorosis.

The influence of biotic factors

Inadequacy of the *Rhizobium* population

At Thilmakha, the *Rhizobium* population was shown to be ten times lower in soils with chlorotic plants than in soils with non-chlorotic plants. However, Wey (pers. comm.) eliminated chlorosis by inoculating groundnuts with a strain of CB 756. But this result could not be confirmed in the field. Since nodulation of hydroponizally grown groundnuts inoculated with a suspension of soil with chlorosis plants did not differ from nodulation of plants inoculated with a suspension of control soil, *Rhizobium* populations alone were not thought to be responsible for the poor nodulation that occurred in the field in chlorotic plots.

Microorganisms antagonistic to *Rhizobium*

Panthier *et al.* (1978) found actinomycetes antagonistic to *Rhizobium* in soils of Senegal, but the numbers of these antagonistic actinomycetes in soils where chlorosis was observed did not differ from that existing in soils where no chlorosis occurred (Table 3). Therefore, the interference of actinomycetes probably cannot be held responsible for the lower nitrogen fixation of chlorotic plants.

Table 3. Number of actinomycetes antagonistic to *Rhizobium* in one gram of soil – Thilmakha (1978). Average of five soil samples (J.J. Panthier, pers. comm.)

	Actinomycetes		Antagonistic actinomycetes	
Soil with chlorotic plants	1.7	10^5	9.5	10^3
Soil with non-chlorotic plants	2.8	10^5	9.4	10^3

Influence of nematodes

In Upper Volta, chlorosis was clearly shown to be caused by nematode attacks (Germani & Dhery, 1973). In Senegal, according to the nematode counts by Germani (pers. comm.), the contamination of roots by *Scutellonema cavenessi* is much greater in chlorotic plants than in non-chlorotic ones (Table 4).

Up to now, it has not yet been possible to reproduce the chlorosis by inoculation of a non-chlorotic (normal) soil with nematodes under laboratory conditions.

Table 4. Number of nematodes *Scutellonema cavenessi* in the roots of chlorotic and non-chlorotic plants – Thilmakha (1978). Average of ten plants

Area with:	Number of nematodes Soil	 Roots
Non-chlorotic plants	200	2 580
Chlorotic plants	880	20 951
Chlorotic plants years before+ no treatment with nemagon	506	16 420
Chlorotic plants years before+ treatment with nemagon	0	0

Table 5. Effect of soil fumigation with a nematicide – Thilmakha (1978). Average of ten plants

Area with:	Dry weight plants gr	Number of nodules	Type of root (Fig. 4)	pH
No chlorotic plants	8.04	28.1	III	5.4
No chlorotic plants+ nemagon	18.12	39.8	III	5.4
Chlorotic plants	3.27	2.5	I -II	5.0
Chlorotic plants+ nemagon	11.81	1.0	III	5.1

In a field trial, the fumigation with nemagon restored the vegetative growth of groundnuts. Nevertheless, chlorosis was not eliminated on the chlorotic areas treated with nemagon. The plants had a perfectly well-developed root system without protrusions but very few nodules.

Control of chlorosis

Two methods for controlling chlorosis have empirically been found to be efficient: liming and organic-matter application. In a field trial at Thilmakha, liming was applied at the rate of 600 kg ha^{-1}, by pelletizing each grain of groundnut. The area covered by the chlorosis has been reduced in the plots treated with lime, but still some yellow plants could be seen and the vegetation had not totally recovered.

Farmyard manure has also been applied since 1973 in the same trial. Every two years, the plots have received 10 tons dry matter per hectare before groundnut planting. After the second application of manure, yellow patches had been reduced considerably, and after the third application, five years later, not a single symptom of chlorosis could be seen. Nevertheless, this rate of manure application is very high, compared to the quantity of organic matter the Senegalese farmers can rely on (Drevon, 1978). So the effect of organic matter should be studied at a lower rate of application at around 2 tons dry matter per ha in the Sahelian region.

Conclusion

This symptom of chlorosis which occurs in acid soils appears to be related to the following characteristics:

(1) Mineral toxicities
(2) Low *Rhizobium* populations
(3) High nematode populations.

It is not yet known whether the decrease in nodulation and nitrogen-fixing activity of the legume results (1) from a poor growth of the plant (due to mineral deficiencies or nematode attacks); (2) from low *Rhizobium* populations or from some mechanism preventing infection and nodulation.

Further investigations are needed in order to elucidate the interactions between the plant, soil mineral factors and soil microorganisms. The results of such investigations should help to develop cultural practices which could promote nitrogen fixation by preventing the effect of limiting factors in Sahelo-Sudanian agrosystems.

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THE PRACTICALITIES OF LEGUME SEED INOCULATION WITH RHIZOBIUM UNDER NIGERIAN CONDITIONS

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Abstract

Seed inoculation with effective rhizobia is an obligatory procedure in legume productivity in several parts of the world. Various methods have been evolved of bringing both partners of the legume/*Rhizobium* symbiosis together for maximum efficiency. The most standard practice is to seed the organism in a carrier (usually peat), which permits long storage. When required, the peat-based inoculum is mixed with an appropriate quantity of water, and a sticker (usually gum arabic) is mixed with the suspension to make it stick to the surface of the seed.

When the inoculated seeds are planted in the soil, the success or failure of the inoculation depends on another set of factors. These include the time for germination of the seeds, whether the testa is carried above soil level at germination or not, the level of the inoculum, its competitive ability with indigenous rhizobia and other soil microflora, soil pH, soil temperature, etc.

These factors are examined as they influence both local and imported strains of *Rhizobium*, and some data are presented to show that the development of our own inoculant service using locally isolated effective strains would be more rewarding than reliance on foreign strains of unpredictable performance.

Introduction

The well documented symbiotic association between legumes and *Rhizobium* species has been successfully exploited, to agricultural advantage, in many parts of the world (Allen & Allen, 1958; Hallsworth, 1958; Nutman, 1956, 1958; Turchin, 1956; Van Schreven *et al.*, 1954; Vincent, 1958; White *et al.*, 1953). Thus, today there are highly prosperous *Rhizobium* inoculant-producing industries with worldwide distribution of inoculants under various trade names (Roughley & Vincent, 1967; Newbould, 1951; Van Schreven *et al.*, 1954; Roughley, 1968; Date, 1969). Many methods have been devised of bringing the two members of legume/*Rhizobium* symbiosis together for maximum efficiency, the most standard being to seed the organism in a carrier, and later mix this with an appropriate quantity of water and a sticker for use as inoculum. The performances of inoculants introduced into Nigeria have so far been unpredictable, local isolates being distinctly superior in many cases (Agboola, unpublished). In this paper it is proposed to examine a number of biological and environmental factors influencing the ultimate performance of inoculants whether the latter are foreign or local.

The dependence of total growth on nodule activity as a measure of rhizobial effectiveness

In temperate countries, adequate nodulation can supply all the nitrogen needed by legumes. This is not our experience in Nigeria. Thus, Ezedinma (1964a, b) demonstrated that the addition of inorganic nitrogen to well nodulated cowpea increased the total growth and grain yield. The question as to when nodules become functional has also been found to be different in temperate and tropical legumes. While nodules are said to be functional as soon as they are formed in temperate legumes (P.J. Dart, pers. comm.), starter nitrogen must be added in subminimal quantities to both inoculated and uninoculated legumes in Nigeria to keep them going during the first three weeks of growth (Agboola, 1971). This apparent time lag between nodule formation and function has been found to be a general phenomenon among tropical legumes (R.A. Date, pers. comm.). However, it has been repeatedly demonstrated that under conditions when nitrogen is in limited supply, total growth depends entirely on nodule activity (Erdman & Means, 1952; Agboola, 1971). When a legume is adequately nodulated with effective *Rhizobium* there is a direct proportionality between total dry matter and total nitrogen as shown in Fig. 1; between nodule numbers and total N (Fig. 2), and between nitrogen fixed and total dry matter (Fig. 3) (Agboola, 1976).

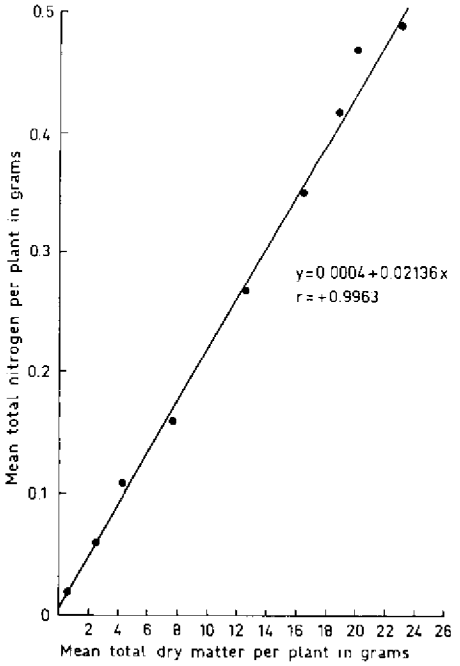


Figure 1. The relationship between total N_2 total dry matter in *Centrosema*.

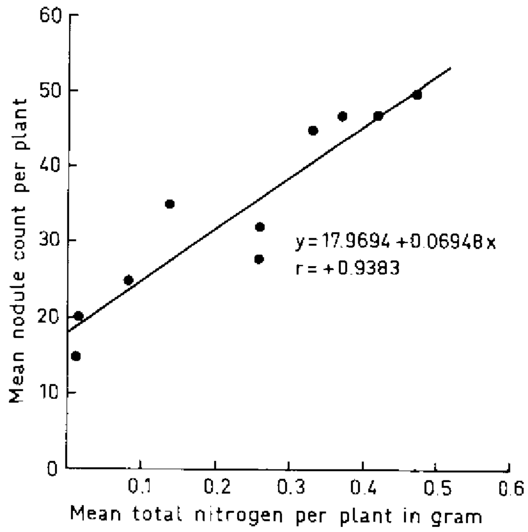


Figure 2. The relationship between nodule number and total N_2 in *Centrosema*.

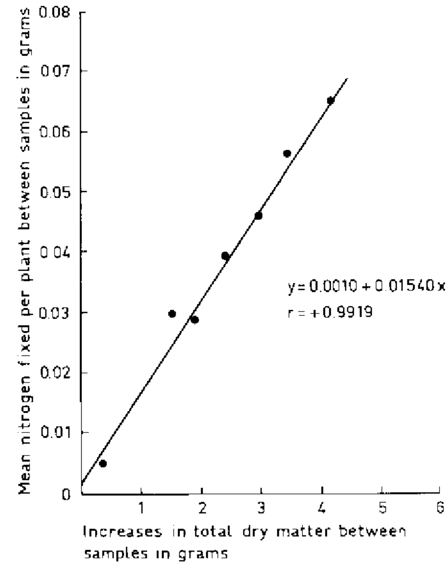


Figure 3. The relationship between total dry matter and fixed nitrogen in *Centrosema*.

Local rhizobia versus imported strains

Ezedinma (1964a) has reported the presence and wide distribution of effective cowpea *Rhizobium* strains in Nigeria. Similarly, Agboola (unpublished and 1971, 1973, 1975) has repeatedly isolated effective strains of local *Rhizobium* for *Centrosema, Stylosanthes*, cowpea, *Pueraria*, and soybean. In tests of imported commercial (Nitragin) cultures and local isolates for *Pueraria*, the latter were found to be distinctly superior to the former (Agboola, unpublished). Similarly it was not possible to demonstrate the effectiveness of some Australian isolates under Nigerian conditions (Agboola, unpublished).

The question then arises as to why most of these 'foreign' cultures are apparent failures in Nigeria. The reasons which readily come to mind are several. These include (a) mishandling of cultures, (b) the bacteria may be dead on arrival due to long storage, (c) the imported strains do not compete favourably with indigenous ones already in the soil, (d) non-adaptability of strains to local conditions. Furthermore, factors of the soil like temperature, organic matter, pH, soil inorganic combined nitrogen are factors of importance in the expression of effectiveness.

Generally, the heavier the inoculum the better the chances of a successful inoculation, success being measured by identifying the bacteria-induced nodules. There is usually a gradual disappearance of introduced strains, with local ones taking over, thus indicating that strain selection should be based not only on effectiveness but also on competitiveness and persistance. Persistence can be measured by the rate of recovery after seed inoculation, the identification methods most commonly used being serology and antibiotic resistance.

A heavy dose of inoculum should normally give a response, and the heavier the better, so as to take naturally occurring strains into account. In most instances the dosage recommended by inoculant manufacturers has to be doubled to obtain any response. Thus,

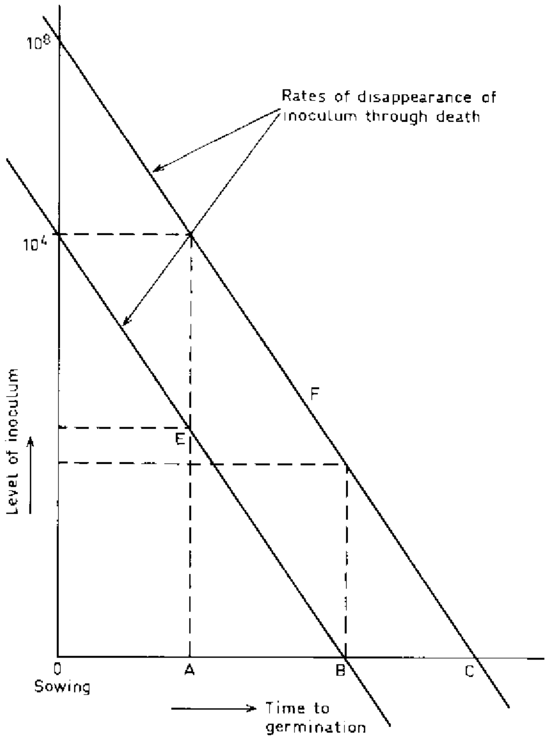
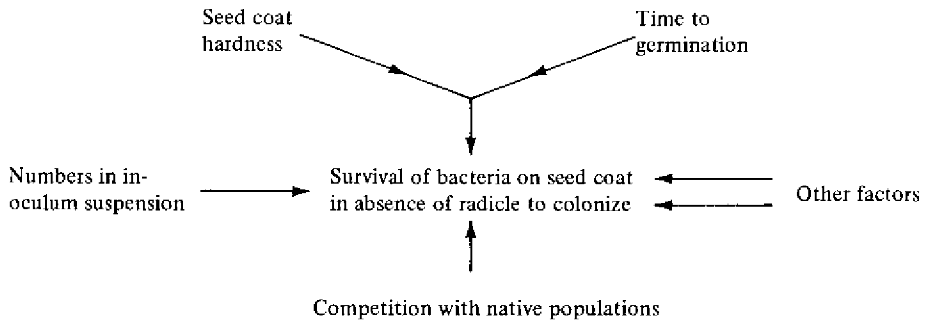


Figure 4. The heavier the dose of inoculum, the more the chances of inoculation success.

universal applicability of commercial strains presupposes that they are adaptable to a wide range of environmental conditions. This is not necessarily so. However, if a locally selected strain proves to be effective, the chances of its being also highly competitive are very high, since it would have been selected from a mixed population in the first instance. Furthermore, it may have been selected by the host (host influence) and will therefore compete favourably from the point of view of invasiveness and aggressiveness.

The germination characteristics of the seed being inoculated should also be taken into account. Take the soybean seed for example. When the seed germinates the whole seed, including the seed coat, is raised above ground-level. The coat is eventually shed. If such seed were inoculated the inoculum would be lost by the shedding of the seed coat. Thus the method of inoculation must depend on the seed being inoculated. An alternative approach might be soil inoculation, or using a particulate material to mix with the inoculum and planting some of this with the seed. In that way, one would be sure of a heavy concentration of inoculum in the immediate vicinity of the root when the seed germinates.

Another important factor in successful seed inoculation is the survival of inoculum in the soil before the seed germinates, i.e., before there is a root for the cells to colonize. Thus, in Fig. 4, suppose a seed inoculated with 10^4 cells of a strain of *Rhizobium* germinates in time 'A'. The death rate is such that only about half of the cells are still alive by that time. Suppose germination does not occur until time 'B', by which time all the cells have died. The inoculation would then fail. However, if a high concentration of inoculum had been used originally, say 10^8, then even at time 'B' a large enough number of cells would still be viable to cause infection. Thus, the ability of a strain to invade and infect root hairs is important, but not the most important. More important is the ability of the inoculum to persist in the soil prior to germination of the inoculated seed. Thus:



Soil factors affecting success of inoculation

Root temperature

With temperate legumes, the optimum temperature range for maximum nitrogen fixation during the first four weeks of growth is 20–25°C (Gibson, 1967). Unfortunately, much less is known of temperature effects on nodule development and functions on tropical legumes. Temperature effects on nodule development have been studied with soybeans (Weber & Miller, 1972) and *Vigna sinensis* (Dart & Mercer, 1965). With *Vigna sinensis* the leghaemoglobin concentration, number, and dry weight of primary and secondary nodules at the final harvest was strongly influenced by the temperature regime. Nitrogen fixation by lines of *Stylosanthes gracilis* and *Pueraria phaseoloides* is influenced by temperature, with some lines showing greater tolerance to higher temperatures than others (Souto & Döbereiner, 1970). A similar study with *Glycine wightii* indicated that plants dependent on symbiotic nitrogen fixation achieved maximum nitrogen fixation when the daily temperature maxima varied between 30° and 36°C (Ferrari *et al.*, 1970). At 36°C, siratro (*Macroptilium atropurpureus*) formed nodules and maintained a relatively high rate of nitrogen fixation. In contrast, *Stylosanthes humilis* nodulated poorly at 36°C, but nodulated plants, transferred to 36°C, fixed nitrogen almost as well as those at 30°C (Gibson, 1972). Thus, in introducing *Rhizobium* cultures from abroad, one is more or less considering the legume host and the *Rhizobium* as independent entities. The two must be considered as a unit, a symbiotic unit. The various results indicated above demonstrate the importance of using species, or lines within species, best able to utilize the growing conditions for the entire season in the areas under consideration. This must be done in conjunction with studies to determine bacterial strain variation in response to temperature, nodule initiation, development, and function. The availability of a suitable strain could readily determine the suitability of certain hosts to particular areas, rather than many presently-done tests where the judgement is made on host growth without regard to symbiotic behaviour.

Fungicides, herbicides and insecticides

These chemicals are becoming commonly used in Nigeria, particularly in large-scale farming. Seed dressing with fungicides is a common practice, and spraying against insect pests is part and parcel of cowpea production. The effects of these compounds on the legume/*Rhizobium* association vary. Agboola (unpublished) demonstrated that simazine, preforan and patoran, three commonly used herbicides, individually depressed nodule formation and function in *Vigna unguiculata*. The six strains of *Rhizobium* tested were tolerant to very high concentrations of the herbicides (up to 10,000 ppm) in petri dishes, thus showing again that one must look at the symbiotic association as a whole and not the individual members. However, simple screening tests should be made of all potential inoculant strains against the commonly used plant protection chemicals. Similarly, all new chemicals should be examined against a range of rhizobia before their use is recommended.

Mineral nitrogen

Another factor with which an introduced *Rhizobium* strain will have to contend is soil mineral nitrogen. Of the various factors affecting nodulation, mineral or combined nitrogen in various forms has received the greatest attention. Despite this, our understanding of the physiological effects of this nitrogen on the formation and function of nodules, and the conditions under which a response can be expected, is far from complete. Broadly speaking, there are three stages during which combined nitrogen may affect nodulation: (1) infection of the root hairs; (2) nodule development, and (3) nitrogen fixation. Nitrate and other forms of combined nitrogen retard nodule development, and when applied in heavy concentration, cause loss of nodule weight and senescence (Gibson, 1972). Nitrogen fixation is also reduced mainly due to effect on nodule structure and integrity. The preference of nodulated legumes for nitrate over atmospheric nitrogen is well known (Allos & Bartholomew, 1957), but the reason is poorly understood. The energy requirements for the assimilation of the two forms of nitrogen are considerable, but similar (Gibson, 1966; Bergersen, 1971). As mentioned earlier, the use of low level "starter" nitrogen is recommended practice with a number of legumes, but the rates and time of application have to be defined in detail. Thus with respect to the Nigerian situation, a lot of efforts will be saved if preliminary experiments are conducted to determine the need for inoculation, before embarking on any inoculation exercise. An initial determination of the nitrogen status of the soil would give a reliable indication.

Water stress

Agboola (1973) demonstrated that nodule formation and function in *Vigna unguiculata* were adversely affected by water stress. Numbers and sizes of nodules were drastically reduced. The studies on the effect of moisture stress on nodule structure and nitrogen fixation with soybeans by Sprent (1971, 1972a, b, c) show the great sensitivity of the symbiotic association to this environmental stress. This aspect becomes particularly significant in the late season cowpea crop in the southern parts of Nigeria. Other forms of stress are known, e.g., salinity and temperature. The general tendency, however, is towards recovery on the removal of the stress. Thus, Wilson (1960) found that saline condition depressed nitrogen fixation, but on removal of the stress, the nodules regained their original shape and nitrogen fixation commenced. Soybean nodules will withstand desiccation to 85 % of full turgor without suffering permanent damage (Sprent, 1972b). The ability of nodule meristems to recommence growth, with a subsequent development of bacteroid tissue, may give this type of symbiosis a greater ability to recover quickly from drought conditions than those with non-meristematic nodules.

Criteria for strain selection

Having established the need for inoculation one must establish the basis for selecting certain strains of *Rhizobium* in preference to others. The most important criterion, of course, is the ability of the strain to form effective nodules on the host. Formation of effective nodules is not sufficient, however. It is the capacity to form these effective nodules under a wide range of conditions which constitutes the recent emphasis on and use of other criteria in selection of strains. Chief among these are competitiveness in nodule formation and survival and multiplication in the soil, particularly in the absence of the host. Additional criteria include prompt effective nodulation over a range of root temperatures, ability to grow well in culture, ability to grow and survive in peat culture, and ability to survive on seed. Other aspects include pH tolerance, pesticide tolerance and nodulation in presence of combined nitrogen. It is extremely doubtful if imported strains can satisfy all these conditions.

Rhizobium carriers

Peat is the most widely used carrier all over the world. However, the availability of processed peat in Nigeria constitutes a major constraint to its use as a carrier for local *Rhizobium.* Carriers must have a high water-holding capacity, provide a nutritive medium for growth of rhizobia and favour their survival both during distribution and when inoculated onto seed. The author is experimenting with bagasse, a by-product in the manufacture of sugar. Bagasse is rich in organic matter and contains a number of essential nutrients. Its water-holding capacity is also high. A 90 % recovery has been made in eighteen-month-old bagasse cultures (Agboola, 1975). Further studies are in progress on other aspects of the suitability of bagasse as a carrier for *Rhizobium* inoculants.

Conclusions

The effectiveness of imported inoculants is not always reproducible under Nigerian conditions. Mishandling of cultures or death of cultures on arrival have been advanced as reasons for reported failures. While these are possible, it is the view of the author that biological rather than physical constraints are responsible. Thus, an imported strain has, presumably, been selected in its own environment, adapted to its own local biological (competitiveness) and environmental (soil) conditions. These conditions are bound to be different from those occurring in Nigeria. Therefore, on being inoculated onto the seed of a Nigerian legume and planted in Nigerian soil, the inoculant is exposed to a totally different set of biological and environmental conditions from those where it was originally isolated. Success of inoculation then becomes a matter of chance.

Fortunately, Nigeria is blessed with a wide variety of legumes, most of which nodulate profusely. Highly effective strains have been isolated for various legumes (Agboola, unpublished, and 1971, 1973). Increases in total dry matter and total nitrogen of inoculated plants of up to five times have been recorded as compared to uninoculated plants (Agboola, 1971, 1976). Since these strains were selected locally, they have been exposed to the host influence and must be highly aggressive competitors among the various strains in the soil. All that is required is to develop an efficient carrier for introducing the organisms into the soil at inoculation. Inoculants must be intelligently used. Thus, the need for inoculation must be pre-determined before embarking on the process. Bagasse is proving to be a very reliable local *Rhizobium* carrier.

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EFFECT OF TILLAGE TECHNIQUES AND FERTILIZER NITROGEN ON THE GROWTH AND YIELD OF COWPEAS IN SIERRA LEONE

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Abstract

The effects of tillage and applied nitrogen on cowpea (Cultivar Temne) were studied in a field experiment. Cowpea growth and yield on mulch tillage plots were comparable to those on conventional tillage. Compared to the conventional plots maximum cowpea grain yields were obtained from mulch tillage at lower nitrogen application. In both tillage techniques, application of 60 kg N ha^{-1} increased plant height, dry matter production, pod number, and grain yield. Based on value/cost ratio analysis an application of 30–60 kg N ha^{-1} to cowpea for any of the tillage methods is recommended. Practical implications of the techniques and application of fertilizer nitrogen are discussed.

Introduction

Cowpeas have been grown in Sierra Leone under conventional tillage (ploughing with a hoe or tractor) without fertilizer in backyard gardens or upland rice farms. The local cultivar "Temne" is grown mainly in backyard gardens that are generally rich in manure. Production of the crop outside the native environment would require a modification of management practices such as nitrogen fertilizer application. There has been no agreement in the literature on the response of crops to nitrogen fertilization under conventional and mulch tillage. Many (e.g., Hood, 1964; Bakermans & de Wit, 1970; Kupers & Ellen, 1970) working with cereals reported that crops under mulch tillage responded less to nitrogen application, while others (Triplett & Van Doren, 1969; Simon, 1978) reported a superior response by maize to nitrogen application under the mulch tillage technique than conventional tillage. Working with cowpea (Cv. Temne) under conventional tillage, Godfrey-Sam-Aggrey (1975) did not obtain significant grain yield increases with five nitrogen rates. The rates (83, 165, 248 and 330 kg N ha^{-1}) were comparatively large, and the recommended nitrogen level of 165 kg ha^{-1} based on a very low value/cost ratio of 1.49 appears uneconomic. A value cost ratio of 2–3 is considered a minimum as an incentive for farmers to use fertilizers (Braun, 1976). On the adaptability of mulch tillage techniques in a specific location, Lal (1975) considered the financial resources of the farmer, nature of the crop, and soil type as major determining factors.

A major objective in this investigation was to examine the effects of tillage techniques and nitrogen application on a potentially high yielding local cowpea cultivar in Sierra Leone and the economic advantages to the farmer.

Materials and methods

The experimental site was previously cropped with maize during the major season of 1977. The experiment was conducted on Njala Soil Series described as gravelly clay loam, low in available nutrients, low in water holding capacity, and deficient in soil moisture for five months of the year; and classified as orthoxic palehumult (USDA system) or Humic Nitosols (FAO/UNESCO system) by Odell *et al.* (1974). A composite sample of the top 15 cm taken before the trial had the following characteristics: pH in saturated H_2O-paste, 4.4; 4.1 % organic C; 0.36 % N, available P (Bray) 5.01 ppm; and 3.02, 0.72, 0.71 meq per 100 g of Ca, Mg and K, respectively. A split plot arranged in a randomized complete block design was used with conventional tillage and mulch tillage as main plots and nitrogen levels at 0, 30, 60, 90, and 120 kg N ha^{-1} as sub-plots. There were three replications. The conventional tillage plots were dug with a pick-axe to a depth of 15–20 cm. This was considered close to the depth for conventional tractor ploughing and more than adequate for conventional hoe ploughing practiced in the area. The plots were later harrowed with a hoe. The mulch tillage plots were sprayed with gramoxone (a paraquat based herbicide) at the rate equivalent to 1.43 litres ha^{-1} of the gramoxone in 172 litres of water to kill the grass one day before planting. Three to four seeds of the local cowpea (Cv. Temne) were planted per hole on 13 September, 1977 in plot sizes of 3.60×2.40 m at a spacing of 60 x 20 cm. Fourteen days after planting, the plants were thinned to one vigorous plant per hill and all plots received 40 kg P_2O_5 ha^{-1} (single superphosphate) and half the nitrogen (Urea) – 10 cm away from the plants in a drill 4–5 cm deep on either side of the plant. Hand weeding was done once at 30 days after planting and the second half of the nitrogen applied immediately. Plant height was measured at 50 % flowering, dry matter was determined at 50 % flowering, the number of pods per plant was recorded at harvest, and grain yield in kg ha^{-1} was calculated. The value/cost ratios were also calculated.

Results and discussion

Growth

There was no significant difference in plant height between tillage means (Table 1). The height of cowpea plants growing on conventional tillage (CT) and mulch tillage (MT) with the same nitrogen level were not statistically different. Plant heights were significantly different for the different nitrogen levels at different cultivations, e.g., plant height of CT with 30 kg N ha^{-1} compared to MT with 60 kg N ha^{-1}. For the same tillage method, plant height was significant for the nitrogen levels studied, with 60 kg N ha^{-1} giving the tallest cowpeas in both tillage methods. Applying the first unit of nitrogen fertilizer did not produce significantly taller cowpeas than the control in either of the tillage methods, but there was a significant increase over the control with the second nitrogen application. Further applications of 90 and 120 kg N ha^{-1} depressed plant height. Extra vegetative growth, mainly branching, can account for this trend. The nitrogen level means were also significant. With nitrogen, cowpea grew taller in the MT than the CT plots. This may be attributed to more moisture conserved by the "killed" grass, which acted as mulch. The MT technique is comparable to the CT and could be superior as regards cowpea plant height.

Table 1. Effects of tillage techniques and nitrogen application on mean cowpea plant heights (cm)

Applied nitrogen level (kg ha^{-1})	Conventional tillage	Mulch tillage	Means
0	33.3	32.1	33.7
30	35.4	39.0	37.2
60	45.4	55.0	50.2
90	38.6	46.7	42.7
120	42.4	50.5	46.4
Means	39.0	44.6	

Tillage means, NS; LSD$_{05}$ Nitrogen level means, 6.25; Nitrogen means within tillage, 8.83; Nitrogen means at different tillage or different nitrogen levels at different tillage, 10.41.

Table 2. Mean number of pods per plant

Applied nitrogen level (kg ha^{-1})	Conventional tillage	Mulch tillage	Means
0	9.6	8.3	9.0
30	11.9	11.6	11.8
60	13.5	15.0	14.2
90	12.9	15.8	14.3
120	11.5	17.1	14.3
Means	11.9	13.6	

Tillage means, NS; LSD$_{05}$ Nitrogen level means, 3.93; Nitrogen means within tillage, 5.56; Nitrogen means at different tillage or different nitrogen levels at different tillage, 4.09.

Pod number per plant

The number of pods per plant was statistically the same for the two tillage methods (Table 2). The MT plots produced a higher number of pods per plant than the CT plots at 120 kg N ha^{-1}. In the other treatments there was no difference between tillage means for the same nitrogen levels. Application of 60 kg N ha^{-1} and above significantly increased the number of pods per plant over the control for the MT plots. Additional nitrogen above 60 kg N ha^{-1} did not, however, significantly increase pod number. Application of nitrogen did not significantly increase pod number in the CT plots. Simon (1978) had a 3.6 % pod number increase of horsebean in CT plots.

Table 3. Mean dry matter production (g m^{-2}) as affected by tillage and nitrogen application

Applied nitrogen level (kg ha^{-1})	Conventional tillage	Mulch tillage	Means
00	45.0	52.6	48.8
30	68.3	155.8	112.1
60	135.9	164.3	150.1
90	120.9	147.6	134.3
120	153.4	156.1	154.7
Means	104.7	135.3	

Tillage means, NS; LSD_{05} Nitrogen level means, 64.19; Nitrogen mean within tillage, 90.78; Nitrogen means at different tillage or different nitrogen levels at different tillage, 68.48.

Dry matter

Dry matter production of the two village methods were comparable (Table 3). Within the same tillage method, nitrogen level means were significant, with 120 kg N ha^{-1} producing the highest dry matter in the CT plots – 153.4 g m^{-2} compared to 164.3 g m^{-2} at 60 kg N ha^{-1} in the MT plots. With sugar beet, Kupers & Ellen (1970) added 30 kg N ha^{-1} more in MT plots to obtain maximum dry matter of tops comparable to CT plots. In the CT plots 120 kg N ha^{-1} had significantly higher dry matter than the control, while at other nitrogen levels there was no significant difference. The first and subsequent applications of nitrogen significantly increased the dry matter in the MT plots over the control. There was, however, no advantage of additional nitrogen after the first application. Dry matter produced for the different tillage methods at the same nitrogen level was the same, except at 30 kg N ha^{-1}. There was no difference in dry matter between 0 and 30 kg N ha^{-1} and 60, 90 and 120 kg N ha^{-1}.

Grain yield

Cowpea grain yields from the CT and MT plots were not significantly different (Table 4). For the same tillage technique, grain yields for the different nitrogen levels were significant. While 90 kg N ha^{-1} was necessary to produce the maximum grain yield of 1270 kg ha^{-1} in the CT plots, 60 kg N ha^{-1} produced the highest in the MT plots – 1280 kg ha^{-1}. Crops on mulch tillage plots are generally reported to require more nitrogen than CT plots (Hood *et al.*, 1964, with barley and kale; Bakermans & de Wit, 1970, with rye, wheat, barley, oats, sugar beet and peas; Simon, 1978, with sunflower) to reach their maximum yield. In this study, maximum yields are accomplished in the MT plots at lower nitrogen application than the CT plots as a result of the presence of grass mulch on the surfaces of these plots. Mulch provided in this technique is reported to conserve more soil moisture than on CT plots (Belvins *et al.*, 1971). With high soil moisture, efficient utilization of fertilizers by crops is generally increased (Danielson, 1972). Differences in yields

Table 4. Mean grain yield (k ha^{-1}) of cowpea as affected by tillage and nitrogen application

Applied nitrogen level (kg ha^{-1})	Conventional tillage	Mulch tillage	Means
0	580	663	622
30	1076	989	1033
60	1217	1280	1249
90	1270	1276	1273
120	1166	1261	1214
Means	1062	1094	

Tillage means, NS; LSD_{05} Nitrogen level means, 162.13; Nitrogen level means within tillage, 229.28; Nitrogen means at different tillage or different nitrogen means at different tillage, 636.44.

from the CT and MT plots at the same nitrogen fertilizer level were non-significant. This strengthens the need for adopting a viable tillage method such as the mulch tillage alternative. Mean grain yields between tillage methods at different nitrogen levels were statistically significant. The control plots in the MT technique were slightly superior to the control plots in the CT technique. This is not in agreement with Hood *et al.* (1964) and Bakermans & de Wit (1970) working with other crops. This trend is attributed to more moisture conserved in the control MT plots. The interaction between tillage and nitrogen rates was significant. Similar significant interactions have been reported by Kupers & Ellen (1970) and Hood *et al.* (1964) working with wheat.

Value/cost ratio

Analysis of the value/cost ratio (VCR) using the present cost of nitrogen at Le 0.39 cents kg^{-1} and selling price of cowpea at Le 0.66 cents (Le 1.00 approx. US$ 0.84) kg^{-1} is shown in Table 5. The two tillage systems gave similar VCRs for the same nitrogen levels except for the first nitrogen unit in the CT technique. This was because the CT plots responded better to the first nitrogen unit than in the MT technique (Table 4). The recommendation of fertilizer rates to farmers on the basis of VCR depends on the ability of the farmer to invest in his farm (Braun, 1976). High VCR is recommended to less well-to-do farmers. In this study the value/cost ratios obtained are several-fold higher than those reported by Godfrey-Sam-Aggrey (1975). The first unit of nitrogen is recommended to low-income farmers for the two tillage systems, while the second nitrogen unit would be recommended for well-to-do farmers.

Practical implications

Increases in crop yield, at the same time as savings in labour, time and money are achieved by eliminating the conventional tillage technique, are some of the major poten-

Table 5. **Comparison of value/cost ratios for conventional tillage and mulch tillage with nitrogen application**

Applied nitrogen level (kg ha^{-1})	Conventional tillage	Mulch tillage	Means
30	27.90	18.36	23.13
60	17.92	17.36	17.64
90	12.94	11.49	12.21
120	8.24	8.42	8.33
Means	16.75	13.90	

tial advantages of the mulch tillage technique over the conventional (Lal, 1975). The comparable and slightly superior growth and yield of cowpea obtained from the mulch tillage plots over the conventional tillage should provide adequate room for thought by agriculturists and farmers. The fact that economic maximum grain yields are achieved under mulch tillage conditions at lower nitrogen application, provides not only savings to farmers but also reduces potential additional losses of applied nitrogen to the ecosystems.

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MINERAL NUTRITION OF COWPEA
(*VIGNA UNGUICULATA* (L) WALP)

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Abstract

Cowpea, like most other legumes, is capable of biological fixation. This ability to fix nitrogen has made the application of combined nitrogen fertilizer questionable. The plant, however, needs a supply of nitrogen for early growth and formation of root nodules. Various other elements have been identified to play important roles in the growth of leguminous crops. This paper reports on fertilization of cowpea with emphasis on nitrogen and phosphorus.

Introduction

Cowpea is widely grown in the humid tropics and will continue to be an important component of the cropping patterns because of its good nutritive value in areas where there is little investment on animal products. Despite the importance of the crop in farming systems, yields are low and inconsistent due to pests, diseases and poor cultural practices.

Like most other legumes, cowpea has the ability to fix atmospheric nitrogen by means of rhizobia living in symbiosis in its root nodules. This ability to fix N has made the application of N-fertilizer questionable. The plant, however, needs a supply of N compounds from the soil for early growth and formation of root nodules. Various other elements like phosphorus, molybdenum, calcium, iron and sulphur have been identified to play important roles in the growth of cowpea.

Nitrogen nutrition

Results of investigations on nitrogen nutrition of cowpea are controversial. Many workers have reported responses to N applications especially at low levels and several have reported depressing effects.

Scientists at the University of Reading working in collaboration with the International Institute of Tropical Agriculture at Ibadan, have carried out a series of investigations on N nutrition of cowpea in simulated tropical conditions in controlled environments. Summerfield *et al.* (1977) grew cowpea (Cv. K 2809) in pots in inflated plastic houses and applied nutrient solutions containing 0, 30, 60, 120 or 240 ppm nitrogen. They found that effectively nodulated plants were vegetatively equal to non-nodulated plants supplied with 60 ppm N and produced significantly greater seed yields. Supplying non-nodulated plants with 120 or 240 ppm N improved yields but not significantly compared with plants completely dependent on symbiotic fixation. Dart *et al.* (1977) varied the application of N at specific periods, *viz.* from emergence to first flower, from first flower to mid pod-fill or from mid-fill to maturity with uninoculated and inoculated control treatments. They found that seed yields of effectively nodulated cowpea plants were 38 % greater than those of non-nodulated plants when both received applied N at concentrations ranging from 60 to 240 ppm. Eaglesham *et al.* (1977) irrigated effectively nodulated pot-grown cowpea plants with nutrient solution containing 25 ppm ^{15}N and determined the relative contributions to total plant N status of inorganic and nodule-fixed N. They showed that maximum rates of N assimilation occurred during pod-fill, with nodules contributing ten times more N than the applied source.

At Ibadan, seed yields of cowpea crops with effective nodulation and symbiosis were not increased by applied N levels up to 180 kg N ha^{-1} (Rachie & Rockwood, 1973; Nangju, 1973). Agboola (1978) showed that the response of cowpea to N fertilizer was affected by the level of organic matter in the soil; on soils with 0.5 % organic matter, grain yield was increased from 800 kg ha^{-1} on the control treatment to 1850 kg N ha^{-1} with the application of 20 kg N ha^{-1}. On soils with 2 % or more organic matter there was no consistent response to N fertilizer.

Other nutrients

Reports on phosphorus nutrition of cowpea in West Africa are few, Tewari (1965) in Ghana noted that a combination of low P (about 125 kg P_2O_5 ha^{-1}) in the absence of applied N produced the highest total number of nodules (effective plus ineffective), while high P in the absence of applied N produced the highest number of effective nodules. Cowpea responds slightly to potassium fertilization (Tewari, 1965) and because of its non-specific role in symbiosis, workers have ignored this element.

Studies at Moor Plantation

The effects of inoculation with local isolates of *Rhizobium* and the application of nitrate N on the development of cowpea were examined in the glasshouse by Ezedinma (1964). Inoculation increased the N content of the plants, but cowpea could not obtain its optimal N requirements through symbiotic fixation alone. Deficiency of N adversely affected growth of inoculated seedlings before nodules became functional. Nitrogen up to 100 ppm applied as potassium nitrate increased the number and weight of nodules and amounts of N fixed (Table 1). Higher levels tended to give lower results. Ezedinma (1964) concluded that small dosages of fertilizer N should be applied to cowpeas at planting in the field in order to offset any retardation in growth and development which might follow the loss of cotyledons at about 4 days after emergence.

Fertilizer experiments have also been carried out in the field at Moor Plantation, Ibadan. Ezedinma (1965) planted the semi-upright local variety 'Kafinsoli early' in

Table 1. The effect of varying N levels on number, weight, yield of plant parts, total m. equiv. (m.e.) of nitrogen per plant and % N content of cowpea at Ibadan (Ezedinma, 1964)

N applied (ppm)	Dry matter yield (grams) per plant	No. of nodules per plant	Wt. of nodules per plant	Fresh wt. of roots (g) plant	m.e. N per plant	% N of d.w.
0	0.5	16	0.3	3.4	1.0	2.5
50	1.6	29	0.5	7.2	2.9	2.4
100	2.9	50	0.7	11.2	5.5	2.6
150	3.7	46	0.8	14.3	7.3	2.8
200	4.2	45	0.7	16.2	7.8	2.6

Table 2. Effect of time of application of fertilizer on cowpea at Ibadan (Ezedinma, 1965)

	Time of placement (days after planting)			
	0	10	20	s.e.
Dry matter yield of tops (g per plant)				
Early crop	51.3	42.3	35.0	3.6
Late crop	12.9	10.4	10.2	0.6
Yield (kg ha^{-1})				
Early crop	594	517	462	72.6
Late crop	352	352	341	58.3

early (April) and late (September) growing seasons. Fertilizer applied consisted of 22 kg N ha^{-1}, 40 kg P_2O_5 ha^{-1} and 22 K_2O ha^{-1} as sulphate of ammonia, superphosphate and muriate of potash, respectively.

The application of fertilizers at planting encouraged greater vegetative development and an earlier flush of flowers. This resulted in an increased proportion of the crop picked at the first harvest and higher total yield than delaying applications till 10 or 20 days after planting (Table 2). The late crop appeared less sensitive than the early one to time of fertilizer application, probably due to a residual effect of fertilizers which had been applied to an early maize crop on the same field.

Application of fertilizers in two bands gave the highest yields but was not significantly superior to a less labourious method of application in one band (Table 3). Application in rings was not as effective in increasing yields as placement in one or two bands. Hence, it was suggested that low levels of NPK be ploughed under just before planting, so that the nutrients will become available to the seedlings from the time they emerge.

In more recent experiments at Ibadan, we investigated fertilization of cowpea in the glasshouse and in the field. In the glasshouse, studies were carried out in 10 litre plastic buckets. The recommended cowpea Cv. "Ife Brown" was used and five nutrient treatments

Table 3. Effect of method of fertilizer application on cowpea at Ibadan (Ezedinma, 1965)

	1 band	2 bands	ring	s.e.
Dry matter yield of tops (g per plant)				
Early crop	46.9	38.0	42.7	3.6
Late crop	13.1	10.3	10.1	0.6
Yield (kg ha^{-1})				
Early crop	550	561	473	72.6
Late crop	341	363	341	38.3

Table 4. Effect of fertilizer application on weight of pods per plant, weight of seeds per plant and shelling percentage of cowpea

	Weight (g) of pods per plant	Weight (g) of seeds per plant	Shelling percentage
$N_0P_0K_0$	22.5	18.5	81.9
P_1K_1	10.5	9.0	85.9
N_1P_1	16.8	14.0	83.6
N_1K_1	11.1	9.1	82.5
$N_1P_1K_1$	13.9	11.6	83.2

were applied: Nil ($N_0P_0K_0$); P_1K_1 (-N); N_1K_1 (-P); N_1P_1 (-K) and $N_1P_1K_1$. Nitrogen was applied at the rate of 40 kg N ha^{-1} in the form of ammonium nitrate. Phosphorus was applied at the rate 40 kg P ha^{-1} in the form of potassium dihydrogen phosphate (for P_1K_1 and $N_1P_1K_1$ treatments) and sodium dihydrogen phosphate (for N_1P_1 treatments). Potassium was applied at the rate of 40 kg K ha^{-1} in the form of potassium dihydrogen phosphate (for P_1K_1 and $N_1P_1K_1$ treatments) and potassium sulphate (for N_1K_1 treatments). Nutrients were applied in solutions.

Weights of pods and seeds were decreased by the application of nutrients compared with the control (Table 4). The application of P+K was the most depressing, whilst N+P was the least depressing. Nutrient treatments had no significant effect on shelling percentage.

In a field experiment, cowpea Cv. "Ife Brown" was sown at a spacing of 30 cm between rows and 30 cm within rows in 4.2x6 m plots. The four fertilizer treatments used were N_0P_0, N_1P_0, N_0P_1 and N_1P_1, where N_1 = 40 kg N ha^{-1} applied as ammonium sulphate and P_1 = 40 kg P_2O_5 ha^{-1} as single superphosphate. All plots received 20 kg K_2O ha^{-1} as potassium chloride.

Nutrient treatment had significant effect ($P < 0.05$) on number of pods; the application of P and the nil treatment (N_0P_0) produced the highest number (Table 5). Weight of pods per plant and grain yield were not significantly affected, although the highest grain yield of 1013 kg ha^{-1} was produced with the application of P.

Table 5. Effect of N and P fertilizers on cowpea

	Number of pods per plant	Weight (g) of pods per plant	Grain yield (kg ha^{-1})
Nil	15	21.6	974
N	12	19.7	952
P	18	19.4	1013
NP	9	17.8	861
S.E. (±)	1.7	1.12	92.5

Discussion

The results of various investigations highlight the importance of integrating biological N fixation with mineral N uptake to produce optimum yields. Cowpea can grow and yield relatively well without the addition of expensive nitrogenous fertilizers (Rachie & Roberts, 1974) once they are effectively nodulated (Summerfield *et al.*, 1977). However, the amount of nutrients removed by most pulse crops is quite large and N fixed by nodules may not suffice for growth. There are numerous reports on the depressing effects of combined N on production, size and function of nodules (e.g., van Schreven, 1958; Tewari, 1965), but large amounts of combined N in excess of those likely to be present in soils are required to produce complete suppression of nodules. According to van Schreven's (1958) report, root-hairs are not infected unless deformed by a secretion of the nodule bacteria. N seems to check root-hair deformation by bacterial secretions.

In contrast, small quantities of combined N have been found to favour infection, N fixation and improve seed yield (Summerfield *et al.*, 1976; Agboola, 1978). Where there is little or no available N in the soil and the plant is entirely dependent upon symbiotic fixation following germination and prior to the development of the symbiotic system, the plant enters a period of N hunger, when all the reserves in the seed are utilized (Whyte *et al.*, 1953; Ezedinma, 1961). Only a starter N should be applied to cowpea not later than two weeks after planting (Agboola, 1978). Adding N after flowering delays leaf senescence and/or encourages leaf production and causes premature nodule senescence (Dart *et al.*, 1977).

The few studies on P nutrition indicate that cowpea requires high levels. This is due to the production by legumes of ample protein-containing materials of which P is an important constituent. According to van Schreven's (1958) report, the number and density of nodules are greatly stimulated and growth is markedly increased by P. Whyte *et al.* (1953) indicated that protein synthesis by legumes is low in soils deficient in P and stressed that applications of superphosphate to the soil usually have the effect of markedly stimulating the number of bacterial flora, including rhizobia.

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THE EFFECT OF MOLYBDENUM AND MAGNESIUM ON THE GROWTH AND YIELD OF COWPEA AND SOYBEAN ON AN ACID UPLAND SOIL

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Abstract

Recent work has emphasized the need for improving efficiency of symbiotic N fixation by rhizobia so as to obtain improved yields of grain legumes. For this to be achieved the right strains of bacteria should be used for inoculation purposes in conjunction with a suitable soil environment.

The acid upland erosional-surface soils in their natural state may not be satisfactory for optimum nitrogen fixation by rhizobia. Work in progress to modify this environment by the addition of fertilizer molybdenum and magnesium to cowpea and soybean which have been inoculated with mixed strains of commercial inoculant is outlined. Molybdenum applied as a seed pelleting material benefited cowpea cultivar Ife Brown.

Introduction

Nangju (1973) demonstrated in the field that cowpea inoculated with indigeneous rhizobia yielded equally well as plants receiving N up to 180 kg ha^{-1}. Eagleham *et al.* (1977) on potted soils showed that at early pod-fill of effectively inoculated cowpea, nodule fixation contributed 10 times more N than that obtained via direct uptake from applied N. Minchin *et al.* (1978), also with potted soils, showed wide differences in the effectiveness of rhizobia strains on cowpea, with the implication of a need for cultivar – strain selection. The need for inoculating soybean, which is exotic to Sierra Leone, is now established following reports by several workers of a positive response to commercial mixed-strains on the Njala soil type.

If the efficiency of symbiotic N fixation should be improved, a combination of two requirements must be met – (1) Use of the right strains for inoculation and (2) Providing a suitable environment for the bacteria to do their job effectively. With regard to the latter, an outline of results has recently been obtained on the response of cowpea and soybean to fertilizer molybdenum and magnesium is the object of this paper.

Properties of the Njala soil type in relation to symbiotic N fixation

This soil occurs on the upland erosional surface in Soil Province G (Odell *et al.*, 1974). Similar soils occur on the same physiographic unit all over the country and are extensively used in the traditional farming system. The soil is now classified as an Oxisol and Table 1 gives some information on its essential properties.

The table shows that with the exception of exchangeable Al all chemical parameters are low. The 'effective C.E.C.' would be much lower than the value shown, which was determined by ammonium saturation at pH 7.0. In addition, there are indications that micro-nutrients such as Mo and Zn are deficient.

Alexander (1967) listed the following as major environmental factors, which influence directly or indirectly symbiotic fixation by rhizobium:

(1) Type of legume
(2) Effectiveness of the bacteria
(3) Inorganic or mineralizable N content
(4) Available P and K
(5) Soil reaction
(6) Secondary and minor essential nutrients.

In addition, physical factors such as soil temperature may influence bacterial effectiveness. It is clear therefore that in its natural state the Njala series may not provide optimum environmental conditions for symbiotic N fixation and that it has to be amended for increased plant vigour.

Table 1. Selected properties of the Njala soil series (adapted from Odell *et al.*, 1974)

Parent rock	Rokel river series sedimentary rocks of Precambrian age.
Annual rainfall	275 cm, 90–95 % of which falls between May and November.
Air temperature	21°C at 9 a.m. and 32°C at 3 p.m.
Soil temperature	27°C at 9 a.m. and 31°C at 3 p.m.
Drainage	Well drained.
pH (water)	4.5 (topsoil)
Organic carbon (%)	2.78
Exchangeable Ca (meq 100 g^{-1})	0.36
" Mg "	0.28
" K "	0.06
" Na "	0.06
" Al "	3.00
Cation exchange capacity (meq 100 g^{-1})	13.22
Base saturation (%)	5.7
Available P (kg ha^{-1})	11.0

Effect of molybdenum on cowpea and soybean

Molybdenum is of special significance to legumes since it is a constituent of the enzyme nitrogenase that catalyzes N fixation, and since acid soils are expected to be deficient in this element a response to this element should be expected.

Cowpea

As with all micro-nutrients, a basic problem in its use in practical agriculture lies with the method of application. Based on pot tests that were carried out at IITA (Nangju, pers. comm.), field trials are being conducted on the Njala series with seeds of cowpea and soybean pelleted with a molybdenum carrier with the aid of an adhesive. Table 2 is adapted from Rhodes & Nangju (1979) and illustrates the response of an improved cowpea cultivar "Ife Brown" (ex IITA), to various treatments on a Njala series.

Experiments in 1974 and 1976 showed that molybdenum applied as a seed coating in the form of commercial Nitra molybdenum at 0.2–0.4 g per 100 g seed either alone or in combination with other pelleting material, improved the growth and yield of cowpea. All plots in this experiment received a basal dressing of 30 kg N, 30 kg P and 30 kg K ha^{-1}.

Field experiments conducted in 1978 on a Njala series failed to show a significant yield response of inoculated local cowpea cultivar "Temne" to the Nitra molybdenum pelleting treatment. The interaction between applied molybdenum and urea on yield was not statistically significant. Nodule weight per plant was larger for seeds treated with Nitra molybdenum compared to untreated seeds, although the difference was not statistically significant. All plots in this trial received P at 60 kg ha^{-1} in the form of basic slag.

Table 2. Response of cowpea cultivar Ife Brown to seed pelleting treatments, and conventional liming

Treatment	Seed yield (kg ha^{-1})	Nodule weight (mg per plant)	Nodules per plant
Without inoculation	764	76	9.9
With inoculation	764	90	9.4
Inoculation+ lime (3 ton ha^{-1})	1025	115	8.7
Lime without inoculation	1057	148	11.1
Inoculation+ Nitra molybdenum coating	956	168	13.6
Inoculation+ basic slag coating	633	79	8.2
Inoculation+ basic slag+ Nitra molybdenum coatings	1089	177	10.9
LSD (P = 0.05)	258	95	5.2

Soybean

Rhodes & Nangju (1979) from an experiment conducted in 1976 showed that soybean cultivar "Pai May Drew" (ex China) did not show any yield response to Mo applied as a seed pellet, on the Njala soil type. Inoculated Pai May Drew cultivar planted in 1978, on the same soil type, again did not show any yield response to this treatment. However, as compared to seeds which did not receive molybdenum, treated seeds appeared to produce plants with fewer but bigger nodules. The interaction between applied urea and molybdenum on seed yield was not significant. All plots in this trial received P at 60 kg ha^{-1} in the form of basic slag.

Effect of magnesium on cowpea and soybean

Godfrey-Sam-Aggrey (1975) applied 73 kg Mg ha^{-1} as kieserite to local cowpea cultivar "Temne" on the basis of reports in the literature of magnesium uptake by cowpea. He went on to recommend for the Njala soil series a dressing of 165 kg N ha^{-1} and 67 kg P ha^{-1}, giving a value cost ratio of 1.49. Since only this single rather high dressing of kieserite was tested it was thought necessary to evaluate lower rates. However, inoculated local cowpea cultivar "Temne" as well as soybean cultivar "Pai May Drew" did not show any significant response to kieserite. Interactions between applied urea and magnesium were not significant. The fact that all plots received P at the rate of 60 kg ha^{-1} in the form of basic slag which may contain a number of secondary and minor nutrients may have masked the effect of applied kieserite.

Rhodes *et al.* (1979) considered the upper petiole contents of N, P, K, Ca, Mg at early bloom of cowpea cultivar "Temne", which had received single superphosphate, sulphate of ammonia and sulphate of potash in varying amounts. They observed that the Mg content correlated best with seed yield at harvest, accounting for as much as 58 % of the total variation and that the N×Mg interaction accounted for 67 % of seed yield variation.

Practical implications

An improved cowpea cultivar (ex IITA) responded to Mo applied as a seed pelleting material. If trials on farmers' fields using the pelleting technique are successful, it would mean a boom to farmers since the simple and convenient method of Mo application would lead to seed yield comparable to liming at the rate of tons per hectare.

Soil analytical data show low levels of exchangeable Mg, which would be reflected in leaf Mg content and be aggravated by the application of potash fertilizers in NPK mixtures. Especially under continuous cropping, Mg fertilization will become necessary when levels supplied incidentally by basic slag fall short of crop requirements.

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WEED CONTROL AND NITROGEN RESTORATION WITH LEGUMES IN UPLAND RICE CULTURE IN SIERRA LEONE

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Abstract

High weed infestation and poor soil fertility are among the most serious constraints in upland rice production, particularly in fields under continuous cultivation. Shifting cultivation has been the traditional practice as a means of counteracting these effects. However, because the availability of land is rapidly declining, alternative methods within the farmers' financial and manipulative ability must be sought. This paper discusses some considerations of a long-term study of the use of legumes to shorten the present fallow period and at the same time to control weeds and maintain soil nutrients.

The environment

Sierra Leone is situated in the southwest corner of West Africa between 7 and 10°N and 13.5°W. Much of the country is lowland and undulating. Its climate is warm to hot with a marked rainy season of seven to nine months. The relative humidity ranges between 30 and 95 % and the mean sunshine is between four and seven hours. The soils include the well drained upland reddish or brownish Oxysols, the lateritic marginal soils between the uplands and the lowlands, the acid soils of annually flooded depressions, and the alluvial soils associated with river basins. The original primary forest is now confined to the forest reserves and the remote mountain tops. The rest of the country is covered mostly by farm bush, but large patches of sole grass and savanna type of vegetation are widespread, especially in the north of the country.

Agro-systems

Rice farming in Sierra Leone is undertaken in five distinct agro-ecological situations; uplands, bolilands, riverain grasslands, inland fresh water swamps and mangrove swamps. Upland farming is carried out in dry land in which direct rain water is the only source of moisture. Bolilands are large saucer-like grass-dominated areas, which become flooded during the rainy season but turn dusty again at the peak of the dry season. Riverain grasslands are grass-covered alluvial plains in the lower reaches of large rivers where flooding is so intense that only floating rice is cultivated. Inland fresh water swamps are found along rivers and streams, while mangrove swamps are associated with the salty tidal sea water and occur in many places along the coast and at river estuaries extending several kilometers inland.

Upland rice culture and shifting farming modifications

As in many other countries in the humid tropics, upland rice farming in Sierra Leone is traditionally under shifting cultivation. It is practiced by over 80 % of the farmers all over the country and accounts for over 65 % of the total rice production (Spencer, 1975). It is thought that development of the upland rice is crucial if Sierra Leone is to achieve self-sufficiency in rice in the 1980's (Spencer, 1977).

The system of upland rice farming depends, among other things, on adequate direct rainfall, soil fertility and weed control throughout the vegetative phase of the crop. While weeding is achieved by hand, soil fertility is restored by bush fallow which ranges between seven to fourteen years (Spencer, 1975).

The effectiveness and drudgery of hand weeding are well known. Development of methods to use herbicides should be extremely difficult due to excessive rainfall, and a very broad weed spectrum which often includes a profuse tree regrowth (Nyoka, 1978). The application of inorganic fertilizers by the peasant farmers appears out of the question at the moment for two main reasons; heavy reliance on the fertility regenerated during the fallow period, and the high cost of inorganic fertilizers.

However, the mounting pressure on land does not allow enough time for the bush to accumulate sufficient nutrients and to regenerate into weed-free forests. The merits of shifting cultivation are therefore gradually diminishing, and new alternatives within the farmer's manipulative and financial ability must be investigated. Four alternatives are suggested here:

Cooperative societies

These could comprise groups of individuals or villages of varying sizes and could enable farmers to obtain machinery, fertilizers, herbicides, etc., with which to embark on some kind of intensive farming, and allow the fallow period of other fields to be prolonged.

Alternative crop husbandry shift to swamprice farming

The campaign to get farmers to move to the swamps had been mounted as early as the 1930's but it has always been met with stiff resistance. The fact of the matter is that upland rice farming in Sierra Leone has strong traditional and cultural implications. It is a way of life and cannot just be abandoned, but could be incorporated in new packages. For example, farmers could be encouraged to open fields in both uplands and swamps in the hope that they would eventually discover which system offered higher returns. This would reduce the amount of bush being cleared annually and would also allow enough time for vegetation to regenerate.

Re-afforestation

In intensively cropped land, most of the tree stumps die off and deliberate replanting of fast-growing wild and economic trees could make the "waste land" usable for rice in a shorter time.

The use of legumes

Nye & Greenland (1960) emphasized that the nitrogen status maintained beneath the forest fallow is adequate and that no long-term fallow with legumes could offer an advantage. In Sierra Leone, however, a stage has been reached at which very little forest is left for rice farming.

Observations on the farmer's fields have shown that in most of the newly cleared fields the nitrogen level appears to be sufficient only for the first four weeks of planting, after which the crop begins yellowing and growth slows down. Is has further been observed that after abandoning a farm, a second crop of maize, millet, cassava, yams and groundnuts produces higher yields in areas previously invaded by leguminous plants such as *Calopogonium mucunoides, Centrosema plumieri,* and *Pueraria phaseoloides.* Yet, farmers remain reluctant to plant rice as a second crop because of the suspicion of a possible high weed infestation. A long-term investigation has thus been launched to determine the extent to which some legumes could be employed to control weeds and restore soil nitrogen under Sierra Leone conditions.

Practicability of the use of legumes

The distribution and status of the forms of nitrogen in selected upland soils in Sierra Leone have been studied by Amara (1974) (Tables 1–4). Evidence from trials in Sierra Leone (Will, 1968, 1969; Das Gupta & Will, 1973; Mahapatra & Kallon, 1976) and other parts of West Africa (Warda, 1976, 1977), suggest that rice responses to nitrogen are small where fallows have been long (more than 10 years), but are high in intensively cultivated land or where the fallows are short. However, Haque (1977) noted that in Sierra Leone

Table 1. Forms of inorganic N in the surface of some selected upland Sierra Leone soils (Amara, 1974)

					Available mineral forms of N			
Soil series	Depth (in.)	Total N (%)	Fixed NH_4^+–N (ppm)	Fixed NH_4^+–N (% of) (total N)	Exch. NH_4^+–N (ppm)	NO_3^-–N (ppm)	Total (ppm)	% of Total N
Mabassia	0–7	0.232	50	2.2	22	6.0	28.0	1.2
Pelewahun	0–15	0.151	20	1.3	17	0.3	17.3	1.1
Pendembu	0–7	0.114	70	6.1	19	4.3	23.3	2.0
Masuba	0–7	0.094	20	2.1	12	0.3	12.3	1.3
Moa	0–6	0.167	70	4.3	46	7.3	53.3	2.2
Manowa	0–10	0.241	40	1.7	35	1.7	36.7	1.5

Table 2. Forms of organic N in the surface horizon of some selected upland soils of Sierra Leone (Amara, 1974)

Soil series	Depth (in)	Org. N (mg g^{-1})	Acid isol. N (mg g^{-1})	Hydrolysable NH$_3$ (mg g^{-1})	Amino acid-N (mg g^{-1})	Amino sugar-N (mg g^{-1})	Unknown Acid soluble-N (mg g^{-1})
Mabassia	0–7	2.242	0.444	0.248	0.620	0.257	0.673
Pelewahun	0–15	1.473	0.340	0.183	0.490	0.203	0.257
Pendembu	0–7	1.047	0.256	0.151	0.310	0.081	0.249
Masuba	0–7	0.908	0.218	0.058	0.220	0.162	0.250
Moa	0–6	1.547	0.333	0.313	0.450	0.149	0.302
Manowa	0–10	2.333	0.468	0.285	0.640	0.162	0.778

Table 3. Percentages of organic and inorganic N occurring in unknown forms (Amara, 1974)

	Organic N				In-organic N		
Soil series	Amino acid-N (%)	Amino sugar-N (%)	Total (%)	Acid insol. N (%)	Hydr. NH$_3$ (%)	Unidentified acid sol-N (%)	Total (%)
Mabassia	27.7	21.4	39.1	19.8	11.1	30.0	60.9
Pelewahun	33.3	13.8	37.1	23.1	12.4	17.4	52.9
Pendembu	29.6	7.7	37.3	24.5	14.4	23.8	62.7
Masuba	24.2	17.9	42.1	24.0	6.4	27.5	57.9
Moa	29.1	6.6	35.7	21.5	20.3	19.5	61.3
Manowa	27.4	6.9	34.3	20.1	12.2	33.4	65.7

Table 4. Nitrogen relationships of some surface upland soils in Sierra Leone (Amara, 1974)

	Organic C (%)	Total N (%)	Organic N (%)	Organic C/ Total N	Organic C/ Organic N
Mabassia	4.37	0.232	0.224	18.8	19.5
Pelewahun	1.68	0.151	0.147	11.1	11.4
Pendembu	1.93	0.114	0.105	16.9	18.4
Masuba	2.05	0.094	0.091	21.8	22.5
Moa	1.70	0.167	0.155	10.2	11.0
Manowa	3.19	0.241	0.233	13.2	13.7

there was no clear relationship between rice response patterns and the major soils, probably because of rapid leaching and denitrification or weed competition and soil acidity problems.

A number of leguminous plants, both wild and cultivated, are available which could be used, the most common ones being *Calopogonium mucunoides, Centrosema plumieri, Pueraria phaseoloides*, pigeon peas (*Cajanus cajan*) and cowpeas (*Vigna unguiculata*). These legumes, in conjunction with others, have been used by many workers, including Webster (1938), Jones (1942), Nye (1958) Dennison (1959), Clarke (1962), Watson & Goldsworthy (1964), for cover during the fallow period. The general observation has been that the crop yields after several years under these legumes have been equal to or greater than those after an equal period under natural bush fallow.

Pigeon peas and cowpeas, which have the additional advantages of being suitable for human food, could be planted immediately after harvesting rice (July–October) and this could ensure the destruction of the weeds that emerge after the last weeding. Pigeon peas would have to remain in the field until the following wet season and the land would be available two to three years after the first rice harvest. In the case of cowpeas, the land would be available during the next wet season.

Seeds of *Calopogonium mucunoides, Centrosema plumieri* and *Pueraria phaseoloides* can be collected by farmers (mostly by children) and sown during the dry season (between January and April), when labour shortage is at its lowest. Depending on the spacing, rainfall, and soil conditions these legumes are expected to cover the whole farm by June. Flowering begins at the end of the wet season (November) and the seeds begin to be shed in January. To avoid a fresh flush of seeds, the legumes should be slashed at the flowering stage. The legumes could be used for animal feed or left to dry or burned at the end of the dry season in order to reduce weed seed population dispersed by wind from the surrounding areas. The scheme would make the land available for rice planting during the second year after the first crop of rice. Alternatively, the area could be replanted with the same legume for several consecutive years after the first crop of rice has been taken. In this case, the legume would have to be slashed at flowering stage, but three regrowths would have to be left out and no burning would have to be carried out until the last replanting. The farm should be planted with fast-growing trees before being finally abandoned.

Problems involved

(a) Wind dispersed seeds are likely to be blown into the farm during the dry season. Two important wind dispersed species which need special attention are *Ageratum conyzoides* and *Pennisetum subangustum.*

(b) Some weed seeds remain dormant or viable in fallow soils for many years and could be a serious source of weed infestation.

(c) The scheme is a kind of intensive farming, care would have to be taken against soil erosion.

(d) Sierra Leone soils are poor in fertility so that inorganic fertilizers would have to be supplemented.

(e) Seed supply and storage difficulties for large scale application are likely to occur.

(f) Because of the high tree density and the gravelly nature of the soil, it would be difficult to incorporate the legumes into the soil at the end of the cropping cycle.

Experimental

The success of the scheme proposed above requires accurate information regarding the various aspects involved in the use of legumes under Sierra Leone conditions. Thus, experiments have been planned to investigate the following:

(a) Nitrogen status in Sierra Leone soils under different fallow periods.
(b) Germination experiments of seeds of *Calopogonium mucunoides, Centrosema plumieri,* and *Pueraria phaseoloides* to investigate:
    (i) Age-related viability/dormancy.
    (ii) Effect of light and flooding on germination.
    (iii) Effect of temperature on germination.
    (iv) Temperature tolerance of seeds.
(c) Investigations on the nodulation potential and on the effect of spacings on nodulation, nitrogen accumulation, and biomass production of the legumes.
(d) Field trials on the use of legumes to control weeds and restore soil N and the effect of these on rice yields.
(e) Based on the results from the above experiments, trials are to be extended to various locations and on farmer's fields all over the country.

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EFFECTS OF PLANT DENSITY AND INCREASING LEVELS OF NITROGEN ON THE RESPONSE AND UPTAKE OF N BY TWO MAIZE (*ZEA MAYS* L.) VARIETIES

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Abstract

Two maize varieties (an early and a late flowering synthetics) were grown at Ibadan, Nigeria, using inter-row spacings of 75 and 90 cm and within-row spacings of 25 and 30 cm. Three rates of N: 50, 100 and 150 kg ha^{-1}, were tested.

Number of cobs and grain weight increased with increasing levels of nitrogen application. Grain yield also increased with increasing plant density, while nitrogen x density interaction was significant. Estimates of recovery of added N were obtained as a measure of fertilizer efficiency. The effects of N application and plant density on nitrogen uptake by the maize varieties are discussed.

Introduction

Several investigators (e.g., Agboola, 1967; Bolton, 1971; Fakorede, 1977; Haggar & Couper, 1972) have demonstrated wide variability in the genotypic response of maize to different levels of soil fertility, and to plant populations. Under the same density or under increasing densities, a maize variety responds differently to varying levels of added nitrogen. The use of an optimum density is essential because maximum exploitation of the factors necessary for crop growth can be fully achieved only when the plant population exercises maximum pressure on all the production factors.

Much of the increases in yield of maize achieved over the past 18 years in the United States, and possibly in other developed countries of the world, have resulted from improved management practices, especially the use of more fertilizers and higher plant densities. An important contribution to greater yields, however, has been made by the identification of maize genotypes that have the genetic potential to produce more grain in response to improved field practices (Prior & Russell, 1975).

The study of the effects of planting density on the yield components of maize genotypes grown on soils that are potentially rich or well supplied with adequate amounts of nitrogen is important in assessing the economic level of performance and productivity. Earlier unpublished studies (S.U. Remison & A. Oyeniyi, National Cereals Research Institute, Ibadan, Nigeria) using two maize cultivars (Farz 23 and 25) have shown a linear

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response to N up to 120 kg ha^{-1} using only a spacing of 75 cm between rows and 25 cm within the row (53,000 plants ha^{-1}).

The present study was carried out to evaluate the response of the two maize genotypes under additional spacings and three rates of nitrogen.

Materials and methods

The field experiment was planted at Ibadan, Nigeria, in the early season of 1978. The total rainfall for the growing period (March–August) at Ibadan was 1231 mm (Table 1). The soil is a loamy sand with a pH of 4.6 and a small amount of organic matter as shown by the organic carbon value of 0.44 % and total N of 0.48 %. The site had received previous P application and soluble P was 15.1 ppm.

Two maize synthetics, designated Farz 23 and Farz 25, both of which were developed by the National Cereals Research Institute of Nigeria were used as test materials. Farz 23 is a yellow floury-flint, late maturing (120–150 days) variety while Farz 25 is white floury and early-maturing (90–110 days).

A split-plot randomized block design with three replications was used. Nitrogen formed the main plot treatments while spacing and varieties constituted the sub-plots. The individual sub-plots were 6x4.5 m. The four spacings used were S_1 = 75x25 cm (53,000 plants ha^{-1}), S_2 = 75x30 cm (45,000 plants ha^{-1}), S_3 = 90x25 cm (45,000 plants ha^{-1}), and S_4 = 90x30 cm (37,000 plants ha^{-1}). Individual plots in S_1 and S_2 consisted of six rows and those of S_3 and S_4 of five rows. For the purposes of observations and data collection, four rows each were used in S_1 and S_2 and three rows, in S_3 and S_4.

Planting was done on 22 March, 1978. Three kernels per stand were planted on the flat and thinned to one plant after emergence. At planting, half of the N and all the P and K were applied as basal dressings. The remaining half of the N was applied 6 weeks after planting. The three nitrogen levels used were 50, 100, and 150 kg ha^{-1}. P and K were applied at the rate of 60 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1}. The source of nitrogen was calcium ammonium nitrate (26 % N). Single superphosphate (18 % P_2O_5) and muriate of potash (60 % K_2O) were used to supply P and K, respectively.

At harvest, data were taken of final stand count, number and weight of cobs, and straw (stover) weight for each treatment in the three replicates. Cobs were shelled and the percent moisture immediately determined from a 200-grain sample in each treatment. Plot grain yields were adjusted to 12 % moisture content and conversion to yield per ha was done using the appropriate conversion formulae. The number of harvested ears per

Table 1. Meteorological conditions at Ibadan in 1978 (March–August)

	March	April	May	June	July	August
Total rainfall (mm)	190	370	198	195	237	42
Maximum temperature (°C)	33.4	31.5	31.2	30.0	26.9	28.0
Minimum temperature (°C)	22.8	22.6	22.6	22.0	21.4	21.0
Total sunshine (h)	190.9	164.3	198.3	163.3	97.3	94.3

plot was converted to ears per 100 plants using the following conversion formula:

$$\frac{\text{number of ears harvested per plot}}{\text{final count per plot}} \times 100$$

pH was determined on a 1:2.5 soil: water mixture using a glass electrode.

Total N in soil and plant was determined by the Kjeldahl method (Bremner, 1960). Organic carbon was by the method of Walkley & Black (1934). Available P was determined by Bray & Kurtz (1945).

Results

Yield and yield components

No varietal differences were observed in grain yields but significant effects of nitrogen and plant population (spacing = S) were obtained (Table 2). N×S interaction was also significant.

Generally, yield increases were obtained between 50 kg ha^{-1} and 100 kg ha^{-1} of N for S_1 and S_2 (53,000 and 45,000 plants ha^{-1}, respectively) with a decline at 150 kg ha^{-1}. At wider (90 cm) row spacings, linear yield increases were obtained (Table 2). From Table 2 it is clear that the mean yield declined by 30 % by going down from 53,000 plants ha^{-1} (S_1 = 3.5 tons ha^{-1}) to 37,000 plants ha^{-1} (S_4 = 2.7 tons ha^{-1}). Most of the yield increases obtained between the highest and the lowest plant populations were obtained by using 100 and 150 kg N ha^{-1}. Increase in the mean yield resulting from increasing N from 50 kg to 150 kg ha^{-1} was 20 %. The increase in mean yields between 50 kg N and 100 kg N ha^{-1} (15 %) was greater than the increase between 100 kg N and 150 kg ha^{-1} (10 %).

The nitrogen effect was significant in the number of ears per 100 plants (Table 3). There was a significant (21 %) increase in the mean number of cobs per 100 plants from 77 at 50 kg N ha^{-1} to 93 at 150 kg N ha^{-1}. A greater proportion (14 %) of the mean increase in the number of cobs per 100 plants was accounted for by increasing N from 50 to 100 kg ha^{-1}. Spacing and interaction effects were not significant.

Table 2. Effect of spacing and nitrogen application on grain yield (t ha^{-1})

	N applied (kg ha^{-1})			
Spacing (plants ha^{-1})	50	100	150	Mean
75 x 25 (53,000)	3.6	3.7	3.2	3.5
75 x 30 (45,000)	2.4	3.6	3.2	3.1
90 x 25 (45,000)	2.4	2.9	3.5	2.9
90 x 30 (37,000)	2.2	2.4	3.6	2.7
Mean	2.7	3.1	3.4	
L.S.D. (P = 0.05)		N means = 0.38 Spacing means = 0.52 Interaction = 0.92		

Table 3. **Effect of spacing and nitrogen application on number of cobs per 100 plants**

	N applied (kg ha^{-1})			
Spacing (plants ha^{-1})	50	100	150	Mean
75 x 25 (53,000)	85	85	89	86
75 x 30 (45,000)	70	95	99	88
90 x 25 (45,000)	79	76	90	82
90 x 30 (37,000)	73	94	92	86
Mean	77	88	93	
L.S.D. (P = 0.05)		N means = 10.8		
		Spacing means = NS		
		Interaction = NS		

Table 4. **Effect of spacing and nitrogen application on ear size (weight, g, per ear)**

	N applied (kg ha^{-1})			
Spacing (plants ha^{-1})	50	100	150	Mean
75 x 25 (53,000)	127.6	133.8	108.8	123.4
75 x 30 (45,000)	133.4	129.6	110.8	124.6
90 x 25 (45,000)	106.4	145.6	143.7	131.9
90 x 30 (37,000)	135.0	121.6	171.0	142.5
Mean	125.6	132.7	133.6	
L.S.D. (P = 0.05)		N means = NS		
		Spacing means = NS		
		Interaction = 33.92		

Table 4 shows that the average weight of ears increased from 123.4 g at 53,000 plants ha^{-1} to 142.5 g at 37,000 plants ha^{-1}. The average size of the ear therefore decreased with increasing plant density.

N uptake in grain and straw

Total N contained in grain and straw ranged from 51.6 to 99.3 kg ha^{-1}, of which 59 % was in grain.

Increasing the N application from 50 to 150 kg ha^{-1} increased the total N uptake. The largest mean N uptake of 89 kg ha^{-1} was obtained when 150 kg N was applied. This was 22 kg ha^{-1} more than when 50 kg N ha^{-1} was applied. This may be related to the increase in grain yield of 0.7 t ha^{-1}.

Population also influenced the total N uptake. The mean total N uptakes (in kg ha^{-1}) were 68, 73, 77 and 83 with respective spacings of 90 x 30; 90 x 25; 75 x 30 and 75 x 25 cm. The difference in total N uptake was only 4 kg between 75 x 30 and 90 x 25 cm spacings. Both had the same plant population of 45,000. With a population of 53,000, the uptake of N was increased by 15 kg ha^{-1} over that of 37,000.

Discussion

Maize yield is determined, among other factors, by the interaction of such yield components as ear size, ear weight, and weight of grains. The two maize genotypes used in this study did not differ significantly in their yield of grains. The higher yield of Farz 23 (by 10 %) over Farz 25 could be attributed to a higher N uptake of 10.4 kg and its ability to accumulate dry matter over a longer period.

Number of cobs per plant was not affected by spacing in this study, but ear size increased as the density of planting decreased. This trend was also reported by Bolton (1971). With more space available to each plant at low density, there was larger leaf area and hence more effective photosynthetic activity per plant. This may have resulted in a larger ear per plant at low density. The increase in yield with increasing density recorded here may be due to increases in number and weight of ears per unit area.

Barrenness, a major adverse effect of increasing the plant density beyond the optimum for a particular maize genotype, was not observed in the maize synthetics used in this study. The number of cobs per plant or per 100 plants (Table 3) did not indicate the possibility of barren plants. Yields also increased linearly with increasing density (Table 2).

It is apparent from the results of this study that the major contribution to grain yield in Farz 23 and Farz 25 is from an optimum combination of nitrogen levels with adequate plant densities. An upward trend in the grain yield also suggests that higher yields might be possible under a plant population higher than 53,000 plants ha^{-1}, provided an adequate amount of N is supplied. Experiments reported by Cooke (1975) indicated that the largest amount of N in combination with the largest plant population gave maximum yield.

Increases in grain yield due to N and population are related to increases in nitrogen uptake in grain and straw. Apparent recovery of applied N estimated from the mean uptake from the two largest amounts of N tested minus uptake from the smallest amount was very low (13 %). This method, used by Mattingly (1974), is bound to underestimate N recovered because yield and N uptake at 50 kg N ha^{-1} was large and efficiency of use of N at this level may probably be much higher. The low response to N in this trial is not unexpected because the area has been cropped for several years resulting in low values of N and organic matter.

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NITROGEN REQUIREMENT OF CORN IN A NEWLY CLEARED LOAMY SAND SOIL AT UYO, NIGERIA: THE EFFECT OF N FERTILIZER AND LIMING MATERIALS

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Abstract

The pH of half plots in a field experiment on the acid loamy sand soil at Uyo, Nigeria was adjusted to about 5.5 with four liming materials: Ewekoro cement fluke dust, hydrated lime, dolomitic lime and hydrated lime plus magnesium sulphate.

Five amounts of nitrogen as calcium ammonium nitrate (0, 50, 100, 150 and 200 kg ha^{-1}) were tested on both limed and unlimed portions in a split-split plot design. Basal dressings of P_2O_5 and K_2O were given at 80 and 120 kg ha^{-1}, respectively. Yields, uptake and apparent recovery of applied N by maize, Farz 27, are presented. The N unaccounted for by crop removal is calculated and the amounts of mineral N recovered in soil under the different treatments after harvest are given. The results are discussed in relation to the efficiency of use of applied N in acid soils of the Eastern States of Nigeria.

Introduction

Maize responds well to N fertilizer in many parts of the country especially in parts of the Northern States of Nigeria, e.g., Bukuru, where yields are over 5.6 t ha^{-1} with 100 kg N. At Samuru, in the Northern Guinea Savanna vegetation zone with a mean annual rainfall of about 1100 mm, concentrated mostly during May to September, Jones (1973) recorded maize yields ranging from 2.7 t ha^{-1} when 56 kg N ha^{-1} was given to 7.6 t ha^{-1} when 224 kg N ha^{-1} was supplied during 1969–1971.

In the Eastern States, where the soils derived from the coastal plains sands are acid and annual rainfall is often over 2000 mm, maize yields have been very small, often less than 1.5 t ha^{-1} even when as much as 100 kg N ha^{-1} has been supplied. One of the factors responsible for the diminished response to N and consequently small yields in this area is probably the acidity problem, which is accompanied by high Al levels in the soil, which may become toxic.

Liming as a means of correcting the soil acidity problem in southern Nigera and improving yields has not been widely accepted, probably because of fear of over-liming and its cost. This is more so when there are only a few experimental data to justify its economic use.

Uzu & Juo (1976) found that with adequate P supply, liming significantly increased both dry matter yield and P uptake by maize grown on three Ultisols (pH 4.2–4.6) from southern Nigeria. Low doses of lime reduced solution Al to < 1 ppm and exchangeable Al saturation to < 25 %. In a greenhouse experiment, Juo & Ballaux (1977) obtained the largest maize growth response (1.3 t ha^{-1}) when the pH of an Ultisol was raised from 4.3 to 5.0 by liming, whilst the highest yield was from pots limed to between 5.5 to 6.0.

In Brazil, Martini *et al.* (1977) showed that imported wheat varieties responded more than Brazilian ones to liming and obtained maximum wheat yields from a Brazilian variety (IAS 52) when liming reduced exchangeable Al < 1.5 meq. per 100 kg and increased soil pH to between 4.8 and 5.7.

Sixteen years (1932–1947) of continuous liming experiments with ground chalk applications of 0–10 t ha^{-1} at Tunstall light sandy soil showed that with the exception of the first two years the crops responded well to liming while crops failed on unlimed plots. The pH on unlimed plots decreased from 4.6 in 1939 to 4.1 in 1947 (Oldershaw & Garner, 1949).

Similar beneficial effects of liming on crop yields have been reported by Bolton (1971, 1977), Johnston & Chater (1975) and Johnston (1977) at Rothamsted and Woburn. Optimum yields of beans and barley were on soils of pH 6.5–7.5 while potatoes responded less to liming.

This work was to see if lime can interact with nitrogen to achieve increased maize yields through better N utilization at Uyo acid soil. The suitability of cement fluke dust as a source of lime was also investigated as suggested by F.O. Uzu (pers. comm.).

Experimental methods

The experiment was conducted during early season 1978 on an acid loamy sand soil derived from the coastal plains sands. Some characteristics of the soil, which was recently cleared of its vegetation (secondary forest), are:

pH	Sand (%)	Clay (%)	Silt (%)	Organic carbon (%)	Total N (%)	C/N ratio	Avail. P (Bray P_1) (ppm)	Exchangeable Cations (meq per 100 g) K	Ca	Mg
3.9	87.4	11.8	0.8	0.92	0.085	10.8	36	0.05	0.51	Trace

Four liming materials (Hydrated lime, Ewekoro cement fluke dust, dolomitic lime and hydrated lime plus magnesium sulphate supplying 60 kg Mg ha^{-1}) were used to raise the pH of half plots of the soil from 3.9 to between 5.0 and 5.5 based on results from laboratory equilibration studies. The amount required was 2.2 t ha^{-1}.

Maize (Farz 27) was grown on the flat at 70 x 30 cm spacing. Five levels of N (0, 50, 100, 150, and 200 kg ha^{-1}) as calcium ammonium nitrate were tested on both limed and unlimed portions in a split-split plot design. Altogether there were 120 sub-plots testing the N rates, each measured 7.5 x 2 m. Half the N was applied two weeks after planting and the rest six weeks later. Basal dressings of P_2O_5 and K_2O were given at 80 and 120 kg ha^{-1}, respectively.

Soil pH was determined on a 1 : 2.5 soil to H_2O mixture. Total N in plant and soil was by the Kjeldahl method (Bremner, 1960). Organic carbon was by the Walkley & Black (1934) procedure. Available P was as described by Bray & Kurtz (1945). Nitrate in freshly sampled soil was extracted with acidified K_2SO_4 at pH 1 and steam distilled (Bremner & Keeney, 1965). Calculations assumed 1 ha equals 2.2 tonnes. Exchangeable cations were leached from soil with N ammonium acetate (Metson, 1956). K was determined on an E.E.L. flame photometer, whilst Ca and Mg were by EDTA titration.

Results and discussion

Effect of nitrogen and liming on grain yield

N had a significant effect on grain yield (P = 0.01) on both limed and unlimed plots (Fig. 1). The first increment of N (50 kg ha^{-1}) gave the largest mean increase of 1.31 t ha^{-1} on limed plots and 0.58 t ha^{-1} on plots that were not limed. The second increment of N also gave large increases in grain yield, especially on plots limed with Ewekoro cement fluke dust (ECF) and dolomitic lime (DL) which were 1.15 and 177 t ha^{-1}, respectively (Fig. 1a). But the mean increase in yield by the second increment of N was 0.66 t ha^{-1} for limed plots as against 0.46 t ha^{-1} for no-lime plots. Although 200 kg N ha^{-1} was required for maximum yields in all the treatments, the result in Fig. 1a suggests a dressing of not more than 100 kg N ha^{-1} for optimum yield at Uyo. This is in close agreement with the currently recommended amount of 75 kg ha^{-1} for maize production by the National Cereals Research Institute, Ibadan.

Differences in yield due to the four liming materials were not statistically significant, which suggests that cement fluke is as good as any other source of lime in improving soil productivity.

Liming had a very significant effect on grain yield (P = 0.01). Averaged over all amounts of N tested, maize grown on limed plots yielded 56 % more grain (range 38–83 %) than that grown on no-lime plots.

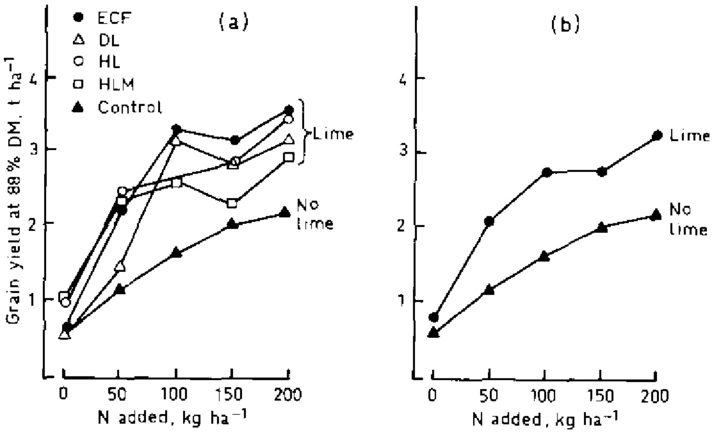

Figure 1. Maize grain yield as influenced by amount of nitrogen supplied and liming material.

The interaction between liming and nitrogen was significant (P = 0.05). Figure 1b shows there was little difference in maize yield between lime and no-lime plots when no N was given. With 50 kg N ha^{-1}, a difference in yield of 1.15 t ha^{-1} was obtained.

Yield of maize straw

Figure 2 shows that N also significantly increased straw yield (P=0.01). Giving 100 kg N ha^{-1} produced almost maximum yields on both limed and unlimed plots. Straw yield on limed plots was on the average 31.6 % larger than that on no-lime plots (P=0.01). Maize grown on plots limed with Ewekoro cement fluke dust (ECF) produced most straw. Averaged over all amounts of N, this was 0.26, 0.81 and 1.04 t ha^{-1} larger than those grown on other limed plots.

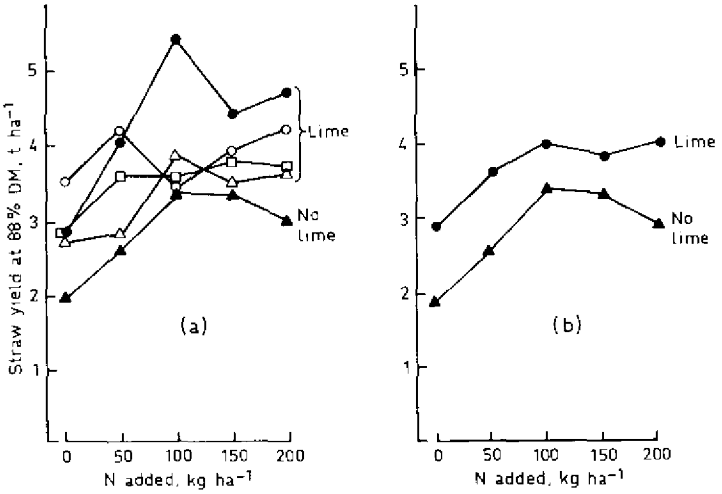

Figure 2. The effect of liming material and N dressing on maize straw yield.

Uptake and apparent recovery of applied N and relationship between yield and N uptake

There were only slight differences in N uptake by maize from plots limed with the four different materials, so uptake and apparent recovery of applied N are presented in relation to N dressings and lime *vs* no-lime treatments (Table 1). More N was taken up when the soil pH was raised from 3.9 to between 5.0 and 5.5. This relates to the effect of liming on grain yield. Increasing N dressing increased the total N uptake, but only a small fraction (23–49 %) was in grain. This suggests that the efficiency of utilization of the absorbed N for grain formation was low. The efficiency of fertilizer N, therefore, not only depends on the ability of the crop to take up applied N, but also to use it for grain production. The conclusion was also reached by Gasser (1962) using winter and spring wheat grown on a light soil. The challenge is to our plant breeders. Table 1 also shows that apparent recovery of applied N was influenced both by liming and N dressing.

Liming increased N recovery whilst increasing N dressing generally decreased N re-

Table 1. **Mean N uptake and apparent recovery of applied N by maize and amounts unaccounted for at Uyo soil at two pH values (3.9 and 5.5)**

N dressing (kg ha^{-1})	Total N uptake (kg ha^{-1})		Total uptake in grain (%)		Apparent recovery of applied N (%)				N unaccounted for (kg ha^{-1})	
					pH 5.5		pH 3.9			
	pH 5.5	pH 3.9	pH 5.5	pH 3.9	Grain +straw	Grain	Grain +straw	Grain	pH 5.5	pH 3.9
0	43.9	30.0	23.0	23.0	–	–	–	–	–	–
50	70.0	45.1	35.6	31.0	52.5	29.6	30.2	14.2	23.9	34.9
100	85.4	54.9	39.7	39.0	41.5	23.8	29.9	14.5	58.5	75.1
150	84.7	68.9	43.0	41.4	27.2	17.6	25.9	14.4	109.2	111.1
200	98.9	68.2	45.5	49.1	27.5	17.5	19.1	13.3	145.0	161.8

covery. The best recoveries of 42 and 53 % were obtained when 100 and 50 kg N ha^{-1}, respectively, were given under limed condition. Other factors may be limiting the efficiency of utilization of applied N in this soil, because Jones (1973) obtained recoveries ranging from 34 to 71.8 % by maize at Samaru given 56–224 kg N ha^{-1}. The very low recoveries when N supplied exceeded 120 kg ha^{-1} suggests that giving greater than this amount to maize at Uyo would amount to waste of the fertilizers. Olsen *et al.* (1970) considered the use of greater than 168 kg N ha^{-1} on continuous corn annually for three or more years a potential hazard in the pollution of underground water.

The relationships between maize grain yield and grain N uptake and Total produce and Total N uptake were slightly curvilinear (Fig. 3 and 4). However, a linear model fitted

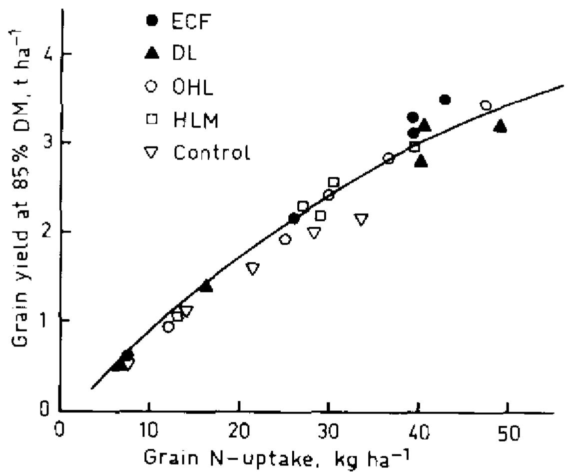

Figure 3. Relationship between grain yield and grain N uptake by maize given increasing amounts of N and grown under limed and unlimed conditions at Uyo.

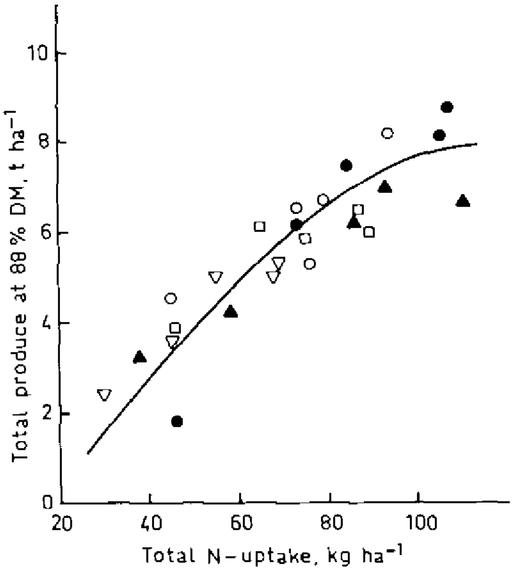

Figure 4. Relationship between total N in grain plus straw of maize. Legend as in Fig. 3.

the two sets of data well and can be expressed by the equations:

(a) Grain Yield (t ha^{-1}) = 0.1244 + 0.0722 x N uptake in grain (kg ha^{-1})

The correlation coefficient (r) was 0.979 and linear regression of grain yield on grain N uptake accounted for 95.8 % of the variance.

(b) Total Produce (t ha^{-1}) = 0.5204 + 0.07148 x Total N uptake (kg ha^{-1})

(r) = 0.898 and linear regression of total produce on Total N uptake accounted for a lesser proportion of the variance, 80.6 %.

N recovered in soil after harvest

NH_4-N found in control plots was similar to those in plots that received N and mattered little if it was included in the recovery calculations or not. Discussion on mineral N is therefore restricted to NO_3-N (Table 2).

Table 2 shows that most of the N applied which was not removed by the crop had been lost from the top 0–15 cm soil after harvest as only between 4–27 % of the N unaccounted for was found. Rainfall was 198 mm from the time of application of the first dose of N fertilizer to the time of application of the second dose. Another 726 mm rain was recorded from the second application to the time when soils were sampled after harvest. A total of 934 mm rain in 103 days was enough to account for the loss of NO_3-N residues from the topsoil. Cunningham (1962), working on a newly cleared secondary forest sandy loam soil in Ghana, found that 203 mm rain in the 63 days leached off almost all the 112 kg N ha^{-1} broadcast as urea or ammonium sulphate 9 weeks after N application and 6 weeks before the first rain from both bare and cropped soils.

Table 2. Nitrate nitrogen in soil after harvest

	N dressing (kg ha^{-1}) at pH 5–5.5					N dressing (kg ha^{-1}) at pH 3.9				
	0	50	100	150	200	0	50	100	150	200
NO_3-N (0–15 cm) (kg ha^{-1})	14.1	19.9	22.5	32.0	26.5	6.0	9.0	9.0	36.2	24.1
NO_3-N as % of amount unaccounted for (0–15 cm)	–	24.2	14.4	16.4	8.6	-	8.6	4.0	27.0	11.2
Recovery of added N in soil 0–15 cm (%)	–	11.6	8.4	11.9	6.1	–	6.0	6.0	20.1	19.1
NO_3-N (0–75 cm) (kg ha^{-1})	62.3	78.0	81.7	102.1	125.7	43.7	56.0	61.9	101.3	12.8
NO_3-N as % of amount unaccounted for (0–75 cm)	–	65.7	33.2	36.4	47.3	–	35.2	24.2	51.8	52.2
Recovery added N in soil 0–75 cm (%)	–	31.1	19.4	26.5	31.7	–	24.6	18.2	38.4	42.2
Total recovery in plant and soil, 0–75 cm (%)	–	83.2	60.9	53.7	59.2		54.8	43.1	64.3	61.3

Wild (1972) and Jones (1975), working at Samaru, Nigeria, have shown that leaching of NO_3-N mineralized from organic matter was very gradual. Nevertheless, downward movement of nitrate N in the profile when N fertilizer was applied was very appreciable and leaching rates of 0.525 cm cm^{-1} rainfall were obtained even though it was thought to be an overestimation (Jones, 1975). Some of the N lost from 0–15 cm was found in the subsoil as the amount of NO_3-N in 0–75 cm soil amounted to 24–66 % of the N unaccounted for by crop removal. When the recoveries in crop and soil, 0–75 cm, were combined a total of between 43–83 % of the N applied was accounted for.

Table 2 also shows that when more than 100 kg N ha^{-1} was given, the proportion of N unaccounted for was 52 % from no lime plots as against 36–47 % from limed ones, which suggests that loss of NO_3-N may be accelerated by liming, especially when amounts larger than that required by the crops are given.

Acknowledgement

The Director, National Cereals Research Institute, Ibadan, granted me the permission to present this paper. Nokoe helped in the design and analysis of the experiment. My thanks also to National Cereals Research Institute staff at Uyo, especially Udom and all the Chemistry staff at National Cereals Research Institute, Ibadan, especially N.J. Ekanem, M. Ehikhamele, and D. Nwokafor for all their help.

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Nitrogen Cycling in West African Ecosystems

DETERMINATION DE LA FERTILISATION AZOTEE DE REDRESSEMENT SUR UN SOL EN OUVERTURE SOUS CLIMAT EQUATORIAL (VALLEE DU NIARI, CONGO)

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Abstract

The yield of maize from virgin plots was shown to increase with nitrogenous fertilizer. Up to 160 kg N per ha the response was linear; thereafter no further increase was noted. This amounts is therefore recommended as the optimum for nitrogen applied to maize on similar tropical virgin soils.

Introduction

L'azote est dans la fumure d'entretien annuelle, l'élément prédominant surtout lorsqu'il s'agit des graminées. Les expériences faisant intervenir des doses croissantes d'azote ne sont donc pas destinées à estimer la fertilisation de redressement. Cependant, lorsqu'il s'agit d'un sol en ouverture qui n'a jamais été cultivé, mis en culture avec enfouissement de la M.o. (Matière organique) c'est un cas particulier, c'est pourquoi nous nous sommes permis de parler de fertilisation azotée de redressement, destinée à estimer les apports d'azote qu'il faut effectuer lorsque la culture à mettre en place est une graminée: le maïs. Apport devant satisfaire la demande qui dans ce cas est très importante: besoins de la plante et besoins des micro-organismes intervenant dans la décomposition de la matière organique enfouie.

La présente note relate les résultats obtenus sur un point d'essai au Centre de Recherches Agronomiques de Loudima (Vallée du Niari, Congo) au cours de la campagne agricole 1977–1978.

Description du milieu

Situation géographique du Centre de Recherches Agronomiques de Loudima

Le Centre de Recherches Agronomiques de Loudima est situé dans le District de Loudima, Région de la Bouenza (Vallée du Niari) sur la ligne du Chemin de Fer Congo-Océan entre la gare de Moutela et celle de Loudima. Altitude: 165 m. Longitude: 13° 05′ S. Latitude: 4° 10′ E.

Climat

Bas-Congolais type Soudano-Guinéen se caractérisant par deux saisons de pluies et deux saisons sèches: 1ère saison des pluies: mars à juin. 2ème saison des pluies: octobre à janvier. Grande saison sèche: juin à septembre. Petite saison sèche: (février à mars. Pluviométrie moyenne annuelle: 1.174 mm. Température moyenne annuelle: 25°C.

Végétation naturelle

La végétation qui recouvre cette région est une savane moyennement arbustive à hyparrhenia diplandra et arenaria. Dans ces savanes, le développement des grandes andropogonacées forme en fin de cycle un feuillage dense. Par contre, au niveau du sol, les touffes sont espacées et en début de saison de pluie une partie importante de la surface du sol est soumise au battage de la pluie et à des écarts de température importants.

Les sols

Ce sont des sols faiblement ferralitiques modaux sur matériaux argileux principalement issus du schisto-calcaire. Le profil de ces sols est formé de niveaux.

1° – Le niveau supérieur (horizons superficiels du sol) présente la morphologie suivante:

0–2 cm: humifère noir (10 YR 2/1), grumeleux fin, avec un chevelu racinaire fin, dense, et une porosité élevée.

2–30 cm Horizon humifère homogène, brun sombre (10 YR 2/2) argileux, structure uniforme à polyédrique de cohésion moyenne.

30–50 cm Horizon d'aspect bigarré par suite d'une pénétration humifère hétérogène essentiellement sur les faces des agrégats polyédriques moyens à grossiers, qui sont colorés en brun (7,5 YR 5; classification Munseu) tandis que la masse tenouse est jaune brunâtre (10 YR 6/6).

En dessous de 50 cm: La pénétration humifère devient peu visible, la structure est de type polyédrique moyen moins cohérent.

L'épaisseur de ce niveau supérieur est très variable, mais généralement supérieur à deux mètres et plus.

2° – Le niveau moyen:

Le niveau est essentiellement formé de gravillons ferralitiques avec parfois des blocs de cuirasse fragmentés.

3° – Niveau inférieur (couche constituée de la roche mère):

Horizon argileux jaune à structure polyédrique.

L'analyse d'un échantillon moyen prélevé à l'emplacement du champ d'expérience se présente comme suit:

Argile:	67,3 %
Limon fin:	12,2 %
Limon grossier:	6,2 %
Sable fin:	9,0 %
Sable grossier:	3,8 %

pH H_2O:	5,9 %
pH KCl:	5,0 %
Matière organique totale:	7,6 %
Signific. carbone méthode (Walkley et Black):	44,4 %
Azote méthode (Kjeldahl):	2,1 %
C/N:	21,1 %
Bases échangeables:	
Ca^{++}	9,10 meq/100 g
Mg^{++}	2,28 meq/100 g
K^{+}	0,17 –"–
S$^{=}$	11,55 –"–
Mn actif pH 7	0,46 %
Cations de réserve:	
Ca^{++}	10,30 meq/100 g
Mg^{++}	14,02 –"–
K^{+}	1,33 –"–
Mn^{+}	0,13 –"–
Somme	21,79 –"–
Phosphore total (Duval):	1,99 o/oo du sol sec
Phosphore assimilable (Olson) :	0,267 o/oo du sol sec.

Expérimentation mise en place au cours de la Campagne 1977–78

Protocole expérimental

La sole réservée à cette expérience est une parcelle d'ouverture, qui n'a jamais été cultivée; son ouverture a lieu en avril 1977.

La méthode utilisée est basée sur une doctrine mise au point par le Professeur Chaminade.

Nous apportons l'azote sous forme d'urée à doses variables, les autres éléments sont apportés à doses constantes.

Dispositif: Bloc 7 traitements
5 répétitions

Les traitements:

N_0 =	0 kg N ha^{-1}	300 kg P ha^{-1}	300 kg K ha^{-1}
N_1 =	40 kg N ha^{-1}	–"–	–"–
N_2 =	80 kg N ha^{-1}	–"–	–"–
N_3 =	120 kg N ha^{-1}	–"–	–"–
N_4 =	160 kg N ha^{-1}	–"–	–"–
N_5 =	200 kg N ha^{-1}	–"–	–"–
N_6 =	240 kg N ha^{-}1	–"–	–"–

Dimensions des parcelles:

Il s'agit de microparcelles de 5 m de long sur 4 m de large.
Ecartement entre lignes: 0,80 m
La microparcelle est ainsi composée de 6 lignes de 5 m.
Surface élémentaire de la microparcelle: 20 m^2
Surface de la microparcelle utile: 16 m^2
(Résultats sur les 4 lignes centrales amputées des pieds des extrémités.)
Ecartement des microparcelles: 1 m
Ecartement des blocs: 2 m

Mode et densité:

- Densité de semis: 50,000 pieds ha^{-1}
- Semis à la main à 3 grains par paquet
- Démariage à 20 jours après semis
- Profondeur de semis: 5 cm
- Mode d'apport d'engrais
- Epandage à la volée
- Urée: 50 % au semis
  45 jours après semis
- Superphosphate triple: 100 % au semis
- Sulfate de potassium: 100 % au semis

Conditions générales de réalisation de l'expérience

L'expérience s'est réalisée dans de très bonnes conditions. La hauteur totale des pluies au cours de l'expérience est de 458 mm régulièrement répartie (35 jours). L'essai est resté en place du 6 novembre au 13 mars 1978.

Plante test

Utilisée: Maïs
Variété: ZM 76
Très grandes potentialités: jusqu'à 9 t ha^{-1} dans les meilleures conditions.

Résultats

Les observations en cours de végétation nous ont révélé l'action très manifeste de l'azote sur le développement végétatif du maïs: très nette différence entre les parcelles N_0 et les parcelles N_5 ou N_6 (Fig. 1).

A la fin de l'expérience les rendements observés sont les suivants:

Traitements:		**Rendement (t ha^{-1}) moyen:**
N_0	0 kg ha^{-1}	0,15
N_1	40 "	0,85
N_2	80 "	1,40
N_3	120 "	2,04
N_4	160 "	2,60
N_5	200 "	2,94
N_6	240 "	3,29

Significatif à 1 % C.V. = 10,5 %
P.P.D.S. (plus petite différence significative) = 0,36 t

Classement: $N_0 < N_1 < N_2 < N_3 < N_4 = N_5 = N_6$

Figure 1. Différence de végétation entre les parcelles N_0 (1er plan) et N_5 (2^e plan).

Discussions

Il existe au seuil de 1 % une différence significative entre les différentes doses d'engrais azoté appliqué.

En examinant ce qui se passe dans les intervalles 0–40, 40–80, 80–120, 120–160, 160–200, 200–240 – nous avons ceci:

0–40 = différence très hautement significative, productivité élevée = 17,85kg
40–80 = différence très hautement significative, productivité moyenne = 13,5 kg
80–120 = différence hautement significative, productivité élevée
120–160 = différence hautement significative, productivité moyenne = 14 kg
160–200 = différence non significative
200–240 = différence non significative

Ainsi donc à partir de 160 kg ha^{-1}, l'azote n'a plus d'effet sur les rendements du maïs.

Conclusion

Cet essai mené au cours d'une campagne nous permet de conclure que le manque d'azote dans les sols en ouverture, agit comme un facteur limitant absolu puisque les parcelles sans fertilisation azotée produisent 0,150 t avec 300 kg de K_{20} et 300 kg de P_{205}. Autrement dit, une fertilisation sans azote sur les sols d'ouverture est sans efficacité sur toutes les plantes sauf les légumineuses:

- Que les apports azotés susceptibles d'apporter une productivité élevée se situent entre 160 et 200 kg ha^{-1}.
- Que le maïs ne semble pas tout indiqué pour servir de tête de rotation. (La variété utilisée ZM 76 a de très grandes potentialités).

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Nitrogen Cycling in West African Ecosystems

GROWTH STIMULATION BY DRIED POULTRY MANURE: IMPLICATIONS FOR NITROGEN CYCLING IN WEST AFRICAN ECOSYSTEMS

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Abstract

Food production in many West African countries is not enough to meet the demands of an increasing population. Starchy roots and tubers form the bulk of the food consumed in these countries, hence attempts at increased livestock production are being made. Poultry products like meat and eggs are harvested within a relatively short period compared with beef, mutton and goat meat. However, chickens are raised on dietary sources of nitrogen, especially groundnut cake, which has been in short supply in recent years. Dried poultry manure has been shown to be a substitute, at low levels, for dietary groundnut cake in poultry rations.

At the same time, poultry manure is readily collected and it is useful as a source of organic nitrogen in the soil. Utilization of poultry manure for this purpose will reduce the level of synthetic nitrogen fertilizer used for crops, thereby reducing the eventual release of nitrous oxide to the atmosphere. The two competing uses of poultry manure as a stimulus for increased food production show the need for a thorough evaluation of systems of food production in the West African ecological zone as part of the study of the global nitrogen cycle and the influence of agricultural activities on the nitrogen cycle.

Introduction

Nitrogen and its compounds occupy a central position in nutrition. In the developing nations of West Africa food production is being emphasized, as several studies and surveys have shown the level of food supply in this area to be marginal. In Nigeria it was recognized that food production policy should be oriented towards improving not only the quantity but also the quality of the diet. Hence the supply of about 80 % of the calories consumed in Nigeria was estimated by the FAO (1965) to be from starchy roots and tubers, and the low level of protein intake from animal sources shows that a minimum satisfactory dietary level has not been attained (Pawley, 1960; Sukhatmo, 1961).

Attempts are being made to bridge this imbalance between supply and demand. Thus, the National Agricultural Development Seminar (1971) pointed out that the prime objective of the livestock programme is to make the maximum feasible contribution towards providing the rising total animal protein needs of the Nigerian population. The policy was envisaged to develop livestock as part of an integrated, inter-dependent, development programme for the country.

Problems of animal protein production in Nigeria

Constraints to the production of animal protein in Nigeria are many and varied. Diseases like trypanosomiasis limit the large-scale production of cattle, sheep and goats to the Sudan and Sahelian zones, where uncertain water supplies interfere with the growth and productivity of these animals. The Guinea zone with adequate rainfall and good pasture growth is infested with tsetse fly, a vector for trypanosomiasis. Although seasonal migrations to the Guinea zone by the nomadic cattlemen occur, the stress of the long trek by the animals results in loss of body weight. In addition, the increasing demand for beef, mutton and goat meat compels us to slaughter younger and less mature animals with consequent reduction in average carcass weight and relatively low harvestable material from the livestock. Indeed, most projections of meat supply indicate a short-fall of at least 380,000 tonnes of meat by 1980, and suggestions have been made that efforts be increased to ensure national production of meat from other kinds of livestock as a matter of urgency and priority (National Agricultural Development Seminar, 1971).

To this end, poultry production has been intensified with major emphasis on the production of chickens. However, feed has been a major limiting factor besetting many Nigerian poultry farmers (Operation Feed the Nation, 1977). Cereal grains are needed both by the human population and the birds; the groundnut cake, which is a major source of dietary nitrogen (amino acids) to the birds, has not been in abundant supply since the last drought in the Sahelian zone and the normal feeding of not only poultry but also the supplementary feeding of cattle have been affected (Muktar, 1974). The critical situation of animal feeds and feeding called for more judicious and economical use of available materials.

Poultry manure

The recognition of the ability of rumen microorganisms to synthesize protein from non-protein substances has been an important advancement in the field of ruminant nutrition (Belascol, 1954). Numerous organic and inorganic non-protein nitrogenous substances are being studied for inclusion in rations of the ruminants. Urea has been used for this purpose, and poultry faeces are also being used as nitrogen supplements for ruminant animals. In Nigeria, growth stimulation in dwarf sheep by poultry manure has been reported (Adeleye & Okoh, 1975; Briggs, 1967; El-Sabban *et al.*, 1970).

In the case of monogastric animals, especially chickens, the possibility of utilizing non-protein nitrogen had been investigated over the years (Featherstone *et al.*, 1962; Rose *et al.*, 1959; Sullivan & Byrd, 1957). Recently, dried or autoclaved poultry manure has been used to improve body weight, food intake and efficiency of food conversion in poultry when purified diets were fed. Also in an attempt to stem the increasing problems posed by inadequate supply of groundnut cake, dried poultry manure had been tested as a replacement for the cake in practical poultry rations. This recycling of the poultry manure proved beneficial at low levels as body weight gain and feed conversion were improved in broilers, while feed required per dozen eggs was reduced. However, the dried poultry manure stimulated more fat in the meat of broilers and depressed body weight of the laying pullets (Ogunmodede *et al.*, 1978).

This findings appears to offer a partial solution to the problem of groundnut cake supply and the related feed problem for poultry. However, other problems may be envisaged in the wider field of primary production. Nitrogen supply is essential not only for the production of animal protein but also for the production of other major food components such as carbohydrates, fat and other nutrients in the plant.

Problems arising from recycling poultry manure in chickens

In Nigeria, a combination of bush fallows and mixed cropping prevails in the agricultural areas. Fallow periods used to be sufficiently long to rebuild soil fertility. In recent years the fallow periods have been reduced considerably in many areas as a result of pressure of land demands. At the same time the poor physical properties of most Nigerian soils have to be improved. Thus, in view of the strategic and universal role of fertilizers in agricultural production, about 250,000 tonnes of various types of fertilizers were purchased and distributed to farmers by the Government of the Federation in the 1976/77 cropping season (Operation Feed the Nation, 1977). This source of industrially-fixed nitrogen for agriculture has been shown as one of the means by which Man has been modifying the natural nitrogen cycles, as the use of nitrogen fertilizer tends to increase emission of nitrous oxide to the atmosphere with consequent diminishing level of ozone. Indeed the total requirement of Man for nitrogen in the form of protein is considerably lower than the present level of fertilizer-nitrogen used, and the stratospheric natural nitrogen cycle is being disturbed significantly by means of agricultural activities.

Furthermore, the current campaign for increased food production in Nigeria recognizes the need for supplying capital input in the form of farm machinery to crop producers. The matchet and the hoe can now be supplemented by mechanized farm implements for land clearing, ploughing and ridging. This practice minimizes the drudgery of farm operations and also opens up vast areas of land within a short period. The land clearing scheme being undertaken by the Government is designed to open up thousands of hectares of agricultural lands in the Federation. Experience showed that in order to make adequate use of the tractor, ploughing must often be started well in advance of planting dates. This was found to be the case when tractors were used for dry season or early land preparation both at Nachingwea in Tanzania and on the Niger Agricultural Project in Nigeria (Baldwin, 1957; Kird, 1963). The exposure of fallow lands in this manner to rain, results in erosion as well as a decrease in the ability of the soil to absorb volatilized ammonia, as plants are not yet present to absorb soluble nitrogen. Hence the much needed nitrogen is lost.

In any case, animal manures supply organic matter useful for replenishing soil humus needed for the maintenance of soil fertility and the stability of the ecosystem. Such manures are not readily obtained in large quantities from cattle, sheep and goats in Nigeria, as the bulk of these animals are made to migrate over specific grazing areas and cattle routes used by the nomads. On the other hand, the intensive poultry production that is becoming widespread in Nigeria offers an opportunity for manure collection and utilization on cropped lands, where cultivation leads to rapid decomposition of the soil organic matter and subsequent loss of soil nitrogen.

There is indeed a dilemma posed by the availability and possible usefulness of the poultry manure in the developing nations of the world. These nations need food, especially good quality protein-rich foods, and chicken meat and eggs could be produced by recycling the manure through the birds. It is true that proteins for human beings could be obtained cheaply from plant sources and so avoid the inefficient conversion of plant proteins to animals. Yet, soil conditions in these countries warrant the application of synthetic fertilizers to farm lands. These fertilizers speed up the oxidation of soil organic nitrogen, resulting in leaching and denitrification. In effect, the poultry manure being produced is required in two major different directions, each divided to ensure not only improved nutrition but also the stability of the ecosystem. A balance will have to be established between utilization of poultry manure for animal feed and its uses for enriching the soil such that production of food from animal and plant sources can occur as much as possible with the aid of poultry waste products.

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Nitrogen Cycling in West African Ecosystems

THE ROLE OF NITROGEN OXIDES IN OXIDATION OF SULPHUR DIOXIDE IN COMBUSTION STACK GASES

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Abstract

Increasing emission of sulphur dioxide concurrent with growing industrialization constitutes a hazard to the natural environment. Changeable atmospheric conditions and excessive contamination of fuel with sulphur causes from time to time especially dangerous situations. For such critical moments the use of the Emergency Gaseous Ammonia Method is suggested.

The presented paper deals with basic investigations of the kinetics and mechanisms of the reactions which might occur when gaseous ammonia is introduced into stack gases.

The presence of water vapour, nitrogen oxides and oxygen in fuel gases was found to cause efficient oxidation of sulphur dioxide and the precipitation of ammonium sulphate takes place.

Introduction

The continuously increasing need for electric energy and the expansion of industry causes the amount of pollutant gases emitted into the atmosphere to constitute an increasing hazard to the natural environment.

Of the gases emitted the most dangerous ones are sulphur dioxide and nitrogen oxides; 11 ppm of SO_2 in the air may seriously affect the human health in 24 hours, while exposure to an average concentration of 0.04 ppm may cause a similar deterioration over a period of one year. Already the average annual concentration of 0.03 ppm SO_2 can damage the plant vegetation.

Smog formation

When emitted to the atmosphere, gases very often form aerosols which apart from corrosive action on metal objects and destruction of leaf surfaces, also cause serious visibility problems. The main processes responsible for formation of smog are photooxidation reactions in the presence of nitrogen oxides, unsaturated hydrocarbons and oxygen. Sulphur dioxide also plays a significant role in the processes and several authors have discussed photochemical reactions for the gaseous mixtures containing sulphur, nitrogen and carbon oxides, oxygen, ozone and olefines (Daubendiek & Calvert, 1975). In studying the formation of aerosols it is necessary to take into account the physicochemical processes of seeding and formation of heteromolecular clusters, the influence of water vapour and UV radiation on the size of aerosol particles.

Laboratory experiments performed with the mixture of NO_2, SO_2 and H_2O exposed to a radiation of 3000–4900 Å wave length showed that the rate of formation of individual seeds is directly proportional to the concentration of SO_2 (at concentrations lower than 1000 ppm) (Wood *et al.*, 1974).

When air at 50 % of relative humidity containing 0.65 ppm of SO_2 was exposed to a radiation of 3500 Å for 4 minutes the concentration of condensation nuclei was found to be 3.10^6 cm^{-3} (Quon *et al.*, 1970). Under atmospheric conditions these initial seedings may become the condensation centers and after growing they are bound to dissipate light and diminish the visibility.

The photochemical oxidation of SO_2 under normal daylight radiation is a slow process, especially when the concentration of sulphur dioxide is low. However, in the presence of NO_2 the reaction is much faster. Studies of the rate of oxidation of SO_2 by ozone, which is present usually at the ground level up to 0.05 ppm, showed very slow reaction but if hydrocarbons were present in the same mixture the reaction was greatly speeded up (Cox *et al.*, 1971).

Since ozone can be formed by the photolysis of nitrogen oxides in the presence of the hydrocarbons which are polluting the atmosphere in significant amounts (mainly exhaust gases of the internal combustion engines) the effect of the reaction between ozone and olefines may cause the increased amount of sulphur trioxide and the increased amount of aerosol. Aerosol formed by photochemical oxidation of sulphur dioxide always contains sulphuric acid.

The general kinetics of the mechanism of photochemical smog formation applicable to different mixtures polluting the air has been proposed by Hecht *et al.* (1974).

Emergency Gaseous Ammonia Method

Studies connected with removal of contaminating gases from the atmosphere and prevention of their emission into the atmosphere have a long history. There are many methods applied nowadays for these purposes. Roughly, they can be considered as being wet and dry methods, with a steadily increasing trend towards application of catalysts. Generally all methods are very costly, requiring additional constructions, equipment and space. None can be regarded as universal because all of them have several limitations. Nevertheless, they are being applied and thanks to continuous alterations and improvements they succeed in removing the majority of pollutants.

One of the problems connected with the prevention of sulphur dioxide entering the atmosphere is the fact that its emission is not constant and under certain conditions might suddenly become especially dangerous. It might happen, for example, when a particular delivery of coal or other fuel used in an electrical power plant is exceptionally contaminated with sulphur, or when the atmospheric conditions prevent the stack gases emerging from the chimneys to reach such heights that they can become more or less safely diluted.

These were the main reasons which called for development of an emergency (intervention) method which, normally at stand-by, could be ready for use at any time and could be put into action and stopped very quickly.

The method suggested by the Electric Power Research Centre in Poland was based on the idea of introducing in such critical moments gaseous ammonia into the stack gases in order to cause the precipitation of solid ammonium salts. This method was called an Emergency Gaseous Ammonia Method.

If this Ammonia Method was to be efficient and successful, the solid products formed should be relatively stable and should not undergo any fast sublimation process resulting in secondary contamination.

The research group of the Research Laboratories of Catalysis and Surface Chemistry of the Polish Academy of Sciences, headed by Prof. J. Haber, undertook the complex investigations of the influence of several factors on the kind and yield of substances being formed when ammonia was introduced into stack gases. The different components of the emitted flue gases, as well as their mutual ratios and the temperature of the reactions, were to be considered.

A special effort was directed towards establishing the conditions under which gaseous ammonia causes the formation of ammonium sulphate, which being a fairly stable compound is considered the least hazardous for the natural environment and is even recommended as a fertilizer for some kinds of soil.

Experimental

Figure 1 illustrates the special vacuum apparatus that was constructed for the studies of the kinetics and mechanism of the reactions between the main components of the stack gases and gaseous ammonia (Haber *et al.*, 1974). It consists of a reactor (R) immersed in a water bath (H) and equipped with a capillary tube (K) used for introduction of gases

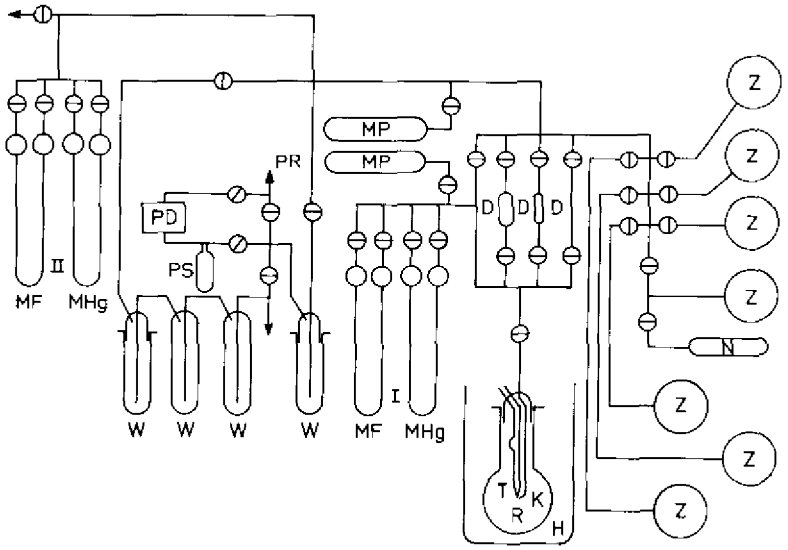

Figure 1. Schematic diagram of the vacuum apparatus: R – reactor, H – water bath, K – capillary tube, T – thermocouple, Z – storage containers, D – feeders, PD, PR, PS – pumps, W – cold traps, MF, MHg, MP – manometers, N – containers.

from storage containers (Z) through one of the calibrated feeders (D). At the outlet of the capillary tube a thermocouple (T) was placed for measuring the temperature changes occurring in the reactor. The set of pumps, rotary vacuum pump (PR), diffusion vacuum pump (PD) and sorption high-vacuum pump (PS) together with 4 cold traps (W) enabled high vacuums to be attained (0.01 Pa). Two sets of manometers, phtalan column (MF), mercury column (MHg) and vacuum pressure recorder (MP) were installed to measure separately the pressure in the reactor and in the high vacuum channel.

Introduction of each component into the reactor caused the pressure to rise sharply, depending on the amount of gas added. When no reaction occurred the increased pressure remained constant, whereas if the reaction caused the number of gaseous molecules to drop the pressure also dropped in time. The temperature effect of introducing a component was negligible for inert gases but noticeable when the reaction was observed.

Results and discussion

Experiments performed at different temperatures confirmed our theoretical calculations that for the average composition of flue gases (6 vol % of H_2O and 0.25 vol % of SO_2) – assuming a stoichiometric addition of ammonia – solid ammonium sulphite can be formed only below 80°C, i.e., after considerable cooling of the gases leaving the stack (Haber *et al.*, 1974; Czarnecki *et al.*, 1974).

Systematic experiments were performed at 25°C. It was found that, depending on the partial pressures of SO_2, H_2O and NH_3, different solid products and their mixtures were formed, i.e., sulphite, bisulphite, hydrated sulphite, pyrosulphite (Najbar *et al.*, 1972; Haber *et al.*, 1973). The calculations, supported by the experimental results, showed that the formation of the product containing the smallest amount of the substrate of the lowest partial pressure was favoured. This implies that the order of the addition of gases was a decisive factor since the last substrate introduced always initially had the lowest partial pressure. All these different products had one property in common, the whole sulphur had the oxidation number 4.

A similar situation occurred when gaseous oxygen was introduced into the reacting mixture. Under the experimental conditions, oxygen did not act as an oxidant but behaved like an inert gas similarly to nitrogen introduced in some comparative experiments.

During the search for an effective oxidant our attention was drawn towards nitrogen oxides[1] often present in the combustion gases. A series of four factorial experiments on two levels of one factor (H_2O), three levels of two factors (SO_2, NO_x) and 4 levels of one factor (NH_3) was performed. The stoichiometric ratios of SO_2 to NO_x were 1: 1, 1: 2 and 2: 1, while NH_3 was added: (a) in a deficient amount, (b) in an excess towards SO_2 only, (c) in an excess towards SO_2 and NO_x. One level of each factor was zero.

The mixture of dry SO_2 and NO_x behaves like an ideal gas. Introduction of NH_3 results in a rather slow reaction, being presumably an independent combination of the separate reactions observed when NH_3 was mixed with SO_2 only and when it was mixed with NO_x only.

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[1] It was assumed that nitrogen oxides received by thermal dissociation of $Pb(NO_3)$ (vessel N in Fig. 1) would at low pressures contain 80 vol % of NO_2 and 20 vol % of O_2.

Reactions proceeding in the presence of water vapour were completely different. Since the introduction of SO_2 into the reactor containing the water vapour caused a very small decrease of the pressure, whereas the introduction of NO_x caused quite a pronounced lowering of the pressure, further addition of the third component (either SO_2 into $H_2O + NO_x$, or NO_x into $H_2O + SO_2$) caused a persisting reduction of the total pressure. Introduction of ammonia into the 3-component mixture resulted in an immediate reaction accompanied by a sharp increase in temperature.

Typical experimental results are shown in Fig. 2. The pressure in the reactor (in hPa) *vs* time dependence is shown by the solid line, while the changes of temperature *vs* time by the dashed line. Moments of addition of each component are marked by arrows.

At the end of each experiment the pressure in the reactor was levelled up to the atmospheric one either by introducing air or nitrogen into the vacuum apparatus. The solid products of the reaction were then washed out with deoxidized water, to prevent any oxidation at this stage of the experiment, and analysed for the presence of SO_3^{2-}, SO_4^{2-}, NO_2^-, NO_3^-, NH_4^+ ions. As a rule 75 % of the sulphur introduced into the reactor as SO_2 was found in ionic form, while only 30 % of the nitrogen introduced as nitrogen oxides was detected in this form. The amount of NH_4^+ ions was generally balanced by the total amount of the anions specified above. Parallel experiments in a special set-up imitating the dynamic conditions in the plume of combustion gases showed that no traces of SO_2 were detectable after ammonia was introduced.

Since losses of some fine precipitate in a form of aerosol were inevitable in our vacuum apparatus, and since NO formed after reduction of NO_x does not react either with ammonia or with water under the experimental conditions, we were satisfied with the amounts recovered, and had reasons to assume that the analysis was reliable.

It was found that in the presence of NO_x the total amount of sulphur was detected as sulphate anion, which meant that the oxidation of SO_2 was complete.

Since the majority of nitrogen oxides in stack gases are present as NO, a separate series of experiments was performed using this component as a possible oxidant of sulphur

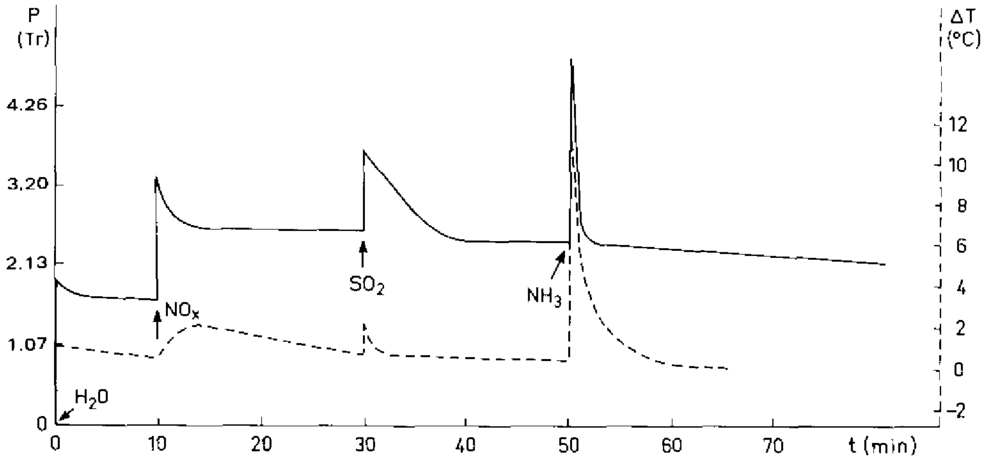

Figure 2. Typical experimental curves. Solid line – pressure *vs* time, dashed line – temperature *vs* time.

dioxide. As expected, NO alone cannot cause the oxidation of SO_2 and the final products were ammonium sulphites. However, introduction into the reactor of stoichiometric amounts of oxygen caused even traces of NO to be enough for complete oxidation of SO_2. NO undergoing oxidation in the presence of oxygen acted efficiently as an oxygen carrier. Since a large amount of air is always present in the flue gases, there is no danger that easily sublimating ammonium sulphite would be formed in the presence of nitrogen mono-oxide.

The experimental results supported by thermodynamic calculations (Czarnecki *et al.*, 1974) together with the reference data (Durrant & Durrant, 1965) enabled us to assume the possibility of the following summarized reactions occurring in the reactor during the different stages of the experiment:

A. Before the introduction of ammonia:

$$H_2O + SO_2 + NO_2 = H_2SO_4 + NO \quad (1)$$

$$NO + \frac{1}{2}O_2 = NO_2 \quad (2)$$

$$2NO_2 + H_2O = HNO_3 + HNO_2 \quad (3)$$

B. After the introduction of ammonia:

$$H_2SO_4 + 2NH_3 = (NH_4)_2 SO_4 \quad (4)$$

$$HNO_3 + NH_3 = NH_4 NO_3 \quad (5)$$

$$HNO_2 + NH_3 = NH_4 NO_2 \quad (6)$$

$$H_2O + NH_3 = NH_4OH \quad (7)$$

The first two reactions, occurring before the introduction of ammonia, have very high equilibrium constants at 25°C, 10^{54} and 10^9 respectively, while the third one is rather low: 0.8. Therefore, for the calculation it was assumed that only reactions 1 and 2 proceeded to the complete exhaustion of one component.

Added ammonia neutralizes acids formed earlier and its excess can be absorbed by water up to 10 % solution (this observation came from separate experiments performed with NH_3 and H_2O only). Since on the basis of separate experiments it was found that the reaction between NH_3 and SO_2 with H_2O is several times faster than the reaction between NH_3 and NO_X with H_2O, it was assumed that reactions (5), (6) and (7) are possible after reaction (4) is completed.

The good agreement between the calculated values of pressure and the measured ones shows that our assumptions were justified.

Concluding remarks

According to our results the introduction of gaseous ammonia into combustion gases could be expected to cause the precipitation of ammonia sulphate and not sulphite. In stack gases there are always large amounts of water vapour present which speed up the reaction, some percentage of nitrogen oxides (either NO_X or NO), and always enough oxygen to enable even NO to act as an effective oxygen carrier.

The Emergency Gaseous Ammonia Method will also cause a removal of a certain percentage of nitrogen oxides, which are turned into ammonium nitrates or nitrites. This may be regarded as an additional advantage of the method since it will increase the nitrogen content in the soil.

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A RE-EVALUATION OF PRESENT CONCEPTS RELATING TO NITRIFIER GROWTH AND PRODUCTION OF NITRATE IN SOIL

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Abstract

The nitrifiers are microorganisms capable of utilizing the energy of the oxidation of ammonium-nitrogen into nitrate-nitrogen in the soil without an organic substrate. Previous well-known studies by Lees & Quastel (1946) established the feasibility of examining the metabolic activity of these bacteria by means of a simple inexpensive re-perfusion technique.

As a result of their investigations, Lees & Quastel (1946) concluded that the nitrifiers oxidized ammonium ions absorbed as part of the soil cation exchange complex. However, a number of objections have recently been raised in the literature refuting this hypothesis.

A series of experiments will be described which will attempt to provide an alternative explanation to replace the questionable credibility of the conclusion of Lees & Quastel (1946) and an evaluation of this work in terms of its possible impact on future studies in biological ammonium oxidation will be undertaken.

Introduction

Nitrogen transformations in the soil are primarily carried out by microorganisms. One of the most important processes involving nitrogen in the soil is nitrification. More precisely, it is a biological oxidation of ammonia-nitrogen into nitrate-nitrogen.

This process owes its importance to the fact that it accounts for all soil nitrogen losses in the form of water-soluble nitrate-nitrogen. A variety of soil organisms are capable of mediating this process (Schmidt, 1954; Doxtader & Alexander, 1966). However, Shattuck & Alexander (1963) demonstrated, through the use of N-Serve, that soil nitrification is basically carried out by the autotrophic microorganisms, *Nitrosomonas* and *Nitrobacter*.

Metabolic studies of nitrification by use of the technique of soil re-perfusion were initially conducted by Lees & Quastel (1946). They concluded from their results that the process was carried out predominantly on the soil exchange complex with the absorbed exchangeable ammonium-ion being preferentially oxidized by the autotrophs rather than solution phase NH_4^+. This theory has been challenged several times (Goldberg & Gainey, 1955; Ishizawa & Matsuguchi, 1963; Doner & McLaren, 1975). However, no experimental scheme has been attempted that might effectively counter the Lees-Quastel argument.

The primary aim of the work reported here was to develop such an argument and to provide a more logical alternative to that advocated by Lees & Quastel (1946). A basic pre-requisite to effectively rebutt any scientific argument is to first attempt to reproduce the conclusion of the original investigation, subject the results of that investigation to reinterpretation in the light of modern concepts, note any discrepancies, and finally attempt to explain these discrepancies by re-examining and modifying the original conclusions to provide a more logical answer. Hopefully, the above requirements were satisfied in the work to be described.

Methods and materials

Figure 1 is an illustration of the basic experimental technique employed. In all essential aspects, it is similar to the technique employed by Lees & Quastel (1946) in their original study. A solution of ammonium sulfate is continuously recycled over a column of soil crumbs. The apparatus, capable of being sterilized as an entire unit, is all glass, connected by autoclavable Tygon tubing. The soil crumbs are held in place in the neck of the flask by glass wool. Air was provided, under positive pressure, through a sterile tube plugged with cotton. It was also freed of traces of ammonia by being subsequently passed through a trap containing 0.05 N H_2SO_4. Periodic sampling of the recycling solution ($(NH_4)_2SO_4$ with added trace elements) was carried out by inserting a 0.5 mm diameter polyethylene tube through the exhaust opening in the flask and into the solution. Samples were withdrawn by means of a graduated 10 ml sterile syringe.

Control of the rate of recycling of the perfusate over the soil was maintained with the use of screw clamps. By this means a fairly constant rate of one drop of perfusate per 1.2 seconds was maintained for each unit set up. This ratio was utilized in all experiments.

Chemical analysis was conducted on the perfusing solution mainly to determine NO_3^-, NO_2^-, NH_4^+ concentration changes as a function of time. Microbial numbers of *Nitrosomonas* and *Nicrobacter* were determined by the most-probable-number technique. The soil used in this study was a Non-calcic Brown soil possessing a pH of 7.3, organic matter content of 0.33 % and C.E.C. of 10 meq per 100 grams, and designated as Hanford Sandy Loam.

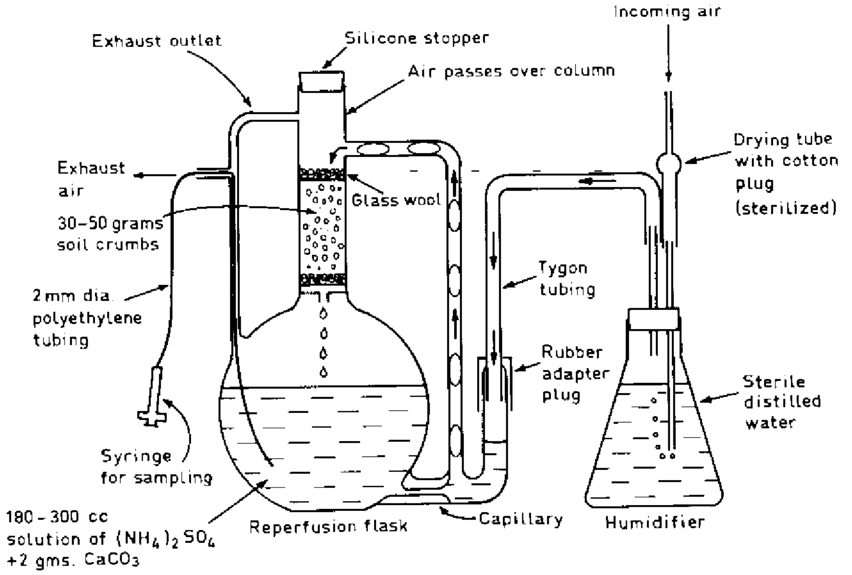

Figure 1. Percolation apparatus used in the experiments.

Results and discussion

Initial results obtained with the above apparatus confirmed basic theoretical similarities with the original work of Lees & Quastel (1946). A sigmoid curve of nitrate production was obtained as well as a significant decrease in pH in the perfusate. Upon repeating the oxidation of ammonia by replenishing the perfusate without disturbing the soil column, a linear curve denoting production of nitrate as a function of time was produced.

However, an experiment is reported in this work that represents a significant departure from the previous study. According to the theory advocated by Lees & Quastel (1946), the rate of oxidation of the ammonium ion is directly related to the cation exchange capacity of the soil in question. No mention is made of the growth of the nitrifiers. If this is true, then by simply amending the soil with acid-washed, sterilized sand (possessing no cation exchange) should decrease the capacity of that soil to oxidize ammonia in simple proportion to the amount of sand added.

An experimentof this nature was conducted by preparing a soil-sand mixture in a ratio of 1:9 (w/w), setting up a re-perfusion unit as described, and monitoring the oxidation of ammonia and the growth of *Nitrosomonas* and *Nitrobacter* organisms during an initial re-perfusion sequence. Table 1 and Fig. 2 indicate the results of this experimental approach. Note especially in Table 1, that the proportional increase in NO_2-nitrogen produced in the soil column compared to that in the soil-sand column is similar

Table 1. Initial growth of *Nitrosomonas* and *Nitrobacter* organisms and production of inorganic nitrogen species as a function of exchange capacity1) of Hanford soil

Perfusion flask No.	Duration of perfusion (days)	NH_4-nitrogen	NO_2-nitrogen	NO_3-nitrogen	*Nitrosomonas*	*Nitrobacter*
		ppm-perfusate			cell counts2)	
Unmixed Hanford Soil (Replicate flasks)						
A	8	90	36	7	1.81×10^5	1.90×10^3
	13	0	45	21	1.80×10^6	5.00×10^3
B	8	75	32	4	7.30×10^4	3.58×10^3
	13	0	50	23	5.10×10^5	6.96×10^4
C	8	80	40	5	1.16×10^5	6.03×10^3
	13	0	45	17	2.50×10^5	3.68×10^4
Hanford soil mixture (10 % soil) (Replicate flasks)						
D	8	90	10	4	3.48×10^4	188
	13	0	35	14	3.10×10^5	5.15×10^3
E	8	95	12	4	1.90×10^4	551
	13	0	28	12	1.20×10^5	3.09×10^4
F	8	80	9	5	4.50×10^4	180
	13	0	38	14	2.60×10^5	9.40×10^3

1) Exchange capacity decreased by adding sand.
2) Cell count determined on basis of cells per gram oven-dry soil.

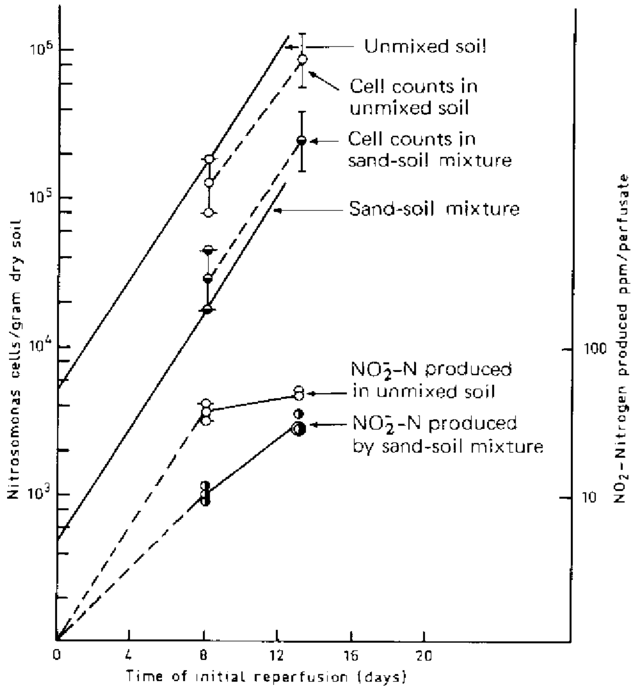

Figure 2. Cell counts and produced nitrite during 12 days of perfusion. Solid lines indicate ideal log growth of cells.

to the proportional increase in *Nitrosomonas* organisms in the soil column as compared to the organisms in the soil-sand column. The ratio between the respective increases in the two sets of experiments (soil versus soil-sand) is 1:4 when the data is taken on the 8th day of the re-perfusion. Collecting data on that particular day was important for two obvious reasons; 1) the growth of *Nitrosomonas* bacteria in the two different sets of experiments was sufficiently advanced at that time to demonstrate distinct differences in population numbers between the experiments in order to make a clear comparison; 2) the growth of *Nitrobacter* appeared not to significantly effect the oxidation of NO_2-ion within that time limit.

Moreover, it is important to note (Table 1) that upon the 13th day of re-perfusion, all traces of NH_4^+-ion had disappeared from the perfusion liquid and that data on the sum totals of (NO_2^- + NO_3^-) solution nitrogen compiled in each replicate flask in both sets of experiments described above do not vary significantly, regardless of whether the replicate flasks are within the same experimental treatment or not. Thus, it can be concluded that as the 13th day of re-perfusion is reached, populations of *Nitrosomonas* are similar in all flasks. (This is indeed the case, as compiled in Table 1.)

However, the uncertainty of the most-probable-number of microbial biomass is quite significant (Cochran, 1950). Thus, if cell counts are determined by this procedure and cited as evidence of proportionate growth directly affecting proportionate rates of nitrification, it cannot be stated with a high degree of assurance that the dilemma between the importance of oxidation of adsorbed ammonium ion versus the importance of cell counts has been settled. More definitive experiments to decisively conclude this argument must await the eventual development of more precise microbial counting using such methods as immunofluorescence microscopy described by Schmidt (1974).

Precision demands increased sophistication and vastly increased costs for much of the newly developed instrumentation needed. Perhaps a more realistic alternative, especially for research workers in developing countries, relative to this particular presentation, would be to alter the conditions of the experiments. Alexander (1965) noted that most-probable-number counts became greatly significant if differences between sets of experiments approach a factor of 10 or more. Therefore, in theory, if the same soil is used, these experiments could be set up to moniter the growth between nitrifiers as related to the oxidations of ammonium in the original soil and the same soil diluted in a 20–30:1 ratio (w/w) with sterile sand. An experiment of this nature is underway in our laboratory.

Conclusion and case for re-evaluation

There are a number of important implications that have been brought forward as a result of this study. Firstly, it can be concluded from the research presented that ammonium

Table 2. Nitrate production and growth of nitrifying bacteria with repeated re-perfusion of ammonium-nitrogen over soil

Duration of repeated re-perfusion (days)	Initial ammonium-nitrogen re-supplied (ppm - perfusate)	Rate of nitrate-nitrogen produced (ppm - perfusate per day)		*Nitrobacter* counts log MPN per gram soil
1st	28	5		5.7
(3 days)	56	15		5.8
pH drop: 8.1–6.0	112	17		7.1
2nd	28	6		6.8
(3 days)	56	8		7.0
pH drop: 8.1–6.0	112	19		7.5
3rd	28	8		6.8
(3 days)	56	9		7.0
pH drop: 8.1–6.0	112	22		7.5
4th	28	10		6.8
(3 days)	56	15		7.1
pH drop: 8.1–6.0	112	33		7.5
			(*Nitrosomonas*)	
20th1)	28	3.2 ppm hr^{-1}	(6.2)	7.0
(24 hours)	56	4.0 ppm hr^{-1}	(6.2)	7.2
pH drop: 8.1–6.8	112	3.7 ppm hr^{-1}	(6.3)	7.1
30th1)	28	5.1 ppm hr^{-1}	(6.2)	7.6
(20 hours)	56	5.0 ppm hr^{-1}	(6.2)	7.5
pH drop: 8.1–6.8	112	4.9 ppm hr^{-1}	(6.4)	7.6

1) Addition of $CaCO_3$-$MgCO_3$ mixture to improve buffering of perfusate.

oxidation in soil is directly a function of the initial numbers of nitrifying bacteria and their rate of growth, in terms of cell increase, and not, as Lees & Quastel (1946) have concluded, a function of the cation exchange capacity of soil. The work of Faurie (1972) and Faurie *et al.* (1975) supports this reasoning.

Secondly, the nitrifying bacteria appear to carry out their activity almost exclusively while being attached to a soil particle surface. This became obvious, when upon repeated replenishing of the flasks with fresh, sterile solutions of ammonium sulfate, the rate of ammonium oxidation of the so-called "enriched" re-perfusion system remained steady (Table 2). If the nitrifiers remained principally in solution, the rate of ammonium oxidation would have greatly fluctuated.

Thirdly, during the course of repeated re-perfusion, the pH of the perfusion appeared to be the single most important factor influencing the rate of nitrate ion production. However, it still has not been demonstrated conclusively whether or not the pH of the medium directly affects the growth of the nitrifying bacteria or the rate of oxidation of ammonia into nitrite and nitrate on a per-cell basis. Further work needs to be done in this area.

It is particularly important to understand precisely how nitrifying bacteria respond to changes in their environmental setting, since any increased input of nitrogen in the form of ammonia will obviously affect the production, and probable loss, of nitrate. It is somewhat surprising that many studies are still being reported that consider population numbers of nitrifying bacteria unimportant (see Sandanam *et al.*, 1978), while attempting to suggest that nitrification rates be utilized as indexes of soil fertility. The use of the process of nitrification either as an index of nitrogen fluxes or soil fertility is questionable unless a thorough examination of the population of nitrifiers in the soil is undertaken.

Acknowledgement

I am greatly indebted to the late Professor A.D. McLaren, upon whose advice and inspiration I began and successfully concluded a somewhat difficult experimental argument.

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Nitrogen Cycling in West African Ecosystems

DENITRIFICATION IN A TOPOSEQUENCE

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Abstract

Microbial production of dinitrogen and nitrous oxide from soil were studied in laboratory media amended with glucose, nitrate and $Na_2S_2O_7$ and incubated at 30°C as well as in the field using diffusion-equilibrium reservoirs placed along a toposequence. Numbers of denitrifiers along the toposequence were also determined. Dinitrogen and nitrous oxide were barely detected in the field, yet both gases were produced in large quantities within 48 hours in the laboratory. Denitrifiers were most numerous in the middle of the toposequence, whereas the gases were produced from soil from the middle through the bottom of the toposequence.

Introduction

Much effort has of late been devoted to studies on biological nitrogen fixation. It has become apparent that it is equally important to find ways to minimize losses of fertilizer nitrogen through denitrification. Clearly, the loss of 91×10^{12} g N per year through denitrification is significant when compared with the gain through fixation of 139×10^{12} g N per year (Söderlund & Svensson, 1976).

The few studies conducted on denitrification in West Africa have usually been laboratory studies, which determine only the potential. Greenland (1962) showed that nitrification and denitrification could occur in aerated tropical soils. Work on the rice soils of Senegal has been published by Garcia and his colleagues (Baldensperger & Garcia, 1975; Garcia, 1973, 1975). Recently, Moormann *et al.* (1977) observed severe nitrogen deficiency in rice in the mid-slope position in a toposequence; they attributed the deficiency to nitrogen lost through denitrification.

Because the soil pH, organic carbon content and temperature of a toposequence were considered adequate to support denitrification (Delwiche & Bryan, 1976), we initiated some field and laboratory studies to assess the extent of denitrification in the toposequence.

Materials and methods

The location

The toposequence used in this study has been described by Moormann *et al.* (1977) and represents a continuum of edaphic and hydrologic conditions from dry land to hydromorphic bottom land. Plots measuring 5×18 m were numbered 1 to 12 from the top to the bottom of the toposequence. During much of the rainy season reduced iron exudes from plots 7–12.

Laboratory studies.

Six soil cores were taken to 15 cm from plots 3, 4, 5, 6, 7, 8, 9, 10 and 11. Soil was sieved through an 8 mm screen. Duplicate 10 g sub-samples of soil from plots 5, 6, 7, 8 and 11 were used to prepare 10-fold dilutions to determine the numbers of denitrifiers by the most-probable number method. NH_4^+–N and NO_3^-–N were determined colorimetrically. Sub-samples of soil were oven-dried (105°C, 24 h).

To study the denitrification potential, 5 g of soil from plots 3–11 was placed in each of twelve 16 ml McCartney vials. Triplicate vials received the following amendments:

Solution A – 10 ml of a 0.2 % KNO_3 solution, pH 7.0.

Solution B – 10 ml of the heterotrophic denitrifiers medium of Parkinson *et al.* (1971) containing 1 % glucose, 0.2 % KNO_3 and mineral salts, pH 7.0.

Solution C – 10 ml of *Thiobacillus denitrificans* medium (Parkinson *et al.*, 1971) containing 0.2 % $Na_2S_2O_7$, 0.2 % KNO_3 and mineral salts, pH 7.0.

Solution D – 10 ml of water.

Vials were tightly closed with Suba-Seal Vaccine Closure No. 25 (Suba-Seal Works, Barnesley, U.K.), flushed several times with helium, and incubated at 30°C under helium atmosphere. One ml of the gas phase of each vial was removed after 48 h with a syringe and analyzed for CO_2, N_2O and N_2 by thermal conductivity gas chromatography (Burford, 1976).

Field study

To assess denitrification in the field, triplicate diffusion-equilibrium reservoirs (Burford, 1976) were buried to a depth of 15 cm in plots 3, 7 and 10. Periodically, 1 ml of gas was withdrawn, the syringe was stabbed onto a rubber bung, and the gas analyzed later for N_2O as before.

Results and discussion

Plots in which much NH_4^+ was found contained little NO_3^- and plots with high numbers of denitrifiers also had the least amount of NO_3^- (Table 1). Denitrifiers abound in this and similar soils (see review by Ayanaba, 1977) and should not limit denitrification. The alternating wet and dry cycles in the mid-slope (Moormann *et al.*, 1977) provide optimal conditions for oxidation of ammonium and dissimilatory reduction of the formed nitrate during wet periods.

When soils were inoculated into three of the solutions, CO_2 (Table 2) and N_2O and N_2 (Figs. 1 and 2) were readily detected. The production of CO_2, albeit in small quantities, by soils incubated with solutions A, C and D, indicates the presence of readily metabolizable carbon compounds. Plots in the downslope position in the toposequence (plots 7–9) apparently contained more carbon as reflected in the higher values of CO_2.

Table 1. Changes in numbers of denitrifiers and concentrations of ammonium and nitrate ions in a soil catena under rice

Plot	Denitrifiers (nos./g O.D. soil)	NH_4^+-N (μg/g)	NO_3^--N (μg/g)
5	5.49×10^3	4.4	11.0
6	3.82×10^4	3.2	2.6
7	5.45×10^5	3.2	1.3
8	2.06×10^5	1.9	2.0
9	N.D.[1]	4.9	1.5
10	2.69×10^4	7.8	0.0

[1] not determined.

Table 2. Production of carbon dioxide after 48 h in three media inoculated with soil and incubated at 30°C. Each value is a mean of three replicate values ± S.D.

Plot	μg CO_2 produced g^{-1} O.D. soil in solution [1]			
	A	B	C	D
3	24.81 ±0.47	1058 ±56	44.57 ±1.02	24.92 ±0.53
4	27.83 ±5.21	1187 ±77	44.52 ±0.46	ND[2]
5	27.27 ±2.58	1428 ±74	47.52 ±2.70	18.39 ±3.83
6	26.21 ±1.68	1374 ±43	42.36 ±1.29	–
7	44.13 ±2.82	1251 ±116	64.28 ±5.48	99.32 ±20.14
8	53.42 ±8.34	1354 ±23	42.14 ±3.35	51.11 ±7.55
9	53.24 ±7.81	1394 ±165	59.05 ±1.53	64.02 ±8.21

[1] Solution A contained KNO_3 and water, Solution B contained KNO_3, glucose and mineral salts, Solution C contained KNO_3, $Na_2 S_2 O_7$ and mineral salts, and Solution D was distilled water. All pH values were adjusted to 7.0.

[2] Soil from this plot was not included in this test.

Denitrification occurred in all soils in three of the solutions (Figs. 1 and 2). No N_2O was detected in solution D. Soils showing the most extensive denitrification (plots 7–9) also exuded iron sulfides in the field. Insufficient observations were made to permit any evaluation of the role of iron in the chemical reduction of nitrate.

Autotrophic denitrification does not appear to be significant except in plots 9 and 11 where more products appeared in the *T. denitrificans* medium than in solution A. Baldensperger & Garcia (1975) found *T. denitrificans* in Senegalese rice soils; its significance *in vivo* was not discussed, however.

In the present work we found that denitrification proceeds when nitrate alone is added to soil. Greenland (1962) found Ghanaian forest and grassland soils to denitrify under laboratory conditions. In cultivated soils he found that carbon, not nitrate, limited denitrification although the amounts required to promote denitrification were less than those required in temperate soils. Debey & Fox (1974) did not consider denitrification

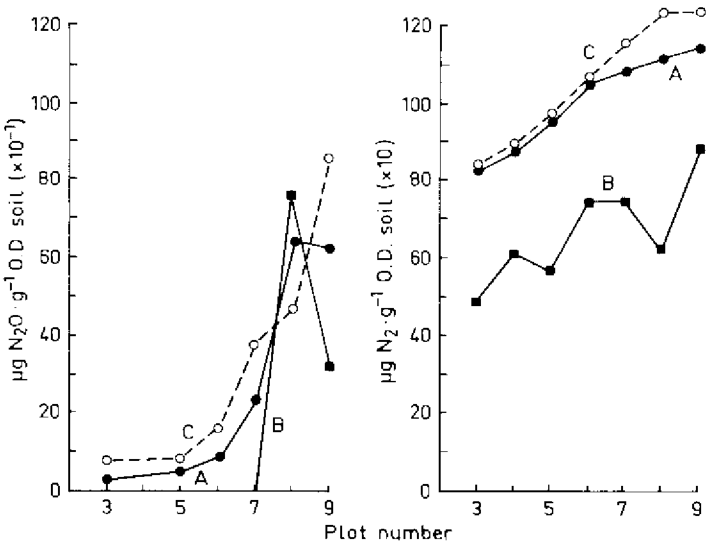

Figure 1. Formation of N_2O and N_2 *in vitro* in three media (see legend to Table 2) during 48 h.

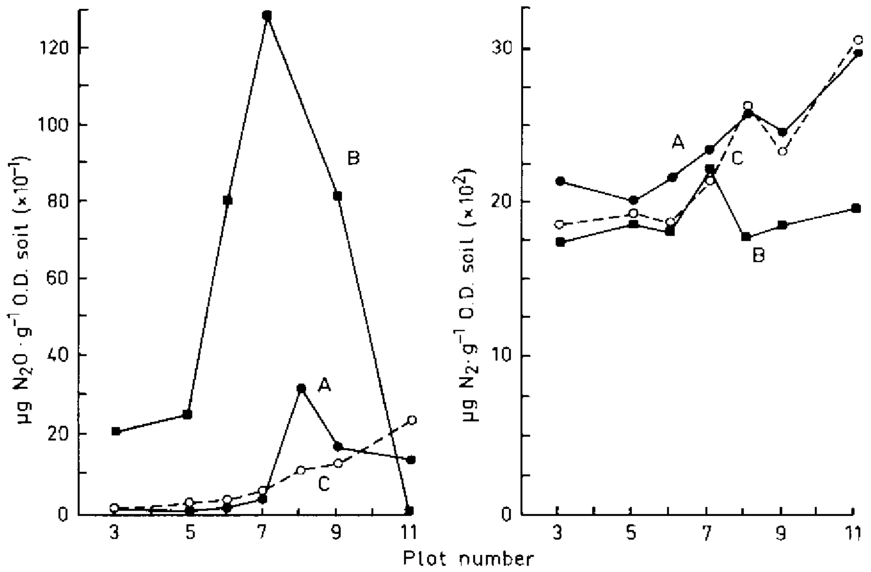

Figure 2. Formation of N_2O and N_2 *in vitro* in three media (see legend in Table 2) during 48 h.

to be significant in three Puerto Rican soils even though denitrification occurred in soils incubated in the laboratory.

No N_2O was detected in the field. Burford (unpublished) detected N_2O in plot 7. The absence of N_2O in solution D inoculated with soil, in addition to low nitrate, suggested there would be no denitrification. It has been reported from Senegal that the rice rhizosphere enhances denitrification, especially in soils low in carbon (Garcia, 1973, 1975). Because organic carbon content is highly correlated with denitrification (Burford & Bremner, 1975; Garcia, 1973) and because organic carbon (range of 0.73–0.96 reported by Moormann *et al.*, 1977) and nitrate (Table 1) are low in the toposequence soils it is not surprising that N_2O was not detected in the field even in the submerged plots. (No attempt was made to detect NO.) Nitrate appears to be more limiting than carbon because when nitrate was added to similar soils and irrigated, N_2O was detected (Burford, unpublished). The production of N_2O and N_2 in solution A substantiates this view. Except in one instance (plot 7, Fig. 2), N_2O was not appreciably increased by the addition of glucose. Denitrifiers can also utilize methane (which was detected in plot 7 by Burford) and hydrogen in nitrate respiration (see review by Delwiche & Bryan, 1976).

Although we could not detect N_2O in the field to corroborate the observed severe nitrogen deficiency in rice grown at mid-slope, the laboratory studies clearly showed that a potential for denitrification exists. Before concluding that denitrification is insignificant under field conditions, one would have to repeat the experiment under altered conditions. For example, early in the rainy season of each year, it is likely that the nitrate content would be adequate for momentary flushes of denitrification since these are times when temporary flooding is likely to occur.

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THE EFFECTS OF FIRE ON ASPECTS OF NITROGEN CYCLING IN OLOKEMEJI FOREST RESERVE, NIGERIA

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Abstract

The soils and plant parts from a fire experimental site at Olokemeji Forest Reserve, Nigeria were analyzed chemically. The whole site was burnt and cleared in 1929, thereafter divided into three plots with the following treatments, respectively: (i) annual late burning (ii) annual early burning and (iii) no burning (protected).

Soil percentage nitrogen in the soil depth 0–10 cm were generally higher in the 'no burning' plot, the lowest values were in the 'annual late burning' plot. Soil depth 10–20 cm showed less variation in nitrogen contents. Nitrogen contents in the litter and ground flora of the 'late burnt' plot were the least.

Soil organic matter increased in the 'annual burning' plots and decreased in the 'no burning' plot with the advance of the growing season, although the highest values were in the 'early burning' plot, during the study period. Soil cation exchange capacity, potassium and available phosphorus values were, however, higher in the 'annual burning' plots.

Higher litter production was observed in the 'no burning' plot, while ground flora biomass was higher in the 'annual burning' plots. Burning, especially 'annual late burning', on the whole retarded tree regeneration, while it encouraged the growth and development of perennial and annual grasses.

Introduction

There has been an increasing awareness of a need for more efficient use of nitrogen and other elements in the management of savanna land. Many systems of agriculture rely heavily on reserves of soil nitrogen to meet nitrogen requirements of plants (Osborne, 1977). Burning is usually the chief means of managing pasturelands and wildlife habitats in various savanna regions around the world (West, 1965; Afolayan & Ajayi, 1976). The use of fire in tropical Africa is to remove the dead litter of previous growth and to enable new herbage develop unhindered (Egunjobi, 1974). However, while numerous studies have been carried out in Nigeria in an effort to characterize soil nitrogen and organic matter in relation to cattle rearing and wild-life management, little work has been carried out on forest/fire and nitrogen relationships.

This present paper deals with some aspects of nitrogen cycling in early burnt, late burnt and fire protected plots in a derived savanna zone of South-West Nigeria, about 50 years after the experiment started.

Experimental site

The experiment was laid down in the Olokemeji Forest Reserve (Lat. 70° 25'N, Long. 3° 32'E). The site lies approximately 32 km West of Ibadan and 35 km Northeast of Abeokuta.

Vegetation and climate

Olokemeji lies in the margin of the lowland rain forest and derived savanna zones (Keay, 1959). The derived savanna is characterized by species like *Daniellia oliveri*, *Butyrospermum parkii*, *Lophira lanceolata* and *Pterocarpus erinaceus*.

The mean monthly minimum temperature is 21.5°C. There is a well marked seasonal change rising from a wet season minimum of under 29°C in July/August to a dry season maximum of over 35°C in February/March. The mean annual rainfall is 1232 ± 61 mm (29 years), the mean annual number of rain days is 106.6 ± 4.7 days (29 years). The rainfall is distinctly of the double maximum type with the two peaks in late June and mid-September (Hopkins, 1965).

The fire experiment

The whole site was burnt on 24 January 1929 and coppiced two days later. The site was then cleared of felled trees, and divided into three plots each of 0.17 ha separated by 3.3 m wide fire tracks. Thereafter the plots received the following treatments:

(i) Plot A – Annual burning, late in the dry season (mid-March)
(ii) Plot B – Annual burning early in the dry season (December)
(iii) Plot C – No treatment. Protected from fire.

The treatments were referred to as 'fierce burning' Plot A and 'light burning' Plot B (Charter & Keay, 1960). The difference is indeed marked, since the grasses are very much drier and more inflammable in February/March. When the fire sweeps through plot A, it produces fierce heat completely burning off the grasses at ground level and scorching all but the highest foliage. In plot B, the burning is incomplete, and patches here and there remain untouched.

Methods

Soil and plant sample collection

For the estimation of the herb vegetation, all aerial portions of plant samples (mainly grasses) were removed from five 1 m^2 quadrats taken at random from each plot at an interval of one month. Care was taken to sample a quadrat only once. The samples were washed and oven-dried at 105°C for 24 hours. Soil samples from depths 0–10 cm and 10–20 cm and litter accumulation were removed from each quadrat in each plot and analysed. Some samples were lost in the laboratory hence the incomplete data.

Soil and plant analysis

Chemical analyses were carried out on air-dried samples passed through a 2–1 mm sieve. Organic carbon was determined by a modification of the Walkley & Black (1934) method. Particle size analysis was done by the pipette method using 2N NaOH as dispersing agent. Exchangeable hydrogen and total exchangeable bases were determined according to the method of Brown (1943). Exchangeable calcium and magnesium were determined by the ammonium acetate extraction method followed by versenate titration. 'Extractable' phosphorus was determined by the Truog (1930) method. Soil nitrogen was determined by the modified Jackson (1958) semi-micro Kjeldahl method.

Plant and litter nitrogen samples were analysed by the semi-micro Kjeldahl method (Metson, 1956).

Results

The effects of burning on the soil and plant matter are presented in Table 1. The protected and the early burnt plots had generally higher soil nitrogen values (except in April) than the late burnt plot. The 0–10 cm top soil in all treatments had higher nitrogen concentrations than the 10–20 cm layer. Values for the other plots were fairly similar. Nitrogen values of the ground flora in the protected plot were slightly higher than in the burnt plots, while the litter nitrogen values in the annual burnt plot were the lowest.

The effects of burning on various aspects of soil characteristics are presented in Table 2. Increased burning caused reduction in the silt percentage content of the soil in the 0 10 cm soil zone. Other aspects of the physical soil (sand and clay) showed less variations.

Soil pH values were highest in the early burnt plot (7.1) and lowest in the protected plot (6.9), the whole site having a basic soil type. Cation exchange capacity values were highest in the late burnt, 14.74 meq./100 g soil. Soil 'available' phosphorus was also much higher in the late burnt plot, while other elements (except magnesium) were less consistent, magnesium and soil organic matter values being lowest in the late burnt plot. The soil sodium content showed the least variation of all elements analysed.

Figure 1 presents the effects of burning on the ground flora (leaves and stems of grasses) and litter biomass during the experiment. Ground flora growth was extremely

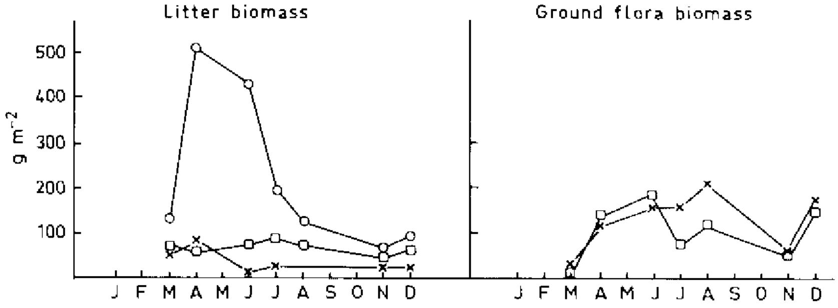

Figure 1. Fluctuations in litter and ground flora biomass in burnt and unburnt plots in Olokemeji forest reserve (x——x late annual burning, □- - -□ early annual burning, o——o no burning). Ground-flora (grasses) were not assessed in the no burning plot.

Table 1. Soil/plant nitrogen and organic matter content plots of burnt and unburnt vegetation in Olokemeji Forest Reserve. (Figures in parenthesis represent standard error values of four replicates)

Month	Soil depth (cm)	Treatment		
		Late burn	Early burn	No burn
	Soil, percentage nitrogen			
April	0–10	0.048 (±0.007)	0.075 (±0.009)	0.059 (±0.009)
	10–20	0.033 (±0.002	0.058 (±0.008)	0.039 (±0.004)
June	0–10	0.051 (±0.016)	0.069 (±0.016)	0.062 (±0.009)
	10–20	0.029 (±0.002)	0.040 (±0.006)	0.031 (±0.009)
July	0–10	0.029 (±0.002)	0.040 (±0.010)	0.031 (±0.002)
	10–20	0.030 (±0.004)	0.026 (±0.006)	0.030 (±0.001)
	Ground flora, percentage nitrogen (excluding roots)			
April		0.70 (±0.05)	0.75 (±0.13)	0.98 (±0.13)
	Litter, percentage nitrogen			
April	Leaves	0.67 (±0.18)	0.88 (±0.13)	0.86 (±0.03)
	Branches etc.	0.25 (±0.02)	0.47 (±0.04)	0.51 (±0.03)
	Organic matter (percentage)			
April	0–10	2.38 (±0.16)	2.99 (±0.36)	2.87 (±0.33)
	10–20	2.16 (±0.29)	2.15 (±0.47)	2.19 (±0.38)
June	0–10	2.32 (±0.13)	2.20 (±0.67)	2.31 (±0.36)
	10–20	1.92 (±0.11)	2.49 (±0.67)	2.15 (±0.32)
July	0–10	2.56 (±0.16)	3.02 (±0.24)	2.30 (±0.16)
	10–20	2.13 (±0.21)	2.20 (±0.25)	1.64 (±0.17)

Table 2. The effects of burning on soil characteristics in three vegetation types in Olokemeji Forest Reserve, April 1976

Soil characteristic	Soil depth (cm)	Treatment		
		Late burn	Early burn	No burn
Sand (%)	0–10	72.2	67.6	72.0
	10–20	79.0	75.1	78.8
Silt (%)	0–10	16.8	21.4	18.3
	10–20	9.3	11.9	9.8
Clay (%)	0–10	11.0	11.1	9.8
	10–20	11.8	13.0	11.5
Organic matter (%)	0–10	2.38	2.99	2.87
	10–20	2.16	2.15	2.19
pH (in water)	0–10	7.1	7.1	6.9
	10–20	6.9	7.2	7.2
Cation exchange capacity	0–10	14.74	13.60	13.61
	10–20	11.61	10.60	8.62
Calcium (meq./100 g)	0–10	5.10	6.72	5.77
	10–20	3.58	4.53	3.25
Magnesium (meq./100 g)	0–10	2.68	2.82	3.00
	10–20	1.57	2.06	1.77
Ca/Mg ratio	0–10	1.89	2.39	3.11
	10–20	2.25	2.14	1.83
Sodium (meq./100 g)	0–10	0.06	0.06	0.05
	10–20	0.04	0.04	0.04
Available phosphorus (ppm)	0–10	6.5	3.6	4.2
	10–20	6.5	3.8	2.6
Nitrogen (%)	0–10	0.038	0.075	0.059
	10–20	0.033	0.040	0.039
Potassium (meq./100 g)	0–10	0.34	0.40	0.26
	10–20	0.09	0.10	0.13

low in the protected plot, an attempt to quantify this was later abandoned, in order not to destroy the young seedlings on the protected plot.

Figure 1 indicates that maximum ground flora production was in June–August and in December, making available over 150 g m^{-2} dry matter for burning in the burnt plots during December and March when the early and late burning exercises were carried out.

Litter production was obviously greater in the protected plot, due mainly to the relatively higher tree density there. Peak litter production was in April, while rapid litter disappearance occurred between June and August at the peak of the rainy season. Litter accumulation showed the least variation in the early burnt plot, but the least litter biomass was recorded in the late burnt plot.

Discussion

This study revealed that the burning phenomenon could be detrimental to the ecosystem, leading to considerable loss of nitrogen in the upper layer of soils without any dependable source of replacement. That the protected plot had the highest nitrogen values supports the view of other workers like Egunjobi (1971), Jones & Wild (1975) and Afolayan (1977). When the amount of nitrogen taken up by the trees (not analyzed) is considered, then the relative poverty of the soils of the burnt plots can be imagined. This is because trees normally immobilize a lot of nutrients.

Secondly, these results were from samples taken at the beginning of the rainy season before leaching effects on the ash deposit on the top soil after burning became serious.

Litter decomposition in the protected unburnt forest takes place fairly rapidly during the May–September peak of the rainy season. The rather limited production of litter by the burnt plots is characteristic of the savanna vegetation. According to Kadeba (1978), the paucity of organic material production in the savanna vegetation is caused by the climatic constraints of the area. The present results indicate that increased tree density contributes significantly to higher organic matter production, which is a dependable source of plant nutrients, and particularly nitrogen.

The rate at which organic matter is accumulated or depleted is strictly controlled by the overall influence of climate and plant communities, human interference and the length of time these factors have been in operation (Jenny 1930). Savanna burning is an annual phenomenon in Nigeria and since over 80 % of the country is savanna, the need to control burning cannot be overemphasized.

Late burning is used to prevent bush encroachment and promote maximum growth of perennial grasses for animal grazing (Afolayan 1977), but the predominantly sandy nature of the savanna soils coupled with the short rainy season and low rainfall characteristic of the area, encourage soil impoverishment, with regard to nitrogen in particular.

This experiment situated in the derived savanna zone of the country confirms the major role played by man in ecological succession.

The study produces some evidence that complete protection from fire could bring about a marked change from savanna to forest vegetation, apart from conserving soil nitrogen. The presence of fire-susceptible species like *Manilkara, Diospyros* and *Hildergandra* in the protected plot further supports this view. It is hoped that the authorities responsible for the management of the Nigerian savanna would consider the multiple land use requirements of the people for agriculture (farms), forestry, environmental conservation (climate, soil and plants) as well as the grazing needs of goats, cattle and wildlife.

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Nitrogen Cycling in West African Ecosystems

NITROGEN LOSS BY BURNING FROM NIGERIAN GRASSLAND ECOSYSTEMS

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Abstract

Nitrogen loss by burning from natural grassland ecosystems in Western Nigeria was studied over a two-year period in three areas, including sites of *Andropogon-Hyparrhenia – Schizachyrium-Brachiaria* grassland in derived, Southern Guinea and Northern Guinea savanna. The production of above-ground herbaceous material and litter fall of leaves, wood and fruit/seed was estimated and the nitrogen content just prior to burning determined. Final estimates of from 12 to 15 kg ha^{-1} yr^{-1} of nitrogen lost by burning were obtained. It is suggested that such loss may be replaced to a considerable extent by rain and blue-green algal crust fixation.

Introduction

Annual burning of grasslands has been occurring for centuries throughout the world. Sometimes the burning is accidental, but more often it is purposefully carried out by man to clear away dead vegetation, to encourage new grass growth for cattle grazing or to drive out wild game for hunting. One important ecological consequence of burning is the volatilization of nitrogen contained in the vegetation. Nye & Greenland (1960) stated that all the nitrogen is lost in burning, and Bartholomew *et al.* (1953) somewhat earlier observed that in burning woody or grass fallow, the nitrogen is almost totally lost as free nitrogen or as volatile oxides. Christensen (1973) recently working in California chapparral, reported that some nitrogen is left in the ash after burning. Metz *et al.* (1961) reported that no nitrogen remains in white ash but that incompletely burned charred remnants may contain from 0.01 to 0.76 % nitrogen.

The amount of nitrogen lost by burning has not been estimated with precision for tropical grassland systems. Nye & Greenland (1960) reported that the nitrogen lost in the burning of grass of high-grass savanna will be around 28 kg ha^{-1}. Estimates for temperate zone systems vary from 4.5 to 5.6 kg ha^{-1} as reported in a study carried out in northern Australia (Norman & Wetselaar, 1960) to an estimate of 30 kg ha^{-1} nitrogen lost from grassland in Oklahoma, USA (Elwell *et al.*, 1941); the value of 11.5 kg ha^{-1} yr^{-1} nitrogen lost by grass burning in the Venezuelan savanna has recently been reported (Medina *et al.*, 1978).

Reported effects of burning on soil nitrogen are somewhat puzzling. Vine (1953) reported only slight decrease in total nitrogen after twelve years of firing an experimental plot near Ibadan, Nigeria (forest-derived savanna area). Egunjobi (1973), working in Oyo, Nigeria (derived savanna), reported that there was no difference between burned and unburned plots after firing although the burned plot had contained slightly more previously, and Moore (1960) reported higher nitrogen in the soil below the burned plots at Olokemeji, southwestern Nigeria (derived savanna) than below the fire protected plot. On the other hand, reports of decreased nitrogen content in the soil below burned areas in the temperate zone exist (e.g., Cook, 1939 in southern Africa; Blaisdell, 1953 in Idaho, USA). It is difficult to reconcile the annual loss of as much as 28 kg of nitrogen per hectare with no change from year to year in soil nitrogen. Grass production in most Nigerian savanna areas does, however, superficially appear to be more or less stable, indicating that as much nitrogen must enter the system as is lost from it. It has been suggested (Daubenmire, 1968) that burning induces an increase in Leguminosae population and thus leads to increased biological nitrogen fixation. Such does not appear to be the case from our consideration of the data from Afolayan's (1977) short-term studies in Kainji Lake National Park, Nigeria (Northern Guinea savanna).

However, before considering such hypotheses of nitrogen stabilization, it is necessary to determine how much nitrogen is actually lost by burning. The present study is an attempt to this end.

Research sites and methods

The study reported in this paper was carried out from October 1975 to June 1978 in five plots at three sites: (1) the fire plots, each 1740 m^2, at Olokemeji Forest Reserve, 7°25'N and 3°32'E, in the derived savanna zone (Keay, 1959) of southwestern Nigeria: Plot A has been annually burned late in the season (March) since 1929 and plot B early (December). Both are high-grass *Andropogon-Hyparrhenia-Schizachyrium* savannas, with A being relatively open and B being woodland; (2) a 50 m × 50 m unfenced plot of high-grass (*Andropogon-Hyparrhenia-Schizachyrium-Chasmapodium*) savanna woodland in Old Oyo Forest Reserve, 8°N, 4°E, in the Southern Guinea zone (Keay, 1969) of Western Nigeria; (3) an open *Detarium-Burkea-Terminalia* moderately low-grass (*Brachiaria-Andropogon-Schizachyrium*) savanna unfenced plot 50 m × 50 m near to Oli River Visitors' Camp in Kainji Lake National Park, 9°45'N–10°23'N and 4°32'E–3°40'E; and a similarly sized unfenced plot in nearly closed *Isoberlinia* woodland (with the grasses *Schizachyrium-Ctenium-Hyparrhenia-Brachiaria*) at Tugan Giwa, Kainji Lake National Park (Northern Guinea savanna; Keay, 1959).

Periodic standing crop sampling of herbaceous vegetation was done in two ways: (i) selected plants of identified grass species were collected to compare above-ground and below – ground biomass in amount and in nitrogen concentration – above-ground results were used; (ii) all herbaceous vegetation from 10 or 20 randomly placed 0.25 m^2 quadrats was clipped 1.5 to 2.0 cm above the ground (the height at which burn most often stops) and sorted by species. The second method was for determining standing crop amount and N-concentration. The samples were oven dried to constant weight and total nitrogen determination (organic and inorganic) made by the Kjeldahl method in this laboratory and at the British Ministry of Agriculture, Food and Fisheries Laboratory in Bangor. Litter was periodically sampled by collection from five 1 m^2 fixed quadrats, originally randomly placed, and from five to ten 1 m^2 quadrats randomly placed at each collection. The litter was sorted into leaves, wood and seed/fruit. Drying and analysis of samples was as for standing crop samples.

For the estimation of standing crop prior to burning, after burning and the amount of nitrogen in grass samples, the Stein transformation, Z (Efron & Morris, 1977), of means was used in an attempt to obtain more reliable estimates than would be obtained by direct use of means. It was not possible to use the transformation on the litter data as samples were insufficient.

Results

Randomly collected ash samples were taken immediately after early and late burning in Olokemeji and shortly after burning in January in Kainji Lake National Park. None contained a detectable amount of nitrogen. It is therefore concluded that nitrogen is completely volatilized from vegetation burned both early and late. A crucial question now becomes that of how much nitrogen is contained in the vegetation at the time of burning. A summary of the results of analysis of grass shortly before burning is given in Table 1. The data are remarkably consistent in indicating a much lower nitrogen content than found in grass earlier in the season (unpublished data). It should also be noted that the highest nitrogen percentage was found in the early burned plot at Olokemeji. Olokemeji is on the forest/derived savanna margin, and the early burned plot is quite different in species composition and physiognomy from the other sites, including the Olokemeji late burned plot, which are more typical savanna.

Table 1. The total amount of nitrogen in the standing crop of grasses prior to burning

Research site[1)]	Sample date	Number of samples	Mean nitrogen content (%)	95 % confidence limit	Z transformation[2)] of mean values
Old Oyo	7 Dec. 1975	11	0.35	0.002	0.35
Old Oyo	4 Nov. 1977	2	0.35	–	0.35
Olokemeji A	10 Nov. 1978	9	0.34	0.0002	0.35
Olokemeji B	13 Dec. 1975	4	0.51	0.005	0.39
Kainji Lake O	15 Nov. 1975	13	0.28	0.003	0.34
Kainji Lake O	23 Oct. 1966	5	0.33	0.0002	0.35
Kainji Lake W	15 Nov. 1975	12	0.28	0.004	0.34
Kainji Lake W	14 Oct. 1976	9	0.34	0.001	0.35
Kainji Lake W	23 Oct. 1977	6	0.41	0.01	0.37
		71			
Grand mean			0.35	0.003	0.35
Range			0.28–0.51		0.34–0.39

1) A – Later (Mar.) burned
B – Early (Dec.) burned
O – Open savanna
W – Woodland savanna

2) $Z = \overline{Y} + C\,(Y - \overline{Y})$

$$C = 1 - \frac{(n-3)\,s^2}{(\Sigma y^2) - (\Sigma Y)^2/n}$$

In Table 2 are presented the data allowing for estimation of the amount of nitrogen volatilized by burning. The standing herbaceous crop obtained before burning varies considerably from plot to plot and from year to year. While the percentage burned varies tremendously when small areas such as quadrats are considered, the overall variation of areal means is considerably less than that of production. Using Z-transformed values, the grand mean of nitrogen lost per year is 8.77 kg ha^{-1}, with a range from 7.36 to 9.61 kg ha^{-1}.

An estimate of 0.83 ± 0.09 % nitrogen as the content of oven dried leaf litter prior to burning was obtained from collections made at plots A and B, Olokemeji, on 10 November 1977. An estimate of 0.89 % nitrogen in oven dried fruit/seed was obtained from only one collection at Olokemeji and so cannot be considered as reliable. The nitrogen content of wood (0.21 ± 0.11 %) was estimated from the results of Kjeldahl analysis of 27 core samples taken from standing trees at Old Oyo and Kainji Lake National Park. This estimate is somewhat too high as it was made from the analysis of living material, whereas wood litter will be partially decomposed and leached. The percentage of litter burned could be estimated only from sampling of Olokemeji plot B, as it was only here that we were able to sample immediately before and after firing. Taking into consideration the amount of litter decomposed during the year, it was estimated that 18.5 % of the year's fall of leaves was burned together with 11.7 % of the year's wood fall and 36.8 % of the year's fruit/seed fall. These figures were used to give the estimates of nitrogen loss from litter burned presented in Table 3.

It is now possible to arrive at an estimate of the total amount of nitrogen lost by burning. These estimates are given in Table 4. A conservative estimate appears to be from 12 to 15 kg ha^{-1} yr^{-1} nitrogen lost from burning of Guinea savanna.

Table 2. Standing crop herbaceous production and estimated nitrogen loss in five research plots at three locations in Western Nigeria

Research site[1]	Mean standing crop prior to burning ($\text{g m}^{-2}\ \text{yr}^{-1}$)	Z transformation of standing crop means[2]	Mean percentage burned	Z transformation of percentage burned[2]	Nitrogen loss ($\text{kg ha}^{-1}\ \text{yr}^{-1}$)[3]
Olokemeji A	358.0	316.1	95.7	85.3	9.43
Olokemeji A	182.4	277.5	53.2	75.8	7.36
Olokemeji B	431.4	332.3	83.8	82.6	9.61
Old Oyo	300.0	303.4	84.9	82.8	8.80
Old Oyo	316.7	307.4	84.0	82.7	8.88
Kainji Lake O	359.5	316.5	71.7	79.9	8.85
Kainji Lake O	287.7	300.7	87.6	83.5	8.78
Kainji Lake W	183.1	277.6	73.0	80.2	7.79
Kainji Lake W	334.4	310.9	100.0	86.2	9.38
Mean	304.3	304.3	82.3	82.3	8.77

1) For research site code, see Table 1.

2) For Z transformation, see Table 1.

3) These values were obtained by using the value for nitrogen content of 0.35 % and the Z values for standing crop and percentage burned.

Table 3. **Litter fall and estimated nitrogen loss in five research plots in three locations in Western Nigeria**

Research site[1]	Leaf		Wood		Fruit/seed	
	Litter fall (g m^{-2} yr^{-1})	Nitrogen loss (kg ha^{-1} yr^{-1})	Litter fall (g m^{-2} yr^{-1})	Nitrogen loss (kg ha^{-1} yr^{-1})	Litter fall (g m^{-2} yr^{-1})	Nitrogen loss (kg ha^{-1} yr^{-1})
Olokemeji A	62.9	0.97	987.0	2.45	0.8	0.03
Olokemeji B	316.8	4.90	330.8	0.82	36.8	1.21
Old Oyo	112.6	1.74	671.9	1.67	15.5	0.51
Kainji Lake O	148.2	2.29	69.6	0.17	1.5	0.05
Kainji Lake W	240.7	3.72	175.9	0.44	27.5	0.90

1) For research site code, see Table 1.

Table 4. **The total amount of nitrogen lost by burning in Western Nigeria grasslands**

Research site[1]	Nitrogen loss (kg ha^{-1} yr^{-1})					
	Herbaceous standing crop	Litter Leaves	Wood	Fruit/seed	Total	Z transformation of total[2]
Olokemeji A	8.40	0.97	2.45	0.03	11.85	12.50
Olokemeji B	9.22	4.90	0.82	1.21	16.15	14.66
Old Oyo	8.84	1.74	1.67	0.51	12.76	12.96
Kainji Lake O	8.59	2.29	0.17	0.05	11.50	12.13
Kainji Lake W	8.82	3.72	0.44	0.90	13.77	13.52

1) For research site code, see Table 1.
2) For Z transformation, see Table 1.

Discussion

Yearly losses of nitrogen from the natural grassland ecosystem are accounted for by migratory grazing, burning and harvesting and leaching and run-off. A considerable amount is also immobilized each year in below-ground biomass and above-ground woody vegetation. In spite of these losses and immobilizations, the Nigerian grassland very often appears stable in fixed carbon production from year to year, indicating that as much nitrogen must enter the system as is lost and not recycled from the amount immobilized. The present estimate of loss from burning of from 12 to 15 kg ha^{-1} yr^{-1} is much lower than the figure of Nye & Greenland of 28 kg ha^{-1} yr^{-1}. This latter figure appears, however, to have been derived from estimates involving the total burning of nearly pure forage grass stands. It is also possible that the nitrogen content of the grass was assessed near peak maturity rather than at the low level found in natural systems immediately prior to burning. Our data, as yet incompletely analyzed, also suggest that the amount of nitrogen in herbaceous material is greater in forest and derived savanna areas than in so-called "true" savanna. This is certainly the case with leaf litter, where leaf fall from the fire protected plot at Olokemeji – typical lowland rainforest vegetation – averaged 0.95 % nitrogen in November, whereas that from plot A, with typical Guinea savanna vegetation, averaged 0.77 % nitrogen, the difference in means being significant as tested by analysis of variance at $P < 0.01$.

Our figures of nitrogen loss are in line with those reported for various temperate situations, such as Grant *et al.* (1963) for England, and Hunter *et al.* (1964) for Scotland. We believe the figures will prove typical for Guinea savanna in West Africa. They are particularly significant in that they strongly suggest that the nitrogen lost by burning may be almost replaced by fixation by blue-green algal crusts (up to 4–8 kg ha^{-1} yr^{-1}; Isichei, 1975) and by rain (4–5 kg ha^{-1} yr^{-1}, Jones & Bromfield, 1970, North Nigeria).

The major remaining amount of nitrogen to be added to the system each year is that needed to replace the nitrogen immobilized in wood and below ground biomass. Part of this amount may be met by nitrogen recycled from litter and the bodies of soil microorganisms. A considerable amount may also be added through biological nitrogen fixation by Leguminosae associations and possibly by grass – *Spirillum lipoferum* associations.

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Nitrogen Cycling in West African Ecosystems

EFFECTS OF VARIOUS RATES OF PARAQUAT DICHLORIDE (1,1'-dimethyl-4, 4'-dipyridylium dichloride) ON NITROGEN TRANSFORMATION IN SOME WEST AFRICAN ACID SOILS

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Abstract

The effects of paraquat were studied in incubated soils in the laboratory and in the field. Paraquat did not have any significant effect on mineralization and nitrification of soil native organic N even at the highest rate (250 $\mu g \cdot g^{-1}$).

No significant effects of either low or high rates (25 $\mu g \cdot g^{-1}$) of paraquat were observed on ammonification and nitrification of soil native N in field-treated plots 30 days after the herbicide had been applied.

Introduction

In recent years most African countries have been increasingly involved in both monocropping for industrial purposes and in developing new cash crops as priorities in agricultural production to improve their economic potentialities. In these new cropping programmes, requiring a new technology for better yield, dramatic changes have been observed in the farming system as a result of spontaneous and massive introduction of pesticides into virgin rural ecological environments.

Herbicides are being used more and more for economic reasons although they have not as yet reached many African rural farms. Paraquat is one of the weed killers whose hazardous effects our lands and rural environments are being exposed to through the extension of industrial plantations.

Many studies have been made on paraquat. Tu & Bollen (1968a) studied the effect of paraquat on microbial activities in soils, Riley *et al.* (1976) demonstrated biological unavailability of bound paraquat residues in soil, etc. However, few of these have been performed under tropical conditions. Only Gamar & Mustafa (1975) studied absorption and desorption of diquat and paraquat on arid-zone soils in the Sudan.

The studies reported here were initiated to determine the effects of various rates of paraquat dichloride (1,1'-dimethyl-4.4'-bipyridium dichloride) on nitrogen transformation in some West African acid soils.

Materials and methods

Soils

In recognition of the fact that management, climate and vegetation are important factors which greatly modify soil properties and thus productivity, 10 soil types were sampled from ecological zones (Guinean zone and Soudanian zone) of two West African countries (Fig. 1). Most of the soils came from the Guinean zone and in this zone the rainfall increases from the west to the east but decreases from south to north, making Onne the wettest site.

For the investigations on the effects of field applied paraquat, the herbicide was applied *in situ* to an Apomu soil located at the IITA (Ibadan) site.

The sampling procedure and soil treatments were described by Ayanaba *et al.* (1976).

The physical and chemical properties of the soil samples used were determined as follows:

(i) Mechanical analysis was performed using the hydrometer method of Bouyoucos (1936).

(ii) Moisture retained at 0.3 bar suction of the fine earth fraction (< 2 mm) was determined using a pressure plate apparatus.

(iii) pH of a suspension of 1:2 soil to 0.01 M $CaCl_2$ was measured using a Beckman Zeromatic pH meter with a combination glass electrode.

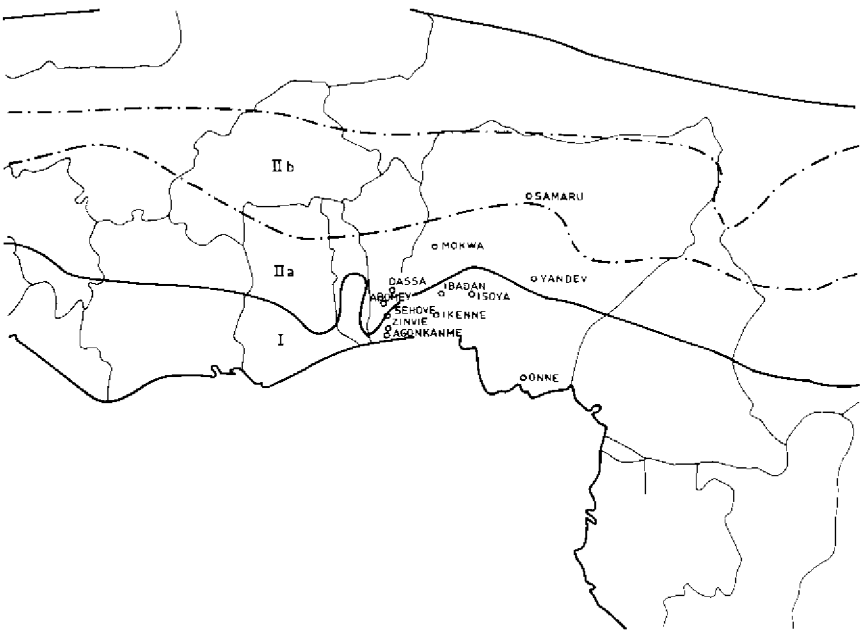

Figure 1. Map of ecological zones of West Africa. Adapted from Devred (1971). I Guinean zone, II Soudanian zone; 0 = Location of sampling.

(iv) Organic carbon was determined by the dichromate wet oxidation method of Walkley & Black (1934).

(v) Effective cation exchange capacity (CEC) and NH_4OAc extractable cations were determined using the analytical method of Schollenberger & Simon (1945).

(vi) Available P in soils was determined by the Bray No. 1 method (Bray & Kurtz, 1945).

(vii) Total N was determined by the Kjeldahl digestion method. The N content of the digest was measured colorimetrically on the Technicon Model II Autoanalyzer.

Mineralization study

A required amount of a moist soil equivalent to 50 g oven-dry weight was placed in a 500 ml wide-mouth bottle. In some samples, 0.125 g of cowpea residues was added. The herbicide was added at different rates with sufficient water to give 60 % W.H.C.

For field application the recommended rate (rr) is 0.50 kg ha^{-1}, which is equivalent to 0.25 $\mu g\ g^{-1}$ of soil (oven-dry basis). For this experiment the following rates were used: 0 rr, 1 rr, 10 rr, 100 rr, 1000 rr.

Samples were incubated for 10 days at 29±2°C in a Gallenkamp incubator. To avoid oxygen becoming a limiting factor, particularly in rapidly respiring soils, the bottles were taken out of the incubator and opened for a minute on the fifth day to admit air. They were capped and re-incubated for the duration of the incubation.

At the end of 10 days incubation for CO_2 evolution, soil samples were stored at -15°C in a freezer until they could be extracted for mineral nitrogen determination.

Extracts of soils for analysis were made by shaking the entire moist soil in each bottle with 200 ml of 2 M KCl for 60 min. and filtered through Whatman No. 60 filter paper. Inorganic nitrogen was determined by steam distillation as described by Bremner (1965).

Nitrification

The soil samples used were air-dried for 3 days at laboratory temperature and stored in polythene bags at about 25°C for one month, prior to incubation.

From each 100 g soil (oven dry basis) was weighed into 250 ml flasks. The moisture was adjusted to 60 % of W.H.C. Paraquat treatments were made by adding the required amounts in sufficient deionized water to give 0, 0.25, 2.5, 25 and 250 μg of cation g^{-1} of soil. The $(NH_4)_2SO_4$ treatments were made with two levels: 0 and 50 μg N g^{-1} of soil.

Before incubation an amount of treated moist soil equivalent to 10 g on an oven dry basis was removed and kept in a freezer (-15°C) until extraction for analyses.

Each bottle was weighed, capped loosely and incubated at 29±2°C in a humid atmosphere for 30 days.

Lost water was adjusted by weekly additions. After 30 days incubation the samples were stored in a freezer until extracted for analyses.

Extraction was done as mentioned above, i.e., 2 M KCl was added in the ratio 1:10 w/v.

The NH_4^+-N in the clear filtrate from extraction was measured colorimetrically on the Technicon Model II Autoanalyzer. Nitrate formed after 30 days incubation was determined using the brucine-sulfanilic acid method (Kahn & Brezenski, 1967).

Effects of field-applied paraquat on microbial activity, ammonification and nitrification of native nitrogen

Paraquat was sprayed on three plots of Apomu soil located at the IITA experimental site at Ibadan. Three rates were used: 0, 0.5 and 50 kg ha^{-1}. The plots were not replicated. Soils were sampled some moments after spraying and 30 days after spraying. Ammonia and nitrate were determined as described above.

Results and discussion

Physical and chemical properties of the soils used

The physical and chemical properties of the soils used are shown in Tables 1 and 2. By design, these soils were selected to give a range of clay contents. The data reflect this variation in clay from 4 to 45 %; the greatest diversity being in the group of soils from the Republic of Benin. Moisture holding capacity also varied quite substantially. Abomey sand, with 5.5 % W.H.C., retained the least moisture at 0.3 bar whereas the most moisture was retained by Kolo sandy clay loam with a value of 58.4 %. The pH varied from 3.7 to 6.3, with the widest range falling in the group of soils from southern Nigeria (Table 2). Organic carbon was uniformly low. Available P and total N likewise showed much variation, several of the soils having less than 0.10 % N.

Physical and chemical properties of the Apomu soil used in the field experiment were determined and have been published elsewhere (Ayanaba & Kang, 1976).

Table 1. Physical properties of soils used

		Mechanical analysis (%)			Moisture holding capacity
Soil	Texture	Sand	Silt	Clay	(%)
Onne	Sandy loam	67.2	15.2	17.6	11.8
Okpannam	Loamy sand	85.2	9.0	5.8	6.7
Adio	Sandy loam	67.2	22.4	10.4	18.4
Kolo	Sandy clay loam	72.2	7.0	20.8	58.4
Alagba	Sandy loam	72.4	14.6	13.0	13.2
Abomey	Sand	92	4	4	5.5
Dassa	Loamy sand	84	11	5	7.5
Agonkanme	Sandy loam	80	10	10	8.5
Sehoue	Clay	35	20	45	47.1

Mineralization

The ability of the treated soils to mineralize native organic N as affected by paraquat was investigated on only five soils (Tables 3 and 4).

Alagba either treated with cowpea residue or untreated did not show any significantly different mineral N from the control. The same lack of response to paraquat was noted

Table 2. Chemical characteristics of soils used

Soil	pH	Organic C (%)	NH_4OAc extractable cations (meq 100 g^{-1}) Ca	Mg	K	Na	C.E.C. (meq 100 g^{-1})	Avail. P (ppm)	Total N (%)	C/N ratio
Onne	3.7	1.35	0.15	0.04	0.09	–	2.86	15.0	0.06	22
Okpannam	4.2	0.94	0.80	0.42	0.30	0.12	1.72	13.3	0.05	19
Adio	4.7	1.42	5.58	2.99	0.28	0.18	9.68	11.7	0.22	7
Kolo	5.5	2.61	18.26	7.61	0.41	0.37	26.46	11.0	0.85	3
Alagba	6.3	1.21	5.36	2.89	0.25	0.16	9.04	5.9	0.16	8
Abomey	5.5	0.73	2.25	0.63	0.13	0.05	3.28	2.5	0.04	18
Dassa	6.0	0.86	3.55	0.90	0.25	0.05	4.93	9.0	0.05	17
Agonkanme	6.1	1.35	4.80	1.77	0.18	0.06	6.99	23.2	0.10	13
Sehoue	6.2	2.98	26.70	7.25	0.65	0.20	34.96	4.0	0.20	15

Table 3. Effect of different rates of paraquat on mineralization of native soil organic nitrogen in soil not amended with cowpea residue.

Soil	Paraquat added ($\mu g \cdot g^{-1}$)					Mean
	0	0.25	2.5	25	250	
	μg of inorganic N per g of soil, oven dry basis a)					
Onne	11.50	12.10	11.67	12.73***	13.61***	12.32
Okpannam	13.71	9.99***	11.36***	12.66	14.91*	12.51
Adio	14.36	14.73	14.74	14.41	15.71*	14.79
Kolo	28.29	24.80***	32.45***	26.94***	25.94***	27.52
Alagba	7.16	6.88	6.91	7.58	6.49	7.00

a) Difference from control significant at P=0.05*, P=0.01**, P=0.001***.

Table 4. Effect of different rates of paraquat on mineralization of nitrogen in soil amended with cowpea residue.

Soil	Paraquat added ($\mu g \cdot g^{-1}$)					Mean
	0	0.25	2.5	25	250	
	μg of inorganic N per g of soil, oven dry basis a)					
Onne	10.62	11.40	11.15	11.40	12.25**	11.36
Okpannam	8.17	7.71	11.75***	12.45***	8.87	9.79
Adio	10.38	12.45***	11.92***	12.23***	12.53***	11.90
Kolo	20.26	26.51***	27.64***	24.42***	26.69***	25.10
Alagba	5.88	6.21	6.38	6.22	5.98	6.13

a) Difference from control significant at P=0.01**, P=0.001***.

for Adio (untreated) and Onne (treated) except at high rate (250 ppm), whereas increased mineral N values were obtained. For Kolo and Adio (treated) mineralization rates were significantly higher than in controls. Paraquat at the recommended rate (0.25 ppm) and 2.5 ppm showed a biomodal response in Okpannam (untreated).

The marked increase in organic N from some treated soils as compared to controls could be the result of stimulated decomposition of protein from dead cells. The increase in inorganic N noted with some soils amended with cowpea residue also could be due to mineralization of the added legume residue. This latter reason is in good agreement with the finding of Anderson & Drew (1976) that mineralization of fresh plant material in paraquat-treated samples increased.

Inorganic-N values were also plotted (Fig. 2) to detect any relationships between soil properties and mineral N content. No correlation was observed between inorganic N and soil clay content or soil pH. Regardless of paraquat treatment, cowpea residue significantly

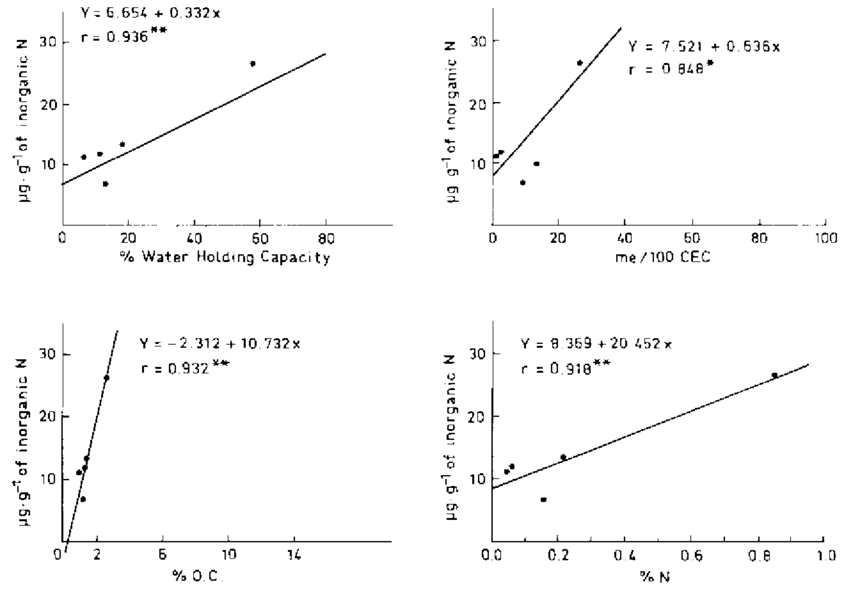

Figure 2. Effect of different moisture characteristics (a), cation exchange capacity (b), organic carbon contents (c) and nitrogen contents (d) on mineralization of native soil nitrogen. * significant at the 0.10 level and ** significant at the 0.05 level.

depressed the mineralization of native soil organic N (0.87 %; $P<0.001$) compared to control.

In general, no correlation was observed between paraquat rates and inorganic N. This is in agreement with the data of Tu & Bollen (1968a), who found the effect of paraquat on the nitrification of the soil native N to be negligible, but their results were obtained after only ten days of incubation.

Nitrification

Increases in nitrate concentrations during incubation are shown in Table 5. No correlations were found between nitrification rates and paraquat additions in unamended soils (Table 6). Amongst those which received ammonium sulfate, inhibition was apparent for Abomey ($P<0.01$), Kolo ($P<0.10$) and Agonkanme ($P<0.10$) (Table 6). The depression of nitrate formation observed was due to the highest dose (1000 rr) of paraquat (Table 5). Certain relationships were observed between some properties of the affected soils and the importance of the inhibition effect (Table 7). An increase in the clay content or C.E.C. lowered paraquat toxicity. This substantiates that both clay and C.E.C. are important in the deactivation of the herbicide as reported in many works (e.g., Tu & Bollen, 1968b; Riley *et al.*, 1976; Gamar & Mustafa, 1975). Within a group of mineral soils, sands showed less adsorption capacity for paraquat (Riley *et al.*, 1976). Furthermore, Szegi *et al.* (1976) observed that Gramoxone showed stronger toxicity to microflora in soils of relatively light mechanical composition than in heavy soils.

A decline in nitrification was also noted in ammonia amended Okpannam loamy sand

Table 5. Formation of NO_3^- for the incubation period as influenced by different rates of paraquat and $(NH_4)_2SO_4$ (50 $\mu g\ g^{-1}$) treatments

Treatment		Nitrate-N formed ($\mu g \cdot g^{-1}$) after 30 days incubation in the soils shown									
Nitrogen source	Paraquat ($\mu g\ g^{-1}$)	Onne	Okpannam	Adio	Kolo	Alagba	Abomey	Dassa	Agonkamne	Sehoue	Mean
None	None	7.1	0.9	5.9	45.4	35.5	12.2	7.9	6.4	23.1	16.0
	0.25	2.8	1.7	10.6	45.8	36.7	11.3	16.6	15.2	9.5	16.7
	2.5	1.9	2.9	9.0	43.5	36.0	12.9	14.6	5.2	26.0	16.9
	25	2.4	2.9	18.4	46.9	43.4	14.0	21.5	20.6	15.4	20.6
	250	3.7	0.6	13.3	47.0	37.1	14.4	22.0	3.5	13.0	17.2
$(NH_4)_2SO_4$	None	3.4	1.5	10.5	85.8	42.5	31.2	20.7	23.3	18.2	26.3
	0.25	4.5	0.5	14.6	89.1	46.6	29.5	28.8	15.5	15.8	27.2
	2.5	5.2	0.8	9.4	79.2	42.8	33.5	30.6	24.2	22.3	27.6
	25	2.7	1.2	17.0	85.5	42.2	29.0	27.8	21.2	21.8	27.7
	250	3.6	0.7	11.7	73.2	42.2	8.9	31.2	17.5	22.3	22.4

Table 6. Correlation coefficients between NO_3^- formed during incubation and paraquat treatments (see data in Table 5)

	Correlation coefficient (r)	
Soil	No $(NH_4)_2SO_4$ added	With $(NH_4)_2SO_4$ added
Onne	0.00	−0.22
Okpannam	−0.57	−0.31
Adio	0.31	−0.10
Kolo	0.55	−0.82*
Alagba	−0.02	−0.39
Abomey	0.69	−0.99***
Dassa	0.59	0.46
Agonkanme	−0.44	−0.87*
Sehoue	−0.37	0.47

*** significant at $P < 0.01$
* significant at $P < 0.10$

Table 7. Interactions between soil properties and toxicity of high paraquat concentration on nitrification in Abomey, Agonkanme and Kolo soils. NO_3^- recovered appeared closely correlated with soil % clay and C.E.C. and inversely correlated with soil % sand

Soil	N_3^-–N as % control	% Clay	% Sand	C.E.C. me/100 g
Abomey	28	4.0	92.0	3.28
Agonkanme	75	10.0	80.0	6.99
Kolo	85	20.8	72.2	26.46

treated with both normal dose (rr) and 10 rr paraquat, in Sehoue soil with rr paraquat but without $(NH_4)_2SO_4$ treatment and in Onne containing all rates of paraquat but without $(NH_4)_2SO_4$. As stated earlier in the mineralization study, all this could be a transient effect on general metabolism rather than on a specific function. Several investigations have been made on how paraquat affects the ability of soil to convert NH_4^+ to NO_3^-. Debonah & Audus (1970), using pre-enriched and fresh soil perfusion columns, found 7 % and 18 % inhibition, respectively, attributed to low concentration (50 ppm) of paraquat. A 50 % inhibition was reported by Anderson & Drew (1976) when 187 times the normal, recommended field rate of paraquat was used. Nitrification seems to be the most sensitive microbial process to paraquat. Debonah & Audus (1967) showed that the herbicide is highly inhibitory to both the oxidation of ammonia to nitrite and nitrate. However, there does not appear to be any report that specifies that *Nitrobacter* is directly affected by the herbicide.

A general observation on nitrification of native nitrogen was that there was no significant toxic effect of paraquat. Indeed, 100 rr showed a mean increased nitrate formation rate of 28 % over the control (Table 7). The finding is in good agreement with the earlier one on mineralization of native N. It receives further support from the report of Tu & Bollen (1968a), which pointed out the insignificant effect of the bipyridinium cation on mineralization of soil native N.

The correlation coefficients (r) between nitrate formation and soil pH were positive, both in soils treated with ammonium sulfate ($r = 0.487$) and soils which were not ($r = 0.561$). The same observation was noted for C.E.C. with $r = 0.497$ (soils treated with $(NH_4)_2SO_4$) and $r = 0.530$ (soils which were not treated). Phosphorus contents were negatively correlated with nitrate formation, with $r = -0.638$ ($P < 0.10$) for soils with ammonium sulfate treatment and $r = -0.712$ ($P < 0.05$) for soils which did not receive any. This confirmed the phosphorus deficiency of soils used.

In summary, nitrification was significantly lowered in some soils by paraquat. However, the depressive effects observed were mainly attached to unusually high doses of paraquat. The toxicity was more pronounced in soil enriched with $(NH_4)_2SO_4$ than in soil which did not receive any.

The effect of the herbicide on nitrogen fertilizer efficiency in crop yield under field conditions remains to be investigated.

Ammonification and nitrification of native soil N

Fresh soils collected from the field plots on the day of spraying and after 30 days, following weight adjustment as usual, were assayed for NH_4^+–N and NO_3^-–N content as earlier described.

Results are presented as means of four observations per treatment and expressed in $\mu g \cdot g^{-1}$ (Table 8). No significant effect due to paraquat treatment was observed either for ammonification or for nitrate accumulation. As much ammonium and nitrate were recovered after 30 days as on the initial day.

Mathur *et al.* (1976), studying the influence of field-applied linuron and paraquat on the microflora of an organic soil, also failed to detect any significant effect attributable to paraquat treatment.

Under field conditions in the tropics, paraquat is expected to be very rapidly decomposed since the chemical is known to be highly sensitive to photochemical degradation (Funderburk *et al.*, 1966; Slade, 1965). None of the identified photodegradation products,

Table 8. Ammonification and nitrification of soil native N

Paraquat ($kg\ ha^{-1}$)	0 day NH_4^+–N ($\mu g \cdot g^{-1}$)	 NO_3^-–N	30 days NH_4^+–N ($\mu g \cdot g^{-1}$)	 NO_3^-–N
0	12.4	6.1	11.0	7.3
0.5	11.4	6.1	11.0	7.1
50	12.5	6.8	12.0	8.0

namely, 4-carboxy-1-methyl-pyridylium chloride and methylamine hydrochloride were particularly known to be toxic to soil microorganisms. However, the chemical itself is. Fortunately, its rapid desorption by certain soil colloids, mainly clay colloids, may not allow any apparent effect of this pesticide on nitrification *in situ*.

Measurement of the products of nitrogen mineralization and nitrification hardly represent a true measure of these processes; rather, what are measured are the differences between production and utilization. In this experiment, leaching and denitrification might be responsible for the non-significant evolution in NO_3^--formation observed.

Acknowledgement

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Nitrogen Cycling in West African Ecosystems

NITROGEN ECONOMY IN SELECTED FARMING SYSTEMS OF THE SAVANNA REGION

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Abstract

The importance of grain legumes and cultivation methods to the nitrogen economy of savanna soils is examined. Under the system in which the haulms of legumes are completely utilized as fodder, the contribution of grain legumes to the nitrogen economy of the soil is mostly through the roots. Comparison of the residual effects of the important grain legumes grown in the area showed that available nitrogen from sole-crop groundnut plots was about 70 kg ha^{-1} N while that of cowpea was about 55 kg ha^{-1} N in the top 30 cm. On the other hand, the inter-cropping of cowpeas, soya beans and maize did not increase available N over that of maize alone.

The traditional method of land preparation, hoe-ridging, was found to result in the greatest amount of nitrogen mineralized early in the growing season when compared with zero tillage, bullock-ridging, and tractor cultivation. Thus, in addition to their roles in soil and water conservation, hoe-ridges appear to be essential in providing early flushes of mineral nitrogen to crops at the beginning of the growing season.

Introduction

Legumes constitute an important part of the cropping system in the savanna zone of Nigeria. It is estimated that about 4.97 and 3.69 million hectares of groundnuts and cowpeas, respectively, are grown in the savanna region of Nigeria (Fed Office of Stat., 1972). In addition, soya beans are also grown in the Southern Guinea Vegetation Zone while lima beans are concentrated mostly around the Jos plateau and the Jema's Platform (Steele, 1965). Bambarra groundnuts are important south of latitude 11° N. Most of these legumes are grown as inter-crops though sole-crop groundnuts are not uncommon. With proper insect control, cowpeas can be grown as sole crops and high yields obtained.

Although legumes are important in the farming system of the savanna zone, very few studies have been conducted on the nitrogen economy of cereal-legume inter-crops and cereal-legume rotation. Steele (1972) reported that millet inter-planted with cowpeas gave higher grain yields than sole-crop millet at the same plant density. Since no measurement of soil nitrogen was made, the result could not be explained in terms of excretion of fixed nitrogen to the ecosystem of the cowpea. However, Henzell & Vallis (1975) and Agboola & Fayemi (1972) have shown that the contribution of N by legumes to companion crops is unlikely except through senescent and dead plant material.

In the savanna region any contribution of N by legumes to succeeding crops is most likely through the decomposition of roots and nuts left in the soil as well as some fallen leaves. This is because of the economic importance of legume haulms in the region. All legume haulms constitute valuable fodder which fetches additional income for the farmer. Therefore the nitrogen economy of such a system requires investigation.

Initial studies on this were conducted by Jones (1973) at Samaru. He found that the mean yields of maize grown after cotton, sorghum and groundnuts were 1290, 1159 and 2959 kg ha^{-1}, respectively, where no fertilizer N was applied.

In another study (Jones, 1974), levels of mineral soil N in the top 30 cm of soil were found to be 42, 46, 53 and 86 kg ha^{-1}, respectively, for cotton, cowpeas, sorghum and groundnuts. Where no fertilizer N was applied, the yields of maize from previous cowpea plots were no better than those from previous cotton and sorghum plots. The results of that study (Jones, 1974) are surprising since one would expect cowpea, which is a legume, to have a higher N content in the roots than cotton and cereals (unless the crop is very efficient in translocating its fixed N to the grain) and therefore should mineralize its root N while the non-legume might even be expected to immobilize soil N.

Hence there was the need to investigate further the contribution of N by grain legumes to succeeding crops under the savanna farming practices. The experiments described below are some of the work which has been done or is still in progress that might help in a deeper understanding of the nitrogen economy of savanna farming systems.

Effect of N content of roots on their transformation

Roots of selected field-grown grain legumes Bambarra groundnut (*Voandzeia subterranea*), cowpea (*Vigna unguiculata* CVS 'NEP 593' and 'Ife Brown') lima bean (*Phaseolus lunatus*), soya bean (*Glycine max*), and pigeon pea (*Cajanus cajan*), were sampled after the grains had been harvested.

The roots were washed with distilled water, dried in an oven at 70°C for 48 h, ground in a Wiley mill and their N content determined using the micro-Kjeldahl method. Five milligrams of N in the form of the various root materials under investigation were added to 45 g of soil contained in wide-mouth 'Kilner' canning jars. Half of the bottles also received 100 mg of $CaCO_3$. The added materials were thoroughly mixed with soil and the moisture adjusted to 60 % of its water-holding capacity and incubated at 30°C for 84 days.

Table 1 gives the root nitrogen content of the grain legumes at harvest. There were differences among legumes in their total N as well as water-soluble N contents. It is also worth noting the difference between the two cowpea cultivars used in this study (Table 1).

Root N mineralization and immobilization were related to the nitrogen content of roots. The legume roots, having low N content (total N of less than 2 %), immobilized N during the 84-day incubation period (Table 2).

Liming of the soil depressed mineralization of added root N. The soil had a pH of 4.9 (in 0.01 M $CaCl_2$) and had been fallow for several years. This depressing effect of lime on the mineralization of added plant residue appears to have received very little attention. There is considerable literature on the effect of liming on the mineralization of native soil organic matter but practically nothing on its effect on added residues. The effect requires further consideration as it could be important in highly acid soils where crop residues and lime are incorporated into the soil.

Table 1. Nitrogen content of legume roots*

	Bambarra groundnut	Cowpea CVS 593	Cowpea CVS IB	Lima bean	Soya bean	Pigeon pea
Total N	3.93	2.53	1.52	2.06	1.38	1.25
Water Soluble N						
Organic	1.93	1.04	0.38	0.73	0.42	0.46
Inorganic	0.17	0.08	0.06	0.08	0.10	0.02
Total	2.10	1.12	0.44	0.80	0.52	0.48

* Adapted from Nnadi & Balasubramanian (1978).

Table 2. Net percentage of total root N mineralized or immobilized after 84 days of incubation as affected by liming*

Legume	Nitrogen mineralized Unlimed	Nitrogen mineralized Limed
	% of added root N	
Bambarra groundnut	48.7	12.4
Cowpea – NEP 593	26.8	4.8
Lima bean	19.1	5.1
Cowpea – Ife Brown	–10.4	– 9.4
Soya bean	–10.4	–27.7
Pigeon pea	–17.4	–15.1

* Adapted from Nnadi & Balasubramanian (1978).

Field trials on the residual effects of cowpeas

The laboratory experiments described earlier showed that there were differences in the amounts of N mineralized after an 84-day incubation period. In particular there was also a difference between the two cowpea cultivars used. It was therefore necessary to check out these results in the field.

In the 1975 cropping season, three cowpea cultivars (NEP 593, 556/2, and Ife Brown), Bambarra groundnuts and sorghum were planted at locally recommended dates. At maturity the crops were harvested and all above-ground residues removed from the field. In June 1976, soil samples were taken from previous legume and sorghum plots after a uniform disc-cultivation. The soils were air-dried and subsamples taken for incubation for the determination of mineralizable N ($NH_4 + NO_3 - N$).

In general, very little difference was found among the cowpea cultivars in their residual

Table 3. Effect of previous crops on mineralized N in 1976

Previous crop	Depth (cm) 0–15	 15–30
	..........ppm N	....
Sorghum	22.5	20.1
Cowpea – NEP 593	38.5	39.9
Cowpea – Ife Brown	31.8	36.2
Cowpea – 556/2	36.0	35.5
Bambarra groundnut	36.0	35.5

Table 4. Available N in previous legume and maize plots (0–30 cm layer)

Crop	Cultivar	Available N (kg ha^{-1})
Groundnut	Mk 374	83.0
Groundnut	M 25.68	80.4
Groundnut	Spanish 205	60.1
Groundnut	2938.71	53.6
Cowpea	140	55.6
Cowpea	NEP 593	55.6
Cowpea	Ife Brown	54.0
Maize	Samaru 1, 2, 3	44.8

N (Table 3). However, mineralizable N values in previous legume plots were higher than in previous sorghum plots.

An experiment similar to the one just described was conducted in 1977 and 1978 using three cowpea, four groundnut and one maize variety. The mineralizable N from the plots where these crops were previously grown is shown in Table 4. The previous groundnut plots had higher levels of available N in the 0–30 cm soil layer compared with previous cowpea plots. The average levels of available nitrogen were 69.3 and 55.1 kg ha^{-1} for groundnuts and cowpeas, respectively. The previous maize plots had 44.8 kg ha^{-1} of available N. The range of available N among groundnut cultivars was quite considerable, varying from as low as 54 to 83 kg ha^{-1}. On the other hand, there was little variation among previous cowpea plots.

The results of the field trials showed that there was little difference among the cowpea cultivars used in the study. As pointed out by Nnadi & Balasubramanian (1978), the density of roots and the length of the period between harvesting and next planting would determine whether or not the root N was mineralized and how soon this occurred. The transformation processes would be affected by environmental factors, especially temperature and moisture. It appears that environmental conditions are sufficiently favourable and the period from the harvesting of the legume to the next planting sufficiently long for the mineralization of root N, even when the nitrogen content is not very high.

The higher levels of available N in previous groundnut plots compared to cowpeas might be due to the fact that it is impossible to recover all groundnut pods during harvest. In fact, it is always observed that previous groundnut plots usually have many sprouting seeds once the rains set in. Such seeds being very high in nitrogen (ca. 4.3 % N) would mineralize rapidly when ploughed down. Since groundnut plants are usually uprooted from the soil and carried off the field, the higher level of available N usually observed on previous groundnut plots has to be explained in terms of unharvested pods, some lateral roots left in soil, and other factors not yet obvious.

Residual effects of inter-cropped cereal/legume systems

In the traditional farming system of the savanna areas, cowpeas are usually inter-planted at very low densities, usually 10–20,000 plants ha^{-1}, among cereals or yams (Steele, 1972). Also the haulms are taken away. This in effect means that the mass of roots per unit area would also be low and the contribution of the legume roots to the nitrogen economy of the soil would be limited. The effects of inter-cropping on the soil are at present receiving some attention. The objective of this study, therefore, is to see how inter-cropping of maize with cowpeas and soya beans affect the N status of the soil.

In the present experiment the legume to maize ratio was 1:2. All plants were planted on top of ridges and all above-ground parts removed from the field after harvest. In the following year mineralizable nitrogen was determined by incubating soil samples from the plots for two weeks at 35°C. The amounts of mineral N present at the end of the incubation period are shown in Table 5.

Previous sole-crop legume plots had higher values of available N than legume/cereal mixtures, although in the case of soya bean the difference between sole soya bean and inter-cropped soya beans was insignificant. But the sole-crop cowpea had a significantly higher available N than the inter-cropped plots. The soya bean crop is noted for its efficiency in translocating fixed nitrogen from the root to the seed. This may account

Table 5. Available N from sole and inter-cropped legumes

Previous crop	Available N ($kg\ ha^{-1}$)
Sole soya bean	32.9
Soya bean + maize	30.0
Sole cowpea	39.3
Cowpea + maize	28.1
Sole maize	27.4

for the relatively lower N values on previous soya bean plots compared with cowpea plots. The population of the legume crops in the mixture was 19,925 plants per hectare, which is near the upper limit of population that farmers would use (Steele, 1972). It appears that farmers would get little or no benefit in terms of residual nitrogen when cowpeas and soya beans are inter-cropped with maize. The experiment has been done only once. More trials are in progress.

Effect of different cultivation systems on nitrogen mineralization

The investigation on the effect of different cultivation methods on the quantity mineralized early in the growing season has been initiated. The experiment is two years old. The preliminary data, which are for the second year, are given in Table 6. The results show that hoe-ridging and zero tillage plots gave higher amounts of N than the bullock method, which in turn gave higher amounts than conventional mechanical tillage methods. The high value for the hoe-ridging method could be due to the concentration of turned-in weeds along the ridge. These weeds, if high in nitrogen, would decompose rapidly in the season. The high value of mineral N on zero tillage plots where weeds were chemically controlled is surprising. One would expect a lower rate of decomposition of weeds on zero tillage plots since the dead plants would be lying on top of the soil.

Table 6. Effects of cultivation methods on mineral N in 0–15 cm layer

Cultivation treatment	Mineral N (ppm)
Hoe-ridging	13.8
Zero tillage	12.1
Bullock ridging	8.2
Mechanical tillage	6.2*

* Mean of six different tractor cultivation methods.

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NITROGEN CYCLING IN A TEAK PLANTATION ECOSYSTEM IN NIGERIA

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Abstract

The nitrogen uptake by above-ground vegetation and cycling through litterfall and litter decomposition in a thinned teak plantation is quantitatively described. A 25-year-old teak stand carrying 1530 trees per hectare and weighing 339.55 metric tonnes contained 951 kg of nitrogen per hectare. Over 70 % of the N was in the tree trunk, 21 % in branches and 8 % in leaves which are shed every year.

Nitrogen return to the soil through litterfall occurred throughout the year and was closely associated with quantity of litterfall. A total of about 49 kg of N was returned to a hectare of ground surface.

Return through decomposition also occurred throughout the year but most rapidly between May and August, or early rainy season. After 12 months about 7.5 kg of N per hectare was still left to which new litter would be added. Application of thinning increased N uptake per tree and its content in the foliage owing to increased biomass production, although stands whose stockings were reduced to one-third ten years earlier showed decreased N requirement per hectare. Thinnings did not significantly affect the rates and patterns of N return. The implications of harvesting and forest fertilization on the management of this ecosystem are discussed.

Introduction

Nitrogen is a key element in forest ecosystems, especially in man-made forest plantations. As a constituent of amino-acids – the building blocks of proteins – it is essential for life of both plants and animals. But despite its abundance as molecular nitrogen in the atmosphere, nitrogen in plant-available form is one of the most widely deficient nutrients in soils and limits primary productivity in many ecosystems. Consequently, the cycling of nitrogen is usually the key to improved as well as continued production of food, fodder and fibre in many ecosystems.

Besides the nutritive value, nitrogen also poses a great pollution threat to the environment if its cycling system is not properly handled. Excess nitrogen from over-fertilization, which for instance finds its way into lakes and other aquatic ecosystems, may cause eutrophication and its associated decrease in floral and faunal species diversity (Smith, 1974; Leak & Martin, 1975; Nwoboshi, 1977; Bolin & Arrhenius, 1977).

According to Crutzen & Ehhalt (1977), the use of nitrogen fertilizers increases the amount of nitrous oxides emitted to the atmosphere which in turn causes catalytic oxidation of the ozone layer in the stratosphere that shields the atmosphere from harmful ultraviolet radiation. Nitrites have also been reported to react with human blood to reduce its oxygen-carrying capacity, while many nitrosamines have proved to be potent carcinogens (Lijinsky, 1975; Magee, 1977). Nitrogen is therefore important in any ecosystem because of its nutritive value and the environmental problems associated with it.

To manage a plantation ecosystem so as to increase productivity while avoiding environmental pollution it is essential to know how nitrogen is cycled, the nitrogen sinks and transfer processes and their rates, in the ecosystem. This enables the forest manager to take into account or at least to foresee the full range of impacts of any proposed silvicultural operation that involves input or output of nitrogen in the plantation ecosystem. This paper provides some crude estimates of nitrogen content and transfer processes in a 25-year-old thinned teak plantation ecosystem in Ibadan, Nigeria.

Materials and methods

The study was carried out in the 1953 plantings of the University of Ibadan teak plantation. The stand which was originally raised at a stocking of 2500 plants per hectare, had by 1967 been thinned down naturally to 1850 stems ha^{-1}. At this time portions of the stand were reduced to one-quarter (heavy thinning) and one-half (moderate thinning) of the standing stocking. Separate portions of the stand were also left unthinned to serve as control. These treatments were replicated three times in a randomised block design using 40 m × 40 m plots.

Nitrogen accumulation in stem wood, stem bark and branches through the 25 years and leaves in the 25th year was arrived at by using the biomass and nitrogen concentration data for the various components to obtain nutrient content. Biomass of the above-ground parts of the trees was obtained by destructive sampling of 20 trees selected in proportion to the diameter size class distribution as previously described (Nwoboshi, unpublished). Biomass of coppice growth in the thinned plots was obtained by harvesting sample areas (11 m × 11 m) in all plots. The nitrogen requirement for the 25th year was taken as that for the mean annual increment of the stem and branch biomass and the foliar nitrogen content for the year since teak is deciduous.

Nitrogen return through litterfall and litter decomposition was obtained from litter dry weight and its nitrogen concentration. Litterfall was measured monthly from a 1 m × 1 m table placed in the centre of each plot just before the flush of new leaves. For litter decomposition studies, the dry weight of the previous year's litterfall on the forest floor was estimated by sampling. Subsequently, 10 boxes (each of 0.5 m × 0.5 m dimension) were used in each plot to enclose random portions of the litter. Each box was covered with nylon mesh to prevent addition of current year's litter and one random box per plot was sampled at monthly intervals to monitor changes in nitrogen content of residual litter and the underlying 0–15 cm and 15–30 cm mineral soil horizons. Nitrogen concentration in all cases was determined by the semi-micro Kjeldahl method.

Results and discussion

The nutrient cycle in the forest ecosystem consists of a series of nutrient pools connected by transfer processes. According to Jorgensen *et al.* (1975) the rate of nutrient transfer

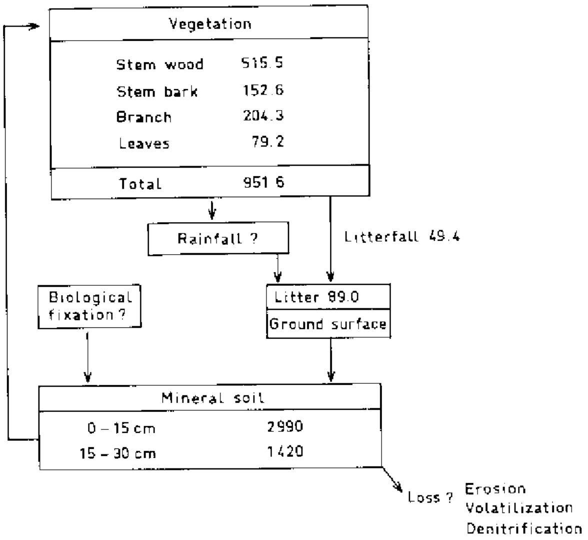

Figure 1. Nitrogen pools (kg ha^{-1}) and transfer paths (kg ha^{-1} yr^{-1}) in a teak plantation ecosystem.

from one pool to another varies between plant species, soils and ecosystems. It also varies with the nutrient under consideration. Generally too slow or too rapid rates of transfer often produce nutrient imbalances which may affect the productivity of the forest ecosystem adversely. The nitrogen pools and transfer paths in the studied teak plantation ecosystem are illustrated in Fig. 1. This shows that the cycling system has three major components: the vegetation, litter on ground surface and mineral soil which constitutes the main source of plant available nitrogen. These are connected by nitrogen uptake, litterfall and litter decomposition. How this cycle operates will be illustrated below by examining nutrient uptake and movement from one pool to another.

Nitrogen uptake

The average nitrogen concentration and content in various components of the aboveground biomass are shown in Table 1. The nitrogen concentration was highest in the

Table 1. Nitrogen concentration and content in a 25-year-old teak stand

Plant part	Biomass (kg ha^{-1})	Concentration (% N)	Total content (kg ha^{-1})	% of total
Stemwood	247 864	0.23	515.5	54
Stem bark	36 242	0.42	152.6	16
Branch	49 694	0.42	204.3	22
Leaves	5 654	1.49	79.2	8
Total above-ground	339 533	–	951.6	100

foliage and decreased in the order leaves, branches, bark and wood. After 25 years of growth, a teak stand carrying 1530 trees per hectare and weighing 339.55 metric tonnes contained 952 kg of nitrogen per hectare. About 70 % of this is found in the tree trunk, the conventionally harvested part of this species, 22 % in the branches and 8 % in the foliage, which is replaced every year. The mean annual nitrogen requirement for this stand taken as the amount of nitrogen required for the annual increment of stem and branch biomass plus that required for the replacement of leaves, has been estimated from data in Table 1 as 114.3 kg ha^{-1}, about 70 % of which goes into renewal of foliage.

Nitrogen return to soil surface

The return of nitrogen through litterfall occurs throughout the year (Fig. 2), with the quantity returned closely following the quantity of litterfall. Other sources of nitrogen return from the trees include seedfall and branch shedding. The peak period of return occurred between November and February, during which over 50 % of the total return, estimated as 49.3 kg ha^{-1} yr^{-1}, was made.

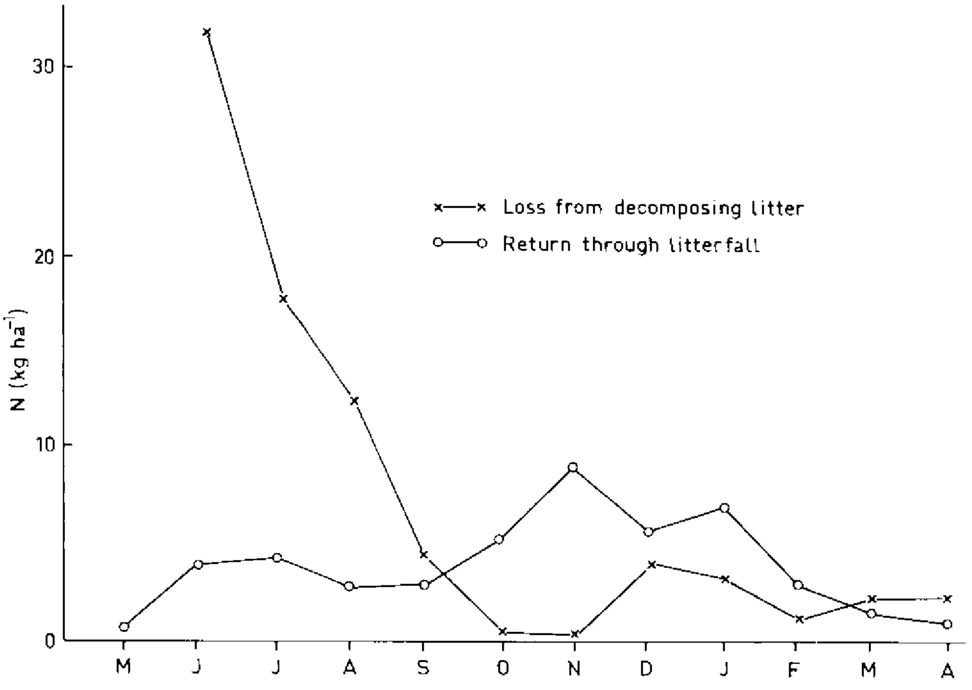

Figure 2. Nitrogen return to ground surface and mineral soil.

Nitrogen return to mineral soil

The nitrogen returned to surface soil as litter is not yet in a form available for re-absorption by the tree roots until it is mineralized through decomposition. As with nitrogen return to the soil surface, nitrogen release through decomposition occurred throughout the year (Fig. 2), but most rapidly between May and August or early in the first rainy season following the litterfall. The nitrogen content of the litter on the soil surface was estimated as 89 kg ha^{-1}. Over 71 % of this was released during the first four months, and after 12 months 81.5 kg or 92% of the nitrogen had been released.

This increased mineralization of nitrogen is reflected in the nitrogen status of the mineral soil underneath the decomposing litter. Both concentration and content in the soil increased with time but decreased with depth (Table 2, control column). The greatest change occurred in the 0–15 cm horizon, in which the nitrogen content increased from 2243 kg ha^{-1} in May 1977 to 3588 kg ha^{-1} in March 1978. The nitrogen status of the 15–30 cm horizon showed comparatively little change with time.

Table 2. Nitrogen concentration and content in 0–30 cm of soil beneath decomposing teak litter

	Control		Moderate		Heavy	
	Conc. (% N)	Content (kg ha^{-1})	Conc. (% N)	Content (kg ha^{-1})	Conc. (% N)	Content (kg ha^{-1})
0–15 cm horizon						
May 1977	0.10	2243	0.10	2243	0.08	1794
October 1977	0.14	3140	0.12	2691	0.10	2243
March 1978	0.16	3588	0.14	3140	0.12	2691
15–30 cm horizon						
May 1977	0.07	1570	0.07	1570	0.06	1346
October 1977	0.06	1346	0.06	1346	0.07	1570
March 1978	0.06	1346	0.07	1570	0.07	1570

Nitrogen cycling in the 25th year

The quantity of nitrogen required for above-ground biomass growth has been estimated as 114.3 kg ha^{-1}. The bulk of this is taken up from the mineral soil and channelled to the various components. Some are also obtained through internal nitrogen translocation, mainly from the foliage. For example, of the 79.2 kg ha^{-1} channelled to the foliage, only 49.3 kg was carried away as litter, indicating a back translocation of 30 kg ha^{-1} before leaf abcission. It has also been earlier shown that the decomposition of freshly fallen and old litter on the forest floor releases 81.5 kg of nitrogen per hectare per year.

A comparison of the nitrogen uptake and nitrogen return through decomposition and precipitation shows a deficit or nitrogen drain of about 33 kg ha^{-1}, which has to be met from the soil nitrogen reserves. This estimate is, however, quite conservative for this stand, since the nutrient requirement was based on the mean annual nitrogen increment in the biomass. Normally, the nitrogen requirement of the stand would increase with age and stand development. The need at the 25th and subsequent years would therefore be much higher than that used in the above calculation, indicating that the annual nitrogen demand will probably be greater than its annual release from organic matter decomposition by a wider margin. If the plantation is to grow at an acceptable rate, this nitrogen deficit must be supplied by the soil nitrogen reserve. However, the high nitrogen content in the 0–30 cm horizon that also carries a mat of teak roots, and lack of any sign of deficiency symptoms on the trees, so far, indicates that the site is not yet nitrogen deficient.

Effect of thinning on nitrogen cycling

The effects of a thinning treatment applied 10 years earlier at the age of 15 are shown in Table 3. While the nitrogen concentration of the various components of the above-ground biomass seemed unaffected by the thinning treatment, nitrogen content of the mean tree increased with the thinning intensity. This is chiefly due to increased growth normally induced by thinning. The greatest increases were in wood and the foliage components. Thinning also induced coppice growth with its additional nitrogen requirement. The quantity of nitrogen taken up by these re-sprouts increased with thinning intensity or the amount of biomass produced which was proportional to the amount of light introduced to the forest floor. However, irrespective of this additional requirement and the greater nitrogen requirement per tree, thinned plots still had, 10 years after the thinning, lower nitrogen demand than unthinned plots.

Table 3. Effect of thinning on nitrogen uptake and distribution in a 25-year-old teak plantation (Figures in parenthesis refer to coppice content)

Thinning	Wood	Bark	Branch	Leaf	Total
	% N				
Control	0.23	0.42	0.24	1.49	
Moderate	0.27	0.49	0.29	1.46	
Heavy	0.35	0.39	0.33	1.48	
	N content of mean trees (g)				
Control	566	176	265	93	1100
Moderate	920	280	340	110	1650
Heavy	1150	260	270	180	1860
	N accumulation (kg ha^{-1})				
Control	515.5	152.6	202.4	79.2	951.7
Moderate	413.4(1.19)	187.0(0.11)	228.1(0.10)	72.5(0.46)	901.0(1.82)
Heavy	402.9(2.02)	91.2(0.56	75.9(0.09)	62.9(1.50)	652.9(4.22)

The quantity of nitrogen returned as litter to the forest floor, or through subsequent decomposition to the mineral was not markedly influenced by the thinning applied 10 years earlier (Figs. 3 and 4). The rate of nitrogen release was, however, higher in thinned than

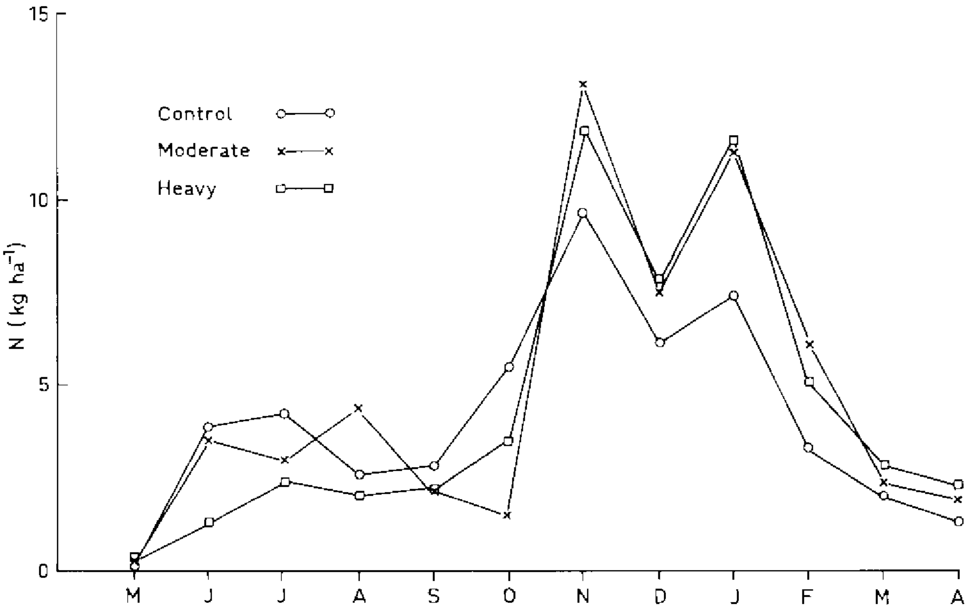

Figure 3. Thinning effects on N return through litterfall.

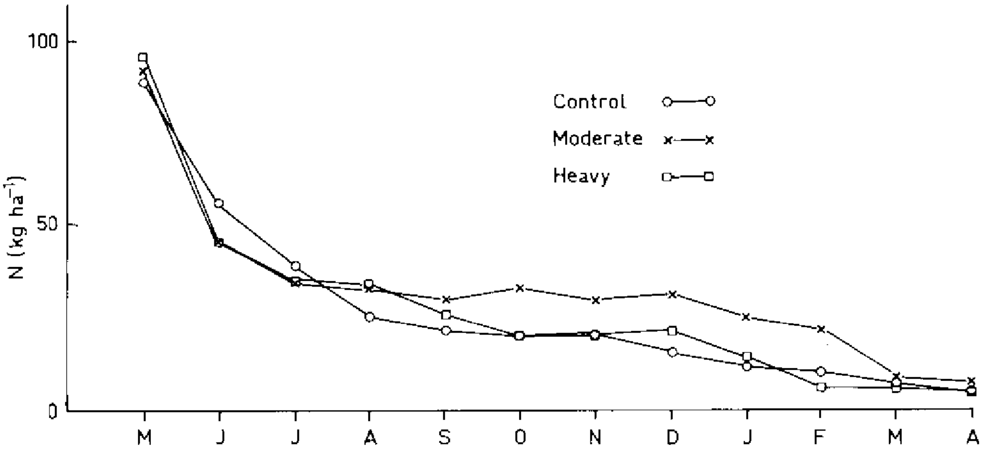

Figure 4. Thinning effects on N changes in decomposing litter.

Table 4. Effects of thinning on transfer rates of N in a 25-year-old teak plantation

	Control	Moderate thinning	Heavy thinning
Nitrogen uptake			
Stem wood	515.5	413.4	403.0
Stem bark	152.6	187.0	91.2
Branch	202.4	228.1	95.9
Leaves	79.2	72.5	62.9
Total	951.7	1101.0	652.9
Mean annual demand	114.4	105.6	86.5
Transfer within the tree			
Leaf content	79.2	72.5	62.9
Litter content	49.4	57.1	53.7
Translocation	30.0	15.4	9.2
Transfer to ground surface			
Litter content	49.4	57.1	53.7
Rainfall	?	?	?
Transfer to mineral soil			
Return decomposition	81.5	84.1	88.9
Return – demand	–33.0	-21.5	+2.4

unthinned plots, especially between May and August. Data presented in Table 4 also show that both nitrogen requirement per hectare per year and nitrogen retranslocation prior to litterfall decreased with thinning intensity. This is attributable to lower total biomass production in the thinned plots. The ability of nitrogen derived from litter decomposition to satisfy nitrogen demands of the standing trees also increases with thinning intensity. In a 25-year-old teak stand, while the unthinned stand required 33 kg of N from the soil nitrogen reserve, stands whose stockings were reduced to a third, 10 years earlier, can balance the nitrogen demand of the residual trees with nitrogen from litter decomposition. These observations support the views of Jorgensen *et al.* (1975) that there is an optimum sustained annual biomass production for each site and that this optimum production depends on the ability of the site to provide nutrients and other factors required for growth as well as on the management practices imposed on the system. Our results thus indicate that at the age of 25, the optimal stocking for this stand, with respect to its nitrogen economy, appears to be about 350 trees per hectare (the heavy thinning grade).

Besides thinning, foresters can also influence the nitrogen economy and cycling in a forest ecosystem through harvesting at the end of the rotation. The magnitude of the influence in this case will vary with the quantity of biomass removed, the nutrient concerned and the manner of its storage in the ecosystem. The total stemwood per hectare may be harvested and carried away from the site with its nitrogen content. For nitrogen in particular, a complete biomass harvest followed by site preparation burning as practiced in agric-silviculture could reduce the nitrogen status of a site to a dangerously low level for any subsequent acceptable rates of growth. This is generally true for elements lost as gases when vegetation burns and those that are stored mainly in vegetation rather than in the soil.

Foresters can also use judicious application of nitrogenous fertilizers to correct any imbalances in the nitrogen cycling system especially where, on nitrogen-deficient soils, nitrogen demand exceeds nitrogen return through nitrogen mineralization by a significant margin. Health hazards often attributed to nitrogen usually arise from lack of appreciation of the nitrogen-carrying capacity of the ecosystem. Quantification of nitrogen in various components and transfer systems of the ecosystem concerned will enable the manager to foresee the impact of his actions on the ecosystem and enable necessary remedial decisions to be made at the right time.

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NITROGEN CYCLING IN A SOIL-TREE SYSTEM IN A SAHELIAN SAVANNA. EXAMPLE OF *ACACIA SENEGAL*

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Abstract

The cycling of N in the soil-tree system was studied in a Sahelian Savanna where *Acacia senegal* is largely represented as isolated trees or in clumps of a few trees. The herbaceous stratum is scarce and irregular in the open but it is dense under the trees. The return of organic matter and N from vegetation to soil by the litter was calculated and the herbaceous litter was found to be an important component under the trees, compared to the tree litter. The decay of organic matter seems to be fast, as only the first centimeters of soil show a greater accumulation of organic matter and N than in the open. The accumulation of N and its repartition was measured. The mineralization of organic N in the top soil was studied, and was found to be relatively important under the trees. Most of it occurred in the beginning of the rainy season and a short period of accumulation of mineral N took place at this time; the mineral N content of soil decreases afterwards during the growth of the herbaceous stratum. Mineral N produced was mainly in the form of NO_3-N, and the possibility of N losses during periods of heavy rainfall is discussed.

Introduction

The need for tree conservation in the Sahel, and the role of trees in the Sahelian ecosystem has been emphasized during the recent years. One aspect of the role of trees is their impact on soil nutrients and on nutrient cycling (Gerakis & Tsangarakis, 1970; Jung, 1969). In the present paper we shall study the nitrogen cycle in a soil-tree system in a Sahelian savanna of North Senegal. *Acacia senegal* was chosen because it is present in a great part of the Sahelian zone and is well represented in the study area. Besides, it has some economic importance as a gum tree and is used for re-afforestation.

The study area was described by Bille *et al.* (1972). The mean annual precipitation is 300 mm falling during a three-month wet season. The relief is a succession of dunes and depressions. The trees are scattered on the dunes and slopes, their density being higher in the depressions. The herbaceous stratum is scarce and irregular in the open, but is dense and higher under the trees. The population of *Acacia senegal* was studied for several years in a protected quadrat (Poupon, 1976).

The N cycle study was undertaken recently in the same quadrat. Twelve trees were studied for total N, mineral N, and mineralization in soil. Sampling was done on several trees to obtain mean values of N content of leaves and wood, and for herbaceous biomass and N content. Biomass of trees was estimated with established relationship between tree girth and biomass.

Accumulation of nitrogen in the vegetation

Accumulation of nitrogen in the tree

The biomass of 21 trees was measured by H. Poupon and relationships were established between tree girth and the different parts of tree biomass: twigs, branches, trunk, roots and leaves. The equations were in the form of $\log y = a \log x + b$ where y is the biomass, and x the girth of the tree.

These equations were used to calculate the biomass of the trees under which soil N was studied. Samples of wood and leaves were analysed for N content (N content of root was assumed to be the same as that of wood). Branches and trunk had the same N content of about 0.48 % (standard error, 0.09 for 13 samples). N content of twigs was 0.62 %, N content of leaves was 3.0 % (standard error, 0.29 for 12 samples). The nitrogen contents in the trees are given in Table 1.

Accumulation of nitrogen in the herbaceous standing crop

The biomass of herbs under the trees was measured in 1976 and 1977 at the end of the wet season, in October, and N content was determined. Because of the low precipitation in 1977 (120 mm) the biomass of herbs was weak, but its N content was higher. Nevertheless, the accumulation of N was lower than in 1976.

The following values, for 1976, are assumed to represent a "mean" year. The biomass of aerial parts under *Acacia* was 0.42 kg m^{-2} (standard error, 0.1 for 8 samples) with a mean N content of 1.07 % (standard error 0.3). The biomass of roots was 0.26 kg m^{-2} (standard error, 0.05) with a N content of 1.66 % determined on one composite sample. The total N immobilized was 8.7 g m^{-2} under the trees and 4.7 g m^{-2} in the open.

In 1977, with low rainfall, the aerial biomass of herbs under *Acacia* was only 0.23 kg m^{-2} with 1.33 % N. The root biomass was not measured but we can estimate the total accumulation of N to about 6 g m^{-2}.

Return of nitrogen to the soil

Nitrogen is returned to the soil by tree litter, leaching of leaves and branches by throughfall, herbaceous litter, roots (Table 2). *Acacia* leaves turn yellow before they fall. Yellow leaves taken off the tree or freshly fallen on the soil were analysed, showing a N content of 2 %, i.e., two-thirds of the N content of green leaves. One-third of leaf nitrogen is withdrawn to the tree before leaf-fall. The N content of yellow leaves was used with the leaf biomass to calculate the annual return to the soil by litter. Annual return by tree roots was not measured.

Throughfall was studied during two years to estimate the amount of nitrogen leached from the tree crown. The N content of rain under the tree and in the open was determined. During the wet season of 1976 (from 330 mm of rain), 2.2 g of N m^{-2} was brought to the soil, of which 1.8 g m^{-2} was washed from the tree crown, and 0.4 g m^{-2} was supposed to have come from the atmosphere. Stem flow was measured on some occasions, but the amount of N returned to the soil in this way was small.

In the studied area all the herbaceous species are annual, so it can be assumed that all

Table 1. Accumulation of N in trees

Tree No.		1	2	3	4	5	6	7	8	9	10	11	12
Girth	(cm)	26	27	35	35	38	39	40	47	48	49	49	57
situation[1]		D	D	D	LS	LS	LS	LS	D	LS	LS	LS	LS
Twigs biomass	(kg)	4.0	4.4	9.0	9.0	11.3	12.2	13.1	20.3	21.5	22.8	22.8	34.6
	N(g)	25	27	56	56	70	76	81	126	133	141	141	214
Wood biomass	(kg)	21	23	38	38	45	47	50	70	73	76	76	106
(trunk+ branches+roots)	N(g)	102	109	181	181	215	227	233	335	351	366	366	511
Leaves biomass	(kg)	0.25	0.26	0.39	0.39	0.44	0.46	0.48	0.61	0.63	0.65	0.65	0.83
	N(g)	8	8	12	12	13	14	15	18	19	20	20	25
Total N	(g tree^{-1})	130	140	250	250	300	320	330	480	500	530	530	750
	(g m^{-2})	23	31	44	10	9	31	32	38	49	32	40	23

[1] D = dune, LS = Lower part of slopes.

Table 2. Annual N return to the soil

Tree No.	1	2	3	4	5	6	7	8	9	10	11	12	Open LS
N in tree litter (g m^{-2})	0.44	0.91	1.70	1.40	0.36	0.28	0.94	0.97	1.24	0.78	0.98	0.52	–
Total N return (g m^{-2})	–	–	–	–	10.9	10.8	11.4	11.5	11.7	11.3	11.5	11.0	4.70
Total N return (g tree^{-1})	–	–	–	–	268	359	116	145	119	187	152	354	–

Table 3. Accumulation of N in soil (0–10 cm)

Tree No.	1	2	3	4[1]	5	6	7	8	9[1]	10[1]	11[1]	12	Open D	Open LS
N content (%)	0.28	0.47	0.43	0.64	0.29	0.51	0.55	0.47	0.76	0.53	0.76	0.80	0.17	0.27
N (g m^{-2})	48	80	73	76	49	88	94	80	90	63	90	136	29	46
N (g tree^{-1})	542	456	328	433	1200	2920	959	1010	918	1045	1188	4379	–	–

[1] measured in 1976, others in 1977.

the nitrogen accumulated in the herbaceous standing crop is returned to the soil each year. The mean values of herbaceous biomass and N accumulation were not used for the small trees where they are probably lower (no measurements were made under them).

Nitrogen accumulation in soil

Total nitrogen in soil was first studied by establishing the profile distribution of N content under the tree. This was done under several trees and the general trend observed was that of the example given in Fig. 1. It shows that except in the soil around the trunk, nitrogen was evenly distributed under the tree crown, and that only the surface layer of soil had a higher N content than in the open.

The N content of the 0–10 cm layer was determined every month in a composite sample for each tree studied. The annual means are given in Table 3. A positive correlation ($r = 0.71$) was observed with the tree girth, which indicates that accumulation of nitrogen in the soil increases during the life of the tree.

Nitrogen mineralization in soil

The profile of potential mineralization, measured by three-week incubations of humidified soils, is illustrated by the example given in Fig. 2. It can be observed that mineralization occurs principally in the first 10 cm of soil and that deeper soil has significant production of mineral N only near the trunk.

Mineralization *in situ* was measured in the surface soil under the crown, taking samples at various distances from the trunk (the depth of sampling was 0–7 cm the first year and 0–10 cm in the second year). Measurements were made every four weeks from June to October, and the results are shown in Table 4.

During the wet season, mineral N was produced mainly in the form of NO_3-N. The two years of measurement had different rainfall (330 mm in 1976, 120 mm in 1977). Nevertheless, the amount of mineral N produced was the same, as there was enough rainfall to achieve the mineralization of the mineralizable N present in the soil.

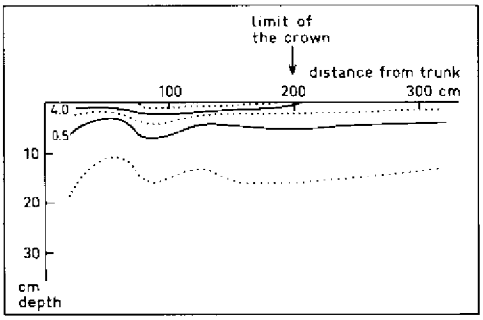

Figure 1. Isolines of total N under an *Acacia* (N o/oo).

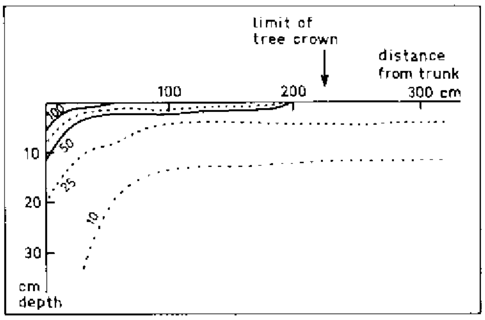

Figure 2. Isolines of mineralizable N under an *Acacia* (NO_3-N μg/g of soil/3 weeks).

Table 4. Mineral N produced in the soil from June to October

													Open	
Tree No.	1	2	3	4^1	5	6	7	8	9^1	10^1	11^1	12	D	LS
(g m^{-2})	3.6	3.8	4.2	8.4	6.2	5.5	14.9	3.1	8.4	7.0	6.3	9.0	2.2	4.5
N(g $tree^{-1}$)	41	22	19	48	153	183	152	39	139	86	83	290	–	–

[1] measured in 1976, others in 1977

The results in Table 4 show a great variability, and the relation between N mineralized and the age of the tree (tree girth) is weak. The mean values were 3.7 g N m^{-2} (30 g $tree^{-1}$) for *Acacia* on the dunes, and 8.2 g m^{-2} (142 g $tree^{-1}$) for trees at the foot of the slopes.

Some measurements were made during the dry season and showed a very low production of NH_4-N, probably due to chemico-physical factors (Dommergues *et al.*, 1970). The amount of NH_4-N produced ranges from 0.5 to 1 g m^{-2} for the whole dry season. Some occasional showers occur during the dry months which may bring about a production of mineral N if the soil is moistened, thus in 1976 there was a mineralization of 5 g N m^{-2} for the whole dry season with two showers.

Possible inputs and outputs

Inputs and outputs have not been measured but some observations were made on this subject. Inputs are mainly due to rainfall and to fixation of atmospheric nitrogen by microorganisms. Nitrogen concentration in rain was low and its contribution to inputs was about 0.4 g N m^{-2} yr^{-1}, as previously noted.

Symbiotic fixation could occur in a leguminous tree as *Acacia senegal*. Seedlings grown in the laboratory as well as seedlings found in the field showed numerous nodules. However, the search for nodules on adult tree roots was negative, except in one out of ten trees sampled. It is possible that symbiotic fixation occurs during the first years of tree life, but rarely in adult trees. In the laboratory it was observed that nodulation was inhibited when seedlings were grown in soil taken from under an old *Acacia*, but not in soil taken from the open. In the latter soil, addition of nitrate inhibited nodulation. The active nitrate production in soil under the tree during the wet season could be partly responsible for the absence of nodules in adult trees, but very little is known on this subject. The dryness is perhaps another factor limiting nodulation. Good nodulation was reported by Orchard & Darb (1956) in *Acacia mollissima* forests in a wetter zone, and they observed that nodulation decreased with increasing soil N. Moore *et al.* (1967) found poor nodulation in an *Acacia harpophylla* forest during a dry year, but observed substantial nodulation in wetter years. Non-symbiotic fixation in soil was not investigated.

Outputs by denitrification seem to be possible, at least in the lower part of slopes and in depressions where the soil can be temporarily waterlogged. Losses of mineral nitrogen were observed once during the wet season of 1976, after a heavy rainfall (Bernhard-Reversat, 1977).

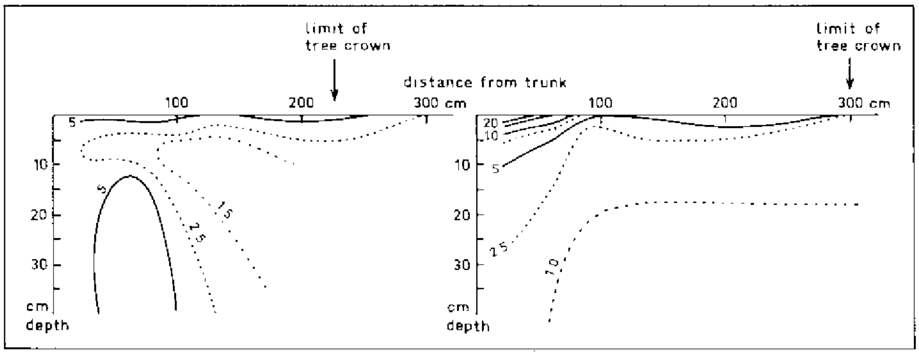

Figure 3. Isolines of NO_3-N under two *Acacia*, A: after the wet season of 1977, B: after a mean wet season, 1975 (NO_3-N μg/g of soil).

Leaching losses of nitrogen from the ecosystem are probably not important as water flow in the soil does not go deeper than 2 m, which is the depth of tree roots, according to A. Cornet (pers. comm.), who is studying the water balance in this ecosystem. Nevertheless, nitrate or soluble organic nitrogen may be leached below the bulk of the herbaceous roots after a heavy rainfall, particularly during a year as 1977 where the herbaceous standing crop was low and the amount of mineral N in it was smaller than the amount produced by mineralization. This could be the explanation for the nitrate distribution observed in a profile established after the 1977 wet season under *Acacia*, and shown in Fig. 3.

Conclusions

Taking the mean for adult *Acacia* situated in the lower part of slopes, the annual flow of nitrogen from vegetation to soil was about 12 g m^{-2}, which is a relatively high value, comparable to some forest ecosystems. It can be assumed that dense *Acacia* stands, like plantations, should have an active N cycle. An important part of the nitrogen flow passes through the herbaceous stratum, and is then available to cattle.

Compared to the nitrogen cycle outside the cover of trees, the nitrogen flow is 2.5 to 3 times greater under the tree, as shown in Table 5. The annual turnover of soil N is 10 % in the open, and 14 % under the tree. The higher N accumulation in herbs under the tree is not only due to a higher biomass, but also to a higher N content.

Table 5. Main flows and stocks of N under *Acacia* and in the open for a year with mean rainfall (means for the lower part of slopes)

	Acacia	Open
N immobilization in vegetation (g m^{-2})	32.6	4.7
N return to the soil (g m^{-2} yr^{-1})	11.3	4.7
Total N in soil (g m^{-2})	86.0	46.0
N mineralized (g m^{-2} yr^{-1})	11.5	4.9

If the year 1976, with mean rainfall, is compared to a year with low precipitation, as 1977, it appears than N flow from vegetation to soil is lowered:

	1976	1977
return by tree leaves	0.8	0.8
return by throughfall	1.8	0.6
return by herbaceous litter	8.7	6.0
Total	11.3	7.4

The production of mineral N in soil was about the same for the two years, as the soil was humid for a sufficient number of days to achieve the mineralization of the mineralizable N. Only if this number of days is not reached should the mineral N production be decreased. However, a succession of several dry years with low herbaceous growth should result in a decrease of mineralizable N.

In conclusion, rainfall is the main environmental factor influencing the nitrogen cycle in the system studied:

- by limiting vegetation growth and thus nitrogen utilization and return,
- by controlling mineral N production in the soil, more or less strongly according to the amount of precipitation,
- eventually by causing denitrification or leaching of mineral N in the soil.

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NITROGEN AND POTASSIUM BALANCE IN MAIZE IN THE HUMID TROPICS

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Abstract

Nitrogen is the primary element limiting maize yields in the humid tropics. On soils derived from sedimentary sandstone (eutric and dystric nitosols) which form a sizeable portion of agricultural land in the humid tropics of Nigeria, potassium is often very deficient and could be more important than nitrogen in maize nutrition because of the low reserves of K in the parent rock. Nitrogen and potassium requirements by the crop are influenced by the pre-cropping status of available N and K. Nitrogen increased yields by 80–100 % when soil nitrogen is less than 0.06 % and when yield increase is not significant the critical soil N is 0.12–0.15 % total N, with C/N ratio of 10 to 12. Significant yield increases (above 30 %) due to K are observed when soil-available K (exchangeable K) is less than 0.15 meq. 100 g^{-1}. The critical levels of N and K in the plant desirable for high maize yields are 3.2–3.4 % N and 2.0 2.2 % K respectively, with an N/K ratio of 1.5–1.6.

Introduction

Nitrogen and phosphorus responses, unlike potassium, are widely reported from many food crops in the tropics (Vine, 1953; Agboola, 1972; Amon & Adetunji, 1973; Jones, 1974). This lack of response to K is often due to low intensity of cropping, low yielding crop varieties and potassium-rich parent rock on which the soils were derived (Heathcote, 1973; Sobule *et al.*, 1975). Trials carried out on soils derived from sandstone indicated that potassium could be more limiting than nitrogen or phosphorus even just after clearing a secondary bush fallow (Amon & Adetunji, 1970; Sobulo *et al.*, 1975). This high response to K was partly due to low reserves of K on this soil compared with soils on basement complex rocks (Sobulo, 1973). Potassium deficiency on sandstone could be aggravated by high nitrogen application. Bromfield (1967) reported a strong depression of K uptake and grain yield using 80 kg N ha^{-1} on soils derived from sandstone on Agege soil series (ferralitic oxisol) in the forest zone of Nigeria.

Nitrogen application up to 100 kg N ha^{-1} and 25 kg K ha^{-1} is recommended for high maize yields in the savanna area where sunlight does not place too much of a ceiling on yield, and 80 kg N ha^{-1} and 25 kg K ha^{-1} for the forest zone in Nigeria. It is likely that at this relatively high rate of N (80--100 kg ha^{-1}) the blanket recommendation of 25 kg K ha^{-1} may be inadequate for optimum maize yield. Interaction with another third element, magnesium, could also occur at this high rate of N (Jones, 1974).

Interaction between K and Mg and the critical Mg/K ratio for high yield of maize were deduced from pot trials by Lombin & Fayemi (1975).

This paper discusses a preliminary study on N and K balance in maize on an oxisol derived from sandstone in tropical western Nigeria.

Materials and methods

History of site

The study was carried out at Ikenne on Alagba soil series, derived from a sedimentary sandstone. The soil is low in K reserve. Total K is 0.02 %. The physical and chemical characteristics of the soil are given in Table 1. The soil is a entric nitosol (FAO classification) and is well drained having a sandy loam texture at 0–30 cm depth but 30–40 % clay below 50 cm. Mean annual rainfall at Ikenne, in the rain forest zone with a tropical climate, is about 130–140 cm.

Table 1. Physical and chemical properties of an Alagba soil series (0–15 cm depth) in 1977 before cropping

pH	Mechanical analysis Sand %	Silt %	Clay %	Organic carbon %	Total N %	Exch. K (meq. $100\,g^{-1}$)	Exch. Mg (meq. $100\,g^{-1}$)	C.E.C. (meq. $100\,g^{-1}$)
5.9	82.0	6.0	12.0	1.4	0.11	0.14	1.20	2.95

Field trials

Four field trials were carried out between 1977 and 1978. The first trial was in the early season (first season) of 1977. Four rates of N (0, 50, 100 and 200 kg N ha^{-1}) and four rates of K (0, 30, 60 and 120 kg K ha^{-1}) were applied in a factorial combination with three replications. The N and K were applied in two equal split doses at planting and at 4 weeks after planting. In the late (second) season of the year, the experiment was repeated using 0, 25, 50 and 100 kg N ha^{-1} but using the same previous rates of K. The change in the rates of N in this trial was because of low response to nitrogen observed in the first trial. In the third trial in the early season of 1978, the effects of applied N and K were investigated in another site but in the same location. The same rates of N and K were maintained. Soil analysis before cropping was carried out for available K and total N. Ear leaf was analysed for K, N and Mg at 7–8 weeks.

Results

The results in Table 2 contain the yield responses to N and K. Response to N was not significant, though yield increase due to N was observed with 50 kg N ha^{-1} and yield depression seemed to occur after that. Response to K was significant, though N and K interaction was not significant. The best yield was obtained with 50 kg N and 60 kg K ha^{-1}. The pre-cropping soil analysis was 0.11 % total N and 0.14 meq. K 100 g^{-1} of exchangeable K. The results of the late season trial were not reported because of the low yields as a result of drought. The residual effect of the N and K applied in the late season is given in Table 3. The results indicated significant response to K but not to N. The best yield of 6119 kg ha^{-1} was obtained with 50 kg N and 120 kg K ha^{-1}. Maize yield was depressed at nitrogen levels of 100 kg N ha^{-1}.

Table 2. Response of early maize to N and K on an Alagba soil series (cropped site) at Ikenne in early season 1977

kg K ha^{-1} / kg N ha^{-1}	Grain yield (kg ha^{-1}) 0	30	60	120	Mean
0	1845	2255	2182	2318	2150 C
50	1936	2691	3245	2291	2541 C
100	1891	2082	2591	2473	2259 C
200	1964	2618	2436	2718	2434 C
Mean	1909	2412	2614	2450	
	B	A	A	A	

N.B. Means with the same or no letters are not significantly different at 5 % probability.

Table 3. Response of maize to N and K on an Alagba soil series (a cropped site) in early season of 1978

kg K ha^{-1} / kg N ha^{-1}	Yield (kg ha^{-1}) 0	30	60	120	Mean
0	4267	5350	5380	5099	5024 C
25	5506	5721	5821	5237	5571 C
50	4906	4955	5341	6119	5331 C
100	4740	5164	5612	5561	5270 C
Mean	4855	5298	5539	5504	
	A	AB	B	B	

N.B. Means with the same or no letters are not significantly different at 5 % probability.

Table 4. Response of maize to N and K on an Alagba soil series (uncropped site) in early season of 1978. There were no significant differences at the 5 % probability level

kg K ha / kg N ha^{-1}	Yield (kg ha^{-1})				
	0	30	60	120	Mean
0	5494	6615	5050	6794	5988
25	6141	5366	5743	6711	5991
50	6707	6360	5936	5620	6156
100	6252	6837	6749	7193	6758
Mean	6148	6294	5869	6580	6223

Table 5. Main effects of N and N/K content on maize in an oxisol in Nigeria. There were no significant differences at the 5 % probability level

kg N ha^{-1}	% N	% K	N/K	Yield (kg ha^{-1})
0	3.11	2.05	1.58	5024
25	3.15	1.88	1.65	5571
50	3.29	1.99	1.66	5331
100	3.19	1.92	1.67	5276

Table 6. Main effects of K and N/K relationship in maize on an oxisol in Nigeria

kg K ha^{-1}	% N	% K	N/K	Yield (kg ha^{-1})
0	3.08	1.95	1.61	4855 A
30	3.19	1.82	1.74	5298 AB
60	3.15	1.97	1.62	5539 A
120	3.33	2.10	1.60	5508 B

N.B. Means with the same or no letters are not significantly different at 5 % probability.

The mean available K on the control plots (receiving no N and K fertilizers) was 0.10 meq. 100 g^{-1}. Response to N or K was not observed in the trial which was carried out on the secondary bush site of 4 years old (Table 4). Pre-cropping soil analysis was 0.12 % total N and 0.25 meq. 100 g^{-1} of K. Plant analysis of the ear leaf (Tables 5 and 6) on a cropped site in 1978 seemed to indicate that a total N content of 3.15 % was adequate for good yield while the main effect of K on yield showed that 1.97 % K in the crop gave the highest yield. Optimum N/K ratio for maximum yield was about 1.60. Similar critical values were obtained for the trial carried out on the secondary bush site.

Discussion

The results of three trials carried out in two years indicated that potassium is more limiting than nitrogen on an oxisol derived from sandstone. Potassium requirement could be as high as 120 kg K ha^{-1} at a moderate nitrogen application of 50 kg N ha^{-1}.

The pre-cropping soil analysis is of vital importance in determining the N and K requirements for maximum yield on the soil.

Response to nitrogen is small and not significant when total N is above 0.12 % and C/N less than 12. Maintenance dressing of about 50 kg N ha^{-1} is required for this nitrogen status.

On the other hand, potassium requirements range from 60 kg K ha^{-1} to 120 kg K ha^{-1} depending on available K status. The critical level of K above which yield response to K is unlikely is 0.20 to 0.25 meq. 100 g^{-1} on this soil. Response to K is certain when the value is less than 0.15 meq. 100 g^{-1}. Plant analysis figures at ear formation seemed to indicate that 3.15–3.20 % total N and 2.0 % K are adequate for maize with a N/K ratio of 1.60.

Deficiency values of N and K lie below 3.0 % and 1.8 %, respectively. Future work is directed towards identifying N and K status at 4 to 5 weeks when the deficiency could be corrected before the flowering stage. The critical N and K values obtained in this study agreed with pooled averages for eight varieties of maize in Nigeria (Agboola, 1972).

The high rate of N and K application has not induced magnesium deficiency in this study. Main effects of K on Mg content in the early season of 1978 were 0.29, 0.20, 0.28 and 0.25 % Mg for 0, 30, 60 and 120 kg K ha^{-1}, respectively, whereas 0.24, 0.30, 0.27 and 0.30 were obtained for 0, 25, 50 and 100 kg N ha^{-1} treatments. The critical value of Mg in ear leaf is 0.25 % Mg (Melstead *et al.*, 1969). It is expected that Mg problems would show up in the next two seasons at rates of K application of 120 kg K ha^{-1}. Future work is directed to evaluating the intensity of cropping before Mg deficiency could be induced.

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Nitrogen Cycling in West African Ecosystems

NITROGEN CYCLING IN THE SAVANNA ZONE OF NIGERIA

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Abstract

N cycling in the soil and soil-plant system of the savanna zone of Nigeria is reviewed, pointing out the inadequacy of the data in certain aspects of the cycle. Biological fixation contributes more than 40 % of the N input to the system, while burning forms the major component of N from the system. Better and efficient use of crop residues and animal and human wastes as well as inclusion of legumes in agricultural systems will increase the efficiency of N cycling in the savanna ecosystem. Except for semi-intensive cropping, the N balance appears to be on the positive side for various agricultural systems in the Nigerian savanna.

Characteristics of the Nigerian savanna

The savanna zone of Nigeria covers an area of 684,000 km^2 between latitudes 7°N and 13°N and longitudes 3°E and 15°E. In such a vast area, there is a great deal of variation in climate, soil type and vegetation. In general the annual rainfall and the length of the rainy season decrease from south to north and the mean annual temperature increases in the same direction (Kowal & Knabe, 1972). These climatic differences affect the severity of weathering and the rate of soil formation as well as the nature of vegetation, the kind of crop that can be grown and the potential dry matter production and economic yield. Keay (1959) recognized four ecological zones in the Nigerian savanna; names of these zones and their main features are given in Table 1.

Soil nitrogen sub-cycle

It is a universal observation that soil N undergoes a continuous transformation from organic to inorganic and back to organic forms. A brief description of this sub-cycle for savanna soils is given below.

Content

Most savanna soils have low native fertility and are low in total N. Jones & Wild (1975) reported a mean value of 0.051 % with a range from 0.008 to 0.29 % for total N. The

Table 1. Characteristics of the Nigerian Savanna Zones (Jones & Wild, 1975)

Feature	Southern Guinea	Northern Guinea	Sudan	Sahel
Annual rainfall (mm)	1000–1500	900–1300	500–1000	100–500
Rainy season (days)	190–250	130–190	80–130	<80
Main trees	*Daniellia olivara*	*Isoberlinia* spp.	*Combretum*, *Acacia*, *Terminalia* spp.	*Acacia*, *Comiphora* spp.,
Main grasses	*Andropogon tectorum*, *Imperata cylindrica*	*Hyperrhenia*, *Andropogon* spp.	*Andropogon gyana*	*Cenchrus* spp., *Aristidia* spp.,
Main food crops	yam, maize, sorghum	sorghum	sorghum, millet	millet
Main export crops	soyabean, sesame	cotton	groundnut	–
Main soil types	Ferrisols Ferrallitic Concretionary Ferruginous	Leached Ferruginous	Non-leached Ferruginous	Arid Brown
Mean organic carbon (%)[1]	1.22	1.09	0.78	0.40
Mean total nitrogen (%)[2]	0.104	0.093	0.067	0.034

[1] Calculated from the equation C % = 0.137 + 0.000865 x where x is mean annual rainfall in mm. (Jones, 1973).

[2] Derived using a mean C : N ratio of 11.7

low N values are closely linked with the generally low levels of soil organic matter, the mean C : N ratio being 11.7. As with the carbon, more than half of the observed variability in soil N content could be accounted for in terms of a multiple linear regression on soil clay content and mean annual rainfall (Jones, 1973). Mean soil N content is the highest in the Southern Guinea zone and decreases to the lowest value in the Sahel zone (Table 1).

Transformation

About 98 % of the soil N is stabilized in the soil organic matter, the remainder being in mineral forms. Organic N must be mineralized before plants can utilize it for their growth. The factors affecting the rate of mineralization in savanna soils have been discussed in detail by Jones & Wild (1975). In general, there is a flush of mineralization when the soil is remoistened after a period of dryness at the beginning of the rainy season; thereafter the rate of mineralization decreases very fast. Mean annual mineralization rate appears to be about 4 % of total N in savanna soils.

Later in the rainy season, when the profile is fairly wet, nitrification of mineralized ammonium takes place. Nitrification is normally slow in these soils due to paucity of nitrifying organisms (Wild, 1972a) and also due to the efficient uptake of NH_4-N by grass and fallow vegetation and inhibitory effect of grass roots on soil nitrifiers (Greenland, 1958; Wild, 1972a).

Immobilization of a certain amount of soil mineral N by microorganisms during organic matter decomposition is inevitable. The balance between mineralization and immobilization determines the availability of N in any soil. This is mostly controlled by the amount, frequency and nature of residues added to the soil.

Nitrogen recycling in the savanna ecosystem

A continuous flow of N takes place from soil to plants, from plants to animal and/or man, and from animals to man (Fig. 1). The return flow of N from plants, animals and man to soil takes place via their wastes. In this process an uncontrolled cycling of N goes on in nature. In the present system of N recycling there are enormous losses and leakages, with the result that there is only a partial return of N to the soil. Indefinite continuation of this system will deplete the soil N reserve and disrupt the environment.

Direct N addition to the soil is effected by rainfall and asymbiotic fixation. When crop and animal production is attempted through intensive agriculture, fertilizer N is used to

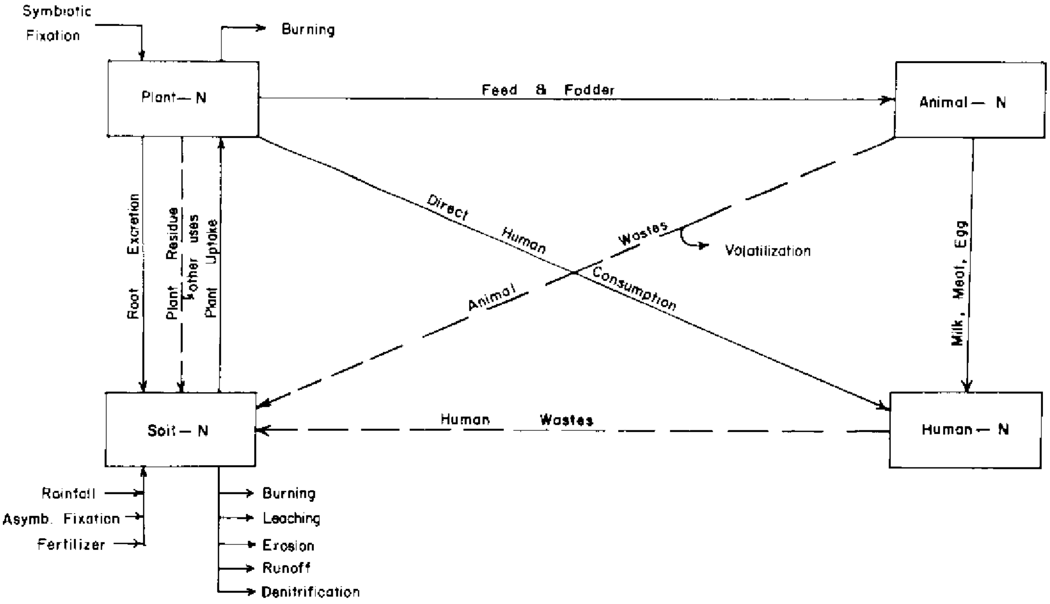

Figure 1. Nitrogen cycling in savanna agriculture.

supplement the natural addition. Symbiotic fixation adds N to the soil through plants, particularly legumes. Animal and human wastes, if properly conserved and utilized, return considerable amounts of N back to the soil. Losses of N from the soil plant system take place through erosion, runoff, leaching, volatilization, denitrification and burning. Crop removal in a sense is not a true loss if there is effective return of plant residues and animal and human wastes to the soil. However, the utilization of animal and human wastes is very poor in the savanna region, a considerable amount of N being lost through volatilization. Additions to and removals from the soil N pool will be briefly discussed in the following sections.

Addition to soil nitrogen pool

Rainfall

Over much of the savanna the annual N contribution from rainfall is not very large. Jones & Bromfield (1970) estimated this addition to be 4–5 kg N ha^{-1} yr^{-1} at Samaru.

Asymbiotic fixation

Free-living N-fixing organisms (*Azotobacter* and *Clostridium*) are usually present in savanna soils of Nigeria (Moore, 1963), but the low availability of P, Mo and energy sources may frequently limit their effectiveness (Jones & Wild, 1975). The very low level of mineral N in the virgin land or bush fallow may induce some fixation of atmospheric N_2 by asymbiotic soil organisms. The amount fixed thus seems to be very small and may not exceed 5 kg N ha^{-1} yr^{-1} in virgin and fallow soils.

Certain tropical grasses have been found to stimulate N_2-fixing activity in their root zones and their importance to the N economy of tropical soils is yet to be ascertained (Kass *et al.*, 1971; Döbereiner *et al.*, 1972). This may account for the fairly good performance of native millet and sorghum in poor savanna soils with very low N content. Balandreau & Villemin (1973) working with a grassland soil in Ivory Coast, estimated the rhizosphere N_2 fixation to be about 9 kg N ha^{-1} yr^{-1}. No such field data are available from the Nigerian savanna either for natural vegetation or for cultivated cereals.

Symbiotic fixation

The rhizobia living in legume root nodules fix N_2 from the atmosphere and make part of the fixed N available to the growing plant. The importance of symbiotic fixation for the N economy of vegetation in the natural ecosystem and of crops in agricultural systems would be very difficult to over-estimate. The most important natural species in the drier savanna is *Acacia albida*, which has been shown to add 15–20 kg N ha^{-1} yr^{-1} to the soil (Dancette & Poulain, 1969). Although tropical forage and grain legumes fix more than 100 kg N ha^{-1} yr^{-1} (Akinola, 1978; Akinola & Davies, 1978; unpublished), a large portion of it is removed in the economic yield both for animal and human consumption. Therefore the amount of N directly added to the soil from legumes is confined to the N contained in fallen leaves, nodules and stubbles. A good groundnut crop has been shown to add to the soil 30 to 60 kg N ha^{-1}, even when both pods and haulms are removed from the field (Jones, 1974; Balasubramanian *et al.*, 1978a). Other legumes can be expected to add similar amounts of N to the soil but there are no quantitative data available for their contribution. The major portion of legume N consumed by animals and man will be returned to the soil via their wastes, if they are conserved and effectively utilized for crop production.

Plant residues

Natural vegetation in the fallow and virgin savanna accumulate considerable amounts of N mainly through biological fixation and uptake from deeper soil horizons. Plant residues accumulate on the soil surface and decompose slowly, releasing mineral N to the soil. There is a great risk of accidental fires destroying such accumulated dried residues.

Crop residues constitute the major plant material added to the soil under cultivation either directly or indirectly through animals. Annual production of crop residues in the Nigerian savanna has been estimated at 31.4 million tonnes which contain 250 million kg of residue N (Balasubramanian & Nnadi, 1977). This works out to a potential addition of 8.8 kg N ha^{-1} of arable land. This is a significant contribution to traditional agricultural systems using no fertilizer N. However, the actual addition depends on how the crop residues are managed. A detailed account of crop residue management in the Nigerian savanna is given by Balasubramanian & Nnadi (1977).

Root excretion

There is no evidence for significant excretion of mineral N by healthy, intact root systems including legume nodules.

Fertilizer

No nitrogen fertilizer is used in the traditional system of pastoralism or arable farming. In the rotational bush fallow system the land is allowed to rest for variable periods during which time restoration of fertility and build-up of soil N are effected. The longer the fallow the better is the build up of soil N.

Maintenance of fertility and crop yields under continuous cultivation is achieved through the addition of manures and fertilizers. Fertilizer use is still in its infancy in Nigeria and the projected mean N consumption for the country is 1.49 kg ha^{-1} of cultivable land in 1978 (FDA, 1977).

The present recommended levels and suggested optimum rates of fertilizer N for various crops are given in Table 2. The present N rates may be adequate for the semi-intensive system of cultivation with moderate crop yields. To achieve the full potential of the new, improved cultivars of various crops, it is necessary to adopt the suggested N rates and this will ensure optimum yield. To achieve full benefits from the applied N, the level of other inputs should also be adequate. Balasubramanian *et al.* (1978b) have discussed in detail how to improve the efficiency of fertilizer N use in Nigerian agriculture.

Table 2. Recommended and suggested rates of N (kg ha^{-1}) for various field crops grown in the Nigerian Savanna

Crops	Present recommendation	Suggested rate1)
Sorghum	32	100
Millet	13	50
Maize	66	120
Rice	70	100
Wheat	25	100
Cotton	32	50
Cowpea	0	0
Groundnut	0	0

1) Suggested rates are intended for very intensive cultivation with a package of improved technology. These N levels can be reduced by half whenever cereals or cotton follow a good legume crop in the rotation. For Sudan and Sahel zones with inadequate rainfall the present recommended level of N is enough for millet, maize and sorghum.

Animal wastes

When grass and legume fodder as well as crop residues are consumed by animals only a small portion (less than 10 %) of the feed N is retained in the body. Therefore a major portion of the feed N is excreted as dung and urine. N gathered in the diet of the grazing animals is excreted only on a fraction of the land surface in any one year. Also more than 50 % of the faecal and unitary N is lost through volatilization due to drying of the urine-soaked soil and dung.

The estimated population of different classes of livestock and their potential manure production in the Nigerian savanna is given in Table 3. Annually about 75 million tonnes of manure containing 96 million kg of N are produced in the savanna zone; mean addition of manure N per ha of grazable fallow and natural savanna is 2.4 kg yr^{-1}.

Table 3. Livestock population (1978) and the potential manure production in the Nigerian savanna (area of the fallow and bush grazing land is more than 40 million hectares)

Class	Population1) in million	Number per hectare	Total manure (10^{12} kg)	N contribution from manure Total (10^6 kg)	(kg ha^{-1})
Cattle	10.86	0.27	65.16	71.68	1.79
Sheep	4.98	0.13	1.25	3.50	0.09
Goats	15.93	0.40	3.98	11.14	0.28
Pigs	0.17	–	0.26	0.26	0.01
Donkeys	2.09	0.05	2.26	3.14	0.08
Horses	0.43	0.01	0.65	0.85	0.02
Camels	0.02	–	0.10	0.12	0.00
Poultry	60.04	1.50	0.72	5.04	0.13
Total	94.52	2.36	74.74	95.73	2.40

1) Derived from FAO (1978). Savanna zone animal population as % of the total for the country needed for this calculation was obtained from Oyenuga (1968).

Animal wastes from slaughter house and poultry processing plants form a potential but under or unutilized source of N in the savanna area. No estimate is available for this source of N.

Human wastes

Man is the ultimate beneficiary of plant and animal N produced in any system. Human society generates enormous amounts of wastes, which include faeces and urine (sewage), rural, urban and industrial wastes, and dead bodies. Human wastes pose disposal problems and threaten to pollute man's own environment. However, these wastes can be properly processed and effectively utilized for crop and animal production as discussed by Singh & Balasubramanian (1977). Assuming the human population of the Nigerian savanna to be 40 million and the N content in human excreta to be 4.7 kg person^{-1} yr^{-1}, the potential contribution of N from human wastes works out to 188 million per year, i.e., 2.75 kg N ha^{-1} of virgin and arable land. At present no measures are practised in the savanna area to conserve and utilize this N source for agricultural production.

Losses of N from the soil-plant system

Burning

Uncontrolled fires, either accidental or intentional, destroy the vegetation and crop residues and N contained in such materials is lost to the atmosphere. Burning losses in fallows have been estimated to be 20 to 28 kg N ha^{-1} yr^{-1} (Vidal & Fauche, 1962; Nye & Greenland, 1960). Annual burning is more destructive than occasional controlled burning.

Erosion

No figures are available for erosion losses from farmers' fields and virgin savanna. Since the Nigerian savanna is a flat country, erosion losses on a regional scale can be assumed to be low. Under experimental conditions at Samaru, mean erosion loss from graded bench terraces of 0.3 % slope was found to be 10 t ha^{-1} yr^{-1} of top soil containing 6.3 kg N (Kowal, 1970).

Runoff

Losses of N in runoff water is possible only from fertilized plots and it is estimated to be 7.4 kg N ha^{-1} yr^{-1} (Kowal, 1970). We can safely assume that N losses in runoff from fallow and natural savanna will be negligible.

Leaching

Throughout the savanna thorough drainage occurs in years of average or more than average rainfall with the possible leaching of N (mainly applied fertilizer N) beyond the root zone, the leaching being most severe in sandy soils. In the fallow and virgin savanna with a predominant grass vegetation, soil nitrate levels are low and leaching losses of native N are small (Wild, 1972b; Jones, 1975). However, in soils under cultivation, presence of any excess nitrate over uptake will be liable to leaching losses. Jones (1976) reported that leaching loss of fertilizer nitrate did not exceed 25 % of the applied N in a Ferruginous soil. No data are available on nitrate leaching from sandy soils. However, it is safe to apply the fertilizer N in two or three split doses to minimize the loss of N in drainage water (Balasubramanian *et al.*, 1978b).

Denitrification

Reports of denitrification losses from savanna areas have been relatively few, and the preponderance of well drained sandy soils of low organic matter content and acid to neutral reaction suggests that on a regional basis losses are not likely to be serious (Jones & Wild, 1975). However, the denitrification losses may be significant in isolated pockets with poor drainage, high soil temperature and some oxidizable carbon (e.g., flood-plain or fadama soils).

Plant uptake

N uptake by native vegetation is in equilibrium with N addition from rainfall and biological fixation. But in cultivated soils this equilibrium is highly disturbed and N removal by crops is highly variable (Table 4) depending on the crop, intensity of cultivation and the type of residue management. When crop residues are incorporated into the soil, N removal in economic yields is less than 60 % of the total N contained in the tops for most of the crops (wheat and rice are exceptions). N absorbed by the crop enters the plant N pool which may be recycled through animal and/or man. When plant residues are burned, N is removed from the cycle and lost to the atmosphere and this is the true loss from the soil-plant system. Losses through cropping become serious when crops (e.g., cocoa) are sold off the farm and/or exported to other countries.

Continuous cultivation without adequate addition of N from external sources slowly depletes the soil N reserve. At Samaru, mean annual losses of 25 kg N ha^{-1} were recorded even after more than 10 years of continuous cultivation, representing an annual decline in total N of more than 4 % (Jones, 1971).

Nitrogen cycling in different agricultural systems

Pastoralism and arable farming are the two major types of agriculture practised in the savanna area. A third of the total area of 68.4 million hectares is under some form of arable farming while the remaining two-thirds is under pastoralism. We shall discuss the N cycling in the two systems separately.

Table 4. Nitrogen removal (kg N ha^{-1}) by different crops grown in the savanna region of Nigeria under three intensities of cultivation

Crop	Level of technology	Average grain yield (kg ha^{-1})	Management: Residue incorporated	Management: Residue removed or burned
Millet	A	700	13.4	31.1
	B	1200	23.2	46.3
	C	2000	31.4	79.8
Sorghum	A	700	11.6	23.8
	B	1200	19.6	38.3
	C	2500	41.3	80.9
Maize	A	500	5.3	9.4
	B	2000	22.0	35.8
	C	3500	50.8	73.3
Wheat	A	700	11.2	13.7
	B	1500	25.5	31.5
	C	2500	55.8	68.8
Rice (upland)	A	600	6.1	8.6
	B	1200	13.2	18.2
	C	2500	30.3	41.6
Groundnut[1)]	A	400	14.8	23.9
	B	900	33.3	55.4
	C	1500	57.0	92.1
Cowpea	A	200	7.6	11.5
	B	800	30.2	46.3
	C	1500	63.0	89.1
Cotton	A	360	8.6	15.6
	B	750	18.8	33.3
	C	1200	31.8	53.8

[1)] Groundnut kernal yield

A = Indigenous or traditional farming without any fertilizer use but with occasional addition of manures and/or unwanted crop residues as in rotational bush fallowing.

B = Continuous cultivation with the present recommended level of fertilizer use as in semi-intensive cultivation.

C = Suggested high level technology with adequate addition of fertilizers and other inputs as in intensive cultivation.

Pastoralism

A very large proportion of the national herd is owned by the Fulani who include nomadic, semi-nomadic and settled groups. While the former category lives in a state of perpetual wandering, the settled category combines cropping and livestock rearing. Major variables of Fulani pastoral ecology have been identified and documented by Van Raay

& de Leeuw (1974), Rains (1975), de Leeuw & Brinkman (1973), de Leeuw (1976), and de Leeuw & Agishi (1978). These studies mainly indicate that:

(i) Herbage production and quality as well as live weight gain in natural savanna is highly variable depending on the season.

(ii) There is a 7-month (Dec.–Jun.) N deficit period for nomadic cattle and a 5-month (Sep.–Jan.) deficit period for sedentary cattle during which time the animals lose weight.

(iii) Carrying capacity of sown pastures is more than three times as that of natural savanna.

(iv) Crop residues, flood-plain or fadama grazing, fallow vegetation and browse constitute the major dry season fodder resources.

(v) Use of feed supplement in the dry season considerably increases the productivity of all grazing systems as shown below:

Grazing system	Live weight gain ($kg\ ha^{-1}\ yr^{-1}$) With feed supplement	Without feed supplement
Natural savanna	100	20
Grass pastures	252	198
Legume pasture	216	162

(vi) Natural pastoral systems can be improved by prevention of accidental dry season fires, control of shrub encroachment, oversowing the grassland with legumes, controlled wet season grazing, better care and use of available crop residues, fallow vegetation and browse, and use of feed supplement wherever available.

Two pasture legumes have been found best suited for savanna conditions. One, *Stylosanthes guanensis,* is a perennial suitable for Guinea savanna zones with a dry period of less than six months; the other, *S. humilis*, is an annual suitable for Sudan and Sahel zones with a longer dry season. These legumes make their most rapid growth at the end of the rains and are eagerly eaten by stock during the dry season.

Introduction of legumes and supplementation of dry season grazing with concentrates (groundnut and cotton seed cake) will significantly improve the N nutrition of savanna cattle and hence its productivity.

Arable farming

Depending on the intensity of cropping, four cultivation systems can be identified: shifting, cultivation, rotational bush following, continuous rainfed agriculture, and irrigated agriculture. Shifting cultivation has almost disappeared from the Nigerian savanna because of high population pressure. Therefore we will focus our attention on the other three systems.

Rotational bush following is the predominant type of farming practiced at present. In this system there is a deliberate alternation between cropping and bush regeneration, the duration of each phase of the cycle depending on soil fertility, weed encroachment and population pressures on the land. Fallow periods are shorter or nil for fields near the homestead and soil fertility is maintained by the use of household wastes and organic manures. Length of fallow period increases and the intensity of manuring decreases as we move away from the house compound. Better preservation and use of all available crop residues and animal wastes will maintain soil N status in this system. Frequent and indiscriminate burning of residues and stubbles should be avoided and, whenever possible, the residues must be incorporated into the soil. However, the low crop yields obtainable in this system will not be enough to support the rapidly increasing population.

Continuous rainfed agriculture is common in areas with high population density, i.e., around cities. Manure and chemical fertilizers are the major N sources for crop production in this system. The presently recommended and suggested optimum N rates for various crops are listed in Table 3. The present rates are enough for cultivars of moderate yield planted at medium densities. For high yielding cultivars with optimum plant density, it is necessary to use the suggested rates of fertilizers.

Irrigated agriculture is taking strong roots in the savanna zone of Nigeria with the development of three major irrigation projects, viz., South Chad Irrigation Project, Kano Project, and Bakolori Dam Irrigation Project. On the completion of these projects about 139,000 hectares of land will be irrigated. In the rainy season, depending on the location of the soil in the toposequence, rice, maize, groundnut, cowpea, etc. are to be grown and sugarcane also is planned to be grown in some project areas (e.g., Bakolori Project). Wheat and tomato are the main crops in the dry season. Preliminary experiments have shown the N requirements for sustained production of two crops in a year to be 200–250 kg N ha^{-1}. Assuming a utilization efficiency of 50 % by the crops every year, 100–125 kg N will be distributed in the soil and hydrological cycle. The practice of double cropping under irrigation will generate not only more grain and cash crops but also substantial amounts of crop residues which can be used for dry season feeding of cattle. Several perennial green fodders, which have shown promise in preliminary observation trials, could be cultivated. The nomadic Fulani will not be able to move their cattle through the irrigated areas which will remain intensively cropped all the year round. The restricted movement of cattle in irrigated areas and the increased availability of crop residues, concentrates and green fodder are highly conducive to stall feeding of cattle and to development of the practice of mixed farming which will generate large amounts of good quality manure needed to maintain the productivity of irrigated soils.

Nitrogen balance sheet for different agricultural systems

An attempt was made to quantify the sources of N addition to and removal from different agricultural systems as practiced in the Nigerian savanna. In this process several sources of information, published and unpublished, have been utilized. Some of the data came from pure estimates by the authors which need critical evaluation by other scientists. In short, the balance sheet can be taken as an approximation which can be refined in the future as and when authentic data become available through research. These data also serve to point out the areas where future research should be concentrated.

For all the grazing systems, the balance sheet is on the positive side (Table 5). This indicates that there is a slow and steady build-up of soil N under traditional and improved systems.

When we look at the data in Table 6 for arable farming we notice that, except for semi-intensive cropping with inadequate fertilizers, there is a small positive balance for

Table 5. Balance sheet of N additions and removals in different grazing systems of the Nigerian savanna

Source	Annual addition or removal (kg ha^{-1}) under Natural savanna	Grass pasture	Legume pasture	Ref.1)
Addition				
Rainfall	5.0	5.0	5.0	a
Asymbiotic and Rhizosphere fixation	15.0	5.0	0.0	b
Symbiotic fixation	20.0	10.0	40.0	c
Plant residues	10.0	10.0	10.0	d
Animal excreta	2.5	7.5	7.5	e
Human wastes	?	?	?	..
Fertilizer	0.0	75.0	20.0	f
Total addition	52.5	112.5	82.5	–
Removal				
Burning	25.0	10.0	10.0	g
Erosion	6.0	6.0	6.0	h
Runoff	0.0	7.0	0.0	i
Leaching	0.0	20.0	5.0	j
Denitrification	0.0	?	?	k
Volatilization	1.0	3.5	3.5	l
Removal in feed	8.0	24.0	24.0	m
Total removal	40.0	70.5	48.5	–
Balance	+12.5	+42.0	+34.0	..

1) a = Jones & Bromfield (1970); b = Balandreau & Villemin (1973); c, d, e, k, l, m = Author's estimates; f = de Leeuw & Agishi (1978); g = Nye & Greenland (1960) and Vidal & Fauche (1962); h, i = Kowal (1970); j = Jones (1976).

arable farming systems. In the traditional bush-fallow system, the N loss during cropping is compensated by N gain during fallow periods. Under intensive cultivation, prudent use of fertilizers maintains soil N status and fertility. But in semi-intensive cropping, the applied fertilizer is not enough and hence there is a decline in soil N content and crop yield with time.

The following assumptions were made while working out the balance sheet:

(i) Legumes play a significant role in all agricultural systems.
(ii) Cereal/legume rotation is taken for continuous cultivation.
(iii) In rotational bush-fallowing, three-year cropping alternates with three-year fallow period.
(iv) Asymbiotic and rhizosphere N fixation are negligible in systems with some fertilizer N input.
(v) Burning of bush fallow and crop residues is severe in traditional systems, restricted in improved pastures and avoided under intensive cropping.
(vi) Erosion increases with the intensity of cultivation.

Table 6. Balance sheet of N additions and removals under different intensities of arable farming in the savanna zone

Source	Annual N addition or removal (kg ha^{-1}) under				Ref.1)
	Rotational bush-fallow	Semi-intensive	Intensive		
			Single	Double	
Additions					
Rainfall	5.0	5.0	5.0	5.0	a
Asymbiotic and Rhizosphere fixation	10.0	5.0	0.0	0.0	b
Symbiotic fixation	25.0	25.0	50.0	100.0	c
Crop residues	10.0	10.0	15.0	30.0	d
Animal excreta	2.4	?	0.0	0.0	e
Human wastes	?	?	?	?	–
Fertilizers	0.0	30.0	65.0	130.0	f
Total addition	**52.4**	**75.0**	**135.0**	**265.0**	–
Removals					
Burning	25.0	25.0	0.0	0.0	g
Erosion	6.0	6.0	12.0	24.0	h
Runoff	0.0	5.0	10.0	20.0	i
Leaching	0.0	7.5	20.0	40.0	j
Denitrification	0.0	0.0	5.0	10.0	k
Volatilization	1.0	1.0	5.0	10.0	l
Crop removal	15.0	35.0	75.0	150.0	m
Total removal	**47.0**	**79.5**	**127.0**	**254.0**	–
Balance	**+54.0**	**- 4.5**	**+8.0**	**+11.0**	–

1) a = Jones & Bromfield (1970); c, d, e, f, k, l, m = Author's estimates; g = Nye & Greenland (1960) Vidal & Fauche (1962); h, i = Kowal (1970); j = Jones (1976).

(vii) Runoff loss is significant only in fertilized areas.

(viii) About 25 % of the applied fertilizer N ends up in drainage water.

(ix) Denitrification is negligible on a regional scale. Flood-plain or fadama soils are exceptions to this rule.

(x) More than 50 % of the N from animal and human wastes and about 10 % of the fertilizer N are lost due to volatilization.

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UTILISATION DE L'ENGRAIS PAR LES CULTURES ET PERTES PAR LIXIVIATION DANS DEUX AGROSYSTEMES DE CÔTE D'IVOIRE

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Abstract

The soil-cycle study of N–15 fertilizer with lysimeter techniques was carried out in agricultural systems at two sites in the Ivory Coast, one a savanna area, and the second a forest zone.

The nitrogen losses from leaching under cropping were very high and linked with the rainfall intensity and the fertilization level. Direct N-fertilizer utilization by crops was low (25–35 %) compared to the sum of soil immobilizations and gaseous losses (65–75 %).

Accordingly, nitrogen-fertilizer losses by leaching are small (3–5 %). However, nitrogen mineralized by organic matter during the crop cycle could be lost in large quantities (50–130 kg ha^{-1} yr^{-1}).

N-fertilization of crops increases the turnover of soil nitrogen and also the N-leaching losses.

Introduction

Dans le cadre des études entreprises par l'IRAT en Côte d'Ivoire sur la fumure azotée des céréales et la gestion des résidus de récolte, plusieurs essais pérennes ont été mis en place dans différentes zones écologiques.

Ces essais sont couplés à des installations de cuves lysimétriques de sol en place de type ORSTOM et l'ensemble permet d'étudier l'influence de divers traitements sur l'utilisation de l'azote engrais par les cultures et son devenir dans le sol.

Cette communication concerne les résultats obtenus pour le riz, le maïs et le coton dans la station de Bouaké (région centrale) et de Gagnoa (région Sud).

Matériel et méthode

Caractéristiques principales des points d'essai

La station de Bouaké (7° 46 latitude Nord et 5°6 longitude Ouest) est située en zone de savane à 1100 mm de pluie par an. Le sol est un sol ferralitique rajeuni et remanié sur roche mère granitoïde. L'horizon de surface (LAS) repose sur un horizon très gravillonnaire plus argileux (26 % d'argile en surface dans les lysimètres) (Tableau 1).

La station de Gagnoa (6°08 latitude Nord et 5°56 longitude Ouest) est située en zone forestière à 1450 mm par an. Le sol est du même type que celui de Bouaké mais plus

Tableau 1. Caractéristiques principales des horizons de surface des sols de Bouaké et Gagnoa

	Argile (%)	Azote total (%)	C/N	pH	C.E.C. me 100 g^{-1}
Bouaké	26	0,12	13	5,5	10,8
Gagnoa	26	0,14	10	5,4	9,4

jaune et la texture dépend de la situation sur la pente (35 % d'argile en haut de pente – 10 % en bas de pente) – (26 % d'argile en surface dans les lysimètres) (Tableau 1).

Les deux stations sont caractérisées par une pluviométrie très irrégulière répartie inégalement en deux saisons pluvieuses.

Dispositifs expérimentaux et méthode d'étude

Les lysimètres du type préconisé par Roose (diamètre 63 cm) (Roose & Tureaux, 1970) sont constitués par des monolithes de sol en place non remanié de profondeurs différentes selon l'enracinement des cultures dans le sol (45 et 80 cm de profondeur).

Le dispositif expérimental est le suivant (Chabalier, 1976).

Bouaké:	8 cuves de 45 cm et 2 cuves de 80 cm
Gagnoa:	4 cuves de 80 cm.

Ce dispositif a pour objet l'observation des effets cumulatifs d'apport d'azote et de paille sur les pertes par lysimétrie.

Bouaké:	1973 – Riz variété "Iguape Cateto" 1974 – Maïs H507 – et Coton variété "Allen 331"
Gagnoa:	1973 – Maïs H507 – 2 cycles 1974 – Maïs H507 – 2 cycles

Les apports d'azote sont fractionnés en deux fois et sont effectués sous forme d'urée (AIEA, 1970). La moitié des cuves reçoit un apport de paille équivalent à 5 t ha^{-1} avant chaque cycle (M1).

En 1973 l'engrais apporté sur les cuves est un engrais marqué par 5 ou 10% d'azote-15. Dans tous les percolats supérieurs à 1 litre (3 mm de pluie) sont quantifiées les teneurs en ions dont $N{-}NH_4$ et $N{-}NO_3$. On analyse l'azote total des percolats (dosage de N-organique) sur un certain nombre de percolats prélevés périodiquement. L'enrichissement en N–15 est alors déterminé. (Dosage sur spectromètre Varian GD150 au CEA de Cadarache-France).

D'autre part, à la fin de chaque culture, on prélève des plantes qui sont pesées et analysées et des échantillons de sol dans l'horizon labouré. La détermination des teneurs en N–15 permet d'effectuer un bilan complet de l'azote engrais dans le système défini par les cuves lysimétriques.

Résultats et discussion

Bouaké 1973

– Culture riz pluvial.

la pluviométrie est de 959 mm
les 8 cuves de 45 cm ont drainé 300 mm
les 2 cuves de 80 cm ont drainé 350 mm
les pertes d'azote essentiellement sous forme nitrique sont de (résultats ramenés en kg ha^{-1}).

		à 45 cm		à 80 cm
		N1 (kg ha^{-1})	N2 (kg ha^{-1})	N1 (kg ha^{-1})
Fertilisation N		+ 60	+ 120	+ 60
Pertes sans paille	M0	– 50	– 62	– 48
Pertes avec paille	M1	– 56	– 80	– 54
	Moy	– 56	– 71	– 51

L'analyse de l'azote marqué dans ses percolats permet de calculer la part d'azote qui vient de l'engrais. Il apparaît que les pertes directes de l'azote provenant de l'engrais sont faibles: 1 % de 60 kg apportés et 4 % de 120 kg.

Les drainages sont peu nombreux et répartis sur deux périodes distinctes: la première période correspond à une lixiviation d'environ 40 kg des nitrates présents dans le sol nu avant culture. La deuxième période correspond à la lixiviation de l'azote pendant la culture, vers fin août à 45 cm et début septembre à 80 cm. Ces pertes sont de 25 kg environ.

Le déplacement vertical de l'azote dans ce type de sol est: Couche 0–45 cm = 0,25 cm par mm d'eau percolante, Couche 0–80 cm = 0,36 cm par mm d'eau percolante.

Bouaké 1974

– Culture maïs/coton.

la pluviométrie est de 1213 mm
les 8 cuves de 45 cm ont drainé 355 mm
les 2 cuves de 80 cm ont drainé 340 mm
– eau utile sur le maïs 282 mm (pluie – drainage)
– eau utile sur le coton 390 mm.

Les pertes moyennes d'azote sous maïs et coton dans la tranche de sol 0–45 cm de profondeur sont (kg ha^{-1}):

		N1 (kg ha^{-1})	N2 (kg ha^{-1})	
Fertilisation cumulée		+ 160	+ 320	Moy.
Pertes sans paille	M0	– 63	– 110	– 86
Pertes avec paille	M1	– 51	– 89	– 70
	Moy	– 57	– 99	

Les pertes sont moins importantes à 80 cm qu'à 45 cm pour le traitement N1 (160 kg): sous 45 cm = 57 kg et sous 80 cm = 40 kg.

La teneur maximum en nitrate se situe mi-septembre avec une autre période de fortes teneurs en mai. Les volumes d'eau drainés correspondants sont respectivement de 220 mm et de 100 mm. On retrouve les valeurs de la vitesse de déplacement vertical de l'azote citées ci-dessus pour 1973.

Les pertes d'azote marqué résiduel provenant de l'épandage d'engrais de 1973 sont faibles:

3 % de 60 kg à 45 cm
3 % de 120 kg à 45 cm
1,4 % de 60 kg à 80 cm.

Conclusions relatives aux lysimètres de Bouaké

Les pertes d'azote par lixiviation sont élevées sur les 45 cm de sol, avec une fertilisation normale, elles sont de l'ordre de 60 kg an^{-1}. Le cycle unique de riz favorise la perte d'azote avant la mise en place tardive de la culture. Les pertes à 80 cm sont plus faibles et de l'ordre de 40 à 50 kg. Cet azote semble provenir essentiellement de la minéralisation de l'azote du sol. On trouve en effet des pertes du même ordre à ces profondeurs sous une savane naturelle non fertilisée.

Les pertes par lixiviation de l'engrais apporté au sol sont très faibles. Sur deux années de drainage, elles sont estimées à 3 kg pour un apport de 60 kg et à 10 kg pour un apport de 120 kg à une profondeur de 45 cm (Tableau 2) et elles sont plus faibles à 80 cm. Cet azote engrais a été peu utilisé par la culture en place 25 à 30 % de coefficient d'utilisation mais fortement réorganisé au sein de la matière organique. Il a favorisé et stimulé également la minéralisation de l'azote du sol.

Tableau 2. Bilan d'un apport d'engrais marqué des cuves lysimétriques de Bouaké (kg ha^{-1} yr^{-1})

	N1	N2
Engrais apporté	60	120
Utilisé par le riz 73	16	28
Utilisé par le maïs 74	3,6	7,2
Utilisé par le coton 1974	0,5	0,7
Pertes par lixiviation 73–74	2,8	9,6
Immobilisé dans le sol fin 74	24,5	38,4
Total retrouvé	47,4	83
Recouvrement %	79	70

Gagnoa 1973

– Culture maïs/maïs.
  la pluviométrie est de 1500 mm
  drainage sous 80 cm = 500 mm
  pertes annuelles d'azote pour 200 kg apportés sur 2 cycles de maïs M1 = 130 kg, M0 = 110 kg.

Les pertes sont réparties à peu près également sur les deux cycles.

La lixiviation des éléments et notamment de l'azote se produit avec le passage d'une lame d'eau percolante de 160 mm sous une vitesse de transfert de 0,50 cm par mm d'eau.

Les teneurs maxima en azote se situent début mai, début septembre et début novembre. Les pertes importantes ont lieu en mars-avril, juin et surtout septembre. La perte d'azote-engrais apporté sur le premier cycle est très nette en septembre, il s'agit cependant de pertes faibles représentant environ 4 % d'azote-engrais apporté. L'enfouissement n'a pas d'effet très net sur cette lixiviation.

Gagnoa 1974

– Culture maïs/maïs.
  pluie annuelle = 1340 mm
  drainage = 380 mm.

La plus grosse partie des pertes a eu lieu pendant le premier cycle pendant lequel le drainage a été de 270 mm. Les intensités maxima de drainage ont eu lieu en mars, juin et octobre. Les teneurs maxima des eaux de drainage en azote sont apparues vers la fin avril – début mai et en octobre-novembre. Ces maxima sont atteints par le passage d'une lame d'eau percolante de 150 mm environ soit une vitesse de transfert de 0,54 cm mm^{-1}

Pertes pour 200 kg apportés sur 2 cycles: M0 = 160 kg, M1 = 157 kg.

Les pertes d'azote engrais résiduel provenant de l'apport d'azote-engrais sur le premier cycle 1973 (100 kg) sont de l'ordre de 6 % de la quantité initiale, soit légèrement plus que l'année de l'application. L'enrichissement maximum se situe vers mars-avril.

Conclusion sur Gagnoa

Les pertes d'azote sont importantes, sous 80 cm de sol. Cependant les pertes d'engrais sont faibles (10 % de 100 kg apportés, en deux ans de drainage). L'enfouissement de paille n'a pas un effet très net sur cette lixiviation de l'azote. Il tend cependant à minimiser les pertes. L'utilisation réelle de l'engrais par le maïs est de l'ordre de 35 % (Tableau 3).

Conclusion sur la lixiviation

Les pertes d'azote sont importantes sous des cultures fertilisées = 50 kg à Bouaké et 130 kg à Gagnoa en moyenne dans les deux systèmes.

Cet azote ne provient qu'en faible part de l'azote-engrais que l'on apporte sur la culture en place, il provient essentiellement de l'azote minéralisé dans la couche supérieure

Tableau 3. **Bilan d'un apports d'engrais marqué des cuves lysimétriques de Gagnoa ($kg\ ha^{-1}\ an^{-1}$)**

	kg
Engrais apporté	100
Utilisation par le maïs 1er cycle	35
Immobilisation dans le sol 0–30 cm après culture	35
Pertes par lixiviation	4
Total – recouvrement (%)	74
Pertes estimées (%)	26

du sol qui est lessivé à des vitesses de l'ordre de 0,3 cm par mm d'eau percolée à Bouaké et 0,5 à Gagnoa.

Il faut admettre que la minéralisation lente mais continue de l'azote du sol favorise beaucoup plus les pertes qu'un apport relativement important d'azote-engrais. Celui-ci est rapidement réorganisé et mobilisé et échappe donc au drainage, mais comme il stimule la minéralisation, il accroît indirectement les pertes par lixiviation (Chabalier, 1976).

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REPORT OF THE WORK GROUP ON THE SAHEL-SAVANNA ZONE

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Introduction

The work group tried to quantify the elements of the N-balance in Sahel and Savanna ecosystems. From site to site, large differences exist in amounts of N in standing crop and in soil organic N. The rates with which these quantities change intra- and interseasonally vary a great deal.

Four cases were selected to provide a framework for the group discussions. They are the extensively grazed areas of Sahel and the Guinea Savanna, and the fields in Sahel and the Guinea Savanna where sorghum is cultivated. The quantifications given below relate particularly to sandy soils, that are predominant in both zones. Not quite correctly, these zones are labelled 'Sahel' and 'Savanna'. These selected cases were sufficiently broad to be of interest to many participants, but sufficiently uniform that specifying average rates and quantities exhibit many of the essential characteristics of the sytems.

The results of these discussions are presented in Tables 1–3, and some of them are briefly discussed in explanatory notes.

There are two disclaimers to these tables:

1. The values given are sometimes based upon direct observations, sometimes they are only intelligent guesses. Each of the values may overestimate or underestimate the real value considerably. Care should thus be taken in any application of this information.
2. Qualities and rates are averages over large areas. Rates which are labelled non-significant in the average site may become quite important or even dominant on specific sites.

Explanatory notes

General characterization

a) Climate

The growing season for annuals is defined as the period between germination and maturity. Especially in the 'Sahel', actual dry matter production may occur only during a fraction of this period.

Table 1. Some general characteristics of the Sahel-Savanna zone. Explanation: ( ) guess, ? no reasonable guess could be made, n.s. $\leq$ 1 kg ha^{-1} yr^{-1} in average, - does not apply, 0 absent. The letters in parenthesis refer to the explanatory notes.

	Feature	'Sahel'	'Savanna'	Units
	Annual precipitation	400–700	900–1200	mm yr^{-1}
	of which	35 % in August	50 % in Aug. + Sept.	–
Climate	rainy season	90–120	180–220	day yr^{-1}
	growing season(a) for annuals	60–100	150–200	day yr^{-1}
	perennials + trees	100–150	200–250	day yr^{-1}
	sorghum	90	150	day yr^{-1}
Natural(b) vegetation	annual grasses	80	30	% soil cover
	herbaceous legumes	5	10	% soil cover
	perennial grasses	15	60	% soil cover
	trees	15	30	% soil cover
Land(c) use	cultivated land	10	35	% of total area
	excessively grazed	10	10	% of total area
	extensively grazed	(40)	55	% of total area
	unused	(40)	0	% of total area
Soil	Physical aspects(d):			
	run-off and run-on in pasture	often high	sometimes high	–
	run-off and run-on in field	low	low	–
	drainage beyond rooting depth	rare	common	–
	rooting depth	50–150	50–150	cm
	water table	very deep	sometimes up to rooting zone	–
	erosiveness	?	?	–
	Chemical aspects (topsoil)(e)			
	C	0.4	1.0	weight %
	N	0.03	0.08	weight %
	P	deficiences are common		–
	K, and other elements	rarely deficient		–
	pH	6.0	6.0	pH water

Table 2. Distribution of N(f) in the soil-plant system (peak biomass; kg N ha^{-1}). For explanations, see Table 1. The letters in parenthesis refer to the explanatory notes.

	Sahel grazing	Savanna grazing	Sahel cult.	Savanna cult.
Herbaceous sp.				
above ground	15	25	17	30
below ground	7	8	5	8
Woody sp.				
above ground	(50)	400	–	–
below ground		250		
Soil organic N	900	2400	900	2400

Table 3. Rates of influx and outflux of N (kg N ha^{-1} yr^{-1}). For explanations, see Table 1. The letters in parenthesis refer to the explanatory notes.

Process	Sahel grazing	Savanna grazing	Sahel cult.	Savanna cult.	Rate influenced by
Fixation(g)					
by rhizobia	2	(10)	0	0	soil water, P, nematodes
by algae	1	5	0	n.s.	soil water, P, light intensity, conc. silt
by bacteria (in rhizosphere or free living)	0	5	?	?	soil water, P, available C
Deposition(h)					
wet	1	2	1	2	precipitation
dry	2	3	2	3	
Manure(i)	0	n.s.	(3)	(5)	cattle management, direct application
Fertilizer (j)	0	0	n.s.	n.s.	–
Total in	**6**	**25**	**6**	**10**	–
Harvest(k)	n.s.	n.s.	9	17	–
NH$_3$-volatilization(l)	n.s.	n.s.	n.s.	n.s.	–
Leaching(m)	0	n.s.	0	n.s.	precipitation
Denitrification(n)	0	?	0	?	soil moisture, conc. NO$_3$, conc. available C
Erosion(o)	2	3	2	5	–
Burning(p)	3	8	3	4	–
Grazing cattle(q)	(3)	(6)	1	3	–
Grazing termites(r)	(4)	(2)	3	4	soil characteristics
Total out	**12**	**19**	**18**	**33**	–
Net balance	**–6**	**+6**	**–12**	**–23**	–

b) Vegetation

The composition of the herbaceous vegetation is given in % soil cover in the lower vegetation story. Trees and shrubs are quantified by a % soil cover in the upper story. These figures vary a great deal from site to site, and can vary considerably over a number of years.

c) Land use

The land use pattern is also quite variable in the countries of the 'Sahel' and the 'Savanna', and also within regions of these countries. Exploitation is generally intensifying as a result of increasing population and land development schemes. The cultivated and excessively grazed lands represent the fraction of the zones exposed to intense exploitation. The fraction cultivated land comprises the soil actually cultivated plus the soils recently in fallow.

d) Physical aspects of the soil

Soils in the Sahel generally are wetted down to 10–150 cm. Roots absorb water from all of this layer. Run-off and run-on is locally important, and can lead to drainage. Run-off increases rapidly once a surface crust become formed, which is common whenever intensive exploitation occurs. Run-off on cultivated land is generally low due to ridges.

The rooting depth depends particularly on the depth of the wetted zone in the Sahel region. In the Savanna, the rooting depth is typically 150 cm, but less where little water infiltrated into the soil due to run-off. Drainage is common.

Generally, the water table is quite deep in Sahel and Savanna. Near rivers and irrigated areas, the water table may rise to the rooted zone, particularly in the Savanna.

Many Sahel and all Savanna soils have sandy top soils, some of which are vulnerable to wind and water erosion without vegetation.

e) Chemical aspects of the topsoil

Under intensive exploitation, the quantity of soil organic matter is supposed to decrease annually 2 %, but it recovers very little under fallow.

Deficiences of P are quite common in both zones. Deficiences of other elements are rare, but may develop after long or very intense exploitation.

The amount of soil organic matter (and thus of C and N) in run-on areas and in valley bottoms, which may form 5 % of the area, is a few times higher than the values given here.

f) Distribution of N in the soil-plant system

The reported values stem from direct observations, and need no comment.

The amount of soil organic matter decreases under intensive exploitation, as indicated below.

Rates of influx of N into the soil plant system

g) N_2-fixation in Sahel and Savanna

- Rhizobia

N_2-fixation by legume trees (e.g., *Acacia*) in the Sahel is negligible because of the lack of nodules, which have been attributed (1) to large accumulation of inorganic nitrogen under the tree litter and (2) to the effect of drought. In the Savanna, legume trees are expected to be as important as herbaceous legumes.

Herbaceous legumes are very irregularly distributed and seldom abundant, but they are nodulated and fix N actively. The total contribution to the N-input of extensively grazed Sahelian and Savanna ecosystem was estimated to be in the order of 2 and 10 kg ha^{-1} yr^{-1}. Sorghum does not harbour rhizobia.

- Blue-green algae

Blue-green algae are sometimes found on the soil surface, particularly under intensive exploitation. Their annual N fixation seems to be of little importance in extensively grazed parts of the Sahel, but much more in the Savanna. The difference of a factor 5 between both zones is probably at least partially due to different ways of extrapolating laboratory observations of a brief duration to annual values for field conditions.

- Free-living bacteria

Since it is difficult to make a distinction between N_2-fixation in the living rhizosphere and in the root litter, figures given in the table include both processes. In the grazed Savanna, N_2-fixation by free-living bacteria is thought to be at least 5 kg ha^{-1} yr^{-1}. The large difference between Sahel and Savanna is attributed partially to difficulties in the extrapolation to field conditions.

This process could even be more important in sorghum fields ecosystems, at least when soil moisture and P are not limiting. Quantitative data are still lacking.

h) Wet and dry deposition

For input, the data given for the two regions are based on very few local measurements. The wet deposition of N represents mainly nitrate in rain, formed by lightning. It is likely that most of the dry deposition of N originates from local plant and soil particles that have become airborne. These particles are therefore considered as an output under 'erosion'. Erosion and/or dry deposition of N can be important on small fields, like those where sorghum is cultivated, but not on a regional scale.

The deposition inputs are also supposed to include some atmospheric ammonia.

i) Manure and crop residues

By keeping cattle on rangelands in daytime and, after the harvest, at night on cultivated fields, a fair amount of manure is brought on these fields. The remainder of the crop after harvest is also in part eaten by cattle. Management practices determine this input almost completely, but these are not well known.

j) Fertilizer

The rate of application of fertilizers on sorghum crops is still nonsignificant on the average.

Rates of loss of N from the soil-plant system

k) Harvests

In grazing areas, the harvest consists of extensive grazing which results in an export of N which is estimated to be lower than 1 kg ha^{-1}.

In cultivated areas, the export of N exists of (1) the harvest of grain and of (2) the utilization of the straw.

(1) The exportation of N in the grain is estimated to 9 kg ha^{-1} (yield: 500 kg of grain ha^{-1} nitrogen content of grain 1.7 %) in Sahelian cultivation and to 17 kg ha^{-1} in Savanna cultivation (yield: 1000 kg of grain ha^{-1}).

An unknown part of it is recycled in manure.

(2) The quantity of N in the straw is estimated to 8 kg ha^{-1} in Sahelian cultivation (yield: 1500 kg of straw ha^{-1} – nitrogen content of straw 0.5 %) and to 13 kg ha^{-1} in Savanna cultivation (yield 2600 kg of straw ha^{-1}).

From a survey done in Senegal it has been estimated that:

- One-third of this N is exported in the straw used in housing (eventually lost through termites and burning);
- Another third is the straw eaten by cattle. A part of it is recycled through manuring practices;
- The last third of the N in the straw is left on the field, is consumed by termites or lost through burning.

A greater emphasis should be given to the study of the harvest of trees which can be quite efficient in Sahelian areas for cattle feeding, especially during the dry season, and for sedentary cattle production.

l) NH_3-volatilization

(1) From decomposing litter. The magnitude depends on N % and degree of contact with the soil. The N % is likely to be low and accumulation above the soil surface is often small. Consequently, NH_3-volatilization is therefore usually of no significance.

(2) Via stomata. Leaves can release NH_3 if the concentration in the surrounding air is low (about 2.10^{-9}). Senescing leaves tend to give off NH_3, even at higher ambient NH_3 concentrations. But in both cases the amounts involved are likely to be non-significant. To what extent pre-harvest losses of N can be attributed to NH_3-volatilization will be discussed below.

m) Leaching

The loss of nitrogen through leaching occurs primarily in the form of nitrate. The actual quantity lost depends on the amount of precipitation, the amount and type of plant cover on the soil, and on the amount of nitrate in the soil. Roots absorb nitrate quite efficiently, so that drainage of water does not always imply leaching of nitrate.

Although most of the soils in the Sahel are sandy, no movement of water occurs beyond the rooting zone. Therefore a crop of sorghum could absorb any nitrate present in the rooting zone throughout the growing season.

In the grazing area of the wet Guinea savanna, very little nitrate is found under the grasses, hence leaching would be unimportant.

In the southern Guinea savanna zone the rainfall is higher than in the Sahel. Also, there is a rapid flush of mineralization at the beginning of the rain. If a sorghum crop is planted early, as in common practice, it will be able to absorb practically all the nitrate that will be produced during the early flush of mineralization. But if planting is delayed then some loss of nitrate could occur.

n) Denitrification

Denitrification in soil is known to depend primarily upon soil moisture, NO_3^- concentration and available C concentration. In Sahelian conditions, denitrification was assumed to be negligible or nil in spite of the fact that locally (e.g., under some trees or bushes) a peak of nitrogen mineralization could occur, which might induce some denitrification at the onset of the rainy season. In savanna conditions, denitrification is expected to be significant – though quantitatively unknown – because the number of anaerobic microhabitats and the concentration of NO_3^-, is higher than in Sahelian conditions, at least at the beginning of the rainy season.

o) Erosion

Erosion is not considered to cause a significant loss of N in the two extensively grazed systems or in the cropped system in the Sahel. In the wet savanna zone heavy rains may occur before the crop is sufficiently developed to minimize erosion losses. An average loss of 5 kg N ha^{-1} yr^{-1} was estimated on the basis of a few measurements. Another estimate of losses of N by erosion can be made by assuming that in the large, grazed areas loss by erosion equals dry deposition. Losses from small cultivated fields may exceed this value.

There is a potential for important erosion losses in this region as a result of overgrazing, clear-cutting and burning for cultivation as well as a result of increased cultivation per se.

p) Burning

In the Guinea and Sudan savanna, burning is almost invariably annual, and most often between December and February. In the Sahel, burning is much more variable, and occurs, on an average, only once every two years. The figures for N-loss were taken from current studies of Isichei and Sandford, carried out in natural, lightly grazed, 'derived', southern and northern Guinea savanna. The loss is based on December to March burnings of heterogeneous savanna, where the percentage burned of litter and standing crop at the time of burning ranged from about 60 % to 95 %, with a mean of 73 %. As much of the tissue N has left the tissue before burning either by leaching, dilution or translocation, the percentage contained at burning varies little with species or time. Tree litter from leguminous species will, however, be slightly higher in N than other leaf litter (0.95 % N compared to 0.77 % N), and herbaceous material from more fertile parts will contain, even at burning, slightly higher N levels than material from infertile soils. The percentage of litter and standing crop which is burned varies greatly from year to year and from site to site, being much higher in homogeneous high grass savanna with few shrubs or trees. The effect of burning also varies with the time of the year, which not only determines the extent of burning but also the relative effects of burning in encouraging growth of graminaceous species at the expense of broadleaved species and vice versa. The percentage burned is positively correlated ($P < 0.05$) with the maximum standing herbaceous crop at the site.

It is very possible that indirect effects of burning are more important in overall N-cycling than the N directly lost by heat volatilization. Of such effects, the possibility of increased erosion, leaching and run-off, change in structure and composition/denitrification may be most important.

q) Grazing by cattle

The figures for grazing are the multiple of the amount of biomass consumed times its N content, minus the N that recycles into the soil from feaces and urine. The latter fraction was assumed to be 50 % of the N-intake of the animals, the remainder being lost by volatilization, though losses of about 80 % of the N-intake by animals have been reported as well. The amounts of N grazed are estimated to one-third of the maximum amount of N in the biomass in the extensively grazed areas, and also one-third of the remainder of the sorghum crop. All estimations are quite crude.

Due to the daily concentration of animals in their night camps, N and P excreted becomes concentrated on a few spots, so that grazing redistributes nutrients unevenly.

u) Grazing by termites

Termites harvest large amounts of dry biomass in some areas, particularly at the end of the dry season. The material is consumed, directly or indirectly, in the nests, where the excretion products are left. Soil analysis shows that all minerals do accumulate in the mounds to concentrations many times higher than in the surrounding soils, except for C and N. These elements apparently get lost from the soil-plant system. Termite mounds have been shown to harbour large populations of denitrifiers, suggesting that denitrification could be an important process in causing these losses.

Some important rates of transfer of N within the plant-soil-system

Mineralization

A fair knowledge exists about the order of magnitude of annual mineralization, resulting from direct observation in incubation experiments, and by implication from the rate of nitrogen uptake in vegetations (e.g., Greenland and Wetselaar, this volume). Its rate depends particularly on the amount of soil organic matter present, on characteristics of this organic matter (of which the C/N ratio has some importance), and on the moisture content of the soil. However, these relations cannot yet be quantified to a precision desired in intraseasonal crop growth studies. Thus, more research to quantify the rate of mineralization is urgently needed for all systems.

Losses of N from the standing crop

Losses of N from the standing crop after flowering have often been observed in annual and perennial grasses and in cereals. In unexploited pastures these losses are particularly large in the month following flowering and at the time of the very first rains of the next season. Processes in the first period are seedfall, which is a transfer of N, and rotting of lodged biomass, during which a part of the N volatilizes. Leaching of nitrogenous compounds by dew or rain might be important as well. In the second period, the removal by termites often plays a dominant role, but is certainly not the only process.

Given the possibility of a large impact of this process on the balance of plant-soil-systems, it is suggested:

1. to survey to what extent this phenomenon occurs in the four systems of cultivation used in the fields and in grasslands, and
2. to investigate which physiological processes underly and regulate it.

Resorption of N

Resorption of N from leaves into branches or storage organs occurs in trees and in perennial grasses. About half of the maximum amount of N that was present in the leaf is still there when it drops. Much of the difference is probably resorbed into stem, roots or storage organs, but the extent to which leaf-leaching or NH_3 volatilization occurs is unknown.

Research on resorption is needed in relation to exploitation of trees and perennial grasses.

Transport of N

Transport of N by tree roots from deep soil layers, not accessible to the herbaceous plants, may contribute to the N-supply of these trees. This process may be important in very special situations only.

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Nitrogen Cycling in West African Ecosystems

REPORT OF THE WORK GROUP ON TROPICAL FORESTS

P.M. Vitousek (rapporteur)

Introduction

Nitrogen cycling in West African ecosystems has received increased attention in recent years, due in part to the developing interest in tree cropping and agroforestry. Natural forest ecosystems provide a valuable reference for comparing the costs and benefits (in terms of nitrogen accumulation and loss) of different management and cropping systems. Consequently, we decided to summarize the information available on West African natural forest ecosystems, and then to compare these systems with managed forests.

Information on nitrogen cycling in natural forest ecosystems is inadequate in many areas of the world. For West Africa, few suitable reference ecosystems can be found in either the moist semi-deciduous forest zone or the rain forest zone. Population pressure, coupled with the traditional system of shifting cultivation, has nearly eliminated natural forests from the area. Still, studies of the wet Banco and drier Yapo forests, Ivory Coast, provide an excellent standard for comparison with natural ecosystems. Similarly, studies at Kade, Ghana, though conducted on a 40–50 year old secondary forest, provide valuable reference information for forests on the boundary between the moist and wet forest zones.

These few forests cannot, of course, be considered representative of the very large and heterogeneous region as a whole. Studies on nitrogen cycling in additional natural ecosystems would be most welcome. Nonetheless, these studies provide a standard against which managed ecosystems can be compared.

The information we had available from the Banco, Yapo, and Kade sites is summarized in Table 1. In all of these studies, more attention was placed on the internal soil-plant cycle of nitrogen rather than on inputs and outputs of nitrogen for the ecosystem as a whole.

The soil nitrogen contents reported in Table 1 represent total nitrogen to a depth of 30 or 50 cm. Asamoa, in this workshop, reported soil nitrogen concentrations for a much broader range of sites to a depth of 150 to 200 cm. If reasonable bulk density values can be assumed, his forest ochrosols (= ustalfs = ferruginous soils) contain ≅ 10,200 kg N ha^{-1} to 150 cm, while his oxisols (= udults = ferralitic soils) contain ≅ 9600 kg N ha^{-1}. These large stores of dispersed total nitrogen deep in the profile should not be ignored in any consideration of forest nitrogen cycling.

The nitrogen pool sizes and internal fluxes in a number of managed West African forest ecosystems are also summarized in Table 1. Both pool sizes and fluxes of nitrogen appear to be lower in the managed systems as compared with the natural forests, but it would be premature to assume that the lower levels are caused by forest management.

Table 1. Pools and fluxes of nitrogen in selected West African forested ecosystems. All pool sizes are in kg N ha^{-1}, while all fluxes are in kg N ha^{-1} yr^{-1}.

								Ibadan teak		
	Banco plateau	Banco talweg	Banco Terminalia plantation	Yapo Terminalia plantation	Yapo	Kade	Ibadan Pine	dense	moderate thinning	severe thinning
Precipitation (mm)	2100	2100	2100	1800	1800	1575				
Soil pH	3.6	4.3	3.9	4.6	4.3	4.9				
Veg. age (yrs.)	old	old	38	22	old	40–50				
Plant nitrogen										
above ground	1400	1400	700	470	1000	1800				
below ground						200				
Soil nitrogen										
to 10 cm	1720	1220	2200	2600	1560		1880(15)			
to 30 or 50 cm	6500(50)	5800(50)			2600(50)	4650(30)		2200(30)	2200(30)	1800(30)
Litterfall	170	158	156	112	113	240	89	49	57	54
Through-fall	60	60	31	15	13	11				
Retranslocation						very low	37	30	15	9

The managed forests reported are younger than the natural ecosystems, and where comparisons are possible they are increasing in nitrogen content more rapidly than are natural forests (Bernhard-Reversat, 1977). Additionally, the sites occupied by the planted forests may have been degraded at the time of planting. Finally, the very high nitrogen in litterfall at Kade (coupled with the very low retranslocation) suggests that the forest was not under any nitrogen stress, and the level of nitrogen in throughfall at the Banco sites was extraordinarily high.

We turned from this summary of nitrogen pool sizes and internal fluxes to a consideration of whole-ecosystem inputs and outputs. We considered it very important that nitrogen inputs and outputs be examined for a complete rotation – from an old forest through clearing and through forest regrowth. Unfortunately, information on the consequences of clearing and regrowth is scanty for natural forests and absent for managed forests. We were thus confined to estimating input-output budgets for a complete cycle of natural forest and for the period of development of managed forests.

The input-output budgets of a number of selected West African ecosystems are summarized in Table 2. The values in this table were estimated by the following procedures.

Table 2. Inputs and outputs of nitrogen from selected West African ecosystems. Where only one value or range of values is reported, it is meant to apply to both the moist semi-deciduous and rain forest zones. Where two values are reported, the upper represents the moist forest zone while the lower represents the rain forest zone. All values in kg N ha^{-1} yr^{-1}.

	Natural Forest			Managed forests	
	Old	Cleared	Young	Teak	Oil palm
Inputs					
Bulk precipitation	10–15 15–20				
Nitrogen fixation	10–20	10 40	20–80 50–150	?	?
Fertilizer	0				
Outputs					
Surface run-off, erosion	<1	10–100	<1	0–15	<1
Leaching	1–5	*	<2	<2	<2
Denitrification	<20	*	<20	<10	<10
Volatilization	?	*	?	?	?
Burning	?	500–1000	0	0	0
Forest product removal, harvest	0	600–1000	0	0	50

* Decreases of 1000 kg N ha^{-1} or more are observed in surface soil (to 30 cm) in the 2–3 years following clearing and burning. We have no basis on which to apportion this decrease among leaching loss from the system, transfer to deeper soil pools, ammonia volatilization, and denitrification.

Inputs

Bulk precipitation

Information on nitrogen inputs in bulk precipitation was collected near Banco and at Kade. Relatively high concentrations were reported at both locations (12 kg ha^{-1} Kade, 21 at Banco). We decided to use a range of 10–20 kg N ha^{-1} yr^{-1} for bulk precipitation in the region, with the higher inputs expected near the coast.

Nitrogen fixation

No direct measurements of nitrogen fixation in forest ecosystems were reported. Fixation at Banco was estimated at no more than 10 kg N ha^{-1} yr^{-1} – we decided to use a range of 10–20 for old natural forests. Rates of nitrogen accumulation in excess of 100 kg N ha^{-1} yr^{-1} were reported in Yangamgi, Zaire. More typically, nitrogen accumulations of 20–50 kg N ha^{-1} yr^{-1} are noted in developing forest ecosystems. These values represent net nitrogen accumulation – inputs minus outputs – and hence they may understate actual nitrogen fixation. Some of the increase may be due to translocation from deeper in the soil, however. No information is available for forests immediately after clearing or for managed ecosystems.

Outputs

Surface run-off – erosion

We assumed surface runoff, and hence loss of nitrogen via erosion, is minimal in most forests. On a catchment basis, streambank processes could still account for some losses of nitrogen erosion in established forests. More erosion would be expected in cleared forests. Its intensity is highly variable depending on the site and climate. Some losses of nitrogen via surface run-off in *Tectona* ecosystems in West Africa have been observed, but their magnitude is poorly known.

Leaching

Losses of nitrogen by leaching were estimated at Banco and Yapo, where they amounted to 5 kg N ha^{-1} yr^{-1}. This value is probably high for the region as a whole, and certainly rapidly accumulating forests can be expected to have lower losses via leaching. Consequently, we estimated leaching losses as being rather low for all of the systems except for the recently cleared site. We will compare losses of nitrogen by leaching, denitrification, and volatilization at the end of the section concerning outputs.

Denitrification

No estimates of denitrification are available for forests of the region, although a high denitrification potential was demonstrated at Banco. Nitrification rates are high in these forests (at least the natural forests), and the soil nitrate pool does fluctuate considerably.

We placed the indicated upper bounds on denitrification in established forests simply by making the assumption that most nitrogen mineralized is taken up again by vegetation, and that it is unlikely that more than 10 % could be lost to denitrification. The lower estimates for managed forests reflect lower rates of nitrogen mineralization in most such forests examined.

Ammonia volatilization

No information on ammonia volatilization is available. Nye & Greenland demonstrated that ammonia gas was present in the atmosphere within the Kade forest, but the source of the ammonia was unknown. Soils, plants, or insect excretion could be responsible. In any case, we assumed that for all of the sites except cleared land, any ammonia volatilization is likely to represent primarily an internal transfer from soil to leaves within the system and not a loss from the system as a whole.

Harvesting

Nitrogen removed by harvesting was calculated by assuming that all nitrogen in wood (≅ 10 cm diameter) and bark is removed from a forest following clearing. Rather large amounts of nitrogen can be removed in this way, but harvesting takes place after substantial periods (≅40 years) of nitrogen accumulation. Harvesting of oil palm nuts has been reported to remove an average of 50 kg N ha^{-1} yr^{-1} for a 20-year period.

Burning

It was assumed that all the remaining plant nitrogen (except roots) would be volatilized during burning within a cleared site. This probably represents a substantial overestimate, since clearing in traditional farming systems leaves live stumps and many stems of up to two metres in height. Moreover, selected useful trees may be left standing. There are further variations in the degree of nitrogen volatilization caused by the time of the year, the amount of drying of residues prior to burning, and the patchiness of debris piles.

Nitrogen losses from cleared sites

Decreases in soil nitrogen of more than 1000 kg N ha^{-1} have been reported in the one-three years after the clearing and burning of West African forests. Soil contents are generally unchanged or a little higher immediately after burning, but they then decrease rapidly. We have no information which would allow us to apportion these losses among leaching from the ecosystem as a whole, leaching to deeper soil layers, denitrification, and ammonia volatilization. The mechanisms which could apportion losses among these pathways are more or less known, but the data which would allow us to determine which mechanisms are important in West African ecosystems are unavailable.

Research sites

Many of the active forest research sites in West Africa are referenced in Table 1. Additionally, the MAB program is sponsoring the Tai Forest project in Ivory Coast, an intensive ecosystem-level study which includes an examination of nitrogen cycling and loss in primary forests, the effects of harvest and forest management, the transition from forest to agricultural land use, and the influence of forest succession on nitrogen cycling and loss. This study will add a great deal to our knowledge of nitrogen cycling in West African forests. If less intensive comparative studies, such as one in progress in the Omo Forest Reserve, Nigeria, can be maintained, the investment in the Tai Forest will be even more valuable.

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Nitrogen Cycling in West African Ecosystems

REPORT OF THE WORK GROUP ON AGROECOSYSTEMS IN THE WET HUMID TROPICS

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Introduction

The nitrogen cycle is described for agrosystems on ferralitic soils subject to average desaturation with rainfall between 1400 and 1800 mm.

The concept of an agrosystem is not used here, as is generally the case, to describe an area geographically limited by definite borders. In fact, considering the scarcity of information available on the repartition of different rotation crops, it seemed preferable to consider the sequence in time of crops on one plot of land. Consequently the agrosystem is defined with respect to crop rotation.

In most cultivation systems in use, the rotation comprises two phases:

- a cropping phase
- a regeneration phase or fallow.

The relative importance and nature of each phase vary significantly according to production systems and their level of intensification. Therefore, it was considered appropriate to describe two types of agrosystems illustrating respectively:

- traditional systems
- improved systems

For each of these, only the cropping phase was the subject of a quantification essay.

Characterization of the agrosystems

Traditional systems

These systems range from intensive cropping systems where fallows are absent or very short in compound farms and areas of high population density to more itinerant long bush or forest fallow systems. The nitrogen content of the soil tends towards an equilibrium which is determined by the relation between the losses occurring for the most part during the cropping phase, and the additions mainly during the fallow phase.

No application of fertilizer is generally made but on compound farms, in areas of more or less permanent cultivation, much use is made of household refuse, small animals pen manure, mulch and sometimes compost. The supply of nitrogen to plants is mainly dependent on the mineralization cycle of the organic reserves of the soil, which is itself related to the climatic cycle.

The planting of associated crops allows a better use of the environmental potentials (water, mineral elements and light energy) and limits the effects of climatic uncertainties and other factors threatening the crops.

The productivity of these systems, although not generally high, is essentially dependent on the length of the period of fallow, which determines the extent of replenishment of fertility lost during the cropping phase.

Improved systems

In these systems, the productivity increase is obtained through the simultaneous improvement of a whole set of farming techniques which, apart from the use of fertilizers, affect essentially:

- the choice of selected plant varieties
- the timing and density of the sowing
- the tillage of the soil
- the battle with predators.

The intensification of production factors aims at an economic optimization of the input/output relationships.

Method of presenting the results

The method used is the one defined by Frissel (1977). The systems studies were restricted to two compartments:

- a plant compartment (P)
- a soil compartment (S)

each characterized by the following fluxes which traverse it:

- inputs $\rightarrow$ X
- outputs Y $\rightarrow$
- transfers Y $\rightarrow$ X

These fluxes, grouped on one side as supplies and on the other side as removals, allow the calculation of a balance and the characterisation of the system's state. They are expressed in kg ha^{-1} and represent a yearly average.

In most cases, in order to integrate the variability of the data from the literature, it was judged preferable to give a range of values rather than an average. This implies a certain lack of precision in the calculation of the balances.

List of fluxes studied

In the plant compartment

- Supplies
  (i) inputs by seed or seedling $\rightarrow$ P
  (ii) transfer by net uptake from soil S $\rightarrow$ P
  (iii) input by uptake from the atmosphere $\rightarrow$ P

- Removals
  - (i) transfer by seed for sowing P → S
  - (ii) output by primary product P →
  - (iii) transfer by plant residues P → S
  - (iv) output by burning P →

In the soil compartment

- Supplies
  - (i) input by waste → S
  - (ii) input by addition of fertilizer → S
  - (iii) input by non-symbiotic N-fixation → S
  - (iv) input by dry and wet deposition → S
  - (v) transfer from plant residues P → S

- Removals
  - (i) output by denitrification and volatilization S →
  - (ii) output by leaching S →
  - (iii) output by erosion and run off S →
  - (iv) transfer by plant uptake S → P

Significance of the extreme values

In the case of traditional systems, the highest values correspond to the cultivation phase immediately after the reclamation of the land. This period is characterized by an excess of supply over demand. This excess is partly lost due to the inadequacy of the farming techniques used. The lowest values correspond to crops grown several years after the reclamation of the land, when the fertility decreases.

In the case of improved systems, the range of values represent different levels of intensification. The lower values correspond to the implementation of the agricultural practices most commonly popularized and spread in rural areas, whereas the higher values relate to results obtained at experimental farms where the whole set of farming methods can be applied in conditions of maximal efficiency.

Results

The results are summarized in Table 1.

Comments on the plant compartment

The average quantity of nitrogen used yearly by plants has been estimated to:

- 40 to 80 kg ha^{-1} in traditional systems,
- 100 to 200 kg ha^{-1} in improved systems.

This nitrogen originates generally from the soil with the exception of leguminous species

Table 1. Example of nitrogen balance for a tropical agrosystem (kg ha^{-1} yr^{-1}). The figures mentioned are based either on: compilation from the literature, extrapolations or calculations.

Identification of fluxes	Traditional systems		Improved systems	
Plant compartment				
Supplies				
input by seed or seedlings	2 to 5		2 to 5	
transfer by net uptake from soil	33 to 66	40 to 80	83 to 166	100 to 200
input by uptake from the atmosphere	7 to 14		17 to 34	
Total supplies	42 to 85		102 to 205	
Removals				
transfer by seed for sowing	2 to 5		2 to 5	
output by primary product	24 to 48	40 to 80	60 to 120	100 to 200
transfer by plant residues	5 to 10		40 to 80	
output by burning	11 to 22		– –	
Total removals	42 to 85		102 to 205	
Balance	0		0	
Soil compartment				
Supplies				
input by waste	<5		<5	
input by addition of fertilizer	0		50 to 100	
input by non-symbiotic N-fixation	<10		<10	
input by dry and wet deposition	10 to 20		10 to 20	
transfer from plant residues	5 to 10		40 to 80	
Total supplies	15 to 45		100 to 265	
Removals				
output by denitrification and volatilization	<20		<50	
output by erosion and run-off	<60		<60	
output by leaching	5 to 50		50 to 150	
transfer by plant uptake	33 to 66		83 to 166	
Total removals	38 to 196		133 to 426	
Balance	-23 to -151		-33 to -161	

which partly use atmospheric nitrogen. The quantity thus fixed through symbiotic fixation has been estimated to:

- 20 to 40 kg ha^{-1} in traditional systems. The quantity is of less importance when the soil is well provided with mineral nitrogen, as a high content of the latter has a lowering effect on the efficiency of symbiotic fixation.
- 40 to 80 kg ha^{-1} in improved systems, for which the increase of fixation when the level of intensification is raised originates partly from the use of selected species with high fixation ability, and partly from the suppression of other limiting factors than nitrogen.

At the rotation level, the relative importance of nitrogen originating the soil compared to nitrogen from the atmosphere depends thus on the relative importance of the leguminous crop in comparison to other crops.

The results mentioned in the table above were calculated assuming the relation to be 1/2, i.e., assuming a succession of three crops, one of them being leguminous.

As to the relative importance of the fractions removed through harvest and the fractions that can be transferred by plant residues, they have been estimated to be 60 % and 40 % respectively of the total quantity used by the plants.

In traditional systems the recovery can be limited by the practice of burning, which can affect up to 70 % of the total residues from farming.

Comments on the soil compartment

Fertilizers are used only in improved systems. The rates most frequently recommended are in the magnitude of 50 kg ha^{-1}. As mentioned above, the aim is to obtain an economic optimum. In less advanced systems inputs are preferably reserved primarily for cash crops, and secondly for cereals.

In more intensive systems the rates can be significantly raised and reach 100 to 200 kg ha^{-1}. The cumulative effect of large inputs, most frequently in the form of ammonia sulphate, causes an acidification of the soil.

The coefficient of fertilizer uptake by plants, which is higher at low rates than at high rates, does not exceed 50 %.

The recovery of plant residues constitutes an essential practice for the maintenance of fertility and the equilibrium of humus balance. Moreover, it allows the reincorporation into the soil of a fraction of the nitrogen taken up from the atmosphere.

The table shows that in the soil compartment, the total inputs remain insufficient to compensate for the losses. In traditional systems the inputs are inferior to the amounts absorbed by plants alone. The deficit results in an impoverishment of the soil that could only be slowed down by the introduction of a sufficiently long period of fallow, which would allow fixation and transfer to the surface of a fraction of the subsoil nitrogen.

Conversely, in improved systems, the supplies are in excess compared to the absorption by plants. Nevertheless, they are necessary for the maintenance of the system's productivity as they result in a significant increase of losses, mainly through leaching, and hence a deficit which increases with increasing supplies.

The maintenance of these systems is dependent on the adoption and use of farming techniques apt to increase the efficiency of fertilizers by reducing losses (e.g., by splitting up the inputs). Besides, the introduction of an improved fallow or a rotation cultivation of fodder based on leguminous crops may constitute a possible solution to the maintenance of a satisfactory nitrogen balance.

Discussion

The method of presentation adopted, which exhibits each compartment as a "black box" illustrates inadequately the whole set of interactions that rule the dynamics of a soil-plant system as well as the processes set in action. For instance, little information is available on the prospection of soil profiles of plant rooting and on profiles of root activity "in situ". The role of deep roots remains to be defined. This is all the more important as erosion phenomena are intensive.

Regarding the plant compartment, which is the best known, some uncertainties remain. In particular, the contribution from biological fixation to the nitrogen cycle is only measured under particular circumstances which makes it difficult to extrapolate and evaluate its significance in the field. The emphasis was placed on these shortcomings, and research focused on their removal must be given priority.

In the soil compartment little information has been assembled concerning the internal nitrogen cycle (mineralization – immobilization). The knowledge of the impact of farming techniques on this cycle constitutes, however, an essential element of a better control of the conditions for nitrogen balance. The use of ^{15}N could be a fruitful method for these studies.

On the other hand, if the intensification results in an opening of the nitrogen cycle, the available data are, at the current state of knowledge, insufficient for an exhaustive and reliable evaluation. In particular, for losses, the variability as well as the number of data cause difficulties. There are several reasons for this. Some are of methodological nature (differences in experimental measurement devices), while others are probably due to inadequate identification of the processes.

Therefore, if the data obtained by different authors should be used for the setting up of a complete balance, it seems indispensable to have access to a certain number of references which take into account the whole complex (climate – soil – plant – farming techniques). For this reason, it is recommended that a network of reference information regarding measurement results can be created.

Finally, it is advisable to once more state that the undertaken quantification essay relates to a single plot and does not take into consideration the redistributions which may occur in the atmosphere. The consequence of this is that deficiences are overestimated in the balance. Therefore, measurements ought to be made on the level of whole geographical units such as, e.g., basin slopes.

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RESEARCH PRIORITIES AND FUTURE CO-OPERATION

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Abstract

The discussion centred on the following items:

1. **Research priorities**
    1. Processes involved in additions and losses of nitrogen from ecosystems
    2. Nitrogen transformations and recycling within the systems
    3. Integrated nitrogen-cycling studies

2. **Research priorities for specific ecosystem types**
    1. The savanna zones
    2. Forests

3. **Future co-operation**
    1. Training courses and manuals
    2. Equipment and analysis facilities
    3. Information exchange and bibliography

General research priorities

Research priorities – inputs/outputs

The group considered that the most important overall objective would be to quantify changes in total soil nitrogen over extended periods of time. Baseline data are badly needed to improve our knowledge of the ecosystem. This enables the prediction and evaluation of the impact of various management practices on nitrogen content and distribution within any given ecosystem.

It was also considered important to monitor the inputs of nitrogen through dry and wet deposition. Since, however, this factor cannot be controlled by man, it is of less importance in attempts at developing suitable management practices. The information is necessary for assessing the overall nitrogen budget of ecosystems, especially those low in total nitrogen, which do not have inputs of extra nitrogen as organic matter or fertilizers.

All work groups stressed the importance of further quantitative information on biological nitrogen fixation, denitrification and ammonia volatilization. The relative importance of these processes in the various systems varies, however. The importance of assessing the changes over time in tree stands of different age was stressed, especially by the forestry group. A dynamic approach, with extended time periods for study, is needed. This is also important in relation to the effect of altered management practices.

Burning was identified as an important factor in many systems that regulates net nitrogen losses.

Research priorities – internal cycling

The importance of understanding the mechanisms involved in N-transformations was emphasized. Only in this way it will be possible to predict the response of a given system to a given set of conditions. It is important to apply mechanism based models that can predict the variability documented through empirical observations. It was, however, also pointed out that there is an important need for rigorous empirical studies to establish the data base necessary for application of the appropriate models. Internal nitrogen dynamics are variable over time and among different soil types, and this variability must be taken into consideration.

The importance of toposequence studies was also stressed.

Research priorities – integrated studies

Integrated studies on nitrogen cycling in specific ecosystems are extremely important in order to obtain an understanding of ecosystem dynamics. These can be performed at several different levels, *viz.*, the farm of experimental plot, the integrated cropping system of a farm, or an entire watershed or catchment basin. Such studies are at present very rare.

It was suggested that it would be very valuable if a certain number of integrated studies could be performed in the major systems of the region. These could then be supplemented by individual process studies and would serve as a reference system for the more specialized studies. This calls for the identification of sites where integrated studies are being performed or could be initiated. The importance of long-term studies in establishing trends was emphasized. Most research tends to focus on short-term efforts. Efficient information exchange between individuals and groups of scientists working on these questions is necessary (see below). As regards forest ecosystems, the importance was pointed out of making intensive comparisons between a few fundamental types of forest system. The MAB Tai forest project in the Ivory Coast and Omo Forest Reserve in Nigeria were mentioned as examples of such studies.

With regard to agro-ecosystems, integrated studies are being performed, especially at ORSTOM and IITA, as well as at IRAT and other laboratories.

Concerning the Savanna zones, the importance of information exchange between the Sahel-Mali project on grazing lands and other grassland studies in the region was emphasized. The importance of more efficient information exchange between the French-speaking and English-speaking regions was noted.

The importance of studying the effect of changes in management practices on nitrogen cycling in the savanna regions was mentioned, although it is not possible at this moment to identify any integrated projects in this area.

It is important, however, not to concentrate all resources into only a few projects. Integrated studies are resource-demanding, and to be widely applicable they must be supplemented by studies with a more limited focus, which may consist of in-depth projects on specific important mechanisms.

Research priorities for specific ecosystem types

The savanna zones

The group decided to use five main criteria for establishing research priorities within the four systems considered, *vis.*:

i) importance of parameter for crop production
ii) state of knowledge
iii) feasibility of regional research
iv) possible environmental impact
v) possibility of manipulating the parameter

Priorities were classified according to four categories: –, +, ++, +++. Owing to time constraints, the research needs in important cropping systems other than sorghum (3 years) – fallow (3 years) were not considered. It was further decided not to discuss specifically the need for further research on the use of nitrogen fertilizer, since this was felt to be adequately handled by such organizations as FAO, IAEA, IITA and WARDA, as well as by national agricultural research institutes.

Table 1 should be regarded as a rough outline only. Local factors will of necessity affect the priorities. It was, however, felt that the list might be useful as a basis for further discussion.

The highest priority was given to the monitoring of soil organic nitrogen over time (tens of years) in all four systems. This was considered very important in judging the impact of management practices on the ecosystem. A loss in soil nitrogen will also be an indication of loss of soil organic matter, which may increase erodibility and decrease the water-holding capacity and aeration of the soil.

Few data are available on the input of nitrogen through dry and wet deposition. This need was, however, not given the highest priority, since this factor cannot easily be managed by man. A certain number of inventory samplings should, however, be made. Although these inputs may be quantitatively small, they may nonetheless be important in systems low in available nitrogen.

The need for nitrogen fixation research varies widely, both with the type of fixation and with the ecosystem. The highest priority should be given to the study of the rhizosphere fixation of sorghum in the wet savanna zone. Although this may not be quantitatively important, nothing is at present known about its rates. The need for studying fixation by legumes – especially legume trees and shrubs – was considered important for the extensively grazed systems of both the Sahel and the wet savanna zones. There is also a need for study of herbaceous legume species at present not used in the region for agricultural purposes.

The use of organic nitrogen in sorghum and millet cultivation, especially in the Sahel region, may be extremely important and should be quantified. This is very much dependent on the socio-economic conditions and cultural traditions and may vary from one subregion to another.

Erosion losses may be important in many areas of the wet savanna zone, in both the extensively grazed and the sorghum cultivating systems, whereas leaching is probably only of importance in the sorghum system of the wet savanna zone.

Table 1. **Research priorities for nitrogen cycling in the Sahel and wet savanna zones of West Africa. In each zone, one extensively grazed system and one grown with sorghum selected. +++ indicates highest priority, ++ high priority, + medium priority, and – low priority.**

	Sahel		Wet savanna	
	Extensive grazing	Sorghum	Extensive grazing	Sorghum
Site character				
Soil N monitoring	+++	+++	+++	+++
Inputs				
Deposition monitoring (dry and wet)	++	++	++	++
N_2-fixation:				
rhizosphere	–	–	++	+++
herbaceous legumes	++	–	–	–
use of legume trees	++	–	++	–
occurrence and fixation by trees	+	–	+	–
blue-green algae	–	–	+	–
Organic–N use	–	+++	–	++
Losses				
Erosion:				
catchment monitoring	–	–	+++	+++
cultivation *vs.* erosion	–	–	–	+++
Leaching:				
survey	–	–	–	+++
cultivation *vs.* leaching	–	–	–	++
Denitrification	–	–	+++	+++
Burning:				
total losses	+++	see harvest	+++	see harvest
after clear-cutting	–	–	+++	–
P availability	+	–	+	–
nitrification stimulation	+	–	+	–
native legume increase	++	–	+	–
erosion losses	–	–	+	–
Harvest:				
survey of use	–	+++	–	+++
utilization of tree legumes	++	–	+	–
human waste	–	+	–	+
Grazing:				
quantifying loss	+++	+	+++	+
termites	+++	–	++	–

Denitrification measurements are generally lacking, and the adaptation of present techniques to field conditions should receive the highest priority. Special attention should be given to the possible losses through denitrification of nitrogen accumulated in termite mounds. It is also important to consider the rate of nitrification, as this regulates nitrate production and possible losses through denitrification and leaching.

Burning losses are probably very important, since burning is a natural part of the management of the savanna zones. Such burning is a regular feature but may not only occur as a part of management practice but may also occur accidentally, to flush out game and may often occur through uncontrolled fires. In the wet zone, specific studies should be performed to assess the losses through burning after clear-cutting. However, burning also has certain beneficial effects, e.g., increase in native legumes, stimulation of nitrification, and availability of phosphorus, which should be considered.

Quantification of nitrogen losses in harvesting, as well as losses from the grazing of cattle and from termites are other research areas that should receive high priority.

Forests

The suggested priorities are summarized in Table 2. It is considered that an analysis of what happens to the massive amount of nitrogen lost from surface soils following forest clearing should have the highest priority, since this loss could have significant effects on both soil fertility and water quality. The determination of the rate of nitrogen accumulation in young natural forest, tree-crop and tree-plantation ecosystems also deserved very high priority.

There are four reasonably likely pathways for the large amounts of nitrogen lost from cleared forest soils: leaching of nitrate from the system, leaching of nitrate deeper into

Table 2. Research priorities for nitrogen cycling in West African forested ecosystems. +++ indicates highest priority, ++ high priority, + medium priority, and – low priority.

	Natural forests			Managed forests	
	Old	Cleared	Young	For forest products	Tree crops
Bulk precipitations	+	+	+	+	+
N fixation	+	+	+++	+++	+++
Erosion	–	+	–	+	–
Leaching	–	+++	–	–	+
Denitrification	–	+++	–	+	+
Volatilization	–	+++	–	+	+
Burning	–	+	–	–	–
Harvesting	–	+	–	–	+
Translocation within soil	–	+++	++	++	++

the soil, ammonia volatilization, and denitrification. Other processes, e.g., erosion, could be important in certain circumstances. The four likely mechanisms would have different consequences: nitrate leaching from a system would decrease soil fertility by removing nitrogen and cations, and could even impair downstream water quality if sufficiently large catchments were cleared; ammonia volatilization and denitrification would decrease soil fertility by removing nitrogen; and nitrate leaching to deeper soil layers would have little long-term effect as long as the nitrate were accessible to the regrowing forest. The possibility that trees may use nitrate leached to lower depths should merit attention. The difference between species in using this nitrogen in deeper soil layers should be investigated.

Although it would be extremely difficult, perhaps impossible, to determine precisely how much nitrogen was lost from surface soil by each of these pathways, an analysis of the probable importance of each should be simple and relatively inexpensive. Nitrate leaching (both to deeper layers of the soil and out of the system) could be determined by installing soil water samplers (either tension plate lysimeters or porous cups) at depths of 0.3 and 2 m within the soil. The leachate would be analysed for nitrate and total nitrogen. If 1000 mm of water moves through the soil, and 1000 kg N ha^{-1} are leached past a given depth after clearing, the mean nitrate concentration in soil water sampled at that depth would be 100 mg NO_3-N. If very high nitrate concentrations were observed at 2 m depth, it would be reasonable to conclude that nitrate leaching from the system was important. If high concentrations were observed at 0.2 m but not at 2 m, either denitrification or nitrate accumulation and/or adsorption were important, the nitrate would be detectable by analysing a salt extract of the deep soil. Nitrate adsorption on positively charged iron and aluminium oxides appears to be a reasonably likely mechanism; an accumulation of 0.4 meq NO_3 100 g^{-1} of soil in the top 2 m of soil could amount to over 1000 kg N ha^{-1}, but this is very variable.

Ammonia volatilization could be estimated by boric acid traps. While such traps are generally considered qualitative at best, a loss by volatilization of 500 kg N ha^{-1} yr^{-1} would amount to 250 mg NH_4-N 50 cm^{-2} of soil surface yr^{-1}, which should be easily detectable and interpretable by using small volume boric acid traps. If these measurements were made before and after clearing on two or preferably more forest sites in West Africa, the possible importance of each of the pathways for nitrogen loss from surface soils could be established or ruled out. If a sufficiently large number of sites were examined, comparisons of results among the sites should yield an insight into the mechanisms controlling nitrogen losses from cleared forests, and these mechanisms could then be examined experimentally.

It was also believed that studies of rates of nitrogen fixation in young forests, particularly young managed forests, are extremely important. The available data (from relatively few sites) suggest the possibility of nitrogen accumulation of up to 100–150 kg N ha^{-1} yr^{-1} in young natural forests, and consequently a rapid rebuilding of soil fertility following forest clearing. If these estimates are accurate (and to the extent that the N lost after land clearing is leached to deeper, though still accessible, soil layers, they are likely to be overestimates), then the relative importance of N fixation in managed forest ecosystems is critically important in maintaining the long-term productivity of the land. Since most managed forests have a much lower abundance of legumes than natural forests in West Africa, lower rates of fixation are to be expected.

There is also a lack of information on the nitrogen fixation potential of leguminous trees in tropical forest ecosystems. This is important because of the differential fixation potentials among the Papilionaceae, Caesalpiniaceae and Mimosaceae. Information on this process could be very useful in developing managed ecosystems, since it would facilitate determination of the extent to which inclusion of high nitrogen-fixing tree species in forests could enhance nitrogen fixation and the overall nutrient balance.

Future co-operation

Training courses and manuals

The need for training was emphasized during the meeting. Of the existing training programmes, the following were particularly mentioned:

(i) IAEA and FAO conduct training courses on the use of ^{15}N in agriculture and forestry. Scientists and research groups in the respective countries should approach national atomic energy or agricultural offices for official requests to be made to IAEA and FAO.

(ii) UNEP/Unesco/ICRO Programme on Applied Microbiology.
Included in the working plan for the SCOPE/UNEP International Nitrogen Unit is a component on training. This calls for two regional training courses to be suggested by the project for support by the UNEP/Unesco/ICRO Panel on Microbiology. The Panel has taken a preliminary decision to hold a regional training course on the applied aspects of nitrogen cycling in West Africa. It is also hoped to hold a second training course within this programme in Bangladesh in 1981.

(iii) National and regional courses are being arranged at various institutes in the region. A number of such courses relevant to nitrogen cycling studies have, for example, been held at IITA. The topics that have been covered are the analysis of nitrogen compounds, and manuals are available. Similar manuals have also been prepared by ORSTOM.

It is recommended by the meeting that information on training courses and manuals should be widely circulated in the region. For this purpose, use can be made of the list of researchers involved in nitrogen cycling studies, which is included in this volume.

Equipment and analysis facilities

It is important to ensure that the results obtained in individual laboratories are correct, and intercalibration should be carried out. Some chains of laboratories, exchanging samples, have already been set up. It is suggested that non-participating laboratories should join existing chains rather than start new ones.

IAEA has a technical assistance programme with respect to the use of ^{15}N, which involves sending experts and equipment to laboratories in LDCs. Requests for such assistance should come from the national agency responsible for atomic energy.

It is important that simple and reproducible techniques are used by the individual laboratories. Standardization of both laboratory and field methodology was considered to be of the utmost importance. These questions could not, however, be discussed fully at the present meeting. It is hoped that the training courses and laboratory manuals mentioned above will help in standardizing techniques. IAEA/FAO and the UNEP/Unesco/ICRO Panel on Microbiology could play an important role in this respect.

It was suggested by the workshop that in certain instances centralized analytical equipment at certain national centres would be useful. There is a gradual trend towards such centralization because of the increasing cost and complexity of equipment.

It was also pointed out that other important problems are those of sample representativeness as well as sample collection and handling. Any recommendations for standardized analyses should also take these items into account.

Information exchange and bibliography

An annotated bibliography on nitrogen cycling in West African ecosystems was prepared as one of the background documents to the present meeting (Nwoboski & Adedipe, 1978). Additional references were later added, and a bibliography on nitrogen cycling studies in West African ecosystems is included in the present volume.

Information exchange is, of course, very important, and special attention should be given to improved exchange between the English-speaking and French-speaking countries in the region. As one step towards facilitating this information exchange, a list of researchers active in the field of nitrogen-cycling studies in West Africa has been compiled and is included in the present volume.

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