International Potash Institute

Nutrient Balances and the Need for Fertilizers in Semi-Arid and Arid Regions

Proceedings of the 17th Colloquium of the International Potash Institute held in Rabat and Marrakech/Morocco 1983

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Chairman of the Colloquium

Prof. Dr. *H. Laudelout*, Soil Science Dept., University of Louvain, Louvain-la-Neuve/Belgium; member of the Scientific Board of the International Potash Institute

Opening Session

Opening Address

Dr. *N. Celio*, former President of the Confederation of Switzerland; President of the International Potash Institute, Bern/Switzerland

I have the honour to declare open the *17th Colloquium of the International Potash Institute*, and in doing so I have great pleasure in extending a particular welcome to:

- The representative of the Ministry of Agriculture of the Kingdom of Morocco, Monsieur *A. Guedira*;
- Monsieur *Bekkali*, Director of the Hassan II Institute of Agriculture and Veterinary Science who has been kind enough to welcome this Colloquium into the bosom of this great establishment which he directs in such a distinguished manner;
- Monsieur *Squalli*, Director General of SASMA;
- Professor *Laudelout*, President of this Colloquium, and all the members of the Scientific Board of IPI;
- The professors, lecturers and research workers of the I.A.V.
- Finally I must welcome the ladies and gentlemen who come from 34 different countries and who, for a week, will take part in our work. We are really grateful to them for coming.

I also have the pleasant duty, in your name, to offer our respectful greetings to the *Kingdom of Morocco*, to *His Majesty the King* and *his people* with our best wishes for prosperity and the future.

The story of Morocco stretches far back through the centuries to the prehistoric era and the Bronze Age. It is liberally sprinkled with the names of heroes which were familiar to us in our schooldays: the Phoenicians, the Carthaginians and their successors, the Romans, the relics of whose occupation can still be admired, and, finally the Vandals and Byzantines who followed the decline of Rome. Present-day Morocco continues to develop her culture and civilization and can be proud of the progress made.

Historic sites, village life, religious monuments and folklore alike testify to the culture which has distinguished this country and its people over the centuries. It was not just pure chance which led our Scientific Board to select this beautiful and sympathetic country for the Colloquium. The people and institutions of Morocco have proven through the policies they have pursued that the future of a nation is based on agricultural productivity. This applies equally to the developing countries and to those which, like Morocco, have already passed through the earlier stages and are approaching the stage of economic development obtaining in the most developed countries. One of the indications of the wisdom of the policies which Morocco has followed is the order which reigns in the monetary field; such order is not always to be found in the so-called developed countries of Europe.

It is time now to come to the particular problems which will occupy our attention during the coming week. The present working cycle of the Institute is concerned with nutrient balance in crop production, and this Colloquium deals with the subject in the context of the arid and semi-arid climates. The Colloquia of 1984 and 1985 will deal with the temperate and tropical climates respectively, while the Congress, to be held in France in 1986, will draw together the conclusions from the three preceding meetings and formulate general conclusions and recommendations on the general theme of the cycle.
Morocco was a natural choice for this Colloquium because here we find within one country conditions ranging from total aridity to adequate rainfall. Further a great range of crops is grown, from extensive cereals to export crops grown intensively.
Our close contacts with scientific organizations in Morocco have shown that the level of research here is high and that many interesting data bearing on our theme are available. Our choice was also influenced by the close and fruitful collaboration which has been established between agricultural research in Morocco and our Mediterranean Mission for which Mons. *A. Saurat* is responsible. This modern and efficient research, which we are ready to recognize, is of the greatest importance to a country where more than half of the population is engaged in agriculture.
The good Moroccan infrastructure and the help we have received from Moroccan institutions has greatly facilitated organization of the Colloquium. Dr. *Agbani* and Dr. *Ghanem*, both collaborators of Dr. *Bekkali*, have been our most active contacts and merit our particular thanks for their friendly and effective cooperation.
The tradition of our institute to bring together each year the best known specialists within a limited scientific field has given us the opportunity, wherever our meetings have been held, to establish contacts which have furthered our work and ensured that we make progress in a friendly atmosphere. It is well to be able to record – in the interests of scientific progress and of world agriculture – that our Colloquia and Congresses have established permanent relationships and brought about exchange of knowledge between the delegations coming from the various countries.
In conclusion, Ladies and Gentlemen, allow me to say how much we appreciate your work and your devotion to the cause of agricultural research. Personally, other than for my peasant origin, I have had little to do with agriculture but I am a lover of nature and I never cease to marvel at the miracle which enables mankind to produce his needs from the soil wherever he may be. My life has been spent in grappling with the problems of finance and economics and this has convinced me that the first obligation for any society is to feed its members and this can only be achieved by working on the land. Production which is renewed each year and which permits humanity to perpetuate itself is riches indeed.
Working for the improvement of the living conditions of the people and above all for those who suffer from hunger is the most noble of callings. For this reason you may take pride in your activity which leads to humanitarian, economic and political progress. Distress and famine often lie at the root of conflict or revolt. Power and compulsion can do nothing to avoid them, they can be prevented only by curing the sickness which is their origin and thus offering the people a life of dignity and satisfaction.

Welcome Address

Dr. *A. Bekkali,* Directeur général, Institut Agronomique et Vétérinaire Hassan II, Rabat/Morocco

Mr. Chairman, Ladies and Gentlemen,

It is a great honour to welcome the 17th Colloquium of the *International Potash Institute* to Morocco and to our Institute. In the first place I would like to welcome each of the many participants from more than 30 countries who have come to take part alongside their Moroccan colleagues. The presence among us of Dr. *N. Celio,* President of IPI and former President of the Confederation of Switzerland, underlines the importance of this scientific meeting devoted to the problems of Nutrient Balances and the Need for Fertilizers in Semi-arid and Arid Regions.
The immense extent of these areas subject to severe climatic constraints poses problems for agricultural development and research which are of great significance in relation to world food supplies.
Much attention is being paid by international institutions to the development of arid and semi-arid areas and particularly to those areas situated on the fringes of the Sahara and in the African Sahel of which more than 300 000 square kilometres are found in Morocco and we can only rejoice at this interest which has shown up the need for further and sustained research if agricultural development of these areas is to become a reality. Your work in this Colloquium will surely make a significant contribution towards self sufficiency and good security in this country and internationally.
It seems particularly significant that this 17th Colloquium of the IPI is being held in Morocco which in recent years has suffered from extreme and exceptional drought.
The themes of this Colloquium: yield potentials, nutrient dynamics and farming systems for the dry areas are of immediate significance for our country. We expect much from your deliberations, much that will make a contribution to the development of arid and semi-arid areas. Surely there will be a positive outcome in the field of crop nutrition and in the identification of scientific and technical routes to the optimisation of agricultural productivity of these regions.
The International Potash Institute, and in this environment we should mention particularly its Mediterranean Mission, has contributed much to progress in plant nutrition through research and transfer of information by way of the high level meetings it has organised between workers in different scientific disciplines and I congratulate them. The improvement of agricultural production in arid and semi-arid regions is an arduous task which demands the cooperation of workers in several fields. Only by common effort and multilateral cooperation can we hope to progress more rapidly towards our aim of assuring food sufficiency in arid and semi-arid regions.

Mr. Chairman, Ladies and Gentlemen, I wish great success to this Colloquium and a pleasant and useful stay to our friends from abroad.

The Importance of Agriculture in the Moroccan Economy

A. Guedira, Economic Affairs Division, Ministry of Agriculture and Rural Reform, Rabat/Morocco

The agricultural sector plays a predominant role in the national economy because the living conditions for the major part of the population still depend directly or indirectly on agriculture which makes major contributions to the GDP and to the development of external trade. Its importance in the national economy also results from active trading between agriculture and other sectors. To explain the role of agriculture it is convenient to consider four headings: employment, gross domestic production, external trade and internal trade.

1. Population and employment

According to the census of 1971 and 1982 the population of Morocco has grown at the rate of 2,4% per annum, from 15.38 millions in 1971 to 20.42 millions in 1982. The rate of increase differs between town and country (respectively 4.4 and 1.4% p.a.) on account of the drift from the land at an increasing rate which presages a reversal of the relative size of these populations by the year 2000. Rural population has increased from 9,97 million (64.8% of total population in 1971) to 11.69 million (57.2% of the total) in 1982.

Regarding employment, the rural area assures employment for 3.2 million people of whom 2.2 million are engaged directly in agriculture, employment being estimated at 4.6 million units. Thus agriculture provides almost a half of total employment.

Over the past 20 years there has been a tendency for contraction in agricultural employment which is partly due to the growth of employment in other sectors. The situation is also explained by the way in which the agricultural labour market operates – with areas of surplus in manpower – and the relative immobility of labour in agriculture which contrasts with the rapid exodus to urban centres.

2. Gross agricultural production

The contribution of agriculture to GDP is estimated at 14.2% for 1981 compared with 18.1 in 1980 and 19.7% in 1969 at constant prices. The lowering of the share of agriculture in GDP in 1981 is explained by the severe drought which obtained in the 1980–1981 season and caused a severe decline in crop yield. For example the yield of cereals in 1980–1981 was only 50% of normal. In the early sixties agriculture contributed more than 30% of the GDP but the decline from this level does not mean that agriculture has not progressed, in fact production increased at 1.8% per annum between 1969 and 1980 at constant prices (1981 is ignored owing to the exceptional conditions).

Agricultural production shows great variation from one season to another, for instance it increased by 6% from 1979 to 1980 and fell by 23% in 1981.

A general description of the contribution of the different sectors of agriculture to total agricultural production, without going into too much detail, shows that cereal growing and livestock husbandry each contribute about ⅓, fruit and vegetables each about 11%. The remainder is made up from market gardening, sugar and oilseeds and forest products.

The utilisable agricultural area extends to 7.8 million hectares or 11% of the total land area (69 Mio ha). Of the 7.8 mio ha, 0,8 million ha (10%) is irrigated in large or smaller scale schemes; 2.5 mio ha (32%) are in favourable climatic areas (more than 400 mm annual rainfall); 4.5 mio ha (58% of utilisable land) is in low rainfall (less than 400 mm) areas or in mountainous areas.

Forest and alfa stands covers 7.6 million ha (11% of total land area). Commonage accounts for 20.9 mio ha (30% of the country) excluding forests.

It should be pointed out that the irrigated area is expanding at the rate of about 18 000 ha per year which puts our country, taking account of the means at its disposal, on a satisfactory level in comparison with other Mediterranean countries (50 000 in Spain, 30 000 in Greece).

3. External agricultural trade

Morocco's total external trade amounted to Dh 5491 million in 1970 and to 34 458 million in 1981 – an annual rate of increase of 17.3%. Over the same period total imports moved from Dh 8471 to Dh 22 455 million, increasing at 18.5% per annum. Total exports increased at 15.4% p.a. between 1970 and 1981 (from Dh 2470 million to Dh 12 003 million). The trade deficit was Dh 1002 million in 1970 and Dh 10 452 million in 1981. Agricultural and food imports accounted for 27.5% of total imports in 1970 and for 28.2% in 1981, the actual cost increasing from Dh 953 mio to Dh 6341 mio (at 20.9% per year).

The contribution of agricultural and food exports to total exports was 59.3% (Dh 1464 mio) in 1970 and 30.3% (Dh 3633 mio in 1981. The rate of increase was 9.5% p.a.

The decline in the share of agriculture in total exports is accounted for by two main factors:

- The increase in mining exports, mainly phosphate, since 1974.
- The protectionist policies of the EEC, our principal outlet, which have limited expansion in exports of early crops, preserves and wine in particular.

The general picture is that agricultural external trade has moved from a large surplus in 1970 (Dh 511 million) to a large deficit (Dh 2708 million in 1981 and this trend appears to be chronic. Thus the ratio of agricultural exports to agricultural imports has changed from 153.6% to 57.3%.

The chief agricultural imports are cereals (essentially soft wheat), dairy products, sugar, oils, wood, fertilizers and other agricultural inputs: the share of these products in total agricultural imports has increased from 62.3 to 80.5% over the period.
The main exports are: citrus, early crops (mainly tomatoes) preserves, wine and cotton which made up 55% in 1970 and 51.4% in 1981.
The geographical distribution of agricultural trade shows that the EEC takes 70% of our exports and supplies ⅓ of imports, while the USA contributes 1/5 of imports and takes only 2 or 3% of exports. Arab and African countries have only a negligible part in our agricultural and food trade, Arab countries taking only 3% of exports. The African countries make a somewhat larger contribution to agricultural and food imports.

4. Internal trade

Trade between agriculture and other sectors of the economy has increased steadily. Between 1969 and 1978 (the most recent year for which statistics are available) the value of intermediates consumed has increased at an average rate of 17% p.a., while its share in gross value of agricultural production has increased from 18 to 26%. Though the data may be imperfect it is clear that there has been an increase in the demand for inputs, but it is not possible to say how much of the increase is due to increased consumption and how much to price increase.
The main essential inputs to agriculture are fertilizers, seed, equipment and plant protection materials. Consumption of fertilizer is increasing at 6% annually. Present consumption of fertilizer amounts to about 200 000 while the potential demand is 950 000 tons of nutrients:
Consumption 81/82 (in tons): 81 000 N/78 800 P_2O_5/40 300 K_2O
Potential demand (in tons): 330 000 N/330 000 P_2O_5/290 000 K_2O.
Progress is being made in the selection and propagation of seeds with 20% self-sufficiency in cereals for which potential demand is 0.45 million tonnes.
Regarding mechanisation, the number of tractors has increased over the years but the recent rate of growth has been low for several reasons, principally the poor farming seasons experienced and price inflation. All tractors are imported. A recent government decision to exempt machinery from tax has had a favourable effect on sales. There are now 25 000 tractors in the country while the potential need is for 70 000.
The use of plant protection materials is increasing but consumption now is only about 15% of the potential.
There has been rapid expansion in agro-industries supported by increased sales from agriculture and increased imports (particularly by oilseed mills and flour mills which are almost exclusively supplied by imports). Local production of both sugar beet and cane is making an increasing contribution to the demand for sugar. Other sectors of the industry (canning, dairy products) are supplied entirely by local production. Government policy designed to improve the share of agriculture in the national economy has been directed to:
- improving the degree of self-sufficiency in basic foodstuffs,
- promotion of agricultural exports,

- reduction of social and regional disparities,
- the development of agro-industries.

Particular efforts are being made to extend the irrigated area thus permitting the introduction of new crops and the exploitation of modern cultural methods. This will result in increased demand for inputs and the establishment of centres for agro-industries around the irrigated areas. We are also much concerned with improving conditions in the climatically unfavourable areas both to increase production and to improve the quality of life of the inhabitants. Measures taken by government include the provision of subsidies and credit, technical advisory work and the setting of product prices at remunerative levels.

Introduction to the 17th I.P.I.-Colloquium

*H. Laudelout**, Soil Science Department, University of Louvain-la-Neuve/Belgium; Chairman of the Colloquium; member of the Scientific Board of the International Potash Institute

It is always worthwhile at the beginning of our proceedings to mention the philosophy underlying the organisation of the colloquia of the *International Potash Institute*, of which this is the 17th. The subject matter of a series of meetings relates to a central theme. The choice of subjects and of speakers competent therein is a main contribution of the Scientific Board of the Institute. The final aim of these meetings is to give light to the agricultural research being carried out in a country and as far as possible to make some contribution to its progress through international contacts.
Experience has shown that the aim is usually achieved despite some criticism of the programmes. Often the criticism is that too much attention is paid to fundamental aspects at the expense of the more practical technological aspects of the subjet and it is only too likely that the present meeting will not entirely escape such criticism.
The reason for the choice of topic for this colloquium and for the way of approaching it is the following: for historical reasons, the technology of agriculture has been developed primarily in the temperate humid regions and it relates to the socio-economic conditions of those regions. The transfer of technology from one region to another is not without risk. This is well understood by those responsible for agricultural research policy in this country and a programme has been worked out that is particularly adapted to the problems of the arid and semi-arid regions. The lectures and communications which you will hear take full notice of the climatic, ecological and soil conditions which determine the agricultural productivity of arid areas with summer or winter rainfall. If all that were required were an understanding of general principles and great capacity for deduction on the part of agronomists, the way forward to intensify the agriculture of arid and semi-arid regions could be found without difficulty. Unfortunately, this is not the case and there remains a need for intensive field experimentation which will be of long duration and far from straightforward. No doubt you will hear much of this in the lectures.

* Prof. Dr. *H. Laudelout*, Département de Science du Sol, Université de Louvain-la-Neuve, Place Croix du Sud 2, B-1348 Louvain-la-Neuve/Belgium.

Chairman of the 1st Session

Dr. *G. W. Cooke,* Honorary Scientist, Rothamsted Experimental Station, Harpenden, Herts./United Kingdom; member of the Scientific Board of the International Potash Institute

1st Session

Yield Potentials in Arid and Semi-Arid Areas

Potential Agricultural Productivity in Summer and Winter Rainfall Areas*

M.V.K. Sivakumar and *A.K.S. Huda***, ICRISAT, Patancheru/India

Summary

The productivity of summer and winter rainfall areas in the arid and semi-arid regions of the world was assessed through an evaluation of the climatic characteristics and potential dry matter production in relation to present productivity. Comparison of the average yield data for several crops in different regions with yields achieved under adequate management at experimental stations indicates that considerable potential exists for improving and stabilizing crop yields. The total biomass production is influenced by the intensity and duration of moisture stresses that frequently occur during the growing season. Fertilizer use in the summer and winter rainfall areas is closely related to the amount of rainfall and the availability of water for supplemental irrigation. Current use of fertilizers in these areas is reviewed and the constraints on yield and on the use of fertilizers are discussed. Further discussion in the course of the colloquium should lead to the identification of the means to alleviate these constraints.

1. Introduction

In the semi-arid and arid areas of the world, in view of the world's increasing population, there is an urgent need to increase agricultural production. The agricultural resources of the rainfed areas are limited, water being the chief constraint to improved production. According to estimates made by the *National Commission on Agriculture,* the percentage of net irrigated area to net sown area by the year 2000 in India is likely to be 41% and agriculture in most of the cultivated areas in India will continue to be mainly rainfed *(Garg [10])*. This will require extension of cultivation to marginal areas, and increased efforts to make efficient use of the available natural and human resources in these areas. Since rainfall is the most important natural resource that should be utilized efficiently, quantification of its availability in different regions and of the effect of water limitation on crop production, is essential to improve existing levels of productivity.

* Paper prepared for presentation at the IPI Colloquium on Nutrient Balances and the Need for Fertilizer in Semi-Arid and Arid Regions, 2–6 May 1983, Rabat, Morocco.
** Dr. *M.V.K. Sivakumar,* Principal Agroclimatologist and Agroclimatologist, and Dr. *A.K.S. Huda,* both: ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), Patancheru P.O., A.P. 502 324 India.

The purpose of this paper is to examine the current agricultural productivity in the summer and winter rainfall zones in the semi-arid and arid areas of the world and current fertilizer use in these regions and to identify the constraints on crop yields and fertilizer use.

2. Basic characteristics of summer and winter rainfall climates in semi-arid and arid areas

The procedures and criteria employed for classification of the arid and semi-arid areas of the world vary widely *(Koppen [20], Thornthwaite [38], Meigs [24], Troll [40], Hargreaves [14],* and *Papadakis [27]).* In this paper we will consider mainly the tropical and subtropical summer and winter rainfall zones identified by *Koppen [20]* and described in greater detail by *Trewartha [39].*
The summer rainfall areas are alternately under the influence of the equatorial westerlies of the Inter-Tropical Convergence Zone during the high sun period, or summer, and of the dry trade winds and subtropical anticyclone during the low sun period or winter. The winter rainfall areas occur mostly in the subtropics that are alternately influenced by middle-latitude westerlies and their wave disturbances in winter, and the stable eastern end of an anticyclonic cell in summer. The winter rainfall zones are typically located on the subtropical western side of a continent *(Trewartha [39]).*

2.1 Summer rainfall climates

The summer rainfall climates are classified by *Koppen [20]* under tropical wet and dry climates, and tropical and subtropical dry climates.
The tropical wet and dry climates are located from about 5 or 10° latitude on either side of the equator up to 15° or even 20° *(Trewartha [39]).* The summer rainfall and winter dry season are characteristically associated with the dominance by contrasting elements of atmospheric circulation in the two seasons. The summer rainfall areas cover almost all continents of the world. The tropical and subtropical dry climates more or less coincide with the more stable parts of subtropical anticyclones and trades in the vicinity of latitudes 20 or 25°N and S *(Trewartha [39]).*
In order to describe the distinct characteristics of the summer rainfall areas, we have selected seven locations from six countries representing a latitudinal range from 12°N to 31°N (Table 1). Except for Asmara (Ethiopia) all the locations are situated in lowland plains.
According to *Trewartha [39]* three temperature periods can be recognized in the summer rainfall areas: the cool dry season at the time of low sun or winter, the hot dry season just preceding the rains, and the hot wet season during the rains. Crops are mainly grown during the wet season and with supplemental irrigation during the dry season. Temperatures may rise very slightly just after the rainy period as a result of clear skies and drier atmosphere. Daily temperatures are consistently high throughout the year, the highest temperatures occurring just before the onset of the rains (Table 2). At Lahore the temperatures from December to February are low. In

Table 1. Geographical attributes of seven locations chosen in the summer rainfall areas of the northern hemisphere.

Location	Country	Latitude	Longitude	Elevation (m)
Asmara	Ethiopia	15°17′N	38°55′E	2300
Bijapur	India	16°49′N	75°43′E	594
Gao	Mali	16°16′N	0°03′W	270
Indore	India	22°43′N	75°48′E	567
Kano	Nigeria	12°03′N	8°32′W	470
Lahore	Pakistan	31°33′N	74°20′E	214
Niamey	Niger	13°30′N	2°07′W	220

Table 2. Mean maximum and minimum air temperature (° C) at selected locations in the summer rainfall areas.

Month		Asmara	Bijapur	Gao	Indore	Kano	Lahore	Niamey
Jan.	Max.	23	30	28	26	13	19	34
	Min.	7	16	14	10	13	5	14
Feb.	Max.	24	33	33	29	33	22	37
	Min.	9	18	17	11	15	8	17
Mar.	Max.	25	36	36	34	37	28	41
	Min.	10	21	22	15	19	13	21
Apr.	Max.	25	38	41	38	38	35	42
	Min.	11	24	25	20	24	18	25
May	Max.	26	39	41	40	37	40	41
	Min.	12	24	27	25	24	24	27
June	Max.	26	33	39	36	34	41	38
	Min.	12	22	28	24	23	27	25
July	Max.	22	30	36	30	31	37	34
	Min.	12	22	27	23	22	27	23
Aug.	Max.	22	30	34	28	29	36	32
	Min.	12	21	25	22	21	27	23
Sep.	Max.	24	31	37	29	31	36	34
	Min.	10	21	26	21	21	24	23
Oct.	Max.	22	31	38	31	34	34	38
	Min.	9	21	26	17	19	17	23
Nov.	Max.	22	30	34	29	33	28	38
	Min.	9	17	21	12	16	10	18
Dec.	Max.	22	29	31	27	31	22	34
	Min.	8	15	17	10	13	6	15

Source: *Griffiths [13].*

the highlands of Ethiopia (Asmara) temperatures are low because of the high altitude. It is relevant also to examine the extreme temperatures that occur in these regions because the crops differ in their sensitivity to withstand temperature stress. Highest temperatures are 48 °C at Gao in Mali and minimum temperatures below 0 °C have been recorded at Indore and Lahore.

Table 3. Mean global solar radiation (MJ/m²/day) at selected locations in the summer rainfall areas.

Month	Asmara	Bijapur	Gao	Indore	Kano	Niamey
January	21.3	20.7	16.4	18.4	18.9	19.3
February	23.3	23.3	20.0	21.4	20.1	20.8
March	24.8	24.5	21.1	23.1	20.6	20.8
April	25.3	24.9	22.1	25.6	20.3	21.0
May	25.6	24.1	22.0	27.0	21.4	21.2
June	23.0	20.5	21.7	22.3	20.3	20.7
July	17.7	17.8	22.2	16.6	18.6	18.9
August	17.4	19.3	21.2	15.3	16.4	17.6
September	22.7	19.7	20.8	18.7	20.1	19.3
October	23.0	20.1	19.9	21.3	21.7	21.0
November	20.8	19.5	18.0	19.2	20.5	24.3
December	20.0	19.2	16.5	17.2	18.8	18.2

* Radiation data for Lahore were not available.
Source: *Griffiths [13].*

Mean monthly solar radiation also is usually high throughout the year (Table 3) except during the wet season when the increased cloudiness causes a reduction in radiation. Such high energy levels, in the absence of other constraints, are indicative of high potential crop productivity.

Rainfall in the summer rainfall climates is highly variable. The coefficient of variability (CV) of annual rainfall is high. For example, for several locations in the semi-arid regions in West Africa *Cocheme* and *Franquin [4]* found that the CV of annual rainfall ranges from 15 to 38%.

Rainfall variability occurs inter-yearly as well as seasonally. Because most summer rainfall areas are located between the *Inter-Tropical Convergence (ITC)* and the dry trades, the monthly rainfall distribution shows marked annual wet and dry periods with the northwards movement of the ITC during summer and its retreat in late summer. The annual as well as monthly rainfall of any one location varies with its latitudinal position. *Kowal* and *Knabe [21]* showed that, for the northern states of Nigeria annual rainfall decreases by 119 mm for every degree latitude. In West Africa, Kano (Nigeria), located at 12°N, receives a mean annual rainfall of 873 mm, while only 270 mm is recorded at Gao (Mali) situated further north at 16°16′. In the summer rainfall areas of northern Australia the mean annual rainfall ranges from 300 mm at 20°S latitude to above 1200 mm at 12°S latitude. In India, however, rainfall variation with latitude is not so simple to explain because of the distinct differences in the atmospheric circulation leading to 'monsoons' over the area.

A substantial proportion of the rainfall usually occurs in a few high intensity storms. The intensity of rainfall usually varies from 20 to 60 mm/hr in most instances, but intensities as high as 120–160 mm/hr are not uncommon *(Miranda et al [25]).* Hence the soil loss that accompanies the runoff caused by such high-intensity storms may be substantial. For example, *Miranda et al. [25]* showed that, over the 5-year-period 1977–1981 at *ICRISAT* Center, in a traditional rainy season fallow system, average soil loss was 6.93 t/ha/year.

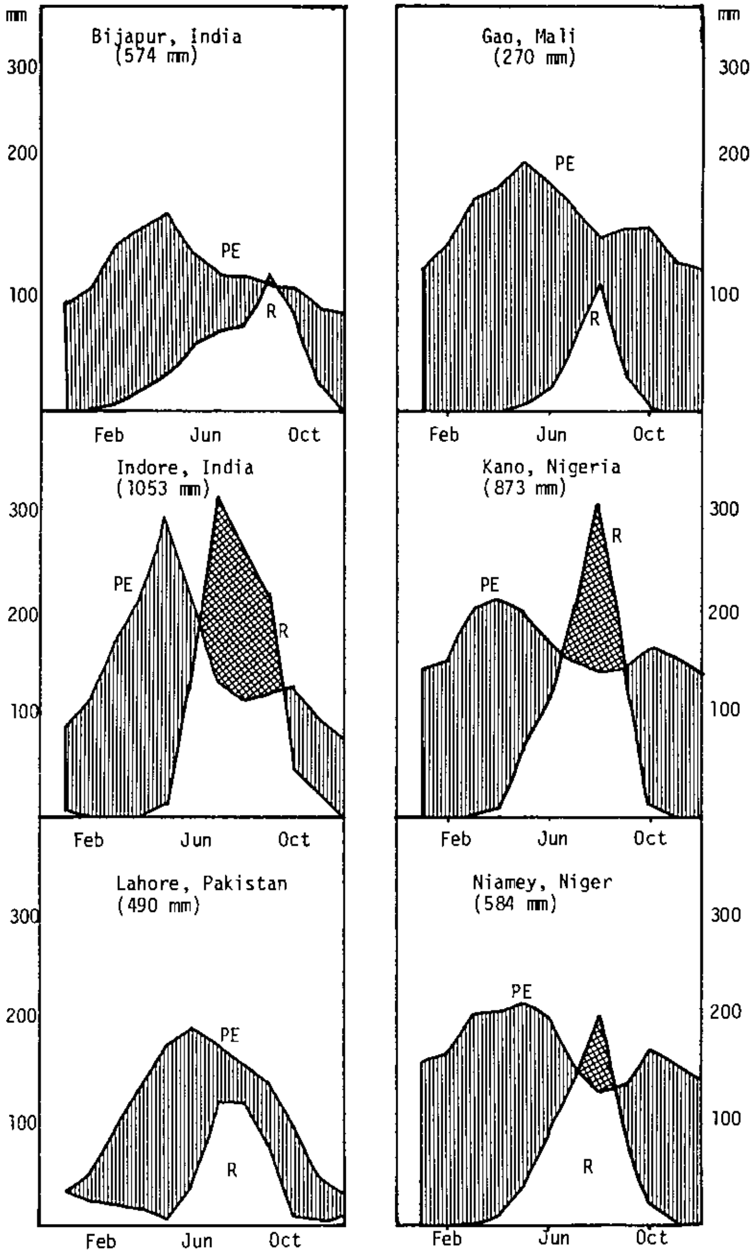

Fig. 1 Monthly variation in rainfall (R) and potential evapotranspiration (PE) at six selected locations in the summer rainfall areas. ||||||||||| Water deficiency; ▩▩▩ soil moisture recharge. Mean annual rainfall for the locations is given in parenthesis.

Because of the high radiation energy and uniformly high temperatures, the atmospheric demand for water is high. For example, in central and northern India the average potential evapotranspiration (PE) in June ranges between 6 and 8 mm/day, while in northwestern India and Pakistan it exceeds 8 mm/day *(Sivakumar et al. [33])*.

High rates of evapotranspiration coupled with low and unpredictable seasonal rainfall often lead to periods of water shortage that have serious implications to the production and even the very survival of crops. The moisture balance diagram (Figure 1) for six locations shows that there is only a 2 to 3 month period during the growing season when rainfall exceeds PE, permitting some soil moisture recharge to be followed by utilization in the succeeding months.

2.2 Winter rainfall climates

Most of the winter rainfall or 'Mediterranean' climates in the arid and semi-arid areas occur in the middle latitudes where the climate may be classified as subtropical to warm temperate. The main features of these areas, according to *Trewartha [39]* are: (1) a concentration of the mean annual rainfall in the winter season, while summers are nearly or completely dry; (2) warm to hot summers and unusually mild winters; and (3) abundant sunshine and meager cloudiness, especially in summer. Denoted as 'CS' (which stands for subtropical dry summer) by *Koppen [20]*, these occur in west Asia (Turkey, Syria, Lebanon, Israel, Jordan, Saudi Arabia, People's Democratic Republic of Yemen, Yemen Arab Republic, Oman, United Arab Emirates, Qatar, Iraq, Kuwait and Iran); North Africa (Morocco, Algeria, Tunisia, Libya, Sudan and Egypt), central Chile, the southern tip of South Africa, parts of southernmost Australia, and central and coastal southern California.

These Mediterranean areas are typically located on the tropical margins of the middle latitudes along the western sides of continents *(Trewartha [39])* that are affected by the stable eastern end of an oceanic subtropical high. In the cool months of the winter the relative warmth of the Mediterranean sea, and the accompanying low pressure trough, make the Mediterranean basin in west Asia and North Africa a region of convergence, with the associated development of fronts and cyclones.

Depending on the temperatures in summer and winter and the amount of rainfall, Mediterranean regions in west Asia may be further subdivided *(Glenn [12])*. In the coastal strips of Turkey, Cyprus, Syria, Lebanon and Israel the summers are hot and dry. In the eastern parts of Turkey and northern and western parts of Iran, dry and warm summers occur. In the western half of the Arabian peninsula and Oman plateau and in the interior parts of Jordan, Syria, and Israel the climate is semi-arid. In southern parts of Iraq and Iran a steppe climate occurs. In the Mediterranean regions of North Africa a similar zonation, also based on average rainfall, has been suggested *(Griffiths [13])*.

As in the case of summer rainfall climates, we use selected locations in different countries to describe the key climatic characteristics (Table 4). In the winter rainfall climate basic features of the temperature show much more variation between different areas in the region than those of rainfall. In west Asia winter temperatures decrease from south to north, from east to west and from low to high elevations. As

Table 4. Geographical attributes of locations chosen in the winter rainfall areas.

Location	Country	Latitude	Longitude	Elevation (m)
Damascus	Syria	33°29′N	36°14′E	729
Amman	Jordan	31°59′N	35°59′E	766
Baghdad	Iraq	33°20′N	44°24′E	34
Tehran	Iran	35°41′N	51°19′E	1191
Algiers	Algeria	36°46′N	3°03′E	60
Rabat	Morocco	34°03′N	6°40′W	75
Tripoli	Libya	32°54′N	13°11′E	20

Table 5. Mean maximum and minimum air temperatures (° C) at selected locations in the winter rainfall areas.

Month		Damascus	Amman	Baghdad	Tehran	Algiers	Rabat	Tripoli
Jan.	Max.	12.3	12.5	15.8	9.4	15.0	17.0	17.0
	Min.	2.5	3.7	4.3	−0.3	9.0	9.0	8.0
Feb.	Max.	14.1	13.7	18.7	11.0	16.0	18.0	18.0
	Min.	3.3	4.3	5.9	0.6	9.0	9.0	9.0
Mar.	Max.	17.8	17.6	22.7	15.8	17.0	19.0	20.0
	Min.	5.2	6.2	9.6	4.0	11.0	10.0	10.0
Apr.	Max.	22.8	22.6	28.7	20.9	20.0	20.0	23.0
	Min.	8.6	9.3	14.6	8.9	13.0	11.0	13.0
May	Max.	28.5	28.0	35.8	30.2	23.0	23.0	25.0
	Min.	12.6	13.4	20.0	15.7	15.0	14.0	16.0
June	Max.	33.6	31.0	41.0	34.2	27.0	26.0	29.0
	Min.	16.1	16.3	23.4	19.8	18.0	16.0	19.0
July	Max.	35.8	32.1	43.4	36.6	28.0	26.0	30.0
	Min.	17.2	18.1	25.3	22.7	21.0	17.0	21.0
Aug.	Max.	36.1	32.8	43.3	36.3	29.0	27.0	31.0
	Min.	17.5	18.4	24.6	22.8	22.0	18.0	22.0
Sep.	Max.	32.4	30.9	39.8	31.0	27.0	26.0	30.0
	Min.	15.3	16.2	21.0	18.0	21.0	17.0	21.0
Oct.	Max.	27.1	27.5	33.4	23.2	23.0	24.0	28.0
	Min.	12.4	13.7	16.2	11.9	17.0	14.0	18.0
Nov.	Max.	19.8	21.0	24.6	16.8	19.0	20.0	23.0
	Min.	7.7	9.6	10.3	6.3	13.0	11.0	13.0
Dec.	Max.	14.0	14.8	17.7	11.9	16.0	17.0	18.0
	Min.	4.1	5.4	5.5	1.7	11.0	9.0	9.0

Source: *Taha et al. [36].*

shown in Table 5, the maximum air temperatures in the winter months in west Asian and north African locations are much lower than those in the warm, dry summer months. The minimum air temperatures also are fairly low, the lowest temperatures being recorded at Tehran. This may be explained partially by continentality and partially by higher altitude. Temperature regimes that are shown in Table 5 have important implications in regard to crop productivity because of the suboptimal temperatures that occur at some locations which can seriously limit growth. The rate of accumulation of heat units or degree days for winter crop also is an important consideration in the assessment of crop productivity.

During the winter months freezing temperatures occur, but with a limited frequency and low severity. In the highlands freezing temperatures are common. For example at Ifrane (1640 m), in Morocco, frosts are reported every month from September to May.

The annual rainfall is concentrated in the period from October/November to April/May. The rainfall distribution in west Asia is very closely related to orography. The mean annual rainfall in west Asia is lower than in north Africa. In the North African Mediterranean zone, precipitation totals in excess of 600 mm/year are confined to very small regions *(Griffiths [13])*. At low elevation snowfall is very rare but, in highland areas, there is usually an abundance of snow. This snow provides a valuable source of water for irrigation in the adjacent lowlands. Since most of the rain falls in the cool season, moisture lost through evaporation is low making it available for crop growth. Mild winter temperatures that permit plant growth also give maximum effectiveness to the modest amount of precipitation.

The reliable rainfall season starts by 25 October at the border of the Turkish mountains, and somewhat later (15 November) in Jordan, and later in Iraq and Iran *(Brichambaut* and *Wallen [2])*. The dates of the beginning and the end of the rainy season, as well as the amount of rainfall and its variability, are factors of importance for crop growth.

Heavy rainfall exceeding 60 mm in a day in many regions of the winter rainfall areas is reportedly uncommon. However, in northern Morocco rainfall in excess of 150 mm/day has been recorded *(Griffiths [13])*. *Taha et al. [36]*, in their description of the climate of the Near East, mentioned that in Turkey a maximum daily rainfall of 231 mm has been recorded.

The low radiation and temperature, coupled with high humidity and low wind speeds in the winter, lead to low evaporative demand in contrast to the high evaporative demand during the growing season of the summer rainfall zones. This pattern permits crop production at relatively low rainfall levels *(Smith* and *Harris [35])*. The moisture balance diagram (Figure 2) shows that, in spite of the low annual rainfall at places such as Damascus, Amman and Tehran, a water surplus often occurs during the growing season. At Damascus, from November to February, average PE rates range from 1.0 to 1.8 mm/day.

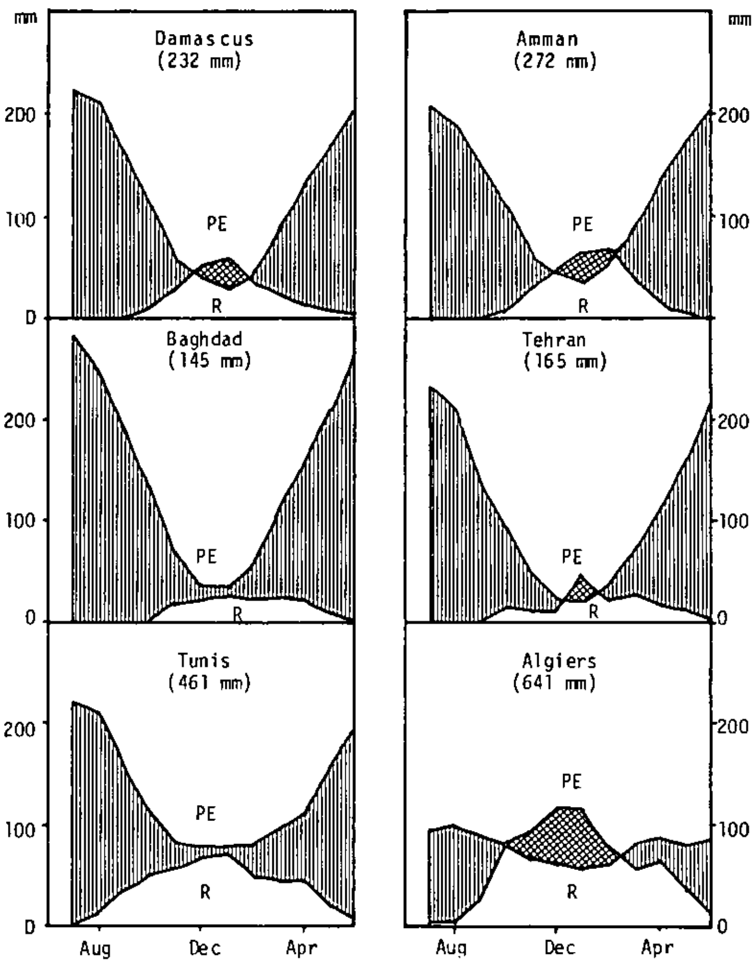

Fig. 2 Monthly variation in rainfall (R) and potential evapotranspiration (PE) at six selected locations in the winter rainfall areas. Water deficiency; soil moisture recharge. Mean annual rainfall for the locations is given in parenthesis.

3. Total biomass and economic yield possible from solar radiation – A case study with sorghum

In the arid and semi-arid regions of the world, due to clear skies and low relative humidities throughout most of the year, the solar radiation is uniformly high. One effective methodology for evaluating the potential for biomass production from solar radiation and rainfall is to use a dynamic crop growth model and simulate the effect of available soil moisture on dry matter production and grain yield.

The crop growth model used at *ICRISAT* is the SORGF model *(Arkin et al. [1])*, a dynamic grain sorghum growth model with a feedback capacity. Daily plant growth in SORGF is a function of the difference between average daily air temperature and a base temperature. Daily dry matter production is based on the amount of intercepted photosynthetically active radiation (PAR). The amount of PAR determines the net CO_2 fixed during day-light hours which will change as either water or temperature becomes limiting. *Huda et al. [15]* validated the SORGF model for the semi-arid tropics using multilocation data, and modified several subroutines. The modified model was used in the simulation reported in this paper.

Sorghum simulations were carried out for three locations in summer rainfall arid and semi-arid areas *i.e.*, Timbuktu, Mali (16°43′ N lat., 3°00′ E long., 263 m elev.), Bamako, Mali (12°38′ N, 08°01′ E, 331 m elev.) and Hyderabad, India (17°27′ N, 78°28′ E, 545 m elev.). Temperature and rainfall data for three locations are given in Table 6. For the simulation a sorghum hybrid, of 110 day maturity duration for which data on the total number of leaves and leaf area of each individual leaf are available from *ICRISAT Center*, was chosen. Normal data on global solar radiation, maximum and minimum temperatures, and daily rainfall data of individual years were used as input data in the simulation.

Cumulative probability distribution of simulated dry matter production for sorghum for the three locations is shown in Figure 3. At Timbuktu, in an arid area, the soil moisture is insufficient to establish a crop during 75% of the years. The simulation indicated that biomass production above 2000 kg/ha could be achieved in only 7% of the years at Timbuktu. On the other hand at Hyderabad in 80% of the years, biomass production could exceed 8 t/ha and in 20% of the years 9 t/ha. At Bamako, the potential biomass production levels could exceed 11 t/ha in 90% of the years.

Table 6. Temperature and rainfall data for the three locations used for sorghum simulation.

Month	Timbuktu			Bamako			Hyderabad		
	Max. Temp.	Min. Temp.	Rain-fall	Max. Temp.	Min. Temp.	Rain-fall	Max. Temp.	Min. Temp.	Rain-fall
	(°C)	(°C)	(mm)	(°C)	(°C)	(mm)	(°C)	(°C)	(mm)
January	30	13	0	33	17	0	29	15	6
February	33	15	0	36	19	2	31	17	11
March	37	18	0	38	23	0	35	20	13
April	40	22	1	39	25	8	37	24	24
May	42	25	4	38	25	63	39	26	27
June	42	27	16	35	23	174	34	24	115
July	38	25	56	32	22	257	30	22	171
August	36	24	81	31	22	337	29	22	156
September	38	24	29	32	22	230	30	22	181
October	39	23	3	34	21	97	30	20	67
November	35	18	0	35	19	10	29	16	23
December	30	14	0	33	17	2	28	13	6

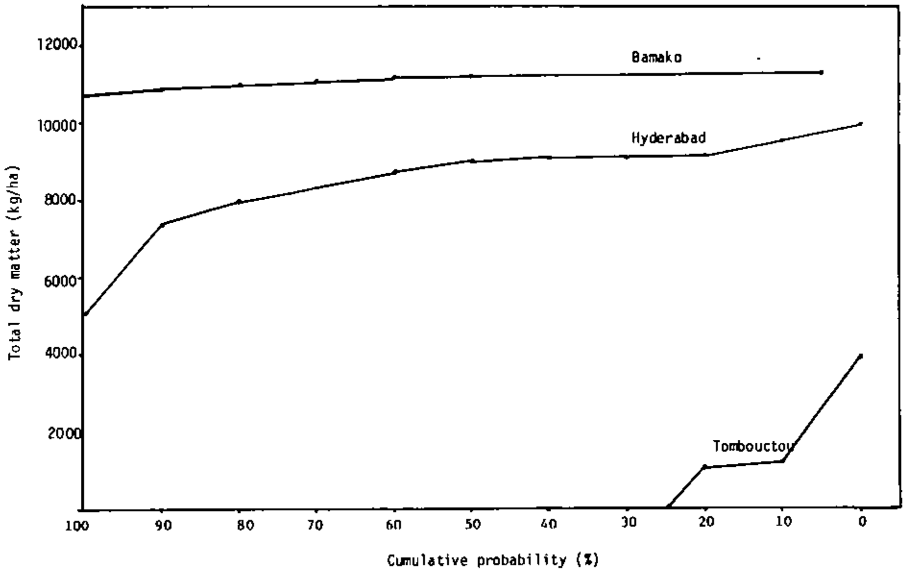

Fig. 3 Cumulative probability distribution of dry matter of sorghum at three locations in the summer rainfall areas.

Experiments conducted at *ICRISAT Center* under recommended fertility and crop management conditions during the rainy and postrainy seasons showed that sorghum biomass production levels of 12 t/ha and grain yields of 6 t/ha are attainable (Table 7).
Results obtained at *ICRISAT* on other crops such as pearl millet, groundnut, pigeonpea, and chickpea also suggest that the potential for crop production is considerable and remains yet to be fully exploited by the farmers.

Table 7. Total dry matter and grain yield (kg/ha) of sorghum hybrids achieved under good management at ICRISAT Center.

Year	Season	Total dry matter (kg/ha)	Grain yield (kg/ha)
1979	Rainy	11 660	4290
	Postrainy	7 644	3832
1980	Rainy	11 937	5640
	Postrainy	11 149	6118
1981	Rainy	10 600	5001
	Postrainy	12 529	5663

Source: *Huda et al. [15].*

4. Present productivity in these regions

Most of the cropping in the arid and semi-arid areas continues to be under rainfed conditions, and a majority of the farmers are small farmers with meager resources. Because of the poor resource base – both physical and socioeconomic – the crop yields are low and production is unstable due to variable weather conditions and the high incidence of diseases and pests *(Kanwar [18])*.

Among crops that are grown in the summer rainfall regions of the world (Table 8), rice, sorghum, millet and pulses are the preferred crops. Sorghum and millet are the main subsistence rainfed crops. Although the percentage contribution of rice and wheat from the region to world production is shown to be higher, these crops are predominantly grown under irrigation or in the higher rainfall zones. About 44% of total pulse production in the world occurs in the summer rainfall regions. Root tubers, vegetables, and maize are the other important crops.

In the winter rainfall zone wheat and barley are the preferred cereal crops because of their tolerance to low temperatures. Vegetables are also grown widely.

Although the currently recorded average yields of these crops when compared to yields achieved in experimental stations are low (Table 9) the potential for achieving higher yields exists. For example, studies at *ICRISAT Center* for *ICRISAT*'s mandate crops, *i.e.*, sorghum, pearl millet, chickpea, pigeonpea, and groundnut showed that the average yields in the semi-arid tropics are far below the yields of these crops achievable under rainfed conditions *(Kanwar [18])*.

Table 8. Contribution (%) to world production of different crops* in the summer and winter rainfall zones.

Region	Wheat	Rice	Barley	Maize	Sorghum	Pearl millet	Pulses	Root tubers	Vegetables
Summer rainfall zones									
Asia	9.55	30.39	1.07	2.71	22.99	34.27	23.49	6.51	6.24
Australia**	2.43	0.15	1.78	0.03	1.30	0.08	0.22	0.19	0.08
West Asia	1.39	0.34	0.72	0.04	1.48	0.12	0.63	0.17	3.24
East Africa	0.22	0.06	0.53	1.01	5.89	3.22	2.47	1.66	3.27
Southern Africa	0.04	0.68	0.01	1.21	0.75	1.18	1.23	4.27	2.11
West Africa	0.01	0.39	–	0.85	24.16	8.48	8.36	3.62	2.93
Latin America	2.96	2.92	0.54	10.23	0.65	14.85	7.10	8.58	4.51
Total:	16.60	34.93	4.65	16.08	57.22	62.20	43.50	25.00	22.38
Winter rainfall zones									
West Asia	4.82	0.09	4.77	0.33	0.03	0.14	2.35	0.81	14.67
North Africa	1.33	0.59	2.14	0.91	0.05	2.24	1.42	0.50	1.58
Chile	0.22	0.02	0.06	0.10	–	–	0.31	0.19	0.17
Total:	6.37	0.70	6.97	1.34	0.08	2.38	4.08	1.50	16.42

* Data compiled from *FAO [8]*.

** Data for Australia include winter rainfall zone also.

Table 9. Present yield levels (kg/ha) of different crops* grown in the summer and winter rainfall zones.

Region	Wheat	Rice	Barley	Maize	Sorghum	Pearl millet	Pulses	Root tubers
Summer rainfall zones								
Asia	1301	2289	833	1367	956	491	547	10 151
Australia**	939	5330	1108	2953	1406	1183	654	24 105
West Asia	2564	3416	1003	1502	997	1018	1322	10 893
East Africa	1068	2123	922	1009	736	851	613	6 139
Southern Africa	2205	1213	2700	718	550	482	700	6 409
West Africa	1637	1155	–	755	582	506	454	6 939
Latin America	1277	2599	1173	1581	1851	1032	751	9 697
Winter rainfall zones								
West Asia	1521	3446	1264	2272	1964	932	949	19 095
North Africa	1274	2341	1047	1797	1345	1904	943	10 728
Chile	1770	2337	2159	3487	–	–	709	10 140

* Data compiled from *FAO [8]*.
** Data for Australia include winter rainfall zone also.

Table 10. Benefit/cost analysis of potentially recoverable yield gaps in important dry-land crops

Item	Sor-ghum	Pearl millet	Chick-pea	Ground-nut
Potential yield on farmer's field kg/ha: (estimate) ..	2282	964	1132	1638
Actual yield on farmer's field (kg/ha: All-India average)	634	459	629	819
(Stage II) physical yield gap (kg/ha)	1648 (72)*	505 (52)	503 (44)	819 (50)
Economically recoverable yield gap (kg/ha)	1319	404	403	655
Economically recoverable gap (Rs./ha)	1121	343	846	1638
Additional expenditure on seed (Rs./ha)	100	40	13.5	125
Additional expenditure on fertilizer (Rs./ha: nitrogen and phosphorus)	293	293	239	239
Total additional expenditure (Rs./ha)	393	333	252.5	364
Benefit/cost ratio	2.85	1.12	3.35	4.5
Total area under the crop ('000 ha: All-India)	16 208	11 715	7870	7105
Yield gap recoverable area ('000 ha: All-India)	8 104 (52)**	5 272 (45)	4722 (60)	2842 (40)
Present level of production (million tonnes: All-India)	10.3	5.4	4.9	5.8
Potential level of production (million tonnes: All-India)	20.9	7.5	6.9	7.7
Percentage increase in the production	104	40	38	32

* Percentage of potential yield levels.
** Percentage of total area under the crop.
Source: *Ghodake [11]*.

Using all-India data on area, production, and prices of four crops grown in semi-arid areas together economically recoverable 'gap' estimates, *Ghodake [11]* made estimates of the potential level of production in India. The yield gap in this analysis is the difference in yields between demonstration trials conducted at selected centers and the farmer's fields. This gap in yield was attributed to two factors only, *i.e.*, genotype and fertilizer. The results of this analysis, suggest a considerable yield gap in the case of sorghum and groundnut, followed by pearl millet and chickpea (Table 10). With small additional expenditure on seed and fertilizer, it was estimated that large increases in the production of these crops could be easily realized.
Kassam [19] carried out an interesting analysis of the productivity of wheat in the winter rainfall regions of North Africa and West Asia. The procedure he used involved compilations of quantitative climatic inventory, length of the growing period (the period when water and temperature permit crop growth), and soil inventories. By an application of the agroclimatic constraints to the constraint-free crop yields, attainable crop yields were computed for the various major climates and growing period zones. *Kassam*'s analysis *[19]* showed that, in the growing period zone of 180–239 days at the high-input level, anticipated yields ranged from 3.6 to 4.9 t/ha. Where the growing period ranged between 120 and 179 days, yields of 2.0 to 3.8 t/ha at the high-input level were anticipated. At the low input level the anticipated yields were 0.5 to 1 t/ha.

5. Effect of water limitation on biomass production and water use efficiencies

In the absence of other limiting factors such as radiation, temperature, nutrients, etc., it is well known that water use by crops and dry matter production are linearly related. This conclusion can also be corraborated by the fact that net radiation (which determines to a large extent the transpiration rates) and solar radiation (which determines photosynthesis) are linearly related *(Monteith [26])*. Hence it may be surmised, as *De Wit [6]* did, that transpiration or water use and dry matter should be linearly related.
Studies conducted at *ICRISAT* with sorghum confirmed that water use and dry matter production are linearly related *(Sivakumar et al. [34])*. The rates of dry matter accumulation and water-use decreased as profile water depletion became more severe, but the ratio between the two remained uniform (Figure 4). Maximum dry matter production was achieved when water is not a limiting factor indicating clearly the potential that exists in the semi-arid environment for crop production.
Since the simulation comparisons for sorghum discussed earlier indicated that at Timbuktu rainfall is limiting for sorghum production, we have investigated the response to supplemental irrigation of 100 mm at three phenological stages, *i.e.*, sowing, panicle initiation, and anthesis. The results of this simulation (Table 11) indicate that, with three supplemental irrigations at the three stages, biomass production could be increased above 9 t/ha and grain yields could reach 5 t/ha.
The growth of a crop during its life cycle and the biomass production is complex in nature, but water is necessary at all stages for maximum biomass production. Water deficiency at a particular stage could affect the plant in a manner that may have a

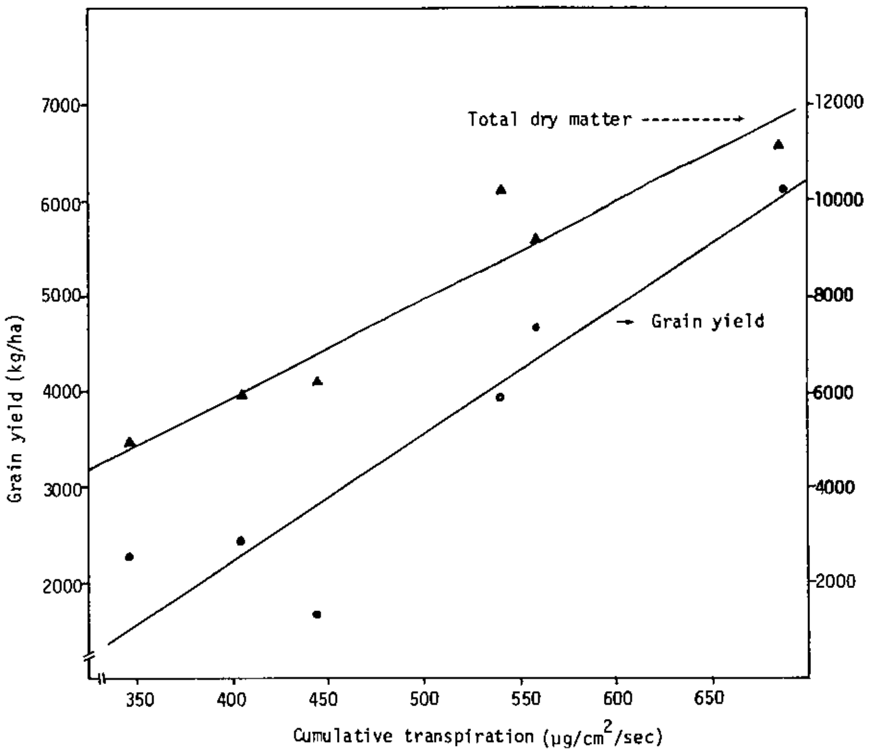

Fig. 4 Relationship of total dry matter and grain yield of sorghum to cumulative transpiration (data poooled over three genotypes).

Table 11. Simulated response to supplemental irrigations at three stages of sorghum growth at Timbuktu, Mali (simulation base: 43 years).

Supplemental irrigation (100 mm)			Total dry matter (kg/ha)			Grain yield (kg/ha)		
Sowing	Panicle initiation	Anthesis	Mean	Max.	Min.	Mean	Max.	Min.
–	–	–	4224	3 996	0	191	1798	0
X	–	–	3833	6 398	3525	1725	2879	1586
X	X	–	4506	7 053	4195	2028	3174	1888
X	X	X	9442	10 886	9099	4249	4899	4094

greater or lesser effect on final productivity. In a study conducted at *ICRISAT Center* on the response of groundnut to moisture stress imposed at different phenological stages, we found that stress imposed from emergence to appearance of first pegs resulted in a slight reduction in the vegetative growth during the duration of

Table 12. Dry matter and kernel yield of groundnut under moisture stress imposed at different stages.

Treatments	Total dry matter (kg/ha)	Kernel yield (kg/ha)
Irrigated control	9750	3152
Stress from emergence to appearance of first pegs	6550	2373
Stress from flowering to last pod set	4750	686
Stress from first kernel growth to maturity	3600	384

Source: *Sivakumar et al. [34].*

Table 13. Water use and water use efficiency for crops/cropping systems grown at *ICRISAT Center,* Patancheru.

Crop/cropping system	Season	Soil	Water use (cm)	Yield (kg/ha)	Water use efficiency (kg/ha/cm)
Sorghum	Rainly	Alfisol	24.0	3700	154
Sorghum	Rainly	Vertisol	35.3	4467	127
Sorghum	Postrainy Rainfed	Vertisol	21.6	2430	113
Sorghum	Postrainy Irrigated (19 cm)	Vertisol	36.9	5990	162
Pearl millet	Postrainy Rainfed	Alfisol	9.6	1110	116
Pearl millet	Postrainy Irrigated (14 cm)	Alfisol	15.5	1860	120
Pearl millet	Rainy	Alfisol	15.9	2226	140
Groundnut	Rainy	Alfisol	19.6	1185	60
Pearl millet/groundnut	Rainy	Alfisol	22.8	1227/ 840	91
Pigeonpea	Rainy	Vertisol	33.5	–	–
Sorghum/pigeonpea	Rainy	Vertisol	33.3	4314 (Sorghum)	130
Maize	Rainy	Vertisol	23.1	3026	131
Maize/pigeonpea	Rainy	Vertisol	21.2	2480 (Maize)	117
Pigeonpea	Postrainy	Vertisol	19.6	1588	81
Maize/pigeonpea	Rainy	Vertisol	24.6	2534 (Maize)	103
Pigeonpea	Postrainy	Vertisol	14.1	1072	76
Chickpea	Postrainy	Vertisol	16.2	1053	65
Chickpea	Rainfed Postrainy Irrigated (6.7 cm)	Vertisol	21.2	1145	54

Source: *Sivakumar et al. [34].*

stress extending up to 30 days *(Sivakumar et al. [34])*. However, once the moisture stress was diminished and the crop received irrigations at 10-day intervals, the recovery from stress was remarkable. When the stress was imposed after kernel growth started, the effect of stress on dry matter production was severe resulting in a low biomass production (Table 12).

In the arid and semi-arid areas where the seasonal variability in rainfall is large, which in turn influences the profile moisture content and distribution, the response to any applied water could be variable. Even within a growing season it was demonstrated with several crops that, depending on the time of planting, the responses could again vary. Under moisture stress, with intercropping systems (where two or more crops are grown together) the relative advantages were shown to be higher than when the crops are grown singly *(Willey et al [45])*.

Water use and water use efficiency data obtained at *ICRISAT Center* for several crops/cropping systems *(Sivakumar et al. [34])* are summarized in Table 13. The data show that sorghum grown on the deep Vertisols during the rainy season or under irrigation during the postrainy season used more water than either a sorghum/pigeonpea intercrop or maize or maize/pigeonpea or pigeonpea. Maximum water use efficiency was recorded in the case of sorghum grown during the postrainy season under irrigation. Maize was the next best crop in terms of water use efficiency. Sorghum/pigeonpea intercrop produced more grain per cm of water used than maize/pigeonpea. Water use by pearl millet was less, but the water use efficiencies of this crop were comparable with those of maize, confirming that pearl millet is a crop to be preferred under low moisture availability conditions. Water use efficiencies of pulse crops grown in pure stands were low. Efficiencies of chickpea and groundnut were comparable, although they were grown in different seasons. Water use efficiency for a millet/groundnut intercrop was better than that of a groundnut crop grown in pure stands. During the postrainy season water use efficiencies of irrigated sorghum were greater, but not those for irrigated millet and chickpea.

6. Water-fertilizer interactions

The influence of water on plant growth and nutrient use is complex, and to a large extent the processes are interdependent. An extreme deficiency of soil water could cause wilting and ultimate death of the plant. But, before such obvious effects set in, the status of nutrients in the soil and the soil's ability to get them may be impaired *(Viets [44])*.

In the arid and semi-arid areas of the world, more fertilizer is used where facilities for supplemental irrigations exist. For example, *Tandon [37]* showed that, in India, irrigated areas form the major loci of fertilizer use.

Significant interactions between moisture and nutrients have been recorded with various crops *(Singh* and *Prihar [32], Meelu et al. [23])*. Depending on the available soil moisture, its management, and fertilizer application rates, crop yields comparable with irrigated agriculture have also been demonstrated. *Meelu et al. [23]* showed that, for rainfed wheat in Punjab, higher doses of N could be profitably used in medium-textured soils with good moisture storage (Figure 5). In investigations on

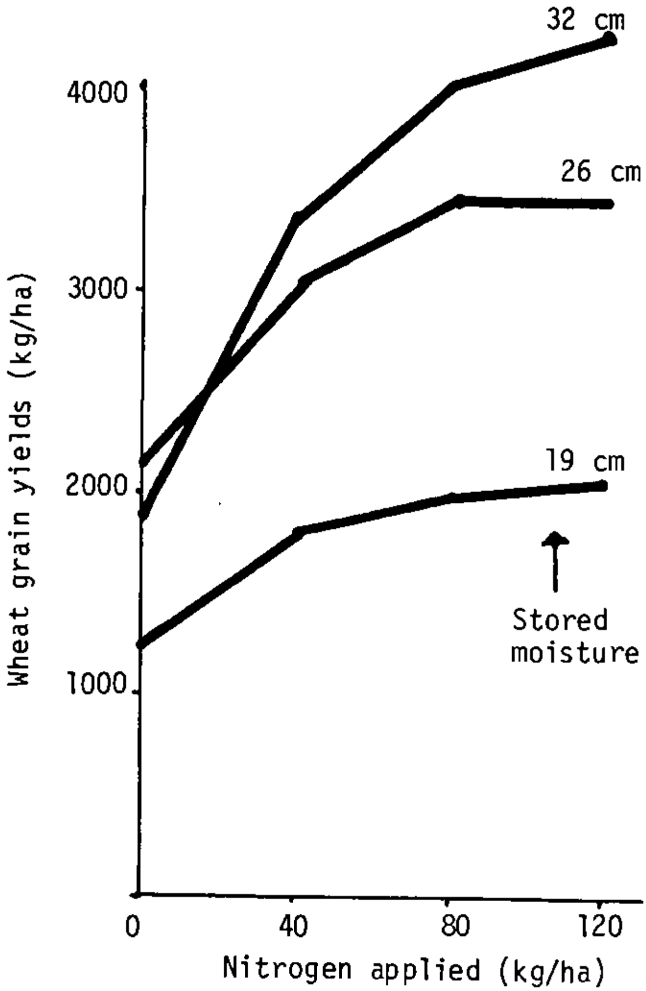

Fig. 5 Response of rainfed wheat to nitrogen on soils having different stored moisture. (From *Meelu et al. [23]*).

the effect of nitrogen and irrigation for summer sorghum, *Venkatachari et al. [42]* showed that the increase in yield was 1100 kg/ha from irrigation alone, 2300 kg/ha from 80 kg N at the lower levels of seven irrigations, and 4900 kg/ha when 80 kg N and 16 irrigations were given.

Jha and *Sarin [17]* found, in an all-India analysis, that farmers favored fertilizer use on heavier soils which retain more water than lighter soils, and that the percentage area fertilized correlated with rainfall. They also found, in a study of selected villages, that irrigation and rainfall during the growing season were the primary determinants for fertilizer use in Sholapur (in an area of undependable rainfall) but not in

Akola (in an area of dependable rainfall), where in none of their equations rainfall appeared as a significant variable.

Under Mediterranean conditions, fertilizer recommendations are tuned to the average rainfall incidence. For example, for rainfed wheat in Turkey in the lower rainfall areas the fertilizer application is restricted to 40 kg P_2O_5/ha; under good rainfall conditions it is 60 kg N + 40 kg P_2O_5/ha. For high yielding varieties under irrigated conditions the recommendation is 80–100 kg N + 60 kg P_2O_5/ha *(De Geus [5])*. In Jordan fertilizers are mainly used for irrigated wheat in the Jordan valley, but small amounts are used in the dry regions with over 450 mm/year of rainfall. In the fertilizer demonstration trials in Morocco for dryland barley in the southern and northern regions, the NPK treatment of 20–60–0 was found to be best, while for irrigated barley the treatment 20–40–40 was the best *(De Geus [5])*.

The interaction between water and nitrogen was described by *Van Keulen [41]* as follows: 'Growth under nitrogen deficient conditions implies a slower rate of accumulation of dry matter, which, combined with a different distribution of the material, leads to a prolonged period in which vegetation does not cover the soil completely. Under such conditions, direct soil evaporation is longer than under non-deficient conditions where a closed canopy is reached earlier. The amount of moisture available for transpiration is thus smaller under nitrogen deficient conditions.' *Rehatta et al. [29]* showed that moisture shortage with equal availability of nitrogen led to reduced uptake of the element showing, thereby, that uptake must be governed by the reduced rate of dry matter production. Hence moisture shortage to plants was assumed to have both a direct as well as an indirect effect on nitrogen uptake: in one case governed by the physical transport processes in the soil, and in the other by the metabolic processes in the plant *(Van Keulen [41])*.

7. Present use of fertilizer

Although current research suggests that for dryland crops fertilizer application is the highest return input *(Chowdhury [3])*, the present use of fertilizer in the summer and winter rainfall zones is low. Data summarized from *FAO Fertilizer Statistics* (Table 14) show that, in the summer rainfall regions as a whole, fertilizer consumption is low. The figures for Asia are high but the fertilizer consumption here is mostly confined to wheat and rice and in irrigated areas. For example, *Shobti [31]* computed that nearly 80% of all fertilizer used in India goes to four crops: rice, wheat, sugarcane, and cotton. Likewise only 16% of the total cropped districts account for 50% of the fertilizer used and it is well known that the bulk of the consumption as well as growth in fertilizer use is in irrigated areas. The farmer's perception of the likely benefits that could accrue from fertilizer application and the support provided through the extension agencies are the major factors contributing to this growth.

Jha and *Sarin [16]*, in their study of fertilizer consumption in the semi-arid areas of India, estimated the mean fertilizer consumption in 112 nonirrigated semi-arid districts to be 18.5 kg N + P_2O_5 + K_2O as compared to 57.5 kg/ha in the 78 irrigated districts in the semi-arid areas. In fact the exact estimate for nonirrigated areas is considered to be even lower than 18.5 kg/ha because this includes the fertilizer received by irrigated areas within 'nonirrigated' districts.

Table 14. Consumption (%) of world fertilizer use* in the summer and winter rainfall zones.

Region	N	P_2O_5	K_2O
Summer rainfall zones			
Asia	7.69	4.58	2.93
Australia**	0.41	2.71	0.53
West Asia	0.52	0.98	0.02
East Africa	0.26	0.21	0.05
Southern Africa	0.42	2.78	0.22
West Africa	0.15	0.24	0.21
Latin America	3.40	7.61	6.00
Total:	12.85	19.11	9.96
Winter rainfall zones			
West Asia	1.39	1.85	0.36
North Africa	1.35	1.26	0.38
Chile	0.08	0.18	0.05
Total:	2.82	3.29	0.79

* Data compiled from *FAO [9]*.
** Data for Australia include winter rainfall zone also.

Table 15. Response of chickpea to fertilizers in experiments on cultivators' fields in India.

Soil type	No. of trials	Yield (kg/ha) without fertilizer	Response (kg/ha) over no fertilizer		
			N_2O	$N_{20}P_{40}$	$N_{20}P_{40}K_{20}$
Calcareous Sierozem ...	68	1153	94	314	464
Alluvial	48	1338	466	798	954
Red and yellow	58	648	238	364	459
Medium-black	69	464	116	428	387
Mean	243	873	208	454	538
% increase over no fertilizer	–	–	+24%	+52%	+62%

Source: *Tandon [37]*.

Data on the nutrient removal by the crops grown in the semi-arid areas, however, suggest use of increased quantities of fertilizer that is far in excess of the estimated current use. Using the present levels of productivity for five major crops (sorghum, pearl millet, groundnut, chickpea and pigeonpea) grown in semi-arid regions of India, *Tandon [37]* estimated that these crops remove 3.2 million tonnes of $N + P_2O_5 + K_2O$/year or, on the whole, 72 kg nutrients/ha. The current use of fertilizers on these crops, however, was estimated at only 0.5 million tonnes or 10–11 kg of nutrients/ha, a figure far below the estimated removal by these crops.

Results of experiments conducted at the research stations of the *Indian Council of Agricultural Research,* and in the trials conducted on farmers' fields however indicate significant yield increases as a result of the application of fertilizers. *Tandon [37]* concluded, from data collected over 243 experiments on cultivator's fields, that the yield increases resulting from fertilizer applications of 24–62% over no fertilizer treatment could be obtained for chickpea grown on four soil types (Table 15). *Kulkarni [20]* showed that 20–30 kg N + 40–60 kg P_2O_5 and 0–40 kg K_2O are the remunerative doses of nutrients per hectare for rainfed groundnut based on experiments on cultivators fields in 13 districts for nine crops grown predominantly in the semi-arid and arid areas of India. *Venkateswarlu [43]* computed yield responses to N application that varied from 15 kg grain/kg N to 23.8 kg grain/kg N. Using these data, *ENSP [7]* concluded that these figures are closely comparable with the data obtained under irrigated conditions, considering that the overall yardstick relating food grain production to fertilizer nutrients is about 10:1. These results confirm the conclusion that fertilizer responses in the semi-arid and arid areas can be high and profitable.

Regardless of the actual supply of nutrients to the crops, the advances made in the area of crop improvement and in raising the average yield levels of cultivars have led to greater efficiency of use of nutrients. The availability of a large number of improved, more efficient, fertilizer responsive cultivars for a number of crops grown currently in the arid and semi-arid areas and the steady increase in the acreage under these cultivars points towards a greater need for fertilizers. For example *Rao [28]* in his analysis of genotype-input-management relations for grain sorghum in India concluded that, at an application level up to 50 kg N/ha, sorghum hybrids and some improved varieties have returned 15–28 kg of grain/kg of nitrogen against 6–8 kg for traditional local varieties. Adoption of such improved cultivars coupled with improved management practices has been shown to give increased net returns. *Ryan et al. [30]* showed in their assessment of prospective soil-, water-, and crop-management technologies that on the Vertisols use of local varieties with fertilizer generated additional profits of $ 55/ha and with high yielding varieties, these profits could be doubled.

8. Current constraints on yield and on the use of fertilizer

a) In both the summer and winter rainfall regions water is the most limiting factor in crop production. Variability in the rainfall at the beginning and end of the season, and unreliability in mid-season, create risks in arable cropping. The length of the growing season which is limited by the duration of the rainy period sets the limits of the areas where rainfed farming is feasible.

b) In the summer rainfall regions high temperatures, increased wind speed, and advective energy increase the atmospheric demand for water. Potential evapotranspiration rates are usually high, reaching up to 2400 mm/year. In the winter rainfall regions, the low average potential evapotranspiration rates on the other hand are advantageous for conserving the low rainfall that occurs.

c) In the winter rainfall areas, mean minimum temperatures and mean temperatures during the growing season could limit crop growth, and sometimes stop or delay crop development.

d) In view of water shortages, lack of suitable varieties that cover the ground quickly, and flower early, and finish grain filling before there is a deficit in moisture, often limits yields.
e) Lack of quick adoption of improved, more efficient, fertilizer responsive cultivars on the farmers' fields is a major constraint.
f) In the summer rainfall regions soil erosion is a problem, and non-adoption of suitable land and water management practices that facilitate drainage and reduce runoff and erosion lead to loss of fertile top soil.
g) Lack of adoption of on the farm of cropping systems and crop management practices that establish a crop at the very beginning of the rainy season, to make most efficient use of moisture throughout the rainy and postrainy seasons for high sustained levels of yield.
h) Soils with shallow depth and low water-holding capacity present problems, even during the rainy season.
i) Due to increased populations and increasing food needs, steeper and more erodable lands are frequently overcropped and overgrazed and forest lands are denuded causing permanent damage to extensive areas.
j) Availability of soil moisture is an important determinant of fertilizer use in the semi-arid areas.
k) Lack of proper extension in the popularization of fertilizer use and the knowledge of the farmer is a major constraint.
l) Fertilizer price and credit are important institutional factors.
m) Regional and temporal differences in seasonal conditions, occurrence of pests and diseases, availability of fertilizer, market and fertilizer distribution network, etc., are important determinants of differences in fertilizer use. *Tandon [37]* computed that mean area per fertilizer sale point is 2.5 times more in the major dryland states than in the rest of India.
n) Lack of suitable management practices that make the best use of applied fertilizer.

9. Conclusions

In the semi-arid and arid areas of the world, where water is the main constraint for agricultural production, analysis of the existing levels of crop productivity suggests that a considerable potential remains to be exploited. In the summer rainfall regions use of improved technologies that include improved seed, fertilizer, cropping systems and water management practices could result in higher productivity and greater net returns to the farmer. In the winter rainfall zones, also, increasing the nutrient supply to the crops is known to give significant yield increases. The climatic features of these areas favor more efficient utilization through a proper choice of crops and cropping systems. A rational assessment of the existing physical and socioeconomic resources could present options that would permit increases in agricultural productivity to be achieved in summer and winter rainfall zones.

Acknowledgments

We thank Drs. *L.D. Swindale, F.R. Bidinger* and *K.L. Sahrawat* for their helpful comments on the manuscript and Mr. *J.B. Wills* for editing the manuscript. We appreciate the help of Mr. *R.L.N. Sastry* with typing and Mr. *G. Thomas* with figures.

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Adaptations of Plants to Limited Water Availability

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Summary

Adaptations of plants to limited water supplies are inheritable traits that enable the species to survive and compete successfully under conditions of drought. The best understood adaptations involve a) morphological and physiological modifications of the soil-plant-atmosphere flow system (SPAS)** in a way that a higher turgidity of cells is maintained over a prolonged period and b) an osmotic adjustment of cells again tending to maintain turgidity of plants. Major adaptive mechanisms within the SPAS consist of regulation of resistances to water flow, reduced interception of radiant energy, an ability to tap larger volumes of soil water through more extensive root systems, storage of water in tissues and a restriction of physiological activities to seasons when initial and possibly final stage of the SPAS (i.e. soil and atmospheric potentials) are most suitable. The osmotic adjustment is mainly the result of an accumulation of inorganic osmotica. An accumulation of organic solutes in plants suffering from water stress is also observed but the quantity is too small to have a significant overall effect. It has, therefore, been suggested, that organic solutes produce an osmotic adjustment only within the cytoplasm.

It is desirable to introduce or strengthen through plant breeding some of these adaptive traits in crop plants.

Numerous biochemical responses of plants to limited water supply are known, but the mechanisms of interaction between biochemical processes and water relations are poorly understood and adaptive values of the changed plant behavior are speculative.

1. Introduction

About two fifths of the earth's land surface suffers from drought, either during the entire year or a considerable part thereof. It is, therefore, not surprising that adaptive mechanisms have evolved permitting plants to cope with the adverse environmental conditions caused by limited water availability. Man, for a long time, has observed and studied adaptive changes in plants and has tried to describe and understand them.

The frequent separation of mechanisms of drought resistance into escape from, avoidance and tolerance of drought is perhaps less useful than it appears. Firstly, many ecologists consider a plant to be tolerant of adverse environmental conditions when it is able to complete its life cycle, *i.e.* it can survive and compete in a particular niche no matter by which physiological mechanism this is achieved. Secondly, all

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**Abbreviation: SPAS: Soil plant atmosphere flow system

resistance mechanisms will be at a cost, and a plant can neither escape nor avoid some consequences of drought at a particular site. Maintenance of turgidity through osmotic adjustment or closure of stomates, both of which are considered typical avoidance mechanisms, will either change the osmolality within the plant or reduce the photosynthetic rate. Both of these physiological responses will affect plant behavior.

I, therefore, prefer to follow a different line for my discussion. The plant, in effect, functions as a conductor of water between the soil as a source and the atmosphere as a sink. Along this soil-plant-atmosphere flow system (SPAS), the water potential changes. It usually drops between soil and atmosphere, but the pattern looks more complicated when solutes are a variable component of the water potential in the SPAS *[26]*. Except for the osmotic adjustment, the known important mechanisms of drought resistance are all related to the SPAS, which, in principle, requires the following parameters for its description:

- an initial stage in the soil and a final stage in the atmosphere, the difference being the overall driving force
- resistances to flow
- capacities (storage of water)
- changes in solute concentrations along the SPAS.

It is theoretically possible to include changes in solute concentrations in the resistance term *[26]*. Adaptive mechanisms operate on one or more of the above parameters. This even includes phenological adaptations to suitable moisture conditions, because intensive physiological activities occur during a period of high soil water availability, *i.e.* when the initial stage of the SPAS permits optimal plant water relations.

Physiologically, however, plants are more likely to respond to turgor pressure and osmolalities than to the total water potential. These various properties are interconnected through the components of the water potential

$$\psi = \psi_p + \psi_\pi$$

(ψ = water potential, ψ_p = its pressure component, ψ_π = its osmotic component).

Of these variables, turgor pressure is dependent on the other two and adjusts itself accordingly. The water potential is largely controlled by the SPAS and the osmolality within the cell by plant solute relations. Turgidity within the plant can be maintained by adaptive mechanisms that modify either the water potential or its osmotic component within the cell. Both possibilities have been employed as adaptive mechanisms.

The flow of water is, for the most part, a consequence of the presence of stomatal openings, the evolution of which was necessary to permit the entry of CO_2 into leaf tissues. To the extent observed, the flow of water has no critical physiological function. Because of stomatal closure, a possible cooling effect through transpiration would disappear and it does so in the very situation in which it is most needed. For this reason, drought resistance in warm, arid climates must be coupled with heat resistance.

It is not always realized that the shoot of a mesophytic homoiohydric plant *(i.e.* a plant of temperate climates) also lives in an extremely hostile environment, and that major adaptive mechanisms had to evolve to reduce the consequences of atmospheric drought on shoot physiology. Many of these adaptations of mesophytic plants are only slightly different and more pronounced in drought resisting plants of arid climates. The adaptations must assure survival of the species under most adverse environmental conditions, but, at the same time, the species must remain competitive. It would appear necessary that only a minimum of energy (assimilates), is reallocated to these survival mechanisms so that an optimum in productivity is still maintained and the plant is kept competitive. Under conditions of extreme stress, however, competition for other factors such as light becomes less important.

In connection with this, we shall not discuss adaptive mechanisms of poikilohydric plants, like lichens and mosses, which can become completely dehydrated and yet resume normal physiological activities following rehydration. These plants are unimportant in crop production.

Morphological and physiological mechanisms of drought adaptation are restricted to that section of the SPAS that lies within the plant and within adjacent boundary layers. Adaptations are not only physiologically and ecologically interesting phenomena. They are potentially useful traits many of which can be bred into cultivated plants. Therefore, breeding for drought resistance should involve changing plant properties in these same regions of the SPAS as natural adaptations are observed. In contrast, the agricultural field operator will of necessity influence the SPAS mainly in regions outside the plant.

Breeding for drought resistance has to consider different aspects, including some that are not directly related to the water economy of the plant. The economic and social structure of a country has to be taken into account. Thus, in an arid climate, the soil water supply will often be limited during most of the growing season. Plants therefore have to be developed which will economize on water in order to produce sufficiently throughout the entire growing period. On the other hand, occasional periods of drought are usually of short duration in temperate, humid climates. Therefore, it might be advantageous to have cultivars that continue optimum photosynthesis at the cost of a more rapid but temporary exhaustion of available soil water. Or, to illustrate another aspect, for the subsistence farmer it is essential to produce a minimum yield each year, whereas large scale commercial farming in developed countries is buffered by global trade and, therefore, will risk occasional crop losses if, thereby, average production (profit) can be maximized *[1, 14]*.

In agricultural practice, man wants to eliminate or reduce many limiting factors such as weeds or pests which play an important role in the natural habitat. Moreover, he must focus his interest on a high harvest index. As a consequence, a breeder might develop cultivars that, under natural conditions, might not be able to survive and compete but which prove to be suitable for crop production.

Adaptations are inheritable traits. Their morphological, anatomical, physiological or biochemical expression can always be present in a plant or it can develop as a response to a stress situation.

Limited water availability causes less than optimum water relations within the plant. The primary site of water stress injury in plants is not known with certainty; there may even be more than one such site, but injuries are most likely related to loss of turgor pressure *[16, 26, 27]*. Turgor pressure is related by means of SPAS to soil water availability, which in turn is expressed by soil water potential.

2. Adaptive changes in the SPAS

2.1 Adaptive changes in the initial (soil-water potential) and final (atmospheric-water potential) stages of the SPAS

Since both the beginning and end of the flow system are located outside the living plant, neither could have been included in the development of adaptive mechanisms. A water collecting morphology together with stem flow could *[34]* increase local soil water potentials. One could also argue that a reduction of runoff in favor of infiltration on land covered by vegetation is adaptive. A stimulation of dew formation by plants *[26]* will improve the terminal water potential of the SPAS. By and large, these mechanisms are probably of little significance and have not been proven to be specific to plants of arid climates.

2.2 Adaptive changes of flow resistances the SPAS

The possibility of changing flow resistances in quick response to adverse moisture conditions is probably the most important adaptation to limited water availability. The mechanism rests in the stomatal apparatus. By analogy to the flow of electricity, a change of flow resistance has a dual effect: 1. An increase in the overall resistance will reduce the flow of water and thus a given limited supply of soil water will last for a longer period. 2. An increase in resistance at a special location within the SPAS will raise the water potential at points below (toward the soil) this location and lower it at points above (toward the free atmosphere). In addition, at any given point along the SPAS system, the larger the original resistance (to water flow) the more effective a given relative change in it would turn out to be. Thus, doubling the small xylem resistance will have little direct effect on the overall water flow rate, whereas doubling the large boundary layer resistance at the leaf surface will change the rate of transpiration substantially. If we study the stomatal apparatus, we recognize the development of a nearly perfect regulatory system. In a sense, this regulatory system is outside the plant in the gaseous phase where the resistance to water flow is highest. This is the phase in the total SPAS where a relative change in resistance is most effective, and where an increase in flow resistance not only leads to conservation of soil water but also simultaneously raises water potential within the plant. Of course, without this protective regulatory mechanism, higher plants as they are known today would be unthinkable.

Physiological regulations of stomatal apertures further demonstrate adaptive values. Not only are stomates responsive to plant water status, but they also seem to close whenever their being open is unnecessary for photosynthesis. Closure at night or with high CO_2 levels will conserve soil water and turgidity within the plant at a time when an entry of CO_2 is not needed.

Morphological and physiological modifications of the stomatal apparatus have evolved in plants of arid climates. Immersing stomates into crypts of the leaf and lining these crypts with trichomes such as those found in *Nerium oleander*, will add to the resistance of water diffusion as any changes that increase the aerodynamic roughness of the leaf would do.

Members of the Crassulaceae and some other plant families absorb CO_2 during the night through open stomates and fix it in the form of malic acid. During the day

when stomates are closed, the stored CO_2 is released and used for production of carbohydrates by photosynthetic reactions. This separation of CO_2 and light absorption permits the plant to impose a high resistance on the flow of water at a time when the transpirational demand would be high. Primary production of these Crassulacean acid metabolism (CAM) plants is low. As a further adaptation, some CAM plants can switch to normal photosynthesis when water relations are adequate.
A separation of the location of light and CO_2 absorption has been recently reported by *Eller and Ruess [8]* for Lithops. The succulent leaves of these plants are embedded in the soil except for a window at the soil surface. Light is absorbed through this window at the soil surface whereas CO_2 enters through stomates of the mantle that is in contact with the soil. Clearly, water loss through these stomates will be smaller.
Cuticular transpiration cannot be regulated. It amounts to only a few percent of the total water loss, and in drought adapted plants it may be reduced to a small fraction thereof thanks to thick cuticulas and waxy layers. An increase in leaf surface roughness through leaf hairs or elevated ribs that stabilize the boundary layer will also reduce cuticular transpiration.
Abscission of leaves during drought has several effects. One is an adaptive increase in resistance to water flow. The Ocotillo *(Fouquieria splendens)* of the Colorado desert of North America will develop mesophytic leaves after rainfall. After a return of the drought the leaves will senesce and eventually drop off. This process can repeat itself several times during the course of a year.
In comparison to the regulation of the boundary layer flow resistance at the leaf surface, other resistance changes have little adaptive value. With limited water availability the root/top ratio increases *[10]*. The root resistance decreases and the leaf water potential increases. However, the principal benefit of an enlarged root system lies in the larger volume of soil water that can be tapped. (see *2.3.1*)
A major challenge to the breeder of cultivated plants is to optimize resistances at the leaf surface. Optima for CO_2 entry and water loss may well be different for rainfed farming, irrigated farming and farming in more humid climates.

2.3 Water storage capacities in the SPAS

Stored water in soil and plants buffers the SPAS against decreases in water potential and turgidity. It is thus a property related to the water potential and it is only effective under nonsteady-state conditions. In analogy to other fields of science the capacity represents the amount of water that can be withdrawn until the water potential drops by one unit. The water can be removed from a leaf tissue, from the soil volume rooted by an individual plant or from the soil volume rooted by a crop, etc. In each case a high capacity means that a relatively large quantity of water can be removed before a certain loss of water potential is observed and vice versa. A high capacity thus means a well buffered system against changes in water potential.

2.3.1 Soil water storage capacities (per unit plant)

Several adaptive mechanisms have evolved with plants to tap larger soil volumes for water. The mesquite, a small tree of the North American desert, is said to reach groundwater 50 m below the soil surface. Jojoba *(Simondsia chinensis)* has already a tap root of 30 to 50 cm before the top appears from a germinating seed. Among crop plants, alfalfa *(Medicago sativa)* can drain deep water reservoirs that are unavailable to other plants and, similar to jojoba, cotton, will allocate a large fraction of the substances mobilized in the germinating seed to root growth. Deep rooting systems in a desert environment are only an advantage if, in the long run, the withdrawn water is resupplied.

Plants respond to drought by producing higher root/top ratios, a change that is adaptive. Annual plants have a relatively lower root/shoot ratio than perennials because their phenological adaptation seems to be effective and because their seeds are their major storage organ. In contrast, perennials must store assimilates in roots *[10]*. Substantial quantities of assimilates are sometimes put into flower and seed, making female plants of *Rumex acetosella* less drought resistant *[37]*. In a natural plant community sufficient assimilate has to be allocated to roots to insure survival, but an excessive allocation will reduce production unnecessarily and make the plant less competitive. Similarly, a plant breeder will try to minimize as much as possible the enhanced allocation of assimilate to roots in order to maintain a favorable harvest index.

The efficiency of stored soil water not only depends on the capacity but also on the rate by which water is removed by plants and by soil evaporation. Reduced growth rates, shedding of plant parts, dying of tillers, reduced production of spikelets and florets *[32]* are adaptive responses that will make a certain supply of water last longer over the various stages of development, particularly in the sensitive flowering stage.

At first sight it might be surprising that nature has often developed extensive superficial rather than deep root systems as adaptations to limited water supplies. In arid climates, precipitation is infrequent and irregular, with intensities which may be high but of mostly short duration. As a consequence, only the top layers of the soil are moistened and water will evaporate unless plants have mechanisms to rapidly absorb it. The fishhook cactus *(Ferrocactus wislizenii)* has an extensive root system only a few cm below the soil surface and the root system of some *Cholla cacti* exceeds 10 m in diameter. Some of these extensive shallow root systems are present permanently, others develop rapidly after rainfall.

Extensive root systems are of little value for a dense stand that has to depend only on precipitation in an arid climate and moreover may be disadvantageous to crops *[29]*. Through allelopathic inhibition of competitors, individual plants enlarge their territory and insure themselves a larger water supply. *Encelia farinosa* inhibits the germination of other species, *Larrea tridentata* its own. In the latter case, this leads to a regular, checkerboard distribution of the species.

Shading of the soil surface by leaf canopies, perhaps mulches from leaf litter, will reduce evaporation from the soil surface and thus increase the water use efficiency of the site. This is equivalent to increasing the soil water capacity for the transpiring plant. A larger root system will not only increase the water storage capacity of the soil on a unit plant basis. Since the soil water content will remain high for a longer period, the resistance to water flow near the root in the soil will increase less rapidly. A lower resistance, however, means a higher turgor pressure.

2.3.2 Capacities within plants

The total water content in a crop is equivalent to the amount transpired within a few hours to a few days. Water stored in such tissues cannot be adaptive in arid climates in the sense of improving survival during long periods of drought. Nevertheless, the small buffering effect that the leaf water content has on the leaf water potential could delay the daily loss of turgidity for some hours and therefore permit a prolonged favorable condition for photosynthesis.

Storage of water assumes a fundamentally different role in some arid climate plants where roots, stems and leaves can function as significant reservoirs. In *Pachypodium succulentum,* the root mass, which consists of 90% water, can exceed that of the top by a factor of 100. Stem succulence is most spectacular in cacti where the Saguaro cactus *(Carnegiea [Cereus] gigantea)* can store several tons of water. Leaf succulence, which is also widely distributed, permits, e.g. members of the Crassulacean family to survive for prolonged periods without any external water. The survival value of stored water is high in these cases. Severed branches of the Saguaro cactus can remain physiologically active and even form blooms after many months.

In all these cases, water storage alone appears insufficient for survival, and combinations with other mechanisms such as wide horizontal root systems, closure of stomates or CAM metabolism are necessary. During prolonged periods of limited water supply there are also some parallel losses of organic substance so that the water content or the state of water in plants changes less than would be expected from the loss of water per plant. *Walter [35]* reports a case of *Opuntia phaeacantha* where, after a 139-day drought period, 60% of the original water had been lost but the water content on a dry weight basis had dropped only to 72%.

Adaptation of root systems is probably one of the major capacity aspects that must be considered for plant improvement through breeding. It is not convenient to breed for large capacities within plants such as are found within some desert plants; but it might be well worth exploring whether even a small increase in water storage of mesophytic leaves might not increase plant productivity, if by this means the noon hour closure of stomates could be eliminated without deleterious effects.

2.4 Interception of radiant energy

The SPAS is not isothermal and the leaf surface temperature strongly influences the rate of water loss to the atmosphere. The leaf temperature is the result of energy fluxes and storage but the fluxes themselves depend again on the temperature. Leaf drop, positioning of leaves parallel to the incident radiation (paraheliotropism), leaf rolling, heterophylly with leaf size depending on drought, increased reflection of leaf surfaces and perhaps even wilting are adaptive mechanisms to reduce excessive interception of radiant energy *[2, 12, 13]*. Closure of stomates will increase leaf temperature which, at the higher vapor pressure, counteracts, to a small extent, a benefit resulting from the higher diffusive resistance. Leaf temperatures may become critical and heat resisting mechanisms will be necessary as adaptations to limited water supplies. One might search in the cytoplasm for heat resisting mechanisms but a reduction of the interception of radiant energy also serves this purpose.

It would be useful to incorporate or develop some of these traits into crop plants. For example, if leaves were to assume a position parallel to the incident solar radiation only when serious drougth or heat damage would occur, the cost of this adaptation would be minimal for an absolutely necessary effect. Leaflet orientation in water-stressed soybeans was considered beneficial to crop production by *Meyer* and *Walker [22]*.

3. Osmotic adjustment

Favorable turgidity can be maintained not only through conservation of water potential in the SPAS but also through an adjustment of the osmolality within a cell. The past decade has seen a real surge of publications in this field, frequently giving the impression of a new discovery *[18]*. However, this is not so. In the first half of this century a number of investigators reported evidence about an osmotic adjustment; this has led *Walter [35]* to postulate his concept of the hydrature and *Eaton [7]* to criticise interpretations of salt injuries to plants which were current at that time. *Richard* and *Wadleigh [30]* also discuss osmotic adjustment of plants suffering from water stress.

Nevertheless, recent efforts have helped considerably to clarify the picture. One has become aware of possible pitfalls such as apparent partial osmotic adjustment when cells lose water and their osmolality increases *[26]*. The knowledge about the composition of osmotica has also increased. Although inorganic solute concentrations (especially those of potassium) usually play a major role in this respect, organic solutes also respond to soil moisture stress *[12, 13, 15]*. The concentrations of glycine betain and of the amino acid proline consistently increase in plants suffering from limited water supply. In osmolalities the increases are rather small, around 50 mmoles l^{-1} (maxima reach 200 to 400 mmoles l^{-1}). This would raise the turgor pressure only by 0.1 to 0.2 MPa, an insufficient amount to maintain cellular turgidity under water stress. If, however, these organic solutes were restricted to the cytoplasm, they could have a significant osmotic effect. Such a localisation of proline and glycine betain has been suggested repeatedly *[12, 13, 15, 36]* and one has even argued that inorganic ions, especially monovalent ones, would be harmful to the cytoplasm *[13]* wherefore they are restricted to vacuoles. A survey of the literature yields examples for preferential proline accumulation in drought and salt resistant genotypes as well as in sensitive plants *[31]*. It is, thus, not possible to postulate a general hypothesis of an osmotic adaptation by proline accumulation. Moreover, other forms of stress also seem to induce a proline synthesis.

This hypothesis is attractive even though evidence for it is difficult to obtain *[36]*. It also tends to disregard that tbe cytoplasm is highly structured and organised, consisting of numerous organelles that themselves are osmotic systems although pressure differences across their membranes are probably small. Swelling and shrinking of organelles are related to their function. The degree of swelling is largely determined by solute distribution within the cytoplasm. Hence, the distribution of organic molecules within the cytoplasm is most likely not homogeneous. Other groups of investigators attribute a protective function to these organic substances rather than an osmotic adjustment *[24]*. A third group of investigators consider the proline accumulation symptomatic rather than adaptive *[5, 14]*.

The osmotic adjustment is usually considered a positive adaptation to suboptimal water relations whereby turgidity is maintained and the plant is claimed to suffer no longer from water stress. There is no question that maintenance of turgidity has positive aspects but the real situation is more complicated. One has always to bear in mind that osmotic adjustment means only that turgor pressure remains unchanged while water potential and osmolality are shifted, and it might very well be that increased solute concentrations have an effect on plant metabolism, *e.g.* on enzyme activities. A further difficulty arises when we consider the case of growing tissues with expanding cell volume where a continuous adjustment must take place. Under limited water availability, this continuous osmotic adjustment requires more time and energy *[26, 27]*. It is thus not unexpected that growth rates are reduced with moisture stress in spite of the osmotic adjustment of mature cells. A third difficulty arises if we consider the consequences of a complete adjustment including one of the guard cells of the stomatal apertures. In this case, stomates remain open and a limited supply of soil water rapidly becomes exhausted *[20]*. For this reason it may be justified to breed plants which are capable of full osmotic adjustment in temperate humid climates, but in semi-arid and arid regions, especially in rainfed agriculture, those plants may be more valuable that can conserve water by a less than complete osmotic adjustment.

4. Phenological adaptations

All plants living in environments where periodic or permanent limitations of water availability are serious problems, must also be able to fully utilise seasons of favorable moisture conditions. According to our terminology, this is equivalent to making use of favorable initial and final water potentials of the SPAS. Even plants like cacti that store water and extend their activities well into periods of drought will rapidly respond to rainfall and utilise the soil water. In many cases physiological activities are triggered by the incidence of favorable moisture conditions, and growth and development are mainly restricted to periods of adequate water availability. Even in such cases, seed maturation may preferably occur during the drier portion of the growth period.

Evolution has developed a number of safety devices that prevent initiation of physiological activities, such as seed germination, after rainfall inadequate enough to assure completion of the plants' life cycle.

Photoperiod regulates many physiological phenomena and it is not astonishing that it is also an adaptive regulator of drought resistance in some species. Although germination is still triggered by favorable moisture conditions, the process occurs only with a photoperiod corresponding to the normally humid season. With the termination of a rainy season, physiological activities come to an end. Thus, plants of the summer humid savanna are more likely to be short day plants, those of the summer dry Mediterranean region long day plants *[10]*.

Other plants such as *Limnanthes alba,* a possible oil crop of the future, sense high temperatures in order to prevent germination at the wrong time. In its native habitat of northern California, this plant grows during the cool, humid winter and seeds mature in spring. Germination is inhibited when temperatures are in excess of 20 to 25 °C. Thus, occasional summer rains which normally add insufficient quantities of moisture for a full life cycle, cannot trigger germination of the seeds.

A number of annual desert plants are neither regulated by photoperiod nor by temperature. Seeds of some of these species can indirectly sense the amount of rainfall by means of inhibitors in their seed coats, the removal of which requires a certain amount of precipitation *[9]*.

Numerous examples are known where bud emergence and shoot growth are triggered by improved moisture conditions and again photoperiod or temperature impose restrictions as to when the trigger can function *[10]*. Drought induces dormancy and leaf abscission in *Lotus scoparius*, but it does so only during the long day season. Dormancy cannot be broken until the return of the short day season during which, however, drought no longer induces dormancy *[25]*. Leaf emergence and abscission of *F. splendens*, which has been described earlier, is an example where the trigger is operative during the entire year.

Also, the agricultural practice adjusts to seasons with suitable moisture conditions. Since such seasons are often short and unreliable, one tends to breed plants which mature early. Since in the Mediterranean climate the rainy season is also cool, a breeding program might have to include resistance to chilling. Ideally, one hopes to develop a crop in rainfed farming which will mature earlier during a season that is deficient in rainfall and would remain productive and mature later with an abundance of moisture. There are indications that such a goal can be achieved.

Considering the irregularity of precipitation even during the rainy season of arid climates, an ability to regenerate from drought injury is adaptive. *Hsiao [17]* reported a recovery of sorghum which produced lateral flower heads and panicles on tillers after the primary panicle had been destroyed by drought. An ability to regenerate at certain stages of development can be a useful trait to incorporate into crop plants. It has the advantage that no reallocation of assimilates is necessary unless the need arises after an exceptionally long period of drought during the rainy season.

5. Cell wall structure

Sclerophyllous cell walls are a frequent manifestation of xeromorphism, especially in shrubs of Mediterranean climates. Since, under extreme drought, the turgor pressure becomes negative, strengthened walls will prevent or delay the resulting collapse of cells *[26]*. Leaves of such plants do not readily wilt, the leaf surface remains fully exposed to light and photosynthesis can continue, provided the entry of CO_2 is not prevented due to a closure of stomates. It might rarely be advisable to introduce sclerophyllism into cultivated plants through breeding.

6. Adaptive biochemical processes

Considering the intricate interdependence of processes within an organism, it is hardly surprising that numerous biochemical alterations of plants to limited water availibility have been reported. It is rather unlikely that all such changes are primary reactions to water stress and their possible adaptive significance is highly speculative. For example, via the operation of stomates, water relations can limit the rate of photosynthesis, but there are reports in favor of more direct interactions. Although such links are possible, none have been demonstrated convincingly. A reduction in the water potential by about 3 MPa – a rather large one – will lower the chemical activity of water by only 2%. This, for most processes, will have only a negligible effect *[16, 26, 27]*. The water potential varies due to changes in pressures and osmolalities, but it is usually not fully realised that these two variables not only affect the potential of water but also that of all other reactants in a system. Without further information, it is not generally possible to predict in which way a process will be affected by a change in the water potential.

Boyer and *Brown [3]* observed an inhibition of the Hill reaction by mild moisture stress in isolated chloroplasts. The function of chloroplasts is probably connected to their swelling and shrinking, two properties that, in vivo, depend on the solute distribution between the interior and the immediate environment *[26, 27]*, and not directly on the water potential which is presumably equal inside and outside an organelle. Perhaps for this reason, *in vivo* light-dependent ATP formation and NADP reduction were rather insensitive to water stress *[33]*.
The role of ABA and other plant hormones has been studied extensively over the past 20 years; *Mizrahi [23]* reported on it at the I.P.I. Colloquium at Wageningen. Parallel to the development of water stress, ABA increases and cyokinins decrease in plant tissue. The level of ABA shows some relation to the function of stomates and, through addition of ABA, stomatal closure can be induced experimentally. It is appropriate to mention at this point that up to now neither a sensor of plant metabolism for water relations nor a primary mechanism of response are known. Therefore, it has been suggested that changes in hormone levels are secondary effects *[31]*. However that may be, a change in plant hormone levels must be expected to induce numerous additional (tertiary) effects.
Very few of these biochemical responses are known to be adaptive to limited water availability. Changed biochemical pathways in CAM plants have been discussed above in connection with the regulation of the stomatal resistance, and C_4 photosynthetic pathways could be beneficial because of a higher water use efficiency *[6, 10]*.
Since the purpose of this paper is to discuss adaptive responses in plants, the reader is referred to literature reviews *[2, 10, 11, 13, 16]* for general reactions of plants to water stress.
A better understanding of biochemical adaptations is highly desirable before the plant breeder can introduce or enhance them in cultivated plants.

7. Hardening

Plants grown in a humid environment, such as cuttings in a mist chamber or plantlets in a Petri dish, require some hardening before being planted in the field. Similarly, many cultivated plants, *e.g.* maize, that had been exposed previously to water stress, will outproduce plants which were not pretreated, during a subsequent period of drought *[4]*. An ability for an acclimation is adaptive. Usually one suspects hardening to have a biochemical foundation. However, in the above study with maize, transpiration of hardened plants was lower and the supply of the soil water lasted longer. In general, mechanisms of hardening are poorly understood and presumably some change in cytoplasmic property is involved *[20, 21]*.
Ouedraogo and *Hubac [28]* recently showed that cotton plants grown under 9-hour light periods become more drought resistant if a 30-minute far red light illumination is added at the beginning of each dark period. In resistant plants, diffusive resistances of stomates were higher due to smaller stomatal apertures. Hence, far red illumination reduced the transpirational water loss and made the soil water supply last longer.

8. The agricultural operator's attempt to modify water relations in crop production

The discussion so far has centered on adaptations in plants to survive and produce under conditions of limited water availability, and on the desirability of incorporating or strengthening adaptive traits into crop plants. Man's influence, however, is not restricted to plant breeding and the everyday farming operation offers numerous possibilities for improving soil-plant-water relations. These interactions again modify the SPAS but, in contrast to the natural adaptation, their primary effect is outside the plant.

Irrigation raises the soil water potential; it fills the soil reservoir and reduces the resistance to water flow in the root boundary layer. The high relative humidity of a greenhouse atmosphere raises the atmospheric water potential, *i.e.* that of the final stage. Shading a greenhouse or a newly planted crop reduces the amount of intercepted radiant energy as do those antitranspirants that increase the reflection of the leaf surface. Other antitranspirants increase the resistance to water flow at the leaf surface and have, hopefully, only slight effects on the entry of CO_2. Planting distances significantly modify the extent of stored water available to the plant.

We thus see that the major natural adaptations to limited water availability and man's interactions to improve water relations, both attempt to modify the soil plant atmosphere flow system.

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Crop Management in Rainfed Agriculture with Special Reference to Water Use Efficiency

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Summary

Water use efficiency (WUE) of rainfed crops in the Mediterranean region is discussed. It is shown that

$$WUE = \frac{TE}{1 + \frac{E_{SC}}{T}}$$

where TE is the seasonal transpiration efficiency of the crop and E_{SC} and T are the two components of evapotranspiration (E_T), namely soil evaporation from under the crop (E_{SC}) and crop transpiration (T). Selected examples of crop management, for instance, fertilizer addition, time of planting, crop morphology, seeding rate and crop rotation were chosen and their influence on the E_{SC}/T ratio was illustrated using recent data from Northern Syria. Management and environmental interactions with TE were also discussed and methods of increasing the moisture available for crop uptake were outlined. It was concluded that although much can be done to increase the available moisture and certain measures can be taken to influence the seasonal TE, the major factor leading to increased WUE is the rapid establishment of crop green area during the cool winter months and the achievement of optimum green area indices.

1. Introduction

Rainfed farming systems in the Mediterranean environments of the Near East and North Africa have evolved over many thousands of years by successive trial and error by generations of farmers. In this process of evolution, the farmer has faced many constraints including pests, diseases, poor soil fertility, unsophisticated tillage implements, limited access to new crops species, and, above all, erratic and often chronically low rainfall. Within the goal of optimizing the profitability of agricultural production, but at the same time wishing to minimize the risk of crop failure in dry years, farmers have evolved stable agricultural systems which, in the past, were

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able to support the communities concerned. In more recent times, with the advent of modern technology and agricultural science, there now exists the potential to increase the productivity of these systems by overcoming many of the constraints faced by the farmers of the past. However, in rainfed agricultural systems, the major constraint, that of low and erratic rainfall, remains the one factor over which neither the farmer, nor the scientist, can exert any influence. Within this limitation, the agricultural scientist of today seeks to find ways in which improved technology can be incorporated into the existing farming systems in a manner which both increases the profitability and stability of agricultural production and yet remains acceptable to and within the reach of resource poor farmers of the region. In testing such improved technology, and in view of the overall constraint of limited moisture supply, agronomists can evaluate crop performance in terms of water use efficiency (WUE), as defined in equation (1).

$$\mathrm{WUE} = \frac{\text{Biological yield} \quad (\text{kg/ha})}{\text{Crop evapotranspiration (mm)}} \tag{1}$$

Such an expression defines the efficiency with which crop systems utilize moisture in units of kg/ha/mm, and allows a relevant comparison between difference agricultural practices *(Bolton [2]; Arnon [1])*.

This expression can be expanded by introducing two further concepts. Firstly, seasonal crop evapotranspiration (E_T) can be expressed as the sum of its two components, namely transpiration (T), and evaporation from the soil surface under the crop (E_{SC}); thus

$$E_T = T + E_{SC} \tag{2}$$

Secondly, biological yield can be expressed as the product of seasonal crop transpiration (T), and seasonal transpiration efficiency (TE). TE defines the efficiency of dry matter production per mm of moisture transpired with units of kg/ha/mm: thus

$$\text{Biological yield} = T \times TE \tag{3}$$

Substituting equation (2) and (3) into (1) we arrive at:

$$\mathrm{WUE} = \frac{T \times TE}{T + E_{SC}} \tag{4}$$

This expression can be simplified further giving:

$$\mathrm{WUE} = \frac{TE}{1 + \frac{E_{SC}}{T}} \tag{5}$$

The presentation of the WUE of total biological yield in terms of the seasonal transpiration efficiency (TE) and the ratio of moisture loss from the soil surface (E_{SC}) to that utilized by the crop as transpiration (T) provides a logical basis from which to discuss how crop management factors can be manipulated to improve WUE.

In the Mediterranean environment, it is common for winter sown crops to complete the major part of their reproductive growth under conditions of soil water profile depletion and increasing atmospheric evaporative demand. There thus exists an optimum balance between moisture use during vegetative growth and that remaining available for the grain filling period. This balance will depend upon crop specific physiological reaction to moisture stress (see *Turner* and *Begg [14]; Fischer [5])*, a detailed discussion of which is outside the scope of this short communication. As indicated, the expression in equation (5) refers to total biological yield and the discussion in this paper will focus on this aspect. Nevertheless data will be presented from recent studies in Northern Syria which indicate that increases in WUE of biological yield are usually closely related to similar increases in WUE of seed yield, a fact evolving from the relative stability of the harvest index of grain crops. In addition, it should also be remembered that in the Near East and North African regions, the economic value of the straw as animal feed is often equal to and sometimes exceeds that of the grain for crops such as lentils and barley, thus conferring greater importance to total biological yield than is common in other regions.

A detailed discussion on the interaction between crop management and WUE encompasses all aspects of crop production which cannot be covered in a paper of this length. Thus only selected crop management practices and their influence on WUE will be presented to illustrate the principles involved.

2. Crop evapotranspiration and its components

The apportioning of E_T into T and E_{SC}, in other words, the E_{SC}/T ratio is the major factor affecting the WUE of a crop (see equation 5). *Ritchie [12]* states that ...'It is possible to separate soil and plant evaporation logically when we know the fraction of the energy intercepted by the plant canopy and the critical soil parameters.' Based on the logic described by *Ritchie*, a field technique utilizing measurements of E_T, E_S (evaporation from a bare soil), GAI (green area index) and K (the extinction coefficient of the crop) has recently been developed *(Cooper et al. [4])*. This technique apportions E_T into its two components and can thus be used to indicate how different crop management practices affect the E_{SC}/T ratio. To illustrate the general trends of seasonal variation of E_{SC} and T of winter sown crops in the Mediterranean environment, an example of this technique is given in which the effects of fertilizer application on barley growth and water use were studied at Breda in Northern Syria. The seasonal variation of GAI, T and E_{SC} are presented in Figures 1 and 2. During the cool winter months, when the GAI and radiant energy interception were low, E_{SC} accounted for almost 100 percent of E_T. As GAI began to rise around 50 days post emergence, T became increasingly larger, and both GAI and T values reached a maximum just before anthesis. During grain filling, as leaf senescence occurred and GAI fell, T values decreased and E_{SC} values rose. This rise in E_{SC} during senescence was associated with atypically late rains just prior to maturity which rewetted the soil surface under the crop. In more normal years such a pronounced increase in E_{SC} during this period might not occur.

From these data it can be seen that the E_{SC}/T ratio is closely related to the GAI and that fertilizer addition has significantly increased this latter parameter, thus re-

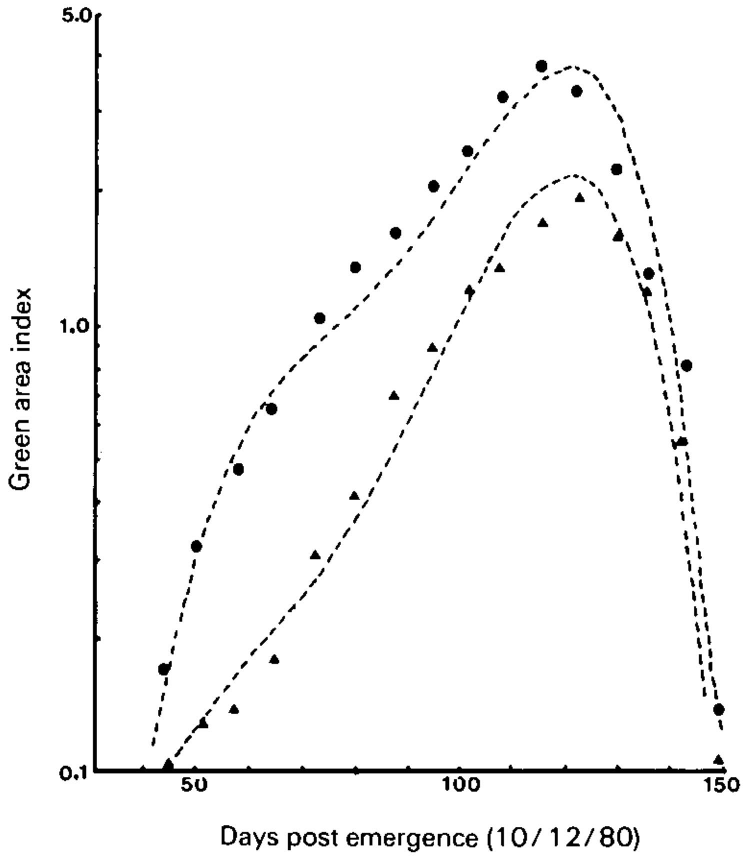

Fig. 1. Seasonal change in GAI of Beecher barley with (●---●) and without (▲---▲) added fertilizer. N. Syria (1980/81).

ducing the E_{SC}/T ratio. This is further illustrated by the data in Table 1. Several points are worth noting in this table which will be enlarged on in subsequent sections. Firstly, relatively small amounts of fertilizer addition have caused a large (42 percent) increase in WUE of biological yield. Secondly, fertilizer addition has hastened crop maturity by 7 days which resulted in a lower total E_T. Thirdly, a very low proportion (38 percent) of E_T was actively used by the crop as T in the unfertilized treatment. It should be emphasized that this crop produced 1720 kg/ha of seed yield compared to a common range of 600–1000 kg/ha in farmer fields. Such crops probably only utilize between 20–25 percent of E_T as T, indicating the enormous potential improvement in WUE.

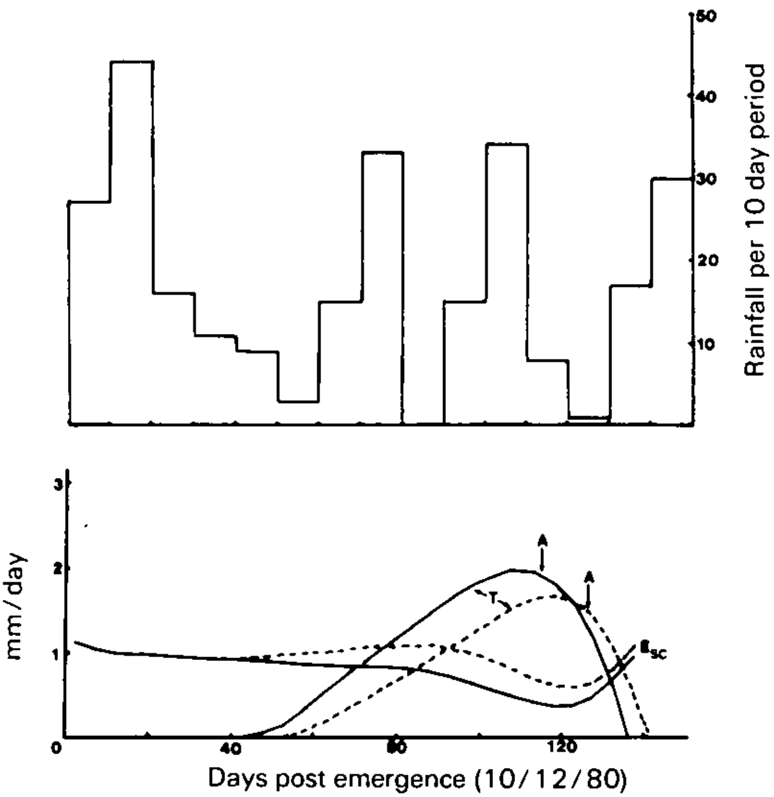

Fig. 2. Rainfall (mm) and seasonal variation of T and E_{SC} of Beecher barley with (——) and without (– – –) added fertilizer. N. Syria (1980/81).

Table 1. Yield and water use components of barley (var. Beecher) grown at Breda, N. Syria (25° 55′ N, 37° 10′ E), 1980/81

	No fertilizer	Plus fertilizer (60 P_2O_5, 20 N, kg/ha)
Maximum GAI	1.8	3.8
Germ.-Maturity (days)	145	138
Total biological yield (kg/ha)	3550	4940
Seed yield (kg/ha)	1720	2130
1000 grain weight (g)	38.1	32.5
E_T (mm)	220	216
E_{SC} (mm)	137	108
T (mm)	83	108
E_{SC}/T	1.65	1.00
WUE (kg/ha/mm)	16.1	22.9
TE (kg/ha/mm)	42.8	45.7

3. Crop management and WUE

In this section, several examples of how crop management can influence the E_{SC}/T ratio, and thus WUE, are discussed and illustrated using data from studies at *ICARDA*.

3.1 Time of sowing

Recently, the selection of chickpea lines resistant to *Aschochyta* blight has enabled the winter planting of this crop to become feasable compared to the more traditional practice of spring planting *(Hawtin* and *Singh [7])*. Studies comparing the crop growth and WUE's of winter and spring sown crops have indicated increases of over 100 percent in the WUE of the winter sown crop. *(Keatinge* and *Cooper [8])*. This is illustrated for two locations by the data in Figure 3 and Table 2. During the winter months, the developing canopy of the winter crop (sown 20/11/80) intercepted energy, albeit to a small extent, whilst the land for the spring sown crop remained bare.
However, at the time of sowing of the spring crop in early March, the GAI of the winter sown crop was increasing rapidly and reached maximum values nearly twice that of the spring sown crop as indicated in Figure 3 where the figures represent the area under the curve as a percent of the winter sown crop at Jindiress. Because moisture was being lost from the bare soil surface throughout the winter months in the spring sown crop (Table 2), there was little difference in the total E_T at maturity be-

Table 2. Accumulated E_T (mm) on selected dates, components of yield and WUE of winter and spring sown chickpea (var. ILC 482) at two locations in N. Syria, 1980/81

Jindiress (36° 23′ N, 36° 41′ E) Date							Maturity date	E_T Germ-Mat.	Biol. yield kg/ha	Seed yield kg/ha	WUE kg/ha/mm [1])	[2])
	2/1	4/2	5/3	8/4	11/5	14/6						
W. Sown	46	104	139	221	377	428	22/5	422	7910	4220	18.7	10.0
S. Sown	48	107	140	204	294	413	14/6	413	3290	1880	8.0	4.6
E_0	49	119	185	324	496	744	–	–	–	–	–	–
R	120	274	338	401	456	456	–	–	–	–	–	–
Tel Hadya (35° 55′ N, 36° 55′ E) Date							**Maturity date**	**E_T Germ-Mat.**	**Biol. yield kg/ha**	**Seed yield kg/ha**	**WUE kg/ha/mm [1])**	**[2])**
	22/12	29/1	1/3	13/4	19/5	11/6						
W. Sown	18	74	108	173	299	311	25/5	311	3550	2090	11.4	6.7
S. Sown	16	71	109	154	251	300	8/6	297	1560	800	5.3	2.7
E_0	26	82	158	350	623	889	–	–	–	–	–	–
R	70	189	247	305	351	357	–	–	–	–	–	–

WUE [1]) and WUE [2]) are of total biological yield and seed yield respectively.
E_0 is accumulated Class A pan evaporation (mm).
R is rainfall accumulated from onset of the season (mm).
Maturity is gauged at 75% crop yellowing.

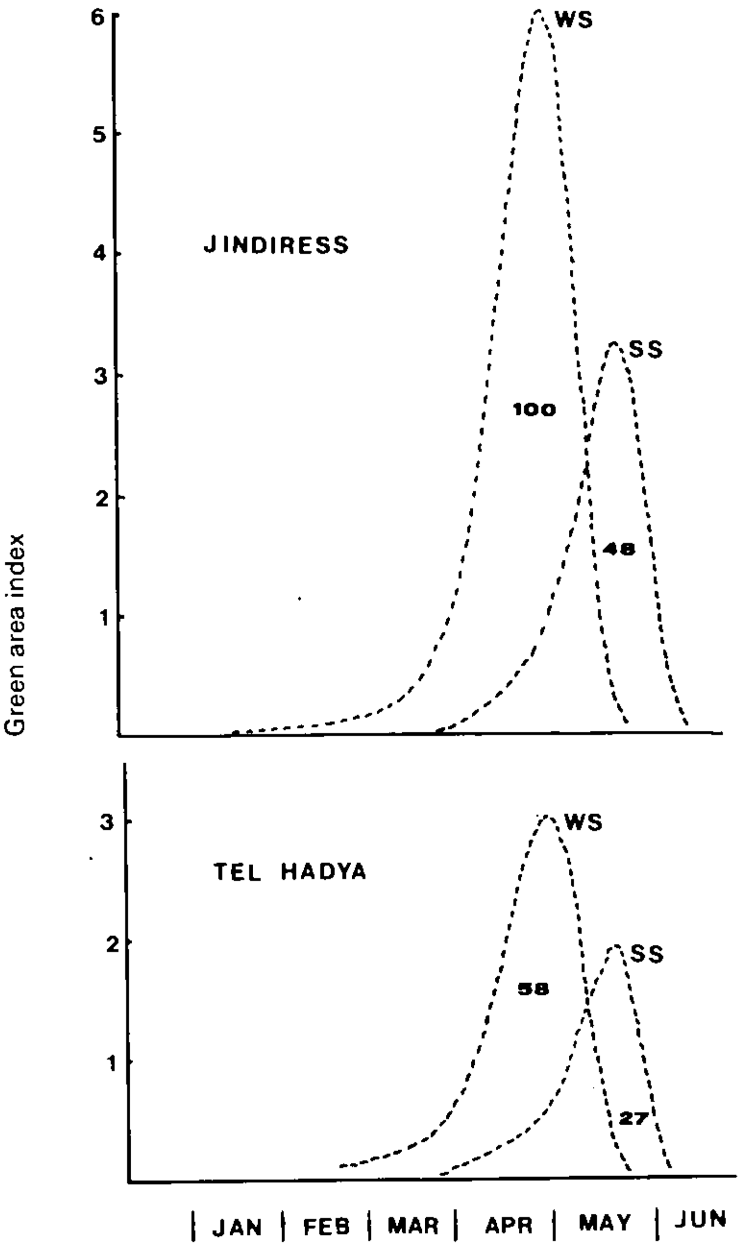

Fig. 3. Seasonal change in GAI of winter (WS) and spring sown (SS) chickpea at two locations in N. Syria (1980/81).

tween the two sowing dates at either location. However, due to the large differences in GAI, and hence the apportioning of E_T into its components, there were highly significant increases in WUE of biological yield through winter sowing both at Jindiress (134 percent) and Tel Hadya (115 percent). Similar increasing in the WUE of seed yield were also found. As would be expected, there is a very close relationship between the area under the GAI curve, in other words green area duration, and WUE.

This is an extreme example of the effect of the time of sowing, but the same principle would apply to early and late sowing of winter crops such as wheat, barley and lentils, although the effect would be smaller.

3.2 Crop morphology and seeding rate

Although interception of radiant energy by the crop canopy is largely determined by the GAI of the crop, the structural morphology of the crop will also play an important role. This is illustrated by the expression:

$$\alpha = 1 - e^{-K \cdot GAI} \qquad (6)$$

where α is the proportion of intercepted radiation and K is the extinction coefficient of the crop and is dependent on the crop morphology *(Monteith [10])*. It is also apparent that for a crop of given morphology, the seeding rate will also have a direct effect on the rate of canopy development. In many crop species, for example cereal crops, the plant can compensate for low seed rates through tiller production, thus giving a more constant number of spikes/ha and a broad plateau in the seed rate/yield relationship. However, in crops such as chickpea, where tiller production, or branching, is not so prolific, manipulation of seed rate can have a much greater effect on canopy development and thus WUE. An example is given which illustrates the effect of both crop morphology and seeding rate on the WUE of chickpea at two locations in Northern Syria (Table 3).

Table 3. The effect of crop morphology and seeding density on the growth and water use of winter planted chickpea at two locations in N. Syria, 1980/81

Variety	Biological yield kg/ha	Seed yield kg/ha	Max GAI	E_T mm	WUE [1]) kg/ha/mm	WUE [2])
Jindiress						
ILC482	7910	4220	4.9	422	18.7	10.0
ILC 72	6660	2670	4.0	450	14.8	5.9
ILC 72 (dense) ..	8380	3240	5.4	445	18.8	7.3
Tel Hadya						
ILC482	3550	2090	2.6	311	11.4	6.7
ILC 72	2960	1330	1.9	311	9.5	4.3
ILC 72 (dense) ..	3870	1780	3.0	317	12.2	5.6

WUE [1]) and WUE [2]) are of biological yield and seed yield respectively.
ILC 482 (spreading cultivar) and ILC 72 (erect cultivar) were planted at 300 000 plants/ha. ILC 72 (dense) was planted at 600 000 plants/ha.
ILC 72 matured about one week later than ILC 482 at both locations.

When ILC 482, a spreading cultivar, was planted at the same seed density as ILC 72, an erect cultivar, the data show that ILC 482 achieved higher GAI, biological and seed yield levels with no increase in E_T. Indeed, since ILC 72 was a longer maturity cultivar, E_T of ILC 482 was lower at Jindiress. Resulting from the different GAI, and thus E_{SC}/T ratio, the ILC 482 cultivar had higher WUE of both biological and seed yield. It is also clear that increasing the planting density of ILC 72 had little effect on E_T, but significantly increased the WUE.

Although the effect of seed rate on WUE is clear, researchers must consider farmer expectations before making firm recommendations. For instance, other results obtained at *ICARDA* would suggest that in many instances barley farmers could save up to 60 kg/ha of seed by using a lower seed rate than is common without seriously effecting the yield potential or the WUE of the crop. However, green stage grazing of barley during the winter months, before tiller growth occurs, is a common practice in the region, and the amount of forage available during early growth will be related to the seeding rate of the crop.

3.3 Fertilizer

The effect of fertilizer on the WUE of a barley crop at one location in Northern Syria has already been discussed in an earlier section. Additional data are presented for Beecher barley in Table 4 to further illustrate this effect at three locations in two cropping seasons. Very large fertilizer responses were found in both seasons at all sites resulting in highly significant increases in the WUE of biological yield. As a result of the relative stability of the harvest index, these increases were reflected in similar increases in WUE of seed yield. As observed before, the addition of phosphate fertilizer increased the rate of development of the barley crop resulting in maturity being advanced by up to 14 days (Jindiress 1981/82). Because of this, the water use of the crop was very often reduced by phosphate addition in spite of the more rapid development and higher maximum values of GAI. This advanced maturity from phosphate fertilizer is very dramatic (see Figure 4) and has important implications in conferring a 'drought escape' mechanism on the crop as well as resulting in increased yield. Lastly, it can be seen that as suggested by Equation (5), there is a linear relationship between the maximum GAI achieved by the crop and its WUE of biological yield. This linear relationship would not hold true for crops with very high GAI's.

3.4 Crop rotations

Crop management factors discussed so far have referred to the seasonal management of a specific crop. However, farming systems in the Near East and North Africa are based on crop rotations. Thus both research workers and farmers strive not only to increase the WUE of specific crop, but also to identify crop rotation systems which maximize the efficiency of water use in the longer term. Because of their long term nature, such trials have to be conducted for several years before the productivity and water use efficiency of different rotations can be fully evaluated,

Table 4. Effect of fertilizer on components of growth, yield and water use of barley (c.v. Beecher) at three locations in N. Syria for two cropping seasons

	1980/81 Jindiress		Breda		Khanasser		1981/82 Jindiress		Breda		Khanasser	
	−F	+F	−F	+F	−F	+F	−F	+F	−F	+F	−F	+F
Maximum GAI	1.8	4.3	1.8	4.6	1.4	2.7	1.8	3.7	1.8	2.9	0.5	0.9
Days germination to maturity	154	148	147	141	142	135	186	172	174	170	171	171
Biological yield, kg/ha	5430	12 480	3840	7540	3100	4980	4320	8680	4540	6130	1330	2390
Seed yield, kg/ha	2250	5020	1620	2580	1350	2200	1440	2930	1320	2220	376	917
Harvest index	0.41	0.40	0.42	0.34	0.43	0.44	0.33	0.34	0.29	0.36	0.28	0.38
E_T, mm	323	376	234	225	229	221	323	315	231	231	210	210
WUE, kg/ha/mm	16.8	33.2	16.4	33.5	13.5	22.5	13.4	27.5	19.6	26.5	6.3	11.4
% Increase in WUE	–	98	–	104	–	67	–	105	–	35	–	81

Fertilizer applied 1980/81 90 kg/ha of N and P_2O_5. 1981/82 60 kg/ha of N and P_2O_5.
WUE is of biological yield.
Barley grown within the 2-course barley/fallow rotation.
WUE = 6.95 Max. GAI + 3.43 (r = 0.96).
The above data are part of a Ph. D. thesis work by *K. Shepherd*

Fig. 4. Yield response and advanced maturity resulting from phosphate application, Breda, N. Syria, 1980/81. Both plots received 60 kg/ha N, but the plot on the left also received 90 kg/ha P_2O_5.

Fig. 5. Residual effects in a uniform fertilized (45 kg/ha N and P_2O_5) block of wheat at Tel Hadya, N. Syria, 1979/80. In 1978/79 the poor growth areas were wheat plots, and the luxuriant growth areas were fallow alleyways.

thus regional data are scarce. However, interest in the region has been focussed on the two course cereal/fallow rotation *(Loizides [9]; Bolton [2])* due to the apparent low amount of water stored under fallow in areas receiving less than 350 mm *(Cooper et al. [3])* and thus the inefficient use of moisture. Nevertheless, there is accumulating evidence to suggest that this time honoured practice can result in higher WUE in spite of moisture loss during the fallow year. This is due to the decline in yield found in continuous cereal production. An example of barley yields following fallow, barley, vetch and lentils are given from a long term rotation trial established in 1980/81 in Northern Syria (Table 5). Even though these results are only after one cycle of rotation, large yield differences can be seen, particularly the yield decline in continuous cereal. Reasons for this widely observed decline are not clear, but are unlikely to be due to moisture and nutrient effects alone. Data in Table 5 show that fertilizer addition only partly alleviates the problem and crop observations indicate that the poor growth in continuous cereal is clearly visisble during the winter months before the onset of moisture stress. This effect is dramatically illustrated for wheat in Figure 5.

In attempts to avoid this yield decline, and yet make more efficient use of the rainfall during the fallow year, scientists in the region have sort to replace the fallow year with suitable grain or forage legumes *(Loizides [9])*. The results have been encouraging, but more work is required on the agronomic management of such crops before these alternative two course rotations becomes widely acceptable. In Northern Syria alone, the potential of additional high quality forage supply for sheep during periods of acute shortages is enormous, and *ICARDA* attaches great importance to this field of research.

Table 5. Yields of crops in different two course rotations at Breda, N. Syria, 1981/82

		Biological yield (kg/ha)	Grain yield (kg/ha)
Barley/Fallow	+ Fert.	5250	1710
	− Fert.	3700	1470
Barley/Barley	+ Fert.	2790	920
	− Fert.	1300	490
Barley/Vetch	+ Fert.	2890	1020
	− Fert.	2380	870
Barley/Lentil	+ Fert.	3380	1120
Vetch/Barley	+ Fert.	1830	–
	− Fert.	1200	–
Lentil/Barley	+ Fert.	2580	860

Fertilizer addition is 60 kg/ha P_2O_5 and 20 kg/ha N to the barley phase of the rotation.

4. Factors affecting transpirational efficiency (TE)

Reference to Equation (5) indicates that WUE is directly proportional to the seasonal TE of the crop, and thus possible ways of increasing this factor are considered in subsequent sections.

4.1 Root/shoot ratio

The farmer is largely interested in 'above ground' dry matter production and it has been this aspect which has been considered in this paper. Nevertheless, the plant distributes its assimilates between the root and shoot, and the ratio of root/shoot dry matter production can be influenced both by management and the environment. There is evidence to show *(Turner* and *Begg [14])* that plants under water stress allocate a greater proportion of their assimilate to root production. This is the likely consequence of the greater sensitivity of leaf expansion than photosynthesis to water deficits *(Wardlaw [15]; Ritchie [12])*. Thus crop management factors which increase the availability of moisture to the crop will not only increase T, but will also increase the TE of biological yield through a decreased root/shoot ratio. There is also considerable evidence *(Novoa* and *Loomis [11]; Scott Russell [13])* to show that plants suffering from nutrient deficiencies, particularly nitrogen and phosphorus, will produce greater root/shoot ratios. Thus correct use of fertilizer will not only increase WUE through its effect on the E_{SC}/T ratio, but will also increase the TE of the crop through a reduction in the root/shoot ratio. This is illustrated by data in Table 6 where it can be seen that although fertilizer addition on barley has increased root dry matter production at both locations, the root/shoot ratio has decreased. It is also of interest to note that the root/shoot ratios here are much higher than those found for barley in temperate conditions where values of about 0.08 are more common *(Gregory et al. [6])*. This is likely to be due to both the higher fertility of the temperate soils and the lack of appreciable moisture stress.

4.2 Vapour pressure deficit

Several workers have pointed to the simple empirical relationship between TE and vapour pressure deficit or potential evaporation. *Fischer [5]* related TE to Class A pan evaporation (E_o) and produced the simple relationship for wheat grown in South Australia:

$$\mathrm{TE\,(kg/ha/mm)} = 102 - 13.0\,E_o + 0.53\,E_o^2 \qquad (6)$$

This relationship appears to be applicable to the Mediterranean region, and illustrates that during the cool winter months, when E_o values are about 1 mm/day, TE values of about 90 kg/ha/mm would be expected. However, as E_o levels rise, TE will fall dramatically, and during the late spring period (March/April) when E_o levels of 5 mm/day may be expected, TE values will decrease to around 50 kg/ha/mm. Growth during winter months is thus 'cheap' in terms of moisture use, and any management practice which increases growth during this period will increase the overall TE of the crop. In view of this, and the importance of achieving rapid ground cover to reduce the E_{SC}/T ratio, factors which could improve winter growth would appear to deserve high priority.

5. Factors increasing moisture availability

This far I have considered how crop management can increase the WUE efficiency of the crop. It is also worth briefly considering how crop management can increase the amount of moisture available for crop uptake. This can be achieved in three ways:

1) Increasing moisture storage in the profile;
2) Reducing evaporation from the soil surface; and
3) Increasing the crop's ability to extract moisture.

Much has been written *(e.g. Arnon [1]; Bolton [2])* on the first two aspects covering topics such as tillage techniques, run-off control, water harvesting, crop residues and weed control. I do not intend to duplicate these efforts but in this section focus more on the third aspect which has received less attention in the past.

5.1 Crop management and extractable water

Traditionally, available moisture is defined as that held in the soil profile between Field Capacity (⅓ atmos.) and Wilting Point (15 atmos.). However, Field Capacity tends to under-estimate the upper limit in heavy textured soils since plants take up moisture which is draining slowly. In addition, Wilting Point over-estimates the lower limit, particularly in the deeper soil horizons where long diffusion pathways to sparsely distributed roots results in wilting occurring at lower soil moisture pressures than predicted. It is thus becoming more common to discuss available moisture in terms of 'extractable moisture' which is a field based measurement and is defined as the difference between the maximum moisture content observed in a discrete depth interval and that observed at maturity *(Ritchie [12])*. This definition is particularly apt for rainfed environments where crops are completing their growth cycle on stored soil moisture reserves, as it allows a direct comparison between treatments at a given location in any year.
Rates of crop transpiration are controlled by the rate of atmospheric demand and the area of transpiring crop surface as long as water supply is not limiting. *Ritchie [12]* states that ...'there is no reduction in transpiration rates until the amount of extractable water in the root zone reaches some threshhold value, following which the process is reduced in proportion to the extractable water remaining in the profile.' This concept was tested in Syria for a range of crops over many locations and some results are illustrated in Figure 6 for chickpea. Here it can be seen that E_T/E_o ratios did not drop below maximum values obtained by the crop until extractable moisture levels fell below 40 percent of their maximum recorded values. It is thus clear that the onset of stressed conditions can be delayed if the crop can be manipulated to increase its ability to extract moisture.

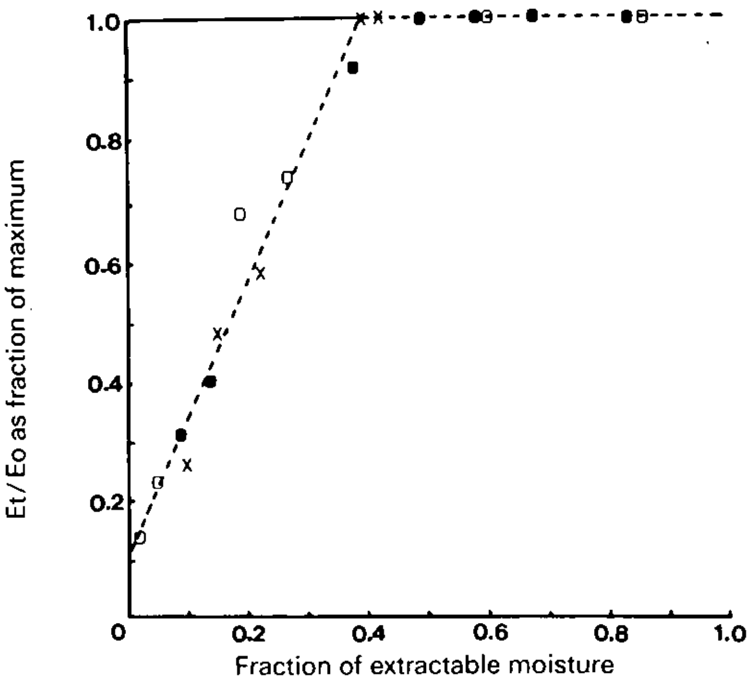

Fig. 6. The influence of extractable moisture on the relative value of the E_T/E_o ratio of winter and spring sown chickpea at Jindiress (●), Tel Hadya (○) and Breda (×) in N. Syria (1980/81) *(Keatinge* and *Cooper [8])*.

Reference to Table 6 shows that although fertilizer addition has reduced the root/shoot ratio, it has also increased total root dry matter production. This observation is supported by data in Table 7 which examines the effect of nitrogen fertilizer (in the presence of adequate P-nutrition) on the extractable moisture of a barley crop at five locations in Northern Syria. It is clear that in the 1979/80 season, nitrogen addition has increased root proliferation and thus the crops ability to extract moisture. It should be added that in years of less favourable rainfall, when extractable moisture levels are lower during the grain filling period, such large differences have not been noted.

Table 6. Effect of fertilizer on root dry matter production of barley (c.v. Beecher) at two locations in N. Syria, 1981/82

	Jindiress		Breda	
	−F	+F	−F	+F
Biological yield (kg/ha)	4320	8680	4540	6130
Root dry matter (kg/ha)	850	1330	880	1000
Total dry matter (kg/ha)	5170	10,010	5420	7130
Root/shoot	0.20	0.15	0.19	0.16

Fertilizer addition was 60 kg/ha of N and P_2O_5.

Table 7. Extractable moisture (cm/15 cm depth interval) under barley (c.v. Beecher) at 5 locations in N. Syria, 1979/80

Long term rainfall (mm)	Jindiress 479		Kafr Antoon 444		Tel Hadya 342		Breda 278		Khanasser 215	
Extractable moisture	+N	−N	+N	−N	+N	−N	+N	−N	+N	−N
15– 30 ...	2.0	1.8	3.6	3.1	2.9	2.3	2.1	1.5	2.1	2.1
30– 45 ...	1.7	1.1	2.9	2.4	2.2	1.7	3.1	1.6	1.8	1.3
45– 60 ...	1.7	1.0	2.5	2.2	1.7	1.4	1.5	1.2	1.4	0.6
60– 75 ...	1.5	0.9	2.2	1.9	1.4	1.1	0.7	0.5	0.5	–
75– 90 ...	1.1	0.7	1.6	1.3	1.1	0.9	–	–	–	–
90–105 ...	0.7	0.4	1.2	1.0	1.1	0.6	–	–	–	–
105–120 ...	–	–	0.9	0.7	0.9	0.5	–	–	–	–
120–135 ...	–	–	0.5	0.3	0.8	–	–	–	–	–
135–150 ...	–	–	0.3	–	0.5	–	–	–	–	–
Total	8.7	5.9	15.7	12.9	12.6	8.5	6.4	4.8	5.8	4.9
% increase ..		47		22		48		33		45

Nitrogen fertilizer addition was 60 kg/ha of N.

6. Conclusion

As initially indicated, only selected crop management practices have been discussed, but the results show that there is great potential for increasing the WUE of crops through simples changes in crop management. Although much can be done to increase the amount of water available to the crop, and certain measures can be taken to influence the seasonal TE, the major factor leading to increased WUE appears to be the rapid establishment of ground cover during the cool winter months and the achievement of optimum GAI's. Such goals are well within the reach of both research scientists and the farmers of the region.

Acknowledgment

Most of this research was conducted as part of a UNDP/ICARDA Global Project on increasing the fixation of soil nitrogen and the efficiency of soil water use in Mediterranean rainfed farming systems (GLO/78/003), funded by UNDP.

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Effect of Potassium on Water Use Efficiency

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Summary

The significance of potassium for optimal utilization of plant-available water with regard to yield production is described. Emphasis is given to the influence of potassium on turgor pressure, the maintenance or increase of turgor pressure being the prerequisite for cell elongation. In addition, the importance of potassium as a significant factor in the mechanism of stomatal regulation is discussed.

1. Introduction

Growth and yield of plants are decisively dependent on the extent to which water is available as substrate or medium for their metabolic processes. At the same time water serves as a medium for the transport of plant nutrients and by means of the turgor pressure it stabilizes the structure of the tissue.

Homoiohydric terrestrial plants encounter a double calamity: On the one hand sufficient turgidity of the tissue has to be safeguarded by the rate of water uptake and the loss has to be kept as low as possible. On the other hand a certain loss of water is inevitable for temperature regulation and adequate photosynthesis in the leaves. A commonly used term in water relations is the so-called 'water use efficiency', which means the ratio of units of CO_2 assimilated to water transpired.

Some examples (Table 1) prove that the water consumption per unit dry matter production can be very different for different species. C_4-plants especially use their water very economically. But the transpiration coefficients of all species are influenced by individual environmental conditions such as for example microclimate and nutritional status.

In general potassium nutrition improves water use efficiency by its involvement in stomatal regulation as well as by affecting growth and dry matter production *(Humble* and *Raschke [32], Höfner [24])*. For example, *Brag [12]* found a negative relationship between transpiration and potassium concentration in *Triticum aestivum* L. and *Pisum sativum* L.; plants with high contents of potassium showed the lowest transpiration rates. *Bradbury* and *Malcolm [10]* report that water use efficiency of Sitka spruce *(Picea sitchensis)* seedlings was greatest when K fertilizer was applied.

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Similar results were obtained by *Linser* and *Herwig [37]* (Table 2) demonstrating potassium nutrition to have a lowering effect on the transpiration coefficients of linseed, in other words K^+ improved water use efficiency. *Koch* and *Estes [34]* reported that K deficient plants of *Zea mays* L. had greater stomatal diffusive resistances than those with higher K rates. This would mean that K^+ lowers the stomatal resistance, but at the same time enables the plant to have a higher CO_2-assimilation rate.
It is the aim of this paper to show how potassium is involved in the different factors influencing plant water relations with special reference to
- tbe maintenance of cell turgidity and
- the regulation of stomatal action.

Table 1. Average transpiration coefficients (g transpired water/g produced dry matter) of various crop plants *(Stocker; Black;* quoted by *Larcher [36])*

C_4-plants		C_3-plants			
maize	370	rice	680	beans	700
sorghum	300	rye	630	potato	640
Amaranthus	300	oats	580	sunflower	600
Portulak	280	wheat	540	water melon	580
		barley	520	cotton	570

Table 2. Potassium nutrition and water consumption of linseed at 2 different soil moisture levels (after *Linser* and *Herwig [37]*)

	40% water capacity		80% water capacity	
	$-K^+$	$+K^+$	$-K^+$	$+K^+$
Yield (g dry matter)	58.5	65.6	64.6	80.4
Water consumption (l/pot) .	34.0	30.1	40.3	40.5
Transpiration coefficient ..	581	459	624	504

2. Effect of K on turgor potential and growth

2.1. General considerations concerning the measurement of turgor potential

The turgor or hydrostatic pressure (ψ_p), the osmotic or solute potential (ψ_s) and the matric potential (ψ_τ) are the three components of the total water potential (ψ) of a plant cell. The relationship between these components is as follows:

$$\psi = \psi_s + \psi_\tau + \psi_p \tag{1}$$

This equation is not only valid for the single cell level but also fundamental to considerations of the water relations of the plant as a whole. In detail ψ_s is a function of the amount of osmotically active substances accumulated in the plant cell. ψ_τ represents capillary, absorption, and hydration forces in the cell wall and the cytoplasm.

The existence of the matric potential is unequivocal *(Wiebe [61], Boyer [8])* but there is some controversy as to the magnitude of this potential. According to *Shepherd [54]* ψ_τ may reach a certain level and should not be ignored. Although it is not quite correct, the general practice is to omit ψ_τ, as this potential is considered to be close to zero in well watered plant tissue *(Wiebe* and *Al-Saadi [62])*. Only under conditions of desiccation does ψ_τ become numerically significant *Wiebe [61], Boyer [8])*.
For these reasons estimates of turgor potential are generally made from the difference between ψ and ψ_s, for methods to measure both these components are available.
More sophisticated methods were described by *Heathcote et al. [23]. Green [21]* inserted a microcapillary into a single algal cell. A similar tehnique, the so-called pressure probe technique, has been developed by *Zimmermann et al. [65]*. The broader application of this technique at first seemed to be limited by cell size, but the continuous refinement of this procedure gives hope that it might be applied even to tissue of higher plants with small cells *(Hüsken et al. [30])*.

2.2. Potassium, turgor potential and growth

Growth, the irreversible enlargement of cells, can already be reduced by low rates of desiccation, long before photosynthesis is affected *(Boyer [9], Hsiao [27])*. In a number of crop plants small decreases of leaf water potentials were able to minimize leaf enlargement significantly. *Boyer [9]* demonstrated that a decline of leaf water potential to -4 bars reduced leaf enlargement of corn significantly, while net photosynthesis was only slowly affected at leaf water potentials lower than -8 bars (Figure 1).
It is the physical force of turgor which has been considered in crucial discussions as the driving force for cell elongation, supplying the necessary push or pressure from inside to expand the cell walls in growing tissue *(Hsiao [25])*.
For the attainment of high yields it is therefore necessary to ensure that the turgor pressure of the plants is always optimal. Here potassium plays an important role as osmotic regulator of the turgor which will be discussed later. According to *Green* and *Muir [22]* and *de la Guardia* and *Benlloch [14]* K^+ was decisively involved in the growth of cucumber cotyledons and sunflower plants. *Arneke [4]* and *Mengel* and *Arneke [38]* were able to detect that bean plants *(Phaseolus vulgaris)* sufficiently supplied with K^+ had a significantly higher turgor pressure than K deficient plants (Figure 2). The higher turgor was paralleled by notahly higher growth rates. *Scherer et al. [50]* believe that K deficiency primarily reduces water retention of the tissue thus lowering the turgor potential and that this will in turn lead to a growth rate depression.
The detectable increase of the turgor pressure by K^+ has to be considered as the consequence of certain regulative mechanisms and this increase will again be followed by physical and chemical reactions. According to the water potential equation, (1) ψ_p, ψ_s and ψ are interdependent, and the osmotic potential ψ_s has to be considered as some kind of 'dynamic factor' which is influenced in the plant by active adaptation or passive changes in water content. Osmotic adjustment is an adaptive mechanism by which the plant is able to maintain the turgor despite a decrease in

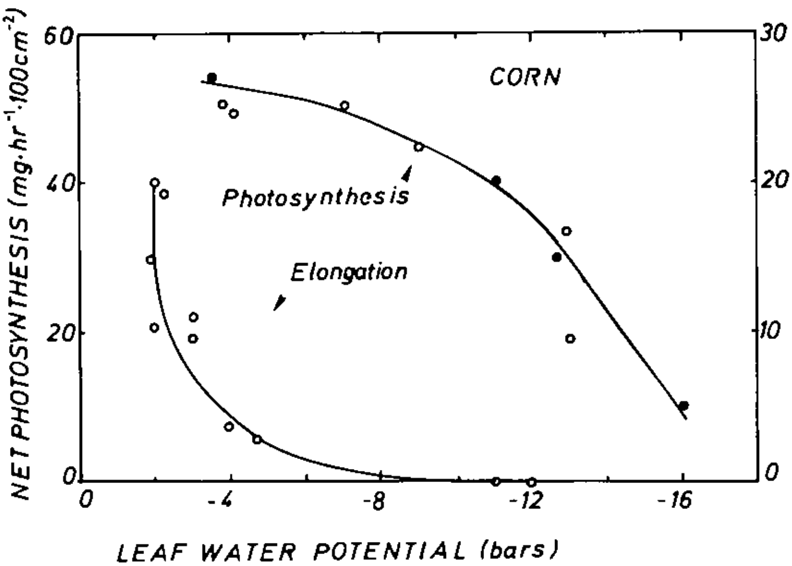

Fig. 1. Rates of leaf enlargement and net photosynthesis in corn at various water potentials. The photosynthesis data were collected from two different plants (leaf elongation in % of well watered controls, redrawn from *Boyer [9]*).

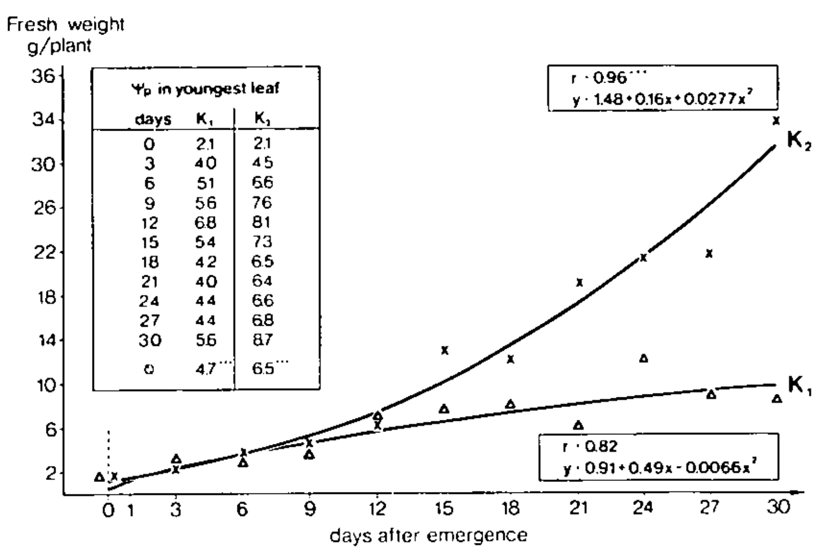

Fig. 2. Increase in fresh weight of *Phaseolus vulgaris* seedlings at 0.1 (K_1) and 4 me K/l nutr. sol. respectively. Inset: Turgor potential of youngest fully expanded leaf *(Arneke,* unpublished).

water potential and tissue water under conditions of increasing water deficits *(Hsiao et al. [29], Turner* and *Jones [58])*.
This allows the plants to maintain leaf growth and photosynthetic activity to some extent under water stress conditions *(Jones* and *Rawson [33])*. Furthermore the decline in osmotic potential induces more intensive utilization of soil water resources by the roots *(Sharp* and *Davies [53])*.
There are many references in the literature on the ability of plants to lower the osmotic potential ψ_s with gradually developing water stress *(Hsiao et al. [29], Turner* and *Jones [58])*.
The total water potential ψ is a reliable indicator of the plant water status. If the species-specific minimum water potential at which the plant ceases to grow is known, the water potential measurement may hold an indicator function. The determination of the turgor pressure appears to be even more reliable, as cell extension can only commence when a threshold turgor pressure is exceeded. According to *Green [21]* and to *Bradford* and *Hsiao [11]* the relationships can be expressed as follows:

$$\text{growth rate} = \frac{dV}{dt \cdot V} = Eg\,(\psi_p - \psi_{p,th}) \qquad (2)$$

where
V = cell volume; Eg = a coefficient termed the gross extensibility of the cell; $\psi_{p,th}$ = threshold turgor below which cell extension will not occur.
As can be seen from the equation the rate of volume increase is related to wall extensibility and the turgor pressure exceeding the threshold turgor pressure.
It is doubtful if the water status of differentiated tissue can satisfactorily characterize these threshold values for growing cells. There is reason to believe that the conditions prevailing in the growing tissue itself play a decisive role. *Michelena* and *Boyer [39]* studying water relations and leaf elongation rates in different sections of a maize leaf found a drastic drop in leaf elongation at the leaf base due to water stress (Figure 3). However, turgor potential remained unaffected at night (Figure 3A) or decreased only slightly by day (Figure 3C). On the other side the differentiated leaf tip no longer elongated as expected, but all parameters, especially turgor potential, responded to increasing water stress by a sharp decline.
It may therefore be assumed that the turgor is not alone responsible for cell elongation. Which other individual factors may also be involved requires further detailed investigation. Cell extensibility (Eg in equation 2) is undoubtedly important *(cf. Zimmermann [64])*. Additionally water conductivity (C) within the plant plays a role. Furthermore the water potential gradient $\Delta\psi$ between soil (nutrient medium) and plant root and $\Delta\psi_p$, which is the difference between turgor potential and threshold turgor have to be determined. *Bradford* and *Hsiao [11]* therefore described the growth rate by the following equation:

$$\frac{dV}{dt \cdot V} = \frac{Eg \cdot C}{Eg + C} \cdot (\Delta\psi + \Delta\psi_p) \qquad (3)$$

It can be assumed that these factors are also subject to specific individual regulatory influence. Water uptake and hydraulic conductivity for instance are regulated by phytohormones *(Fiscus [19])*. Evidence is also available from giant algal cells where

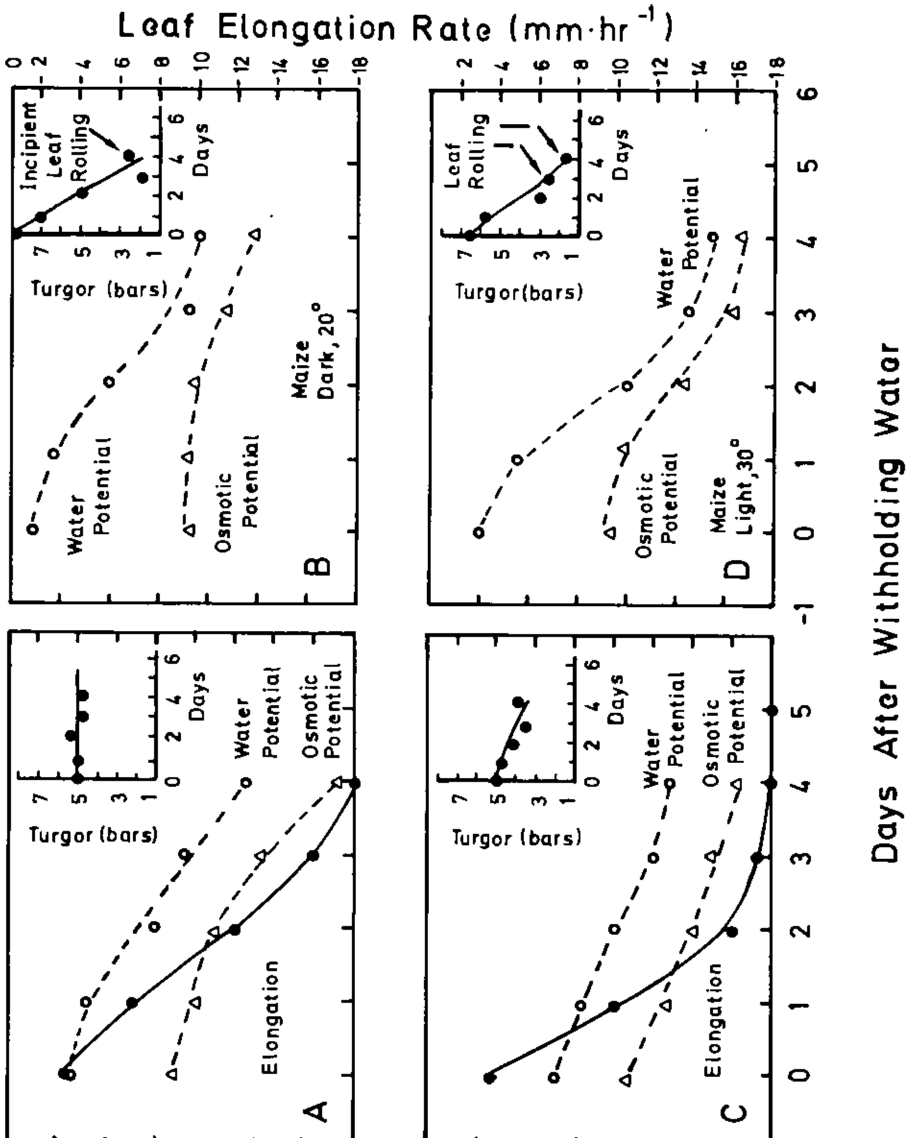

Fig. 3. Elongation rate, water potential, and osmotic potential along the 5th leaf of 20-day-old maize plants from which water had been withheld for various times. A, C: Elongating region: B, D: leaf tip. Measurements were made during the dark (A, B) and light period (C, D). Inset: turgor calculated from water potential and osmotic potential (redrawn from *Michelena* and *Boyer [39]*).

the hydraulic conductivity is directly influenced by the turgor potential *(Zimmermann [64])*.
From the data and formula given it follows that K nutrition of crops affects water use efficiency by its effects on osmotic and turgor potential, on osmotic adjustment, water uptake and water retention. Turgor potential is *inter alia* a driving force of growth and consequently dry matter production being the numerator in the equation for water use efficiency.
Turgor potential on the other hand is also the controlling mechanism for stomatal aperture and for transpirational water loss to be discussed in the following section.

3. Potassium and stomatal regulation

Optimal utilization of available water by the plant depends largely on effective stomatal regulation. Thus, the stomatal function must be understood as a mechanism for 'resolving the dilemma of opposite priorities': Preventing excessive water loss while ensuring sufficient CO_2 uptake *(Raschke* cited by *Lange* and *Lösch [35])*.
Earlier work in Japan *(cf. Hsiao [27])* had already accounted for the relationship between K^+ and stomatal movement, but this passed, almost unnoticed in the West. *Yamashita* (cited by *Hsiao [27])* observed that reduced stomatal opening was associated with K^+ deficiency, an effect that was later confirmed by *Graham* and *Ulrich [20]*. Unaware of the studies in Japan *Fischer [16]* found that stomata in epidermal strips of *Vicia faba* opened readily in light only when floated on solutions containing K^+.

3.1. Plant material and methodology

Stimulated by the publication of *Fischer [16]* various techniques were applied to detect that K^+ is accumulated by a factor of 2.5–20 in the guard cells with stomatal aperture (Table 3). Commonly epidermal strips sampled from leaves are used for this purpose.
Details on the methodology of biochemical analysis on isolated guard cells are given in the works of *Outlaw et al. [41]* and *Outlaw [40]*. Particularly promising seems to be the use of isolated guard cell protoplasts, and the fusion of guard cells and mesophyll cells may cast a new light on guard cell metabolism *(Scheurich et al. [51])*.
Additional evidence supporting the significance of K^+ in stomatal regulation comes from the studies of toxines. A fungal toxin (from *Helminthosporium maydis)* that causes rapid stomatal closure in the susceptible maize strain also causes a loss of stainable K^+ from guard cells *(Arntzen et al. [5])*. The toxin fusicoccin that induces abnormally large stomatal opening causes excessive K^+ accumulation *(Squire* and *Mansfield [56])*.

3.2. Potassium fluxes during stomatal opening

Under almost all conditions changes in stomatal opening are associated with changes in guard cell K^+ regardless of the parameters that induced the change. They may be light intensity or light quality *(Hsiao et al. [28])*, water stress *(Hsiao [26])*,

Table 3. Changes in guard-cell K^+ and related parameters associated with stomatal opening (extracted from *Hsiao [27]*)

Method of K^+ determination	Species	K^+ in guard cells*		Stoma $\Delta\pi/\Delta$ aperture	References
		Closed stomata (pmol cell^{-1})	Open stomata (pmol cell^{-1})	Observed (bar μm^{-1})	
Radioactive label	*Vicia faba*	–	–	1.4	*Fischer* and *Hsiao [18]*
Radioactive label	*Vicia faba*	0.25	1.5	2.0	*Fischer [17]*
Electron microprobe	*Vicia faba*	0.10	2.1	1.6	*Humble* and *Raschke [32]*
Extract of quasi-isolated guard cells	*Vicia faba*	0.28	1.4	1.2	*Allaway* and *Hsiao [2]*
		(mol m^{-3})			
Electron microprobe	Tobacco	200	500	–	*Sawhney* and *Zelitch [49]*
Electron microprobe	Maize	–	400	–	*Raschke* and *Fellows [46]*
Microelectrodes	*Commelina communis*	100	450	–	*Penny* and *Bowling [43]*

* Guard-cell volumes were 5000 μm^3 for open stomata *(Fischer* and *Hsiao [18]).* 2400 μm^3 and 1300 μm^3 respectively from open and closed stomata *(Humble* and *Raschke [32]),* and 5000 μm^3 at incipient plasmolysis *(Allaway* and *Hsiao [2]).*

CO_2 concentration *(Pallaghy [42])* or various metabolic inhibitors *(Fischer [17]).* Pronounced changes in guard cell K^+ have been found to be associated with stomatal movement in a large number of species *(Hsiao [27]).*

Some examples will illustrate the order of magnitude of K^+ activity (Table 4). An increase of stomatal aperture of *Vicia faba* from 2 to 12 µm increased the K^+ content in the guard cells by 4 peq. The increase of volume content of 2.2 pl stoma^{-1} when stomata opened was accompanied by a difference in the osmotic pressure of 20 atm according to a change in solute content of 5.4 posmol. In epidermal strips of *Commelina communis Penny* and *Bowling [43]* and *Penny et al. [44],* observed an increase of K^+ values from 95 (with stomata closed) to 448 meq l^{-1} K^+ with open stomata (Table 5). It is conceivable that the epidermal cells adjoining the guard cells are effective ion reservoirs during stomatal movement. This is demonstrated very convincingly in Figure 4 with the data of the authors mentioned above as presented by *Raschke [45].* With stomata closed, the gradient of K^+ activity increased from the guard cell via the inner and outer subsidiary cell to the epidermal cell. With stomata open, the gradient of K^+ activity was reversed from the outside to the inside. *Penny* and *Bowling [43]* calculated the driving forces on K^+ fluxes when stomata open or close. It can be seen in Figure 4 that the energy required is proportional to the quantity of K^+ transported from cell to cell. Here it may suffice to state that during stomatal movement there is no change in total K^+-content in the stomatal complex, but only in the distribution between guard cell and subsidiary cells.

Table 4. K and Cl content, volume, osmotic pressure and solute content of pairs of guard cells from open (after 3 h light) and closed stomata of *Vicia faba* (Data from *Raschke [45]*).

Stomata	Aperture µm	K content* peq stoma^{-1}	Cl content* peq stoma^{-1}	Volume** pl stoma^{-1}	Π atm	Solute content posmol stoma^{-1}
Open	12	4.24	0.22	4.8	37	7.2
Closed	2	0.20	0.00	2.6	17	1.8
Difference between open and closed	10	4.04	0.22	2.2	20	5.4

* From electron probe microanalysis.
** Volume of a pair of guard cells at incipient plasmolysis: 2.2 pl .

Table 5. Gradients in ion concentration across stomatal complexes of *Commelina communis.* Data from *Penny* and *Bowling [43]; Penny et al. [44];* based on *Raschke [45].*

Cell type	Ion concentration (meq l^{-1})			
	K^+		Cl^-	
	closed	open	closed	open
Guard cell	95	448	33	121
Inner lateral subsid. cell	156	293	36	62
Outer lateral subsid. cell	199	98	55	47
Epidermal cell	448	73	117	86

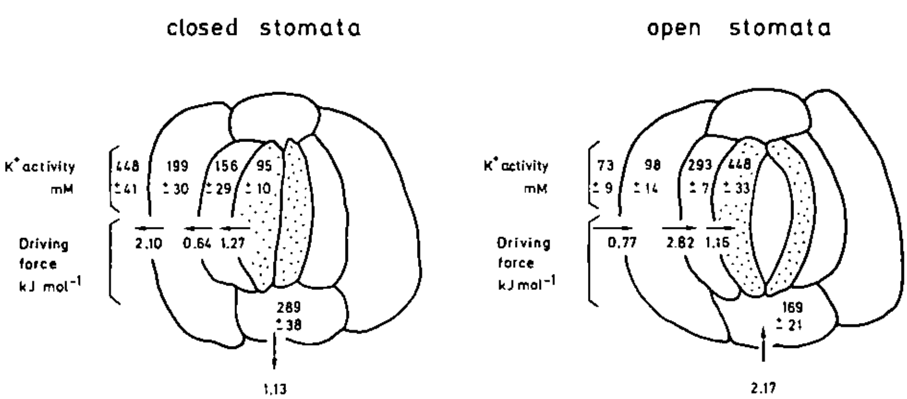

Fig. 4. K^+ activity in cells of stomatal complex of *Commelina communis* with open and closed stomata, and the calculated driving force on K^+ required to maintain the observed differences in cellular K^+ activity. (Data adapted from *Penny* and *Bowling [43]* and redrawn after *Hsiao [27]*).

It is still unknown exactly where these K^+-quantities (and total osmotics) are located in the guard cell (cytoplasm, vacuole?) *(Raschke [45])*. Furthermore the mechanism by which the guard cells can absorb as well as release these large quantities of ions in a short time are not yet completely understood, as there appear to be no plasmodesmata between the guard cells and the subsidiary or epidermal cells *(Chabot* and *Chabot [13]*, or closed *(Allaway* and *Milthorpe [4])*.
For decreasing the osmotic and increasing the turgor potential guard cells can take up K^+ without an accompanying anion; electroneutrality is maintained by excretion of H^+ into subsidiary cells *(Raschke* and *Humble [47])*. This expulsion of H^+, probably by a light-dependent proton pump *(Zeiger et al. [63])*, effects an increase of pH in the guard cell and might be the initiating step for stomatal opening. The continuous supply of H^+ is provided by the synthesis of organic acids, mainly malate. The amount of H^+ released by epidermal strips of *Vicia faba* during stomatal opening was titrated and found approximately equal to the estimated amount of K^+ required to produce the observed stomatal opening *(Raschke* and *Humble [47])*. The question as to how far the exchange of H^+ for K^+ will lead to alterations in the electrical potential and pH between the individual cells of the stomatal complex has been answered differently by various authors *(cf.* survey given by *Hsiao [27]* and *Raschke [45])* and apparently requires further elucidation.

3.3. Potassium-balancing guard cell anions

The data of Tables 4 and 5 for *Vicia faba* and *Commelina communis* indicate that Cl^- can only be accounted for as counterion to K^+ in stomatal movement to a minor extent. As S and P appear to be of no importance in guard cell regulation, the majority of the counterions to K^+ must therefore be of organic nature and most probably divalent *(Raschke [45])*. Today it has been unequivocally accepted that malate is this organic molecule. *Allaway [1]* for example was able to show that about one half of the K^+ in the opening guard cells of *Vicia faba* was balanced by malate. The epidermis of *Commelina communis* contained about 180 pmol mm^{-2} and that of *Vicia faba* 390 pmol mm^{-2} malate during stomatal opening of about 14 μm. According to *Travis* and *Mansfield [57] (C. communis)* and *van Kirk* and *Raschke [59]* these amounts of malate were able to balance all the K^+ ions in the guard cells. Depending on the species, other acids of the tricarboxylic acid cycle *(e.g.* citrate) seem to be sometimes involved in stomatal regulation *(Raschke [45])*.
But recent publications raise doubts as to whether malate plays the dominant role as K^+ balancing anion in all plant species. *Schnabl* and *Raschke [52]* investigating the stomatal mechanism of *Allium cepa,* a species containing no starch in its guard cells, found it to be likely that malate is not involved in stomatal regulation of onion plants, in spite of the fact that epidermal cells of *A. cepa* contain malate. In Table 6 two typical plants with different dominance of anions are compared, *Vicia faba* and *Allium cepa.* In the absence of Cl^- stomatal opening of *V. faba* is accompanied by a distinct increase of malate (2.1 peq/stoma) an amount nearly sufficient to compensate the amount of K^+ (2.3 peq/stoma). Adding KCl to the floating medium increases the Cl^- content of the guard cells and reduces the number of malate ions, but the participation of malate in stomatal movement remains obvious.

Table 6. Changes of contents of K^+ and Cl^- of pairs of guard cells and malate contents of isolated epidermis of *Vicia faba* and *Allium cepa* during stomatal movement. Epidermal strips were floated for 4 h on 100 mmol solutions of K iminodiacetate = KIDA (no Cl^-) or KCl. (Data from *Raschke* and *Schnabl [48]* and *Schnabl* and *Raschke [52]*).

Species	Nutrient supplement	Treatment	Aperture μm	K^+ peq stoma^{-1}	Cl^- peq stoma^{-1}	Malate peq stoma^{-1}
Vicia faba		KIDA	5.3	2.30	0.24	2.10
		KCl	7.5	1.41	0.64	0.70
*Allium cepa**	*None*	*KIDA*	*−2.6*	*−0.25*	*0.04*	*−0.99*
		KCl	*4.0*	*0.44*	*0.42*	*−0.74*
	5 mmol KCl	*KIDA*	*0.9*	*−0.11*	*−0.16*	*−0.21*
		KCl	*3.0*	*0.24*	*0.39*	*−0.84*
	5 mmol K_2SO_4	*KIDA*	*−0.9*	*−0.06*	*−0.02*	*−0.67*
		KCl	*1.2*	*0.22*	*0.07*	*−0.75*

* *Allium cepa* plants were cultivated with Hoagland solution without supplement or supplemented with KCl or K_2SO_4.

In contrast to *V. faba* epidermal strips of *A. cepa* were unable to open their stomata on solutions containing K iminodiacetate, probably because of the lack of an absorbable anion. Under all experimental conditions no accumulation of malate was detectable. Therefore *Schnabl* and *Raschke [52]* believe that because of the absence of starch the guard cells are not able to produce malate in osmotically relevant amounts. Cl^-, if available, seems to be necessary for stomatal opening. But its role becomes complicated, when K_2SO_4 has been supplied previously to the plants (Table 6). Even a later floating of epidermal strips of these plants on KCl solution did not lead to a significant accumulation of Cl^- in guard cells. The counterion of K^+ in these cases is unknown.

It may be concluded that there are plants which are not able to produce malate in their guard cells and which therefore use other anions for stomatal regulation, like Cl^-, for example. Consequently the supply of chloride to certain crops might be of decisive practical importance, and this possibility is discussed in the following: Plants of *Cocos nucifera* need certain amounts of KCl for yield production *(von Uexküll [60])* (Figure 5). If KCl is missing, fronds of *C. nucifera* show wilting and reduced growth *(von Uexküll,* personal communication). Data on the stomatal regulation of *C. nucifera* are not yet available and it is not known, whether guard cells of this plant produce malate. But if *C. nucifera* needs Cl^- as stomatal osmoticum it may be assumed that plants are not able to control the stomatal mechanism correctly in the absence of Cl^-, a presumption which calls for further detailed investigation.

3.4. Other cations than K^+

Humble and *Hsiao [31]* found that in principle all alkali metal ions induced stomatal opening in light (Figure 6). With K^+ and Rb^+ low concentrations in the floating medium are sufficient to induce opening reactions, whereas comparable opening on

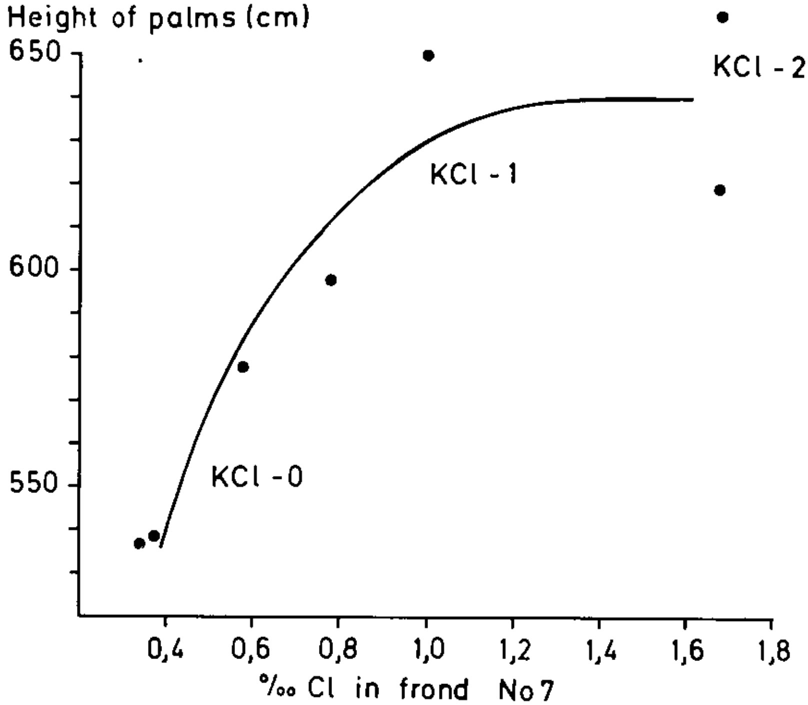

Fig. 5. Relation between the height of 3 year-old *Cocos nucifera* palms and the chlorine content in frond Nr. 7 (Redrawn from *v. Uexküll [60]*).

Na^+, Li^+ or Cs^+ required concentrations some orders of magnitude higher, thus reaching concentrations that do not occur in glycophytes in most natural situations. Some halophytes probably are an exception, however, particularly with regard to Na^+ (*cf.* literature references of *Hsiao [27]*).

3.5. Osmotic effects of potassium salts

The rapid uptake of large quantities of K^+ and Cl^- in the guard cell and the internal production of malate lead to a decrease in the osmotic potential of the guard cell. Water inflow is stimulated, consequently turgor pressure increases and stomata open.

According to *Bearce* and *Kohl [6]* osmotic potentials of -4.2 atm μm^{-1} are required to increase the aperture of guard cells in *Chrysanthemum* and *Pelargonium*. *Edwards* and *Meidner [15]* found values between -0.34 atm μm^{-1} for *Tradescantia virginiana* and -1.7 atm μm^{-1} for *Triticum vulgare*.

The data in Table 4 show that an increase of aperture by 10 μm requires an increase in the solute content of a pair of guard cells by 5.4 posmol $stoma^{-1}$. The increase in K^+ content was 4 peq which would give rise to an increase in solute content of about 7 posmol $stoma^{-1}$, if K^+ was associated with a monovalent ion. The osmotic pressure difference is given as 20 atm.

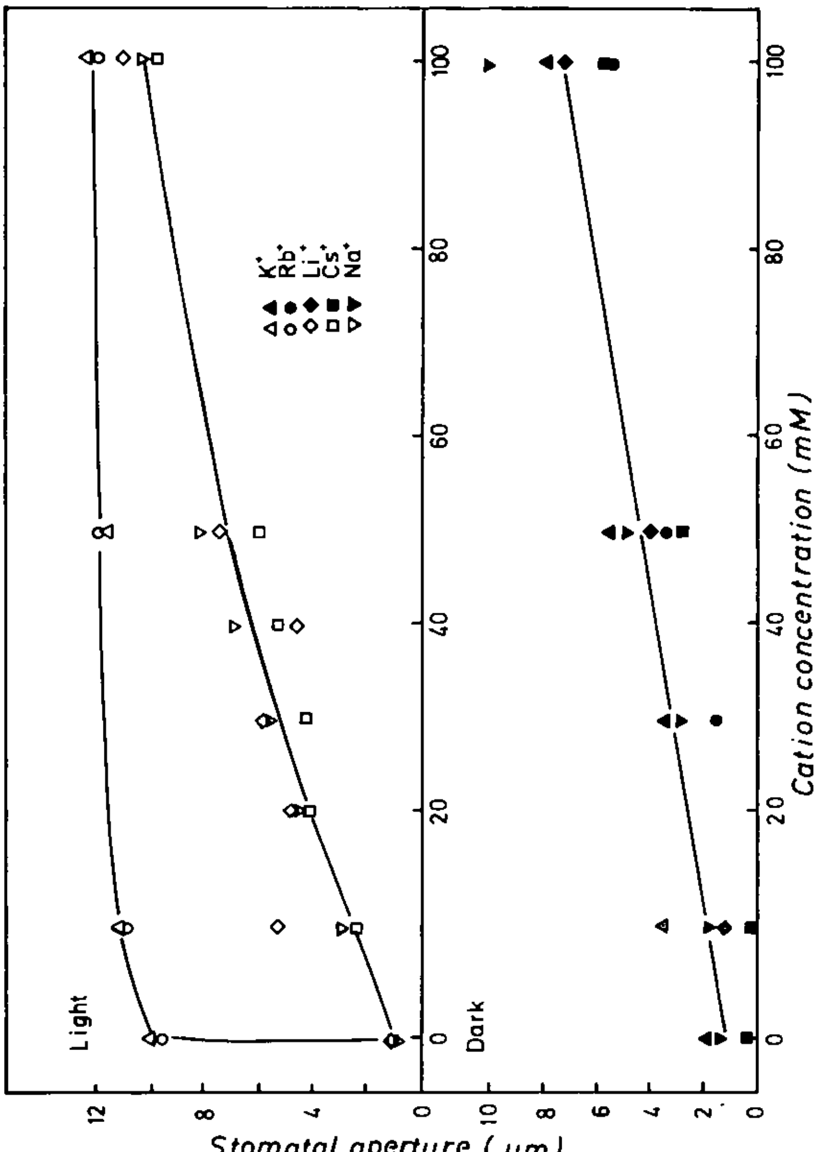

Fig. 6. Stomatal opening in *Vicia* epidermal strips as dependent on monovalent cations in the floating medium (redrawn from *Humble* and *Hsiao [31]*).

As for the K^+ content, there is no change in the total osmotic potentials and turgor pressure of a stomatal complex, but only in the distribution of these potentials between guard cells, subsidiary cells and epidermal cells. Such differences between and the maintenance of osmotic and turgor potentials within the stomatal complex require metabolic energy.

4. Conclusions

On account of its role as one of the most important osmotics in the plant, potassium decisively influences the efficiency of the utilization of available water by the plant. Adequate K supply, besides other mechanisms, mainly affects two important factors:

- The turgor pressure is kept constant, so that all metabolic processes can proceed unimpaired. In the growing tissue a sufficiently high turgor exceeding the threshold value ensures continous cell elongation which is the prerequisite for satisfactory yield production.
- Potassium is decisively involved in the mechanism of stomatal regulation. Optimal stomatal regulation, particularly in situations where soil water supply is poor, allows the plants to use their water economically, so that the ratio of water consumption and dry matter production is balanced in favour of the latter.

Both aspects are summarized once again in Figure 7 showing that only at K contents >1% in dry matter is the transpiration coefficient low or vice versa water use efficiency high (right) and secondly demonstrating that only plants adequately supplied with K are able to withstand an induced water stress by immediately closing their stomata and reducing their transpiration (left).

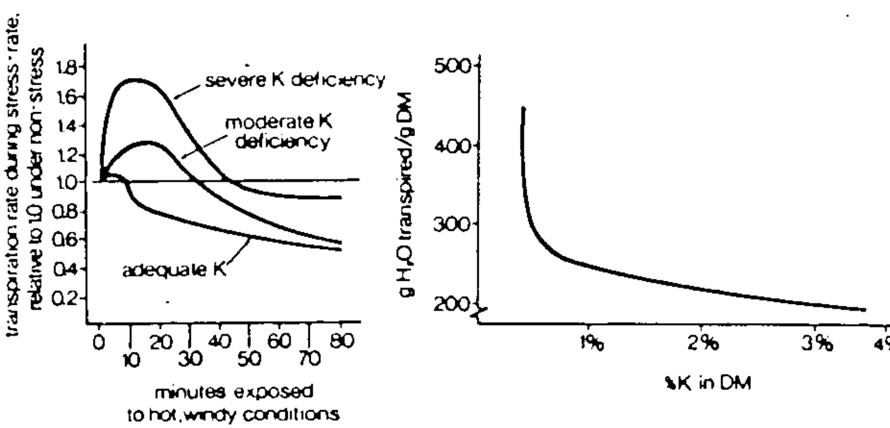

Fig. 7. Influence of K nutrition on transpirational water loss (after *Skogley [55]*) (left). Relationship between K content in alfalfa leaves and transpiration/g dry matter produced (after *Blanchet et al. [7]*) (right).

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Co-ordinator's Report on the 1st Session

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Yield Potentials in Arid and Semi-Arid Areas

These areas have two kinds of climates: a) summer rainfall and b) winter rainfall; their agricultural productivity was discussed in the main paper by *M. V. K. Sivakumar* and *A. K. S. Huda* of *ICRISAT*. The authors gave an account of the characteristics of these contrasted climates and described the use of a growth model for sorghum to assess productivity. The present production in different regions was discusssed in relation to the limitations which water supply imposes on the production of biomass. They showed how water supply interacted with the supply of nutrients from fertilizers to raise productivity and water use efficiency (WUE). The present use of fertilizers in these regions, which is rather small, was discussed and the constraints which now limit both yields and the use of fertilizers were assessed.

The present unsatisfactory position was illustrated by calculations which showed that while the crops now grown remove, on average, 70 kg/ha of nutrients annually, the fertilizers now used supply only 10–11 kg/ha. Water is the key to productivity and using fertilizer as well increases the return from the available supply by increasing WUE. For example, figures given showed that fully irrigated sorghum yielded 1100 kg/ha without fertilizer; with only 7 irrigations, but with 80 kg/ha of N, yield was doubled – to 2300 kg/ha and with the full application of 16 irrigations this amount of N more than doubled the yield again and 4900 kg/ha of grain was produced.

The measures that will lead to improvement in output in the two kinds of climate were outlined: In summer rainfall regions improved technologies will involve using more fertilizer on improved varieties grown in better cropping systems and with better water management. In winter rainfall regions the crops grown and the management systems must be carefully chosen and nutrient supplies must be increased. For both kinds of climates there must be careful assessments of both physical and socio-economic resources so that options that result in higher productivity will be developed for use by farmers. A very important conclusion from this paper was that for several crops in the different regions the yields achieved under good management on experimental stations indicate that there is a great potential for improving and stabilizing the yields obtained by practical farmers.

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Having established the potential of the regions in crop production, and the way in which true potential in any one year is determined by the actual climate of that year, the Session went on to consider how scientific work can help farmers to achieve the present potentials, and then how the potentials already recognized may be increased further.

Adapting plants to limited water availability

The first thing to recognize is that we cannot change the climate, but perhaps we can, by scientific work, change the plants so that they make better use of the environment. This was the topic of *J. J. Oertli*'s paper which described some of the ways in which plants have become adapted to limited amounts of available water. These adaptations could be based on biophysical or biochemical processes. Professor *Oertli* described the ways by which Nature has adapted plant performance and morphology so that the plants not merely survive, but they succeed in these arid and semi-arid environments. He gave a fascinating account of the ways in which plants adapt to these difficult environments by regulating turgidity so that stomata open to take in CO_2 whenever photosynthesis is possible, but that they permit only the minimum of water to escape to the air. Improved storage of water within plants was illustrated as were the special adaptations achieved by a) the development of both deeper root systems, and of more extensive shallow root systems, and b) by lessening evaporation from soil by securing a good ground cover, and c) allelopathic inhibition of competitors.

This paper illustrated well the potential for improvement by scientific work related to plant breeding where man's objective is to accomplish quickly what Nature has done slowly – by modifying plants to fit their environment better. The points made in the paper should be studied by plant breeders, and by the physiologists who work with the breeders. At present the ways in which biochemical processes in plants interact with water relations are not well understood and more work is required on this subject so that breeding for resistance to water stress may have a more scientific basis.

The role of management in making more efficient use of water

The Session then went on to consider how management practices in rain-fed agriculture may improve water use efficiency. The paper by *P. J. H. Cooper* of *ICARDA* (presented by his colleague *K. Harmsen*) discussed the effects of changes in factors such as time of planting, crop morphology, seeding rates, and crop rotation, on making the maximum use of resources. The possible gains that could result from further improvements in management were stressed. The factor that appeared most likely to make the maximum use of the available water in winter rainfall regions was the establishment of a full crop cover as early as possible in the cool winter months so that maximum use would be made of the rainfall and that evaporation from the soil surface would be lessened. In this connection fertilizer had a vital role: if correctly applied, fertilizer gives good early growth and so makes the maximum use of the water available in the soil at seeding, and of the rain that falls afterwards.

The effect of potassium on water use efficiency

This general account of the value of fertilizer in improving water use efficiency naturally led to a consideration of the large effect that potassium has on the use of water by crops and the topic was discussed by *M. G. Lindhauer* who described two effects that result from an adequate supply of K. The first effect is that turgor pressure is maintained by a good potassium status so that all metabolic processes proceed unimpeded: In particular a sufficient turgor pressure is essential to ensure continuous cell elongation – which is a vital process in producing the yield that we need. The second effect is the regulation by potassium of the activity of the stomata. If stomata regulation is optimal, then plants will use their water most economically to optimize the ratio of

$$\frac{\text{water used}}{\text{dry matter produced}}.$$

The evidence provided showed that a sufficient level of K in the plant was needed to maximize the use of the available water by closing the stomata at appropriate times, and so reducing transpiration to withstand water stress while producing the maximum yield possible from a given amount of water.

General conclusions

The papers presented to the Session showed that considerable progress has been made in our understanding of the production that is possible in these climates where annual rainfall is normally too little for maximum crop growth. Clearly further gains in our knowledge, and therefore in our ability to improve crop growth, will come from continued research along the present lines that were described; in particular practical advances in crop performance will result from breeding which fits plants better to their environment by developing characteristics which enable them to resist water stress, and to produce yield with minimum transpiration.

In these objectives fertilizers have a very important part to play by quickening and improving growth. But I did feel that there is still a serious lack in our research on water/nutrient interactions. Although the speakers produced qualitative evidence to show the importance of such interactions, there was no account of research which established the nature and magnitude of the full interactions between water and N, water and P, water and K, and the much more difficult multi-factorial research needed to show how N, P and K together interact with available water to produce yield.

I believe that increased emphasis should be given to such research by all who are concerned with growing crops in regions where water supplies are less than optimal. I see the ultimate objective as a model which is comprehensive enough to take account of radiation and rainfall in all regions of the world and whicb can be used to establish potential yields for all these regions. This may seem an academic exercise – but I cannot consider that it is. We need this full information on nutrient/water interactions for two main purposes:

In the first place we need the information to enable us to plan the control of soil fertility to produce maximum economic yield. This will only be achieved when we have a full knowledge of the materials and processes involved in crop production. In the world of engineering such knowledge of materials and systems allows man to fly to the moon; similar complete knowledge will ultimately be essential to agricultural scientists who accept that their mission cannot be considered to be completely accomplished until they can produce at will on a site, by using appropriate inputs (which will include water and nutrients), the maximum yield that genetic potential and solar radiation make possible.
In the second place this information on water/nutrient interactions is needed by plant breeders. These scientists need quantitative information on these interactions to aid their vital work which is planned to produce plants that are better adapted to resist the stresses to growth that are caused by shortages of water in these climates, and by the special properties of soils in the arid regions.

Improving the efficiency of fertilizers by special methods of application

Neither in this First Session, nor at other times during the Colloquium, did we consider the use of special methods of applying fertilizers which are designed to maximise their efficiency. This section of this Report outlines the advantages of special placement methods and the facts that must be considered in choosing the methods of application that will give the highest efficiency.
The scientific objective of improved methods of fertilizer application must be to ensure that the uptake of applied nutrients by a crop, or a series of crops, should be complete (that means that 100% of the nutrients applied as fertilizers should ultimately serve a useful purpose in crop production). Achieving this objective will bring maximum benefit to the farmers, and to their nation, from their expenditure on fertilizers. It also implies no losses of nutrients to the environment and it must be stressed that the purposes of the soil scientist concerned with fertilizer efficiency, and of the environmental scientist concerned with eliminating pollution of air and water, are identical and the two should work together. Research that is planned to improve fertilizer efficiency must take account of processes occurring at the soil/root interface. For this purpose nutrients may be divided into two groups – those that are fully mobile in soil water (*e.g.* inorganic nitrogen fertilizers), and those that have very limited mobility (*e.g.* P and K fertilizers).

Mobile nutrients are used efficiently when they are placed in the zone of the soil from which roots will extract water. But, because they are mobile they will be liable to loss by leaching; if leaching is likely to occur careful attention to the correct timing and form of the dressing will be important. This statement applies particularly to inorganic nitrogen fertilizers. A further cause of loss is the volatilization of ammonia released from ammonium salts or urea applied to the soil surface. This pathway of loss is particularly likely to occur in calcareous soils – which are common in many arid and semi-arid regions. These losses by volatilization can be avoided by placing the dressing well below the soil surface, preferably at least 10 cm deep. On soils which are very rich in calcium carbonate it may be necessary to use nitrates rather than ammonium salts or urea to secure high efficiency.

Rice grown in flooded soils presents special problems in securing high efficiency of the nitrogen fertilizers that are so essential for good yields. The pathway of loss of nitrogen resulting from the denitrification of nitrates has been recognized for many years and to avoid such losses ammonium salts or urea are widely used. But only in the last 10–12 years have we realized that there may be large losses from these forms of fertilizers resulting from the volatilization of ammonia from the surface of the flood water and that this mechanism may be largely responsible for the commonly reported low efficiencies of N-fertilizers used for flooded rice. Experimental work has shown that these losses may be prevented by the placement of granules of urea or ammonium salts in the anaerobic zone of the flooded soil where the roots are growing. There are also gains from slowing the action of these fertilizers by coatings which lessen the rate at which they dissolve. (Sulphur-coated urea is a good example). Progress is also being made by slowing the hydrolysis of urea by the use of urease inhibitors. By these methods virtually complete recovery of urea-N applied to flooded rice has been achieved in experiments and good progress is being made with developing practical equipment for farmers to use to secure correct deep placement.

Relatively immobile nutrients (here we are mainly concerned with P and K) must be placed in zones of the soil where roots are, or will be, active. This will facilitate the quick uptake that gives the stimulus to early growth that is so important in making full use of available water in the winter-rainfall regions. There are several important advantages from the placement of high local concentrations of immobile nutrients in restricted zones of the soil:

1) These high concentrations of nutrients stimulate the growth of roots and facilitate maximum uptake.

2) Interference with uptake by other ions present in the soil is minimized. This is particularly important in calcareous soils where high concentrations of calcium ions (and of magnesium) may depress the uptake of potassium; the remedy is to place potassium fertilizer close to seed or roots – a method which has been shown to be twice as efficient as broadcasting the K on calcareous soils.

3) When broadcast fertilizer is mixed with a large volume of soil, fixation to form relatively insoluble materials occurs rapidly. These 'fixed' nutrients usually retain a slight solubility and become available to later crops but they cannot give the stimulus to promote rapid early growth that high concentrations of nutrients provide, and the rate of recovery is not under the control of the farmer. Placement of fertilizer in bands minimizes contact between soil and fertilizer and so lessens fixation and maintains a high local concentration of nutrients.

Deep placement of fertilizer may have advantages when shortage of water in surface soil inhibits nutrient uptake. Experiments have already shown that gains in yield can result from placing fertilizer supplying P and K in the subsoil and machines have now been devised to apply fertilizer in this way.

Foliar application of nutrients is a form of placement which may have advantages when soils are dry. Experiments in Iraq have shown that N-fertilizer applied as a spray to the leaves of wheat can be more efficient than the same amounts of fertilizer applied to the soil. This method of application is widely accepted for applying micro-nutrients, but it also has a general place in nutritional research: When we wish to check whether the soil is supplying sufficient of a particular nutrient to the roots of a crop, a foliar application should be tested; if the yield is increased by the spray the implication is that uptake by the roots is not providing sufficient nutrients to realize the full potential of the crop. There is a strong case for much more field experimentation to examine the value of foliar applications of both macro- and micro-nutrients in the arid and semi-arid regions.

Future research on methods of applying fertilizer

Although the principles that determine the advantages of methods of placing fertilizer to roots (or to leaves), outlined in the preceding paragraphs are clear, more research is required to extend our knowledge and assist in our objective of making fertilizer more efficient. The main alternative methods of applying fertilizer to be taken up by roots are, 1) broadcasting on the soil surface, 2) broadcasting followed by mixing with surface soil, 3) band placement beside the rows of seed or of established crops, 4) point placement in the root zone, and 5) combinations of broadcasting and placement. Comparisons of these methods in field experiments are needed to determine which should be used to secure high efficiency of applied fertilizers. The designs of the experiments needed will depend on whether mobile or immobile nutrients (or both) are being tested, and on the climatic patterns of individual regions.

We also need more information on the physiological mechanisms of nutrient uptake by roots, and also by leaves – about which we know little. To aid our work in the climatic regions we are now considering we also need much more information on the nutrient/water interactions in the root zone. It is possible that the band or point placement, which gives advantages through improved early growth of both root and shoot, may have disadvantages later in the season if the extra root growth takes up so much water that the fertilizer is then in soil that is too dry for a satisfactory rate of uptake. Such questions can only be resolved by careful field experiments where there is adequate scientific monitoring of weather, of soil conditions, and of crop performance. When the gains from special methods of fertilizer application have been established in general terms by field experiments, the extra research needed to provide background information on soil/root relationships will be fully justified because it will lead to refinements in the advice given to farmers which should result in even greater improvements in fertilizer efficiency.

Chairman of the 2nd Session

Prof. Dr. *H. Beringer,* Director, Büntehof Agricultural Research Station, Hannover/Fed. Republic of Germany

2nd Session

Nutrient Dynamics in Arid and Semi-Arid Areas

Nutrient Mobility, Root Growth and Root-Induced Changes in the Rhizosphere as Factors of Nutrient Availability in Soils of Semi-Arid and Arid Areas

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Summary

The dynamics and availability of nutrients in soils are determined not only by chemical equillibria and binding of nutrients in the bulk soil but also by nutrient mobility, root growth (extension and surface area) and root-induced changes in the rhizosphere. This holds true in particular for conditions where soil water availability and/or soil fertility are low. Examples are given of the importance of mass flow and diffusion of solutes in relation to soil water content and root growth rate. Depending on soil and plant factors, the ion concentration at the soil/root interface usually differs substantially from the bulk soil. Furthermore, at this interface (rhizosphere) root-induced changes in pH and redox-potential and the release of organic compounds (root exudates) can considerably affect solubility and availability of mineral nutrients. Examples are presented for these changes, and for the direct and indirect role of root exudates for microbial activity and hence nutrient availability in the rhizosphere.

1. Introduction

The dynamics of nutrients in soils can be described by chemical equillibria in which capacity, intensity and rate are the decisive factors. From the viewpoint of soil fertility and plant nutrition, however, it is of primary interest which fraction of the soil nutrients is available for the plants. This availability is usually defined as the fractions of soil nutrients which are extractable for example with salts, acids, chelators or water. However, this approach does not consider two important factors:

1. *Nutrient mobility and root growth.* Under field conditions only those 'chemically' available nutrients which reach the root surfaces either by mass flow or diffusion are in fact available for plants. Thus, soil water content, root growth and the interaction between them are of overwhelming importance for nutrient uptake and plant

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growth. This holds true in particular for semi-arid and arid regions where the soil water content becomes a limiting factor for a considerable part of the growing season.

2. *Plant induced changes in the rhizosphere.* At the soil/root interface ('rhizosphere') the availability of nutrients can be considerably influenced by the plant root itself. Both mobilization and immobilization of nutrients can occur, either by root-induced changes in pH, by release of reducing and chelating substances or by the much higher microbial activity in the rhizosphere compared to the bulk soil.

This review provides examples of the influence of these 2 factors on nutrient availability in soils, particularly under conditions of low soil water contents.

2. Solute movements in soils, mass flow versus diffusion

The importance of nutrient mobility in soils for nutrient availability has been stressed by *Barber [1962]* in a mass flow/diffusion concept. At high water availability soil solution moves as mass flow to the roots driven by water consumption (transpiration) of plants. If water is absorbed by the plant roots relatively faster than ions (high transpiration rates in combination with high salt concentrations in the soil solution) an accumulation of ions at the root surface can be predicted *(Barber et al. [1963]; Elgawhary et al. [1972]; Renger* and *Strebel [1976])*. Experimental evidence for such accumulation near root surfaces has been presented for sulphate by *Barber et al. [1963]* and *Wray [1971]*. At high concentrations of both calcium and sulphate in the soil solution, gypsum is precipitated near tbe root surfaces *(Malzer* and *Barber [1975])*. This mass flow driven salt accumulation at the root/soil interface is of particular importance in saline soils (see section 4).

The other main driving force for nutrient movement towards plant root surfaces is diffusion, driven by ion uptake and a corresponding decline in the ion concentration at the root surfaces ('depletion zone'). The importance of diffusion and its role in the nutrient supply to plant roots depends upon both soil and plant factors. Among soil factors the water content is of distinct importance for the effective diffusion (D_e) according to the formula

$$D_e = D_l \ \Theta \ F_l \ dC_l/C_x$$

D_l = diffusion coefficient of the ion in free solution

Θ = fraction of soil volume occupied by solution = cross section for diffusion

F_l = impedance factor, caused by the tortuous pathway of ions through pores (increase in path length and thus decrease in concentration gradient, increase in water viscosity; anion adsorption/repulsion)

$d\ C_l/C_x$ = concentration gradient solution/root surface

There is general agreement *(Barber et al. [1963]; Mengel et al. [1969]; Renger* and *Strebel [1976])* that for nutrients like phosphorus and potassium whose concentrations in the soil solution are low compared to the demand of plants, transport by mass flow to the root surfaces is of minor importance. In contrast, in many soils mass flow is considered to be more than sufficient for calcium and magnesium transport to the roots. An example of the relative contribution of mass flow for delivering nutrients to plant roots under field conditions is shown in Table 1. These data were calculated from field experiments under conditions of moderate rainfall during the growing season. From Table 1 it is evident how difficult it is to generalize about the relative contribution of mass flow and diffusion even for mineral nutrients like potassium.

The relative contribution of mass flow also changes during the growing season and differs from year to year according to the amount and distribution of rainfall during the growing season. An example of the changes during the growing season is shown in figure 1 for nitrate. In this field experiment water availability in the top soil was sufficiently high for mass flow of nitrate only during the early stages of growth. The relative contribution of mass flow and diffusion for ion transport to plant root surfaces also depends upon the plant species as both rates of transpiration and ion uptake vary considerably between species. These differences are not only evident from field data (Table 1), but can also be demonstrated under controlled environmental conditions; in the case of potassium for example transport to the root surfaces in maize is primarily by diffusion but in onion, mass flow is of major importance *(Baligar* and *Barber [1978])*. Since mass flow and diffusion occur simultaneously in solute transport to root surfaces, the term 'apparent mass flow' = transport of ions to the root/soil interface, has been recommended by *Nye* and *Tinker [1977]*.

Table 1. Relative contribution of nutrient transport by mass flow to the roots as compared to the nutrient uptake during the growing season. Field experiments *(Renger et al. [1981])*

Plant species	Soils	Relative contribution of mass flow (total uptake = 100)				
		K	NO_3^--N	Mg	Na	Ca
Sugar beet	Parabrown earth (loess)	7	100	60	–	640
Spring barley	Podsol (sand)	130	110	180	610	770
Spring wheat	Parabrown earth (loess)	4	40	150	2500	1700

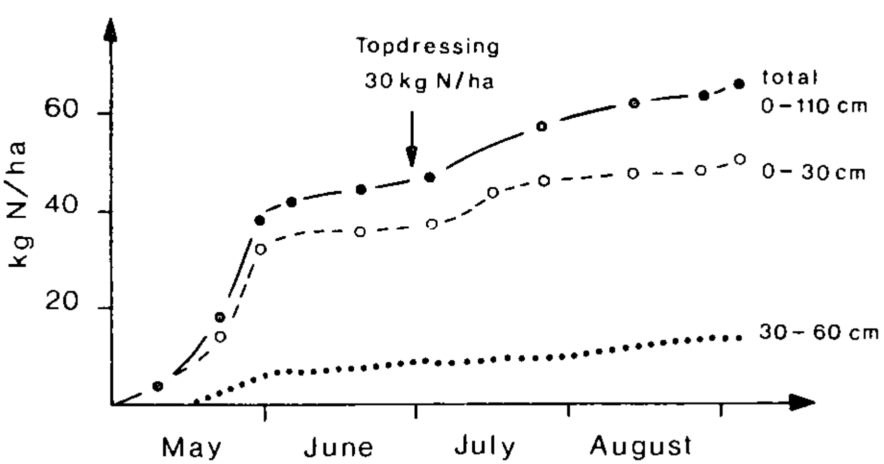

Fig. 1. Cumulative supply of nitrate-N by apparent mass flow to roots of spring wheat *(Strebel et al. [1980])*.

3. Effect of soil moisture

With decrease in soil water potential solute movement is affected in various ways:
a) Decrease in mass flow to roots
b) Decrease in diffusion coefficient (volume, impedance factor)
c) Increase in concentration of certain ions (*e.g.* chloride, nitrate, calcium, magnesium).

An example of the relationship between soil water content and ion diffusion rate is shown in Table 2 for potassium. The decrease in diffusion rate at low water availability is evident, particularly at low levels of exchangeable potassium. Similar relationships between soil water content and ion diffusion have been obtained also for calcium and magnesium by *Schaff* and *Skogley [1982]*.

Although the effects of soil moisture levels on solubility of plant nutrients and on mobility can be calculated with reasonable accuracy from soil data only, detailed interpretations and conclusions for the transport to the root surfaces and ion uptake by plants are extremely difficult. With decrease in soil water potential for example the unsaturated hydraulic conductivity of the soil adjacent to the root (soil/root interface) may be several orders of magnitude lower than in the bulk soil *(Zur et al. [1982])*. This increase in root/soil contact resistance to water flow affects not only water uptake by plants and contact between roots and soil but also the diffusion rate of ions to the root surfaces. Furthermore, root growth rate which is a main prerequisite for ion movement by diffusion to root surfaces is affected. It is not surprising therefore, that at low water availability in soils, for example, boron deficiency in plants is common *(Kluge [1971])* or that plant phosphorus contents decrease *(Sharpley* and *Reed [1982])*; this decrease can be compensated to some extent by increase in phosphate fertilizer application. These various aspects of soil moisture levels on nutrient availability are treated in more detail in the following sections.

Table 2. Relationship between soil water content (%), exchangeable potassium and diffusion rate of potassium *(Mengel et al. [1969])*

Exchangeable K^+ me/100 g soil	K diffusion (mg $K^+/cm^2/48$ h) at soil water contents of 4%	10%	20%	40%
0.41	2	4	8	10
4.10	40	55	78	95

4. Ion concentration at the soil/root interface

Calculations of ion transport to root surfaces by mass flow and diffusion have to be tested by measurements of the actual concentrations at the root/soil interface. For phosphorus, clear evidence for a depletion zone around the roots has been presented, mainly by autoradiographic methods *(Bhat* and *Nye [1973; 1974])*. With quantitative autoradiography, *Claassen et al. [1981]* and *Hendricks et al [1981]*

could demonstrate that plant roots decrease the concentration of the soil solution within the rhizosphere down to 1 µM phosphorus *(Hendricks et al. [1981])* and 2–3 µM potassium *(Jungk et al. [1982])*. This depletion of potassium within the rhizosphere can enhance potassium supply from the non-exchangeable fraction *(Jungk et al. [1982])* and accelerate weathering of clay minerals *(Sarkar et al. [1979])*.
Depletion or accumulation of a certain mineral nutrient in the rhizosphere depends not only on concentration in the soil solution and mass flow but also upon plant species. Plant species can differ in both transpiration rate (*i.e.* intensity of mass flow to the root surfaces) and in ion uptake rate. This is shown in Table 3 for calcium. In ryegrass with low uptake rate for calcium, this element is seen to accumulate in the rhizosphere. In contrast, in blue lupins with their distinctly higher uptake rate of calcium there is depletion around the roots.
Accumulation of ions in the rhizosphere is of particular importance in saline soils in connection with irrigation. There is a close positive correlation between water uptake (transpiration) per unit root length and accumulation of chloride and sodium at the root surface (Table 4).
As a result of this salt accumulation in the rhizosphere, water availability decreases correspondingly (Table 5). The osmotic potential in the rhizosphere soil solution increases within 4 days after irrigation at all salt levels. The relative increase is lower

Table 3. Estimated supply of calcium to the roots of 4 plant species compared with the calcium uptake (according to *Barber* and *Ozanne [1970]*)

Species	Water consumption ml/2 plants	mg Ca/2 plants supply	uptake	Difference
Arctotheca calendula (Capeweed)	6	0.6	0.4	+0.2
Lolium rigidum (Wimmera ryegrass)	28	2.8	0.6	+2.2
Lupinus digitatus (Blue lupin)	80	8.0	9.0	−1.0
Trifolium subterraneum (Subterr. clover)	56	5.6	4.1	+1.5

Table 4. Relationship between water uptake (varied transpiration) per unit length of root, and sodium and chloride accumulation around corn roots *(Sinha* and *Singh [1974])*

Water uptake (transpiration)	Chloride bulk*	loose**	close***	Sodium bulk	loose	close
ml/cm × 10	mg/100 g soil					
0.38	31	41	58	22	34	41
0.46	36	43	65	28	33	45
0.82	43	66	97	36	49	68
0.95	44	64	128	38	57	90

* bulk soil
** loosely adhering soil
*** closely adhering soil

Table 5. Osmotic potentials of the rhizosphere soil solution of onions in relation to the chloride concentration of the irrigation water *(Schleiff [1980/81])*

Osmotic potential (−MPa) of rhizosphere solution	Cl^- concentration (me/l) in irrigation water 13	23	39	52
4 h after irrigation	0.50	0.65	0.65	0.90
4 days after irrigation	2.35	2.40	2.80	2.80

at the high salt levels, presumably as a result of more severe inhibition of water uptake. Thus, average values for soil salinity, *e.g.*, EC values in water saturated soil samples, do not sufficiently reflect the actual salt concentrations and thus water availability at the soil/root interface *(Schleiff [1977]; [1980/81])*.

5. Role of root growth and root surface area

In contrast to mass flow, diffusion as a factor for ion mobility is important only in the immediate vicinity of the root surface. Root growth rate and root surface area are therefore of decisive importance for the availability of these nutrients in the soil which reach the root surface mainly by diffusion, *i.e.*, for phosphorus and potassium in particular. Length of root hairs is a dominating factor in the extension of the depletion zone of potassium and phosphorus around roots *(Bhat* and *Nye [1974])*. An example for this importance of root hairs is shown in Figure 2.

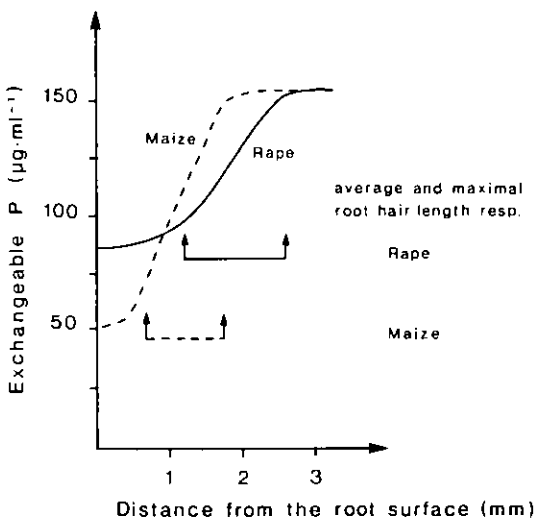

Fig. 2. Concentration gradient of phosphate around roots in relation to root hair length (According to *Hendricks et al. [1981]*).

Thus it is possible to demonstrate, a close positive correlation between uptake rate of potassium per unit root length and volume of the root hair cylinder in a comparison between various plant species (figure 3).

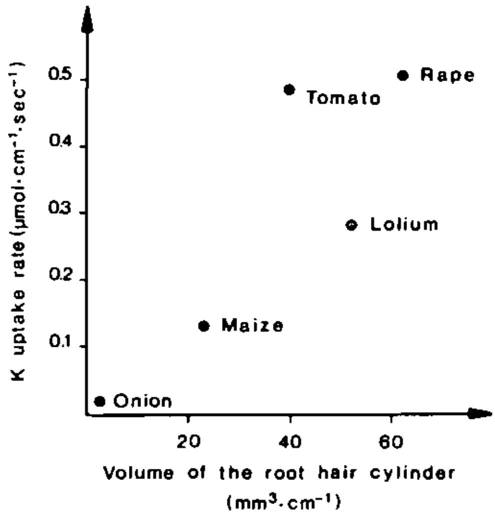

Fig. 3. Uptake rate of potassium per unit root length in relation to the volume of the root hair cylinder. The different plant species were grown in a silt loam soil with 21% clay *(Jungk et al. [1982])*.

Intensity of root hair formation is also quite variable within a plant species. Increasing nitrate concentrations for example decreases both the number *(Munns [1968])* and the length *(Bhat et al. [1979]; Jungk,* personal communication) of root hairs. In white clover, selection of genotypes with long and short root hairs respectively considerably changed the efficiency in phosphorus uptake from soils in favour of the genotypes with long root hairs *(Caradus [1982])*.

The depletion zone around roots is also affected by the buffering capacity of a soil for nutrients and by the concentration gradient between the bulk soil solution and the soil solution at the root surface. For potassium for example, with increasing clay content, the extension of the depletion zone decreases and the equilibrium concentration at the root surface increases *(Jungk et al. [1982])*. In the same soil, increase in potassium concentration in the soil solution by fertilizer application, for example, increases both the diffusion coefficient and the extension of the depletion zone around the roots (figure 4).

Growth rate and surface area of roots are much affected by soil physical conditions, soil strength and water content in particular. With decrease in soil water content the resistance to penetration increases steeply, especially in clay soils *(Wiersum [1969])*. Roots extend more rapidly in wet than in dry soils (or soil areas), both as a direct effect of the water potential and as an indirect effect of mechanical soil strength.

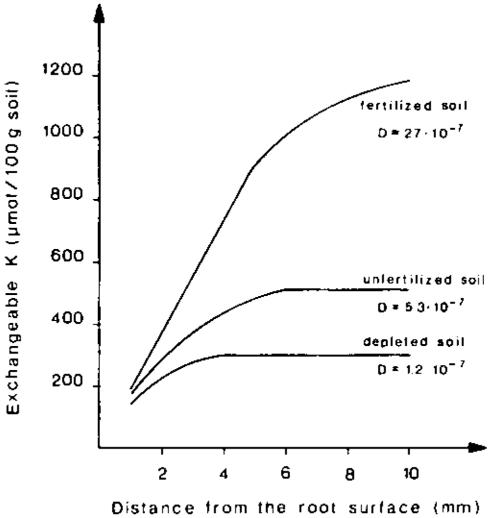

Fig. 4. Depletion zone of potassium around maize roots grown in a silt loam soil with various potassium levels. D = diffusion coefficient cm^{-2} sec^{-1} (According to *Jungk et al. [1982]*).

Although there are differences between plant species, in general this depressive effect of soil strength on root elongation is quite dramatic (figure 5).
As roots are unable to decrease their diameter *(Wiersum [1957]; Russell [1977])*, root growth is restricted to certain pore sizes. Plant species with a large proportion of fine roots and particularly long root hairs are therefore less affected by increase in mechanical strength of soil. Furthermore long root hairs ensure better contact between soil and plant and improve water movement from fine soil pores to the plant.
Root surface area can be largely increased also by root infection with mycorrhiza. In crop plants vesicular-arbuscular (VA) mycorrhiza (endomycorrhiza) is the dominating type of this symbiosis. VA mycorrhiza increases particularly the availability of soil phosphorus to plants. Transport of phosphorus within the mycorrhizal hyphae from the soil into the roots can occur over several cm *(Rhodes* and *Gerdeman [1975])*. There are also indications that the affinity of the fungi cells for phosphorus is higher (lower K_m) as compared to root cells *(Cress et al. [1979])*. Mycorrhizal infection is stimulated by phosphorus deficiency and suppressed by high phosphorus availability in soils *(Menge et al. [1978])*. In soils low in available phosphorus VA mycorrhiza can considerably increase plant growth and particularly plant phosphorus concentrations (figure 6). Similar data have been obtained by *Yost* and *Fox [1982]* in field experiments with soybean and cowpea.
Poor correlations between available soil phosphorus determined by chemical extraction methods and both plant growth and phosphorus concentrations in plants can therefore be at least partly the result of various degrees of VA infections. Fur-

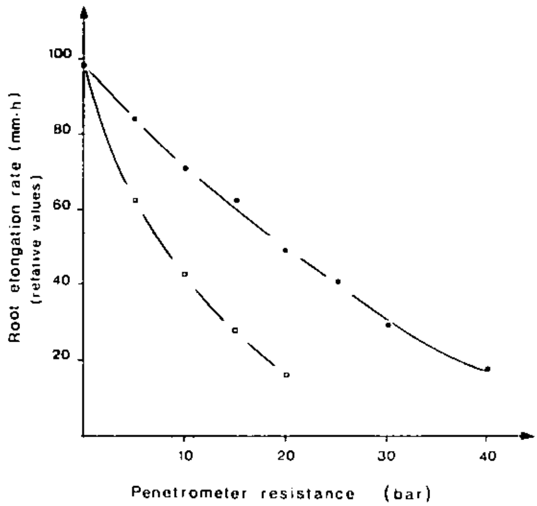

Fig. 5. Root elongation rates as function of soil strength (Data recalculated from *Taylor* and *Radcliffe [1969]*). •——• peanuts; ▫——▫ cotton.

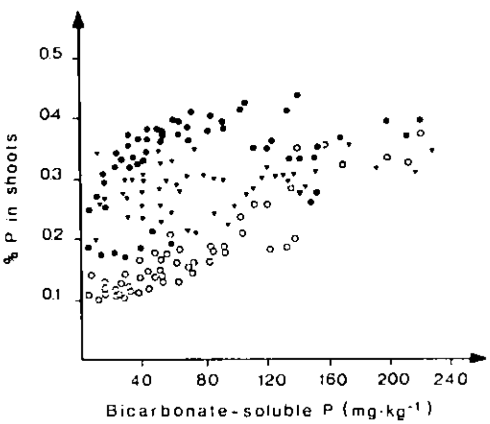

Fig. 6. Relationship of % phosphorus in shoots of onion and soil bicarbonate – soluble phosphorus.
• irradiated soils, plants infected with Glomus mosseae
∘ irradiated soils, plants not infected
▾ unirradiated soils, plants naturally infected
(According to *Stribley et al.* [1981])

thermore, lack in plant responses to fertilizer phosphorus can be caused by a shift in the ratio of phosphorus uptake mycorrhiza/host roots *(Menge et al. [1978])*. At least in soybean such a shift can be combined with unexpected side-effects such as steep decline in zinc content of the plants *(Lambert et. al. [1979])*. Obviously, in this case VA mycorrhiza also improved the zinc nutrition of the host plants.

The importance of VA mycorrhiza for phosphorus nutrition of higher plants depends on plant species and soil phosphorus status. There are distinct differences between plant species in establishing such a symbiosis *(Menge et al. [1978]; Graw et al. [1979])* and in the families of Chenopodiaceae and Cruziferae, VA mycorrhiza are completely absent. Other plant species obviously do not rely on VA mycorrhiza even when only sparingly soluble phosphates are supplied. An example for these genotypical differences is given in Table 6.

Among other factors (Section 8), one reason for these genotypical differences is the interaction between VA-mycorrhiza and root hairs, as both increase the surface area of the roots. Plant species without root hairs (*e.g.* leek, onion) therefore rely much more on VA mycorrhiza for utilization of phosphorus from sparingly soluble phosphates than others with long and abundant root hairs (Table 7).

Table 6. Effect of VA mycorrhiza and phosphate application on growth (shoot dry weight, g) of *Capsicum annuum* and *Helianthus annuus (Graw et al. [1979])*

Species	VA	P application as MCP*	HA**	Al-P
Capsicum annuum	–	0.54	0.03	0.11
	+	0.85	0.54	0.87
Helianthus annuus	–	6.83	5.76	6.45
	+	6.47	5.22	6.01

* Monocalciumphosphate ** Hydroxyapatite

Table 7. Interaction between VA mycorrhiza, rhizobial infection and phosphorus nutritional status in two plant species grown on a phosphorus deficient soil (according to *Crush [1974])*

Species	Treatment	Fresh weight g	Nodules*	Shoot % P	VA infection %
Stylosanthes guyanensis	– VA	0.47	0	0.20	0
	+ VA	1.63	5	0.44	74
	– VA + P	0.91	5	0.58	0
Lotus pedunculatus	– VA	2.54	4	0.29	0
	+ VA	2.01	4	0.27	54
	– VA + P	3.86	5	0.53	0

* 0 = none; 5 = numerous

	Root diameter mm	% of roots with hairs	Length of root hairs µm
Stylosanthes	285	6	108
Lotus	229	99	809

This table also demonstrates an interesting interaction between VA mycorrhiza and rhizobial infection in legumes. Infection and development of root nodules and thus N_2-fixation is highly dependent on sufficient phosphorus supply. On soils low in (chemically) available phosphorus VA mycorrhiza can therefore substantially increase N_2-fixation and growth rate of legumes. This interaction has been established also under field conditions *(Azcon et al. [1979]; Islam* and *Ayanaba [1981]).*
With decreasing soil water content both solute transport to roots and root growth rate decrease. Under these conditions root hair development and/or VA mycorrhiza become increasingly important for maintaining a sufficient surface area and for shortening the distances for diffusion of nutrient to the uptake sites. Thus, VA mycorrhiza has a favourable effect on plant growth and on water use efficiency particularly at low soil water availability *(Sieverding [1981]).*

7. Nutrient availability and soil water distribution

Within the soil profile the concentration of (chemically) available nutrients is usually much higher in the topsoil than in the subsoil. Especially in rainfed agriculture during the growing season periods of low water availability in the topsoil can limit nutrient uptake from this horizon. Under these conditions both root growth into the subsoil and uptake of water and nutrients from the subsoil are of great importance *(Fox* and *Lipps [1960]; Garwood* and *Williams [1967]).* Even under European conditions the contribution of nutrients from the subsoil can be quite important as shown for phosphate in Table 8.

Table 8. Uptake of phosphate by spring wheat and delivery of phosphate as function of soil depth and time. Parabrown earth (loess) *(Fleige et al. [1981])*

		Booting stage	Anthesis	Milky stage
		P uptake (kg ha^{-1} day^{-1})		
		0.345	0.265	0.145
Available P mg/100 g (CAL)	Soil depth (cm)	Delivery of P from various soil depths (%)		
11.5	0–30	83.3	58.8	67.4
4.5	31–50	8.1	17.8	15.5
2.5	51–75	5.9	16.3	12.0
2.0	76–90	2.7	7.1	5.1

Despite the much lower phosphate concentrations in the subsoil, uptake rates can be quite substantial, particularly later in the growing season. Under the same conditions the contribution of the subsoil for the potassium supply to spring wheat plants was even higher and made up about 50% of the total uptake *(Grimme et al. [1981]).*
Also in the case of nitrate, under limited rainfall during the growing season, delivery by mass flow is of importance only early in the season (figure 1) and diffusion becomes increasing important, particularly in the subsoil (*Strebel,* personnal communication).

The utilization of water and nutrients from the subsoil depends on its penetrability for roots. High mechanical resistance *(Wiersum [1957; 1969]; Russell* and *Goss [1974])*, lack of oxygen *(Geissler [1969])*, accumulation of ethylene *(Crossett and Campbell [1975])*, high salt concentrations and particularly low pH (high aluminium concentrations) restrict root growth *(Rios* and *Pearson [1964])* and thus utilization of water and nutrients from the subsoil. As calcium ions are phloem-immobile, the high demand of growing root tips for calcium has to be satisfied exclusively by direct uptake by the root tips from the soil solution. Improvement of root growth by liming acid soils therefore depends on uniform distribution of lime within the soil profile (Table 9).

Table 9. Root elongation growth of cotton as affected by liming of an acid subsoil (pH 4.6). Application of the same amount of lime, but differently distributed (according to *Pearson et al. [1973])*

Percentage of subsoil-mass limed	Distance between limed layers (cm)	Relative root length
unlimed	–	32
10	4.5	38
20	4.0	57
40	3.0	57
60	2.0	70
100	–	100

Subsoil liming *(Howard* and *Adams [1965])* particularly for plant species with high aluminium sensitivity *(Pearson [1974])* is therefore a quite effective procedure to increase availability of water and nutrients in the subsoil. Under conditions where either subsoil penetration is restricted or water is available only in the top soil, nutrient supply to plant roots might vary drastically during the growing season. Close correlations can then be observed between rainfall, root growth and nutrient uptake, reflected for example in seasonal changes in occurance of zinc deficiency symptoms in citrus *(Nair* and *Mukherjee [1970])*.

8. Root-induced changes of the rhizosphere

Conditions at the soil/root interface (rhizosphere) usually differ considerably from the bulk soil. Ion concentration can be lower or higher (see section 4). Roots, however, do not act only as 'sink' for nutrients transported to the root surfaces by mass flow and diffusion *(Brewster et al. [1976])*. Roots can modify conditions within the rhizosphere by changing the pH and O_2 concentration, release of chelating and/or reducing substances, and by root exudates as substrates for the rhizosphere microorganisms. The range of these changes and their importance for the mobilization and immobilization of mineral elements within the rhizosphere will be demonstrated in a few examples.

a) Changes in pH

Differences in cation/anion uptake by roots have to be compensated for by stoechiometric changes in release of H^+ and OH^- or HCO_3^- from the roots. Depending upon the type of nutrient supply the pH in the rhizosphere can therefore be higher or lower than in the bulk soil. For example, nitrogen supplied either as ammonium (cation) or nitrate (anion) shifts the cation/anion uptake ratio and the pH in the rhizosphere as shown in Table 10.

Table 10. Effect of nitrogen form on the pH of the bulk soil and rhizosphere soil* and the phosphorus content in the shoots of soybean (after *Riley* and *Barber [1971]*)

pH of the soil**	Changes in soil pH after 3 weeks bulk soil with		rhizosphere soil with*		Rhizosphere soil pH	% P in shoots
	NH_4^+	NO_3^-	NH_4^+	NO_3^-	(data recalculated)	
5.2	5.0	5.4	4.7	6.6	4.7	0.21
6.3	5.9	7.0	5.6	7.1	5.6	0.17
6.7	6.6	7.0	6.3	7.2	6.1	0.15
7.8	7.8	7.8	7.2	7.4	7.1	0.13

* strongly adhering soil

** unfertilized, uncropped soil, but pH adjusted with $Ca(OH)_2$

In soils with low pH buffering capacity (*e.g.* absence of $CaCO_3$) the pH within the rhizosphere can differ by 2 units depending on the nitrogen form. As a consequence of these differences, nitrogen supplied as ammonium rather than nitrate has a favourable effect on uptake of phosphorus (uptake rate $H_2PO_4^- > HPO_4^{2-}$) by plants *(Riley* and *Barber [1971]; Soon* and *Miller [1977])* and also on uptake of iron, zinc and manganese *(Sarkar* and *Wyn Jones [1982])* and thus for example on overcoming 'lime chlorosis' *(Farrahi-Ashtiani [1972])*. Monitoring pH continuously in an undisturbed soil/plant system supplied with ammonium, *Schaller* and *Fischer [1981]* demonstrated changes in pH at the soil/root interface of peanut from 5.5 (bulk soil) to 3.5 (interface); with maize however, pH remained at 5.5 or decreased only slightly (*Fischer*, personnal communication). This interaction between plant species and changes in rhizosphere pH by the form of nitrogen is well established and related at least in part with the cation exchange capacity of the plant material *(Smiley [1974])* and whether nitrate is reduced preferentially in the roots or in the shoots *(Keltjens [1982])*.

Certain plant species like buckwheat show preferential uptake of cations over anions even with nitrate nitrogen supply. These plant species are therefore quite efficient in acidification of the rhizospere and in utilization of rock phosphates *(Fried [1953]; Raij, van* and *van Diest [1979])*.

Other plant species like rape are able, under phosphorus deficiency, to shift the ratio cation/anion uptake in favour of cations: As a result of this the pH in the rhizosphere decreases leading to an increase in desorption of phosphorus, solubilization of non-exchangeable phosphorus and increase in phosphorus concentration in the rhizosphere soil solution (Table 11).

Table 11. Time course of dry matter production, phosphorus concentration and pH in the rhizosphere and ion uptake of rape plants grown in a soil low in available phosphorus (data from *Grinsted et al. [1982]* and *Hedley et al. [1982]*)

Age of plants (days)	g dry matter per vessel	μM P in rhizo-soil solution	pH in rhizosphere	Uptake of cations and anions*
0	–	5.17	6.1	–
7	0.16	2.56	6.3	cat<an
14	0.89	0.82	6.5	cat<an
20	1.89	1.40	5.3	cat>an
28	3.69	2.47	4.3	cat>an

* N supplied as $Ca(NO_3)_2$

A similar acidification of the rhizosphere as with ammonium nitrogen (Table 10) or under phosphorus deficiency (Table 11) can be observed in legumes utilizing symbiotically fixed nitrogen *(Aguilar* and *van Diest [1981]; Mengel* and *Steffens [1982])*. Nitrogen fixation is correlated with a relative increase in uptake of cations over anions. As a consequence of this, rhizosphere pH decreases and phosphorus utilization from rock phosphates, for example, increases correspondingly (Table 12).

Table 12. Effects of nitrogen sources on acidity and alkalinity generated by roots of alfalfa plants, on the soil pH and on the utilization of rock phosphate *(Aguilar* and *van Diest [1981])*

Treatment	Generated acidity	alkalinity	pH of soil (H_2O)	mg P in plants per pot	Yield g dry matter per pot
	me/g dry matter				
$-P$ $+N_2$ ...	0.5	–	6.2	4	4.7
Sup. P $+N_2$ ...	1.0	–	5.1	138	44.5
Rock. P $+N_2$ ...	1.5	–	5.3	49	26.9
$-P$ $+NO_3$ ..	–	1.1	6.3	1	2.5
Sup. P $+NO_3$ ..	–	0.8	7.5	122	49.9
Rock. P $+NO_3$ ..	–	0.8	7.3	23	18.8

Enhanced H^+ efflux from roots and corresponding acidification of the rhizosphere is also a typical response of so-called 'Fe-efficient' plant species to iron deficiency *(Brown* and *Jones [1974])*. These plant species are therefore able to dissolve and utilize effectively sparingly soluble iron-III compounds *(Marschner et al. [1974])* as long as the bicarbonate concentration in the rhizosphere does not counteract this acidification *(Venkatraju* and *Marschner [1981])*.

Transport of O_2 from the shoot through an aerenchyma into the roots and subsequent release of O_2 into the rhizosphere is another important aspect of root-induced changes in the rhizosphere. As this mechanism is a typical feature of plant species adapted to waterlogging (lowland rice *e.g.*) this aspect is not further treated in this paper.

b) Root exudates

Root exudates which are released in larger amounts particularly in response to mechanical impedance of the substrate *(Barber* and *Gunn [1974]; Schönwitz* and *Ziegler [1982])* are another important factor influencing nutrient availability in the rhizosphere. Apical meristems of roots produce permanently 'mucigel' which contains a substantial proportion of polygalacturonic acid, a quite effective substance in mobilizing both phosphorus and iron *(Nagarajah et al. [1970])*. The 'two-phase effect' in the uptake of these both mineral nutrients *(Jenny [1965]; Matar et al. [1967])* might be at least in part explained by these root exudates. Root exudates seem to be responsible also for the ability of plant roots to take up micronutrients like zinc from soil layers with extremely low water availability *(Nambiar [1976])*. Production of 'mucigel' is furthermore an effective mechanism to protect the apical meristem of roots from aluminium-injury *(Horst et al. [1981])*.

Root exudates with distinct chelating and/or reducing properties are released by roots in response to iron deficiency *(Takagi [1976]); Olsen et al. [1981])*. Enhancement of iron mobilization from iron-III oxides *(Olsen et al. [1981])* but also manganese oxide *(Marschner et al. [1982])* by these root exudates can be demonstrated. As result of this iron deficiency induced root response, manganese toxicity may occur on calcareous soils *(Moraghan [1979])*. In root exudates from wheat organic acids seem to be the compounds responsible for the effectiveness of these exudates in dissolving manganese oxides *(Godo* and *Reisenauer [1980])* and in mobilization of phosphate from rock phosphates *(Moghimi et al. [1978])*.

Certain plant species of the *Proteaceae* develop so-called 'proteoid roots', dense proliferations of rootlets of limited growth. 'Proteoid roots' can be observed also on the root system of *Lupinus albus*. The rhizosphere of these root zones is characterized by low pH and high concentrations of reducing and chelating substances with particular effectiveness in mobilization of manganese, iron and aluminium *(Gardner et al. [1981, 1982b])*. Formation of these 'proteoid roots' is enhanced by low phosphorus availability in the soil and can be considered as another effective mechanism for mobilization of at least phosphorus and manganese but presumably also iron in the rhizosphere (Table 13).

Table 13. Effect of phosphorus supply on growth and mineral composition of *Lupinus albus* grown on a calcareous soil, pH 8.6 *(Gardner et al. [1982b])*

	Superphosphate added, g/pot			
	0	0.133	0.334	0.667
Shoot dry weight, g	1.93	1.96	2.01	2.02
% proteoid roots	46	36	28	16
% P in shoots	0.17	0.19	0.20	0.23
ppm Mn in shoots	1500	1550	1500	1150
ppm Fe in shoots	200	175	235	220
Rhizosphere: pH	8.2	8.2	8.1	8.1
ppm H_2O-extract. Mn	18.7	24.4	16.7	5.3
ppm H_2O-extract. Fe	1.5	0.7	0.9	0

It seems worthwhile to extend the search for changes in root morphology in response to nutrient deficiency also to other plant species. Formation of 'proteoid' type roots with their correspondingly high capability to change the soil chemical properties in a certain part of the rhizosphere might be more abundant in the plant kingdom.

c) 'Rhizodeposition' and microbial activity

Between 20–40% of the photosynthetic products are translocated into the roots and utilized for root growth and respiration, or released into the rhizosphere ('rhizodeposition' according to *Sauerbeck* and *Johnen [1976]; Sauerbeck et al. [1981]; Barber* and *Martin [1976]).*

Some of these root exudates are quite effective in mobilization of mineral nutrients (see above), the majority of the 'rhizodeposition', however, is utilized as substrate for the rhizosphere microorganisms. The population density of microorganisms within the rhizosphere is therefore much higher than in bulk soil. This high microbial activity at the root soil interface has various effects on the dynamics of mineral nutrients in the rhizosphere and on the availability of nutrients for the plants. A considerably higher turnover-rate of soil organic phosphorus in the rhizosphere *(Helal* and *Sauerbeck [1981])* indicates that the presumed low plant-availability of this phosphorus fraction might need reconsideration. Although higher rates of phosphorus mobilization from rock phosphates *(Paul* and *Sundra Rao [1971])* or in general phosphates in calcareous soils *(Khalafallah et al. [1982])* by so-called phosphorus dissolving bacteria in the rhizosphere can be demonstrated, this effect seems to be of less importance in comparison to, for example, the VA mycorrhiza *(Azcon et al. [1976])* or root-induced pH changes (Section 8a).

Rhizosphere microorganisms can furthermore affect the nitrogen nutrition of plants in various ways. Higher rates of denitrification in the rhizosphere can be observed at low redox potentials *(Trolldenier [1971])*, particularly when root exudation is enhanced by deficiency of potassium or phosphorus *(Kraffczyk* and *Trolldenier [1979])*. On the other hand, nitrogen fixation in the rhizosphere by free living bacteria can contribute to the nitrogen nutrition of crop plants growing on soils low in available nitrogen. A substantial contribution, however, is limited to certain and specific 'associations' ('semi-symbiosis') between N_2-fixing bacteria and higher plants like *Azotobacter paspali* and *Paspalum notatum (Doebereiner* and *Day [1976])* or *Azospirillum crococcum* and several plant species with C_4 carbon pathway like sorghum and maize *(Bülow* and *Doebereiner [1975]).*

Although also in temperate climates significant increase in crop yield (wheat) and in nitrogen content can be demonstrated after soil inoculation with Azospirillum *(Rynders* and *Vlassak [1982])*, 'associations' witb free living N_2-fixing bacteria are much more effective at high soil temperature *(Trolldenier [1982])* and thus in tropics and subtropics *(Glatzle [1981])*. The surprising results obtained by *Kopp [1981]* in field experiments in a semi-arid region on an annual gain of 100-200 kg bound nitrogen in rotations even without legumes might be attributed to a large extent to these 'associations'.

Furthermore, N_2 fixing microorganisms are effective producers of phytohormones like IAA. Inoculation with these microorganisms causes dramatic changes in root morphology, formation of abundant and long root hairs for example *(Glatzle [1981])*. Considering the importance of root morphology for nutrient availability in soils, effects of rhizosphere microorganisms, especially N_2-fixing microorganisms, on root morphology deserve more attention in future research on nutrient availability in soils. This holds true in particular for soils with low fertility levels or low rates of fertilizer application in combination with restricted nutrient mobility in the soil solution due to low water availability.

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Soil Nitrogen Mineralization and Nitrification under Moroccan Conditions

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Summary

The results presented here are fundamentally similar to what is known for the soil of temperate regions. The soil contains a certain amount of organic nitrogen that will undergo mineralization with a time constant equivalent to a half-life the order of magnitude of which is about 100 days. Compartmental analysis of the behaviour of soil nitrogen in Moroccan soils would undoubtedly demonstrate the existence of other fractions, some of them with longer half-lives, the latter being of little agricultural interest.
Other fractions also exist that have shorter half-lives and are contingent upon partial sterilization effects which occur after the summer drought and the onset of the winter rainfall.
The low level of the biomass in those soils makes it difficult to obtain an accurate determination of those more labile fractions.
On the other hand, most of the organic nitrogen is very likely stabilized in fractions which mineralize so slowly that its agricultural usefulness is negligible.
Nitrogen manuring in Moroccan soils could be improved by calulating the probability of its response from climatic data during early and late winter as well as from short duration incubation tests on representative soil samples which would supply the basic data to be combined with the climatic factors.

1. Introduction

Nitrogen manuring in temperate countries is based on a body of empirical and fundamental knowledge which has been developed during the last century.
No such body of knowledge exists for the arid and subarid non-irrigated agriculture. Since the intensification of agriculture in the countries situated in arid climates demands the use of nitrogen fertilizers or at least that nitrogen supplied by the soil be used as efficiently as possible, investigations on this subject must be carried out in parallel with all other investigations on mineral manuring.
For this reason, a programme on the fundamental aspects of nitrogen manuring has been initiated at the *Institut National Agronomique Hassan II* in Rabat, Morocco in 1970 by the *Soil Science Department* of the Institute. The purpose of this paper is to report some results of this programme.

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Investigations on the ability of the soil to supply nitrogen to the plant may develop along two lines. First the amount of mineral nitrogen in field soils may be measured in the course of the year in order to arrive at an understanding of the net effect of rain and temperature on the amount of mineral nitrogen present in the root zone of cultivated plants. Published information on this line of investigation exists for Morocco: *Chiang C. et al. [1972], Chiang C. et al. [1973], Stitou M. et al. [1979].*
Complementary to this approach, laboratory experiments should be carried out in order to arrive at some quantitative information regarding two crucial parameters, firstly the amount of organic nitrogen which is susceptible to undergo mineralization, secondly the rate constant which characterizes this process and thirdly the influence of soil moisture and temperature on this rate constant. Stating that the information desired is the fraction of organic nitrogen present in the soil which will become available during the course of a growing season follows from the above, since the amount of available nitrogen will be determined by the amount of organic nitrogen in various compartments and the rate constants associated to them.

2. Material and methods

All samples studied came from the plough layer of three representative soils of Morocco. The first one, designated as MA came from the Romani region, east of Rabat at the *Agricultural Experimental Station of Merchouch.* The elevation was about 450 m, the soil is developed from Tortonian conglomerates under fairly level topographical conditions. The other two series of soil samples designated as KL and KS came from El Koudia, south of Rabat. They are typical red Mediterranean soils developed on dune sandstone, sandy in the surface horizons and more clayey in the lower horizon while the first soil is more akin to the vertisols.
The analytical characteristics of the soils may be found in Table 1.

Table 1. Characteristics of the soil studied

	MA	KL	KS
Clay content (%)	43.5	11.3	7.6
Fine silt	23.7	14.5	15.5
Coarse silt	22.4	21.1	12.9
Fine sand	7.1	35.9	53.4
Coarse sand	3.7	17.3	10.7
Specific surface ($m^2.g^{-1}$)	173	32	18
Moisture equivalent (%)	22	12	9
Carbon (%)	0.74	1.03	0.64
Nitrogen (%)	0.07	0.104	0.07
C/N	10.9	9.9	9.3
pH	6.4	6.9	6.3
Active limestone (%)	3.0	0.8	0.9
Exchangeable cations:			
Ca (mE/100 g soil)	17.9	4.1	3.5
Mg	2.8	1.7	0.3
K	0.84	0.46	0.43
Na	0.52	0.39	0.09
Cation exchange capacity	25.6	8.3	5.6

They were obtained by the usual techniques of extraction with neutral N – ammonium acetate for the exchangeable cations followed by adsorption spectrophotometry. The moisture equivalent was determined by centrifuging at 1000 *g* during 320 min samples previously water-saturated.
The specific surface was determined by ethylene glycol absorption according to *Dyal* and *Hendricks [1950]*.
Active limestone was determined according to *Drouineau's* method *[1942]*.
The mineralization experiments were carried out by incubating 20 g soil samples after air drying, sieving at 2 mm and homogenizing. The soil was mixed with an equal weight of acid-washed sand. Before incubating, the soil-sand mixture was placed in a percolation tube and washed first with 250 ml of a 0.01 M $CaCl_2$ solution and then by 25 ml of a nitrogen-free nutrient solution containing: 0.002 M $CaSO_4$; 0.002 M $MgSO_4$; 0.005 M $Ca(H_2PO_4)_2$; 0.0025 M K_2SO_4. The samples were then incubated at the indicated temperature and individually analyzed at the completion of the indicated time lapse by displacing ammonium and nitrate nitrogen with 4 successive fractions of 0.01 M $CaCl_2$, the volumes of which were 100, 50, 50 and 50 ml, each washing being followed by suction under 60 cm Hg. It was shown that only after four washings (with 100, 50, 50, 50 ml) the amounts of mineral nitrogen became negligible. The procedure above is similar to that described by *Stanford [1972]*.

3. Results

3.1 Laboratory studies

3.1.1 Soil moisture and temperature

The three soils studied were incubated at various moisture contents during 15 days and the amount of mineral nitrogen produced was determined at the end of the incubation period which occurred at 4 different temperatures 20, 25, 30 and 35 °C.
Figure 1 shows that a 5% increase of the moisture content had a large effect on the amount of mineral nitrogen produced but that the second increment had a much smaller effect. It is noteworthy that the response to temperature increase *i.e.* the slopes of the nine graphs of Figure 1 were not appreciably influenced by the moisture content.
A more detailed investigation of the effect of soil moisture on the combined rates of mineralization and nitrification is presented in Figure 2.
Clearly, the saturation of the pore space, once slightly above the moisture equivalent, caused a very rapid decrease in the production of nitrate-nitrogen while ammonium-N always showed a tendency to keep on accumulating. The total mineral-N produced decreased markedly at higher moisture content probably through denitrification. Putting the observations on a quantitative basis is rather difficult but nevertheless necessary if they are to be used for predictive purposes.
Regarding the effect of temperature, it seems that the mineral nitrogen production was linearly related to temperature with correlation coefficients of 0.96 or better. If

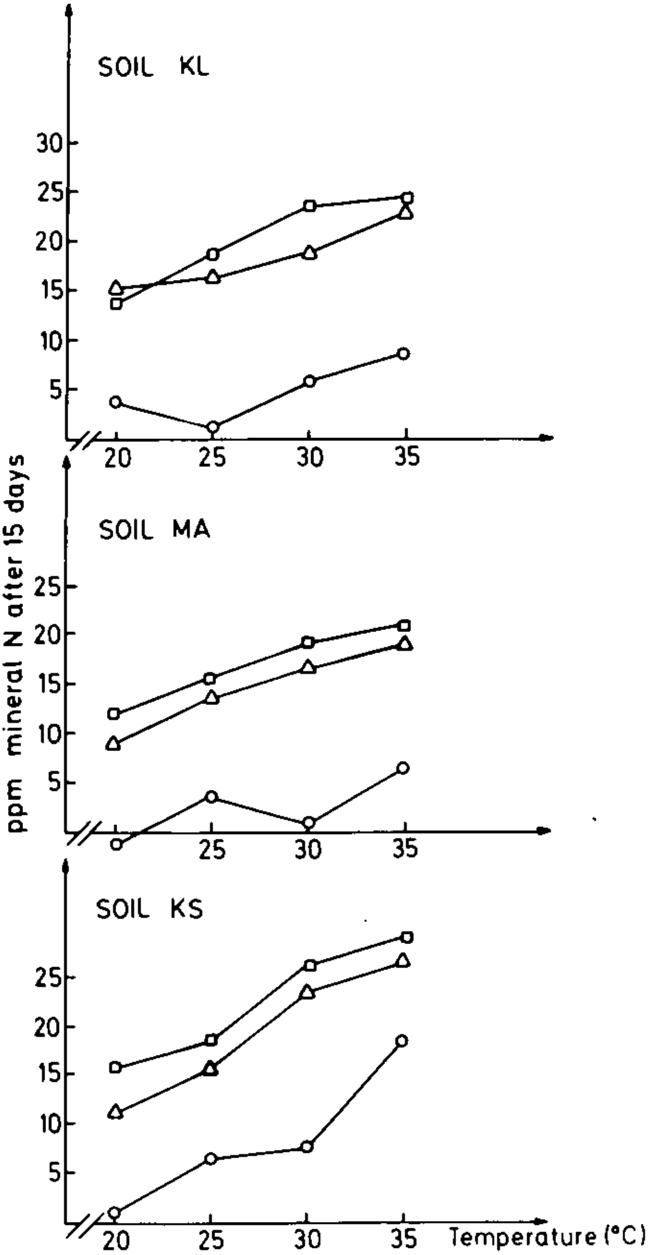

Fig. 1. Total mineral nitrogen produced at three moisture contents (soil KL and KS 5, 10 and 15%, soil MA 10, 15 and 20% in the order -○-, -△-, -□-) and at 4 different temperatures (20, 25, 30 and 35 °C).

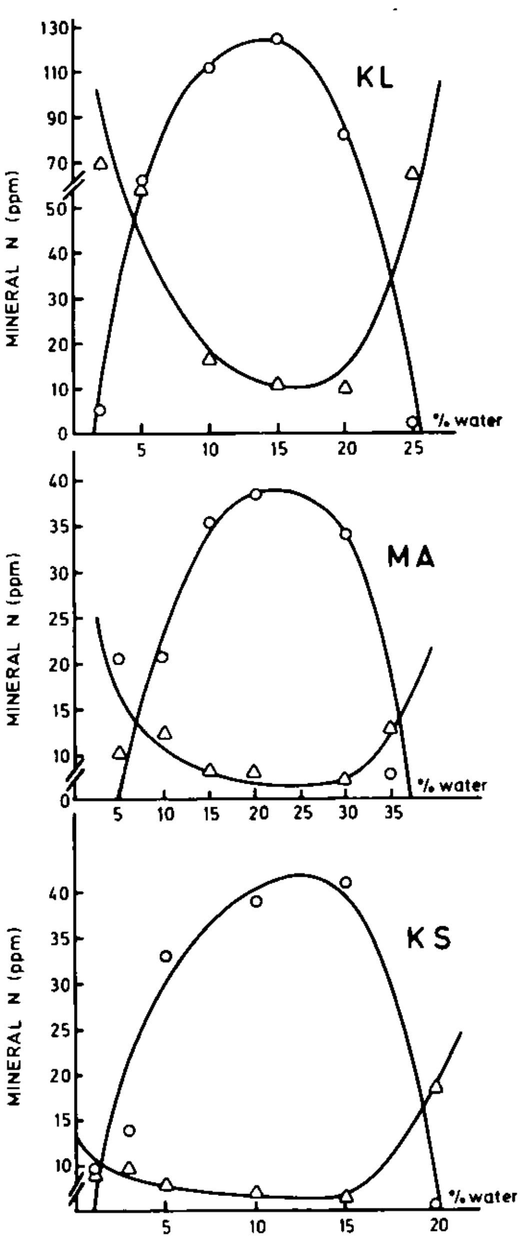

Fig. 2. Influence of moisture content on mineralization and nitrification rates. –O– for NO_3-N produced during the incubation period –Δ– for NH_4-N. Incubation temperature is 30 °C for the 3 soils.

the medium moisture content is considered, we find with t for centigrade temperature:

- Soil KS at 10% water content: $N = 0.51.t - 5.01$ ($r = 0.96$)
- Soil KL at 10% water content: $N = 1.0.t - 10.5$ ($r = 0.98$)
- Soil MA at 10% water content: $N = 0.6.t - 1.7$ ($r = 0.99$)

The quality of the experimental results did not allow a more basic calculation of the temperature effect such as a semi-logarithmic plot of the rate of mineral nitrogen production vs. reciprocal of the absolute temperature.

However, the experimental data on African soils summarized by *Dommergues* and *Mangenot [1970]* show that the initial part of the temperature response curve of soil microflora between 10 and 35 °C is linear within the experimental error.

3.1.2 Effect of pH on mineral N production

Changing the pH of the soils prior to the incubation by adding calcium hydroxide or sulphuric acid for obtaining final pH values in the range of 5 to 9 allowed the determination of a fairly broad pH zone for the production of mineral nitrogen at the optimum moisture content (0.9 of the moisture equivalent) and at 30° C. Figure 3 reproduces the result obtained for the amount of NO_3-N observed after a 15 day-incubation period. For this experiment, the MA soil, richer in colloids, was used.

3.1.3 Determination of the amount of mineralizable N

Two parameters are of importance for estimating the amount of mineral nitrogen: one is the fraction of total organic nitrogen that will be mineralized and the other, the rate at which the mineralization and nitrification processes will occur.

The half-life of the organic matter which could be calculated from the pseudo first-order plot of the mineralization experiments varied from 42 to 95 days (Table 2).

This half-life was calculated from a semi-logarithmic plot such as the one shown in Figure 4 where the linearity was obtained by adjusting for the two unknown parameters N_o and k the integrated first-order equation:

$$N = N_o \exp(-kt)$$

where N is the amount of mineralizable organic nitrogen at time t.

Instead of this method of calculation similar to the one used by *Stanford [1972]*, four parameters could be adjusted to the experimental results as done by *Jenkinson* and *Ayanaba [1977]*. We believe that the accuracy of our results did not justify this treatment.

When the amount of mineralizable N is investigated as a function of the season, results such as those depicted in Figure 5 were found during the 1982 growing season.

In Figure 5, the two lines represent the initial amount of mineral nitrogen at the start of the incubation period and the amount found at the end of the incubation period.

The amount of mineral-nitrogen found in a bare soil in the field between November and April depends on the vagaries of climate and was fairly high due to the drought prevailing during the 1981–82 winter.

It is very likely that this drought did not allow the proliferation of the microflora observed at the end of the summer and its remineralization later during the winter.

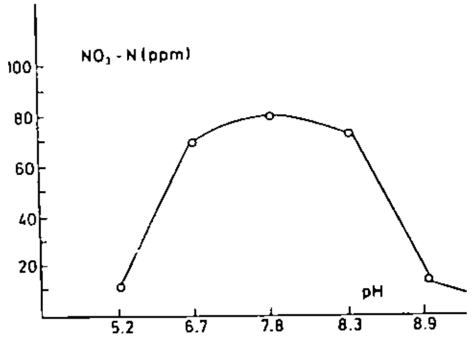

Fig. 3. Effect of pH on amount of nitrate produced after 15 days at optimum moisture content and at 30 °C. pH changes obtained by adding calcium hydroxide or sulphuric acid.

Table 2. Total organic nitrogen, mineralizable nitrogen and rate constant for mineralization

Soil	Mineralizable N ppm*	Organic N** %	k (day^{-1})*
KS	94	0.11	.016
MA	166	0.13	.012
KL	196	0.18	.007

* Calculated from adjusting the first-order kinetics to the mineralization experiment.
** Actual organic N content of the incubated samples.

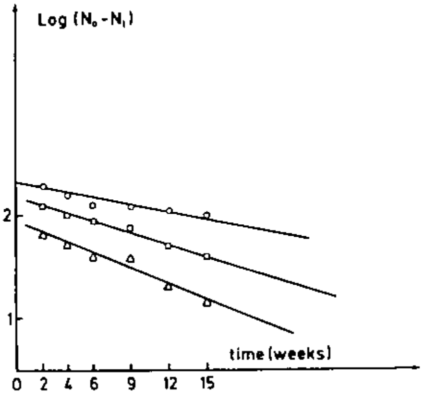

Fig. 4. Pseudo first-order plot of the kinetics of organic nitrogen mineralization. The initial value N_0 and the rate constant k are obtained by adjusting first-order kinetics to the experimental data. –O– soil KL, –□– soil MA, –Δ– soil KS.

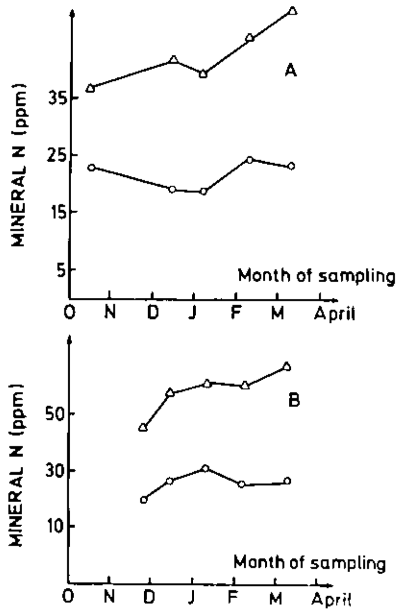

Fig. 5. Amount of mineral nitrogen found in soil in the field according to month of sampling (lower curves) and after 15 day-incubation period in the laboratory. A: MA soil, B: KS soil.

The two lines are roughly parallel which may mean that the amount of mineralizable N was not dependent on the season at least for the year investigated.
The aims of these measurements was essentially to find out whether the month of sampling could have an influence on the amount of mineralizable nitrogen as determined in the laboratory. We present in the following paragraph data on the evolution of the mineral nitrogen content of the plough layer during two very contrasted winter periods.

3.1.4 Seasonal changes of mineral nitrogen content in the field
Figures 6 and 7 show the evolution in the field of the mineral nitrogen content of the soils studied.
The winter rainfall characteristic of North African climates determines lower temperatures and a higher soil moisture content.
This is of course the average condition but the amount, frequency or even occurence of rainfall in the wintertime may be exceedingly variable from one year to the next.
Light rainfall occurring after the summer drought may lead to enhanced mineralization of organic N which is evidenced by an increased NH_4-N content followed very soon by an increase in NO_3-N. If the rainfall then increases markedly, nitrate is leached and even though mineralization and nitrification continues the NO_3-N content becomes very small. Such an evolution is evidenced in Figure 6 for the sites of the KL and KS soils at El Koudia during the 1970–71 season.

Figure 7 shows the changes for another year (1981–82) in the heavier soil at Merchouch. The changes in mineral nitrogen follow the same pattern after the summer month with a decrease after the late winter rains occurring in December and January.

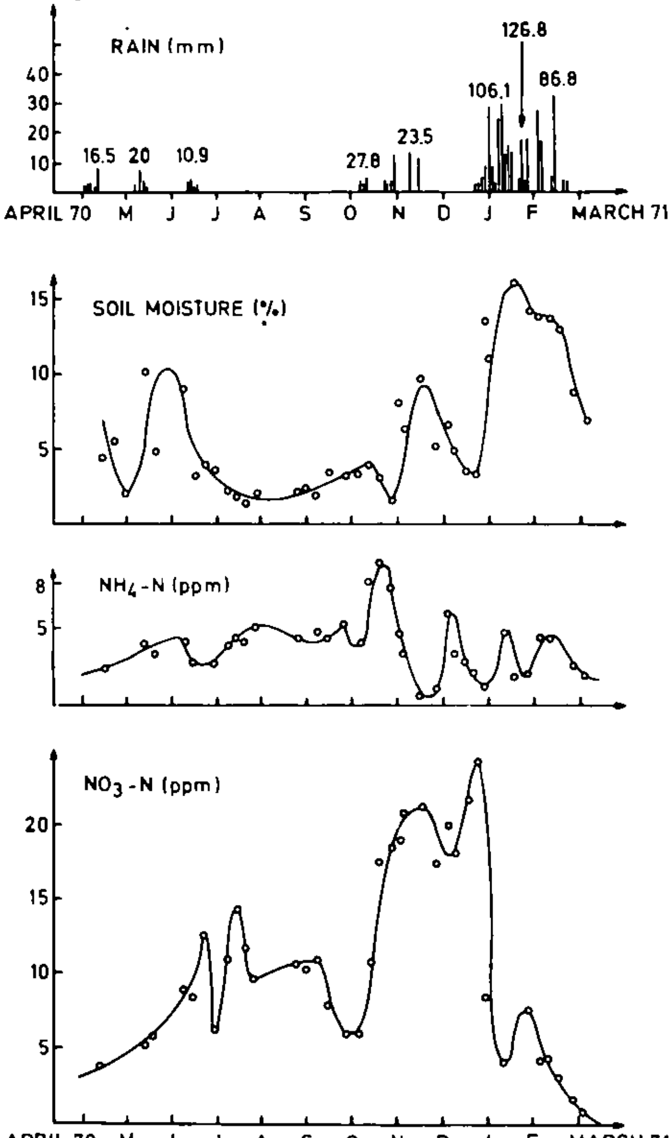

Fig. 6. Pattern of evolution of nitrate and ammonium in the soil at El Koudia (site of KS soil) in the plough layer during the 1970–71 winter.

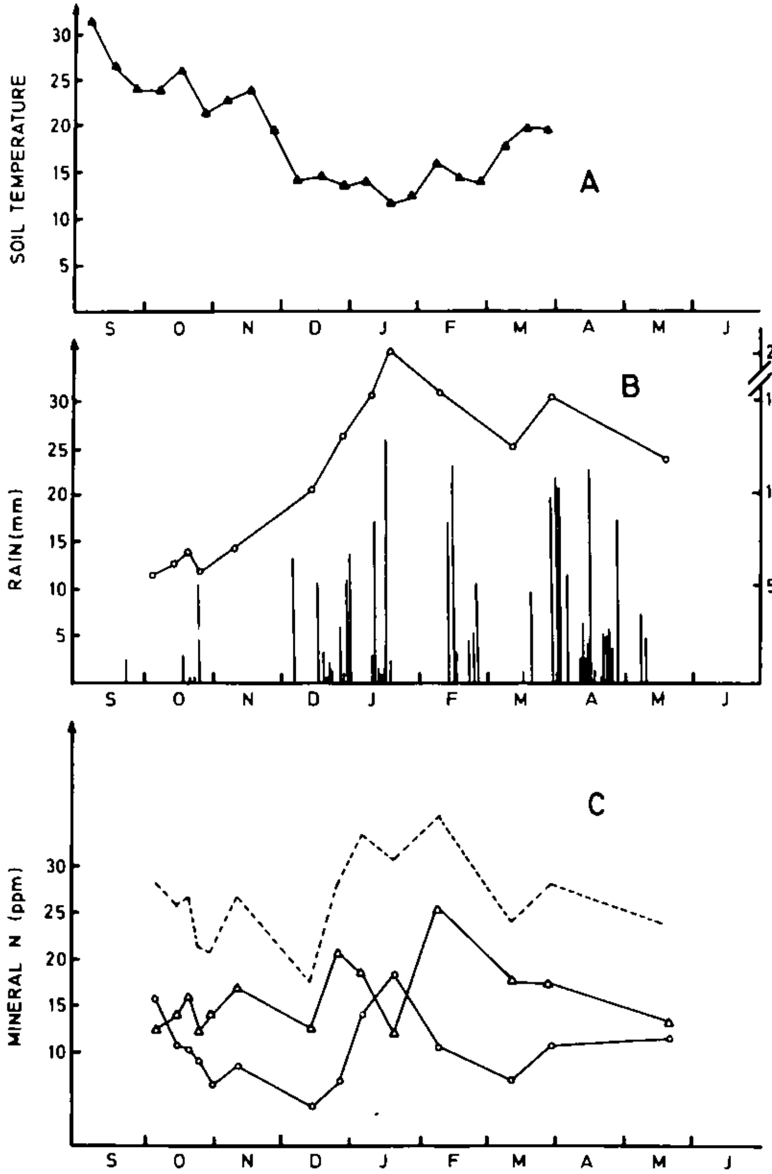

Fig. 7. Soil temperature (A), soil moisture and precipitation (B), mineral nitrogen content (C) in the MA soil during the 1981–82 growing season (September to July). – – – – Total mineral nitrogen, –Δ– Nitrate-N –O– Ammonium-N.

These two sets of data demonstrate that, in spite of the variability associated with samples taken in the field, that light rains occuring in the late autumn and early winter followed by a moderate amount of percolation will determine the amount of nitrogen available to the growing crop. Low rainfall in the early winter limiting seed germination followed by heavy rains in the late winter washing down nitrate from the root zone should be the least favourable conditions of climate conditions.

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Nutrient Dynamics in Arid and Semi-Arid Areas – Phosphate

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Summary

The paper discusses the behaviour of phosphorus in Moroccan soils of the arid and semi-arid areas. The P fixation capacities of these soils cover a wide range from low to very high and saturation of the latter is a difficult problem. Following this discussion advice for the use of fertilizer P in the arid and semi-arid areas of Morocco is summarized.

1. Introduction

Everyone is agreed that phosphate fertilization is a complex matter despite the availability of numerous results of profound research. As this paper will show, the problems are particularly severe in arid and semi-arid areas because of limited water availability. This paper will discuss the dynamics of phosphorus in the soil and the experience of SASMA in the phosphate fértilization of crops.

According to *Gachon [1982]* the devising of a rational scheme for phosphate fertilization depends upon the state of our knowledge of the following five points:

a) Determination of crop requirements
b) Potential phosphorus supply in the soil
c) Utilization of this potential by crops
d) Determination of the phosphate status of the soil needed to satisfy crop demand
e) Determination of maintenance requirements

Gachon has emphasized the complexities of the problem. Here we shall be mainly concerned with point (b) above.

2. Phosphorus dynamics

Gachon's [1976] description of the equilibria between forms of phosphorus in the soil is illustrated in Figure 1. On one side we have the pool of diffusible ions, on the other are the phosphate ions which are in relatively stable molecular combination. The equilibria between the different forms of P are controlled by physico-chemical and biological mechanisms.

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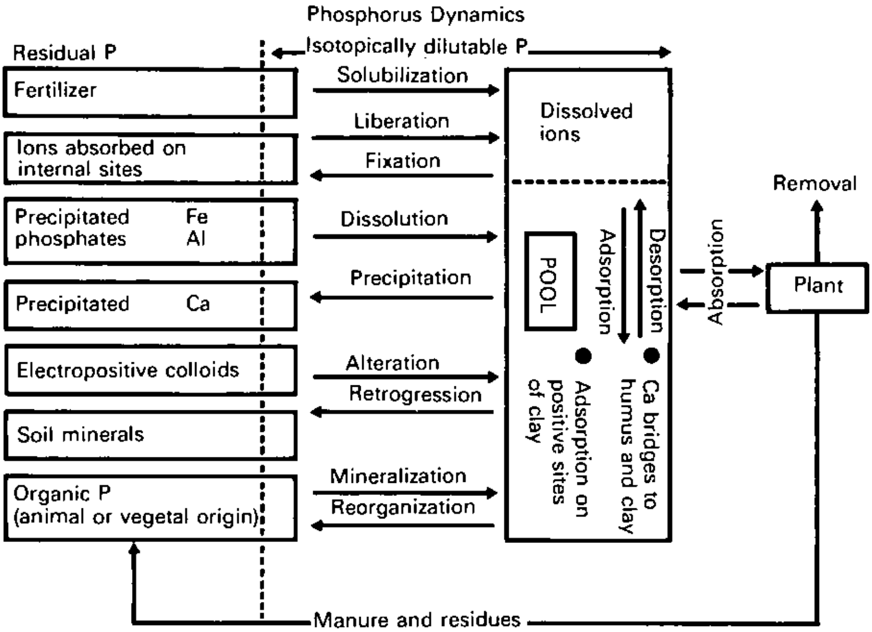

Fig. 1 Phosphorus dynamics

2.1 The pool of diffusible ions

This expression was used by *Barbier (Duthil [19])* to describe the mass of phosphate ions in a state of continuous agitation on and near to the surface of the soil colloids. Each of these ions has the same chance as any of its neighbours to escape the attraction of the exchanger and pass into solution; it is a dynamic equilibrium. According to *Gachon* these ions comprise only a small proportion of total soil P: 15 to 30% (for a soil depth of 30 cm and apparent density 1.3, 4 parts per thousand of total P_2O_5 represents 15 600 kg/ha P_2O_5). We believe that in calcareous clay soils this mass of ions is very small.
Distribution between the solid and liquid phases only reflects the continous passage from one to the other and is controlled by the positive charge density on the exchanger. The PO_4 ions are large, relatively immobile and are strongly retained. Any addition of a salt solution immediately displaces the equilibrium.
The capacity of a soil to absorb phosphorus is called the fixation capacity. The higher the P fixation capacity, the lower will be the P concentration in the soil solution. Phosphate ions in solution represent an infinitessimal part of the pool of assimilable P (0.1 to 1.5 mg P_2O_5/1) in cultivated soils *(Gervy [1970])*.
The pool of diffusible ions can be divided into three:

Water soluble P
P attached to humus and clay by Ca bridges
P adsorbed on positively charged sites on soil colloids.

2.1.1 *Water soluble P*

The 0.1 to 1.5 ppm P_2O_5 dissolved in soil water represents only up to 500 g P_2O_5 per hectare. If crop uptake is 1 kg/day, the solution must renew itself twice a day. It is thought that this content is independent of the moisture status of the soil. P in the soil solution is in the form of more or less dissociated soluble phosphates. Orthophosphoric acid (H_3PO_4) dissociates one to three hydrogen ions according to pH, the lower the pH the more the phosphate is hydrogenated. PO_4 ions are large, heavy and slow moving in the solution, hence their resistance to leaching.

2.1.2 *P fixed by Ca bridges*

Bi- and trivalent cations, mainly Ca, serve as bridges between phosphate ions and the clay-humus complex.

2.1.3 *P adsorbed on positively charged sites*

Al^{3+} ions are exposed at the broken edges of the clay lattice and can exchange OH ions for PO_4. Isotopic dilution techniques have shown that the mass of these ions is not a fixed quantity and estimates of this vary according to the method used. In Figure 1, the dotted line is inserted to show that such methods result in a higher value for exchangeable P than that given by chemical methods. In reality, many of the P reaction products in soil can be considered partly residual and partly exchangeable.

2.2 Forms of P not included in the pool

For each form of 'residual' P there are various degrees of fixation. The portion which is easily available to plants is traditionally called exchangeable and many methods have been devised to measure it. The method of isotopic dilution is widely accepted as giving good correlations with agronomic results. Nowadays the term 'labile' is increasingly used in place of 'exchangeable' and this expresses the isotopically dilutable fraction and includes all the P ions in the pool plus a part of each of the other forms. Some of the non-labile forms are extracted by the 5 first steps in *Chang* and *Jackson's [1957]* method. The remainder is called 'residual phosphorus'.

2.2.1 *P in organic matter*

Other than P attached through Ca bridges, P is combined in the organic matter and this is only mobilized when the organic matter is broken down hy biological activity. Conditions favouring the mobilization of P are almost the same as those favouring mineralization of N. At pH 6–7 rates of mineralization of N and P are identical but as pH rises the rate of mineralization of P increases more than that of N. Mineralization of both is favoured by alternate wetting and drying and by high temperature (40–50°). It should be born in mind that the P content of organic matter is ⅙ that of N.

P liberated by mineralization of organic matter can be incorporated in the microflora or in neoformation products. If sufficient energy is available P is immobilized in microbial bodies.

One can speak of C/P ratio as one speaks of C/N ratio: 'P starvation occurs at a C/P ratio above 200'. For this to occur, the microbial population must remain active or survive. Reorganization of P into the microbial body is rapid but mineralization of this is slow and variable. The measurement of water soluble P takes no account of this P, some of which can become available quite rapidly. Such considerations explain the fact that though the market gardening soils of Oualidia, where much P fertilizer has been used, show very low water soluble P content and high citric soluble content (highly calcareous soils) they can support very good crops of tomato.

P immobilized in the microflora can originate both from organic matter and from the labile pool and sometimes it is found that the labile pool is reduced following application of organic manures, while reserve P increases. Such is the case at Azemmour where organic matter increases citric soluble P (*Dyer*'s method) but decreases *Morgan* P. It is general experience that straw during rotting down decreases the P fixation capacity of the soil. Without doubt this is due to the microorganisms which attack the straw storing P in their bodies or in humus; later the P status improves again.

2.2.2 P at internal sites

PO_4 ions like K ions can be blocked between the layers of clay minerals but since they are larger this can only happen when the interlayer space is 10 Ångströms and this occurs only in swelling clays. Burning and alternate wetting and drying leads to recovery of some of this P.

2.2.3 Soil minerals

These may contain P originating either from parent rock or from fertilizer.

2.2.4 Fertilizer P

Some particles of fertilizer may not have been dissolved.

2.2.5 Electro-positive colloids

Iron and aluminium hydroxides have a particularly high capacity for fixing P but it is only the colloidal fraction of these hydroxides that adsorb PO_4 ions strongly. The combination is stronger than that with the positive sites on clays because the ion is attracted by a mass of positive charges rather than by isolated sites surrounded by negative charges. It is probable that in non-calcareous soils most of the P is retained in this way by the hydroxides.

2.2.6 P precipitated by Al or Fe

More usually the P is retained as Al or Fe phosphate, sometimes as chelates. It seems that P has the highest affinity for Al, then Ca then Fe. Its affinity for Al has been used to neutralize Al toxicity. It seems that P availability is best within the pH range 5.7 to 7 where there is less available Al and Ca.
It was thought earlier that iron and aluminium phosphates were exclusively residual but it now appears that a part contributes to the exchangeable fraction.
In hydromorphic and submerged soils P combined with Fe is very labile, thus some rice soils are exceptional in not responding to P fertilizer.
Volcanic soils have large P reserves which can be mobilized under hydromorphic conditions.

2.2.7 P precipitated by Ca

The dynamics of phosphorus in a calcareous medium has been studied by *Arvieu [1980]*. Phosphorus is rendered insoluble through two distinct processes:

- Adsorption of P at the surface of calcium carbonate, measurable only in dilute solutions;
- Precipitation of calcium phosphates when their solubility products are attained.

While the formation of calcium phosphates has been confirmed, the mechanisms involved and the factors controlling them are only partly understood, and the adsorption of Ca remains hypothetical. According to *Arvieu* the most plausible hypothesis is that chemical reaction forming cells of Ca phosphate occur on the surface of the $CaCO_3$ and these in turn form hydroxyapatite (HA) or octocalcium phosphate (OCP) depending on P concentration of the solution and environmental conditions. There is no fundamental difference betwen this and the first stage of precipitation, though there may be implications as to the energy of combination and the possibility for ions so fixed to pass into solution.
It is well established that phosphates introduced into calcareous soils find themselves largely converted, more or less rapidly, into calcium phosphates: dicalcium dihydrogen phosphate (DCPD) octocalcium phosphate (OCP), hydrated tricalcium phosphate (TCPH), amorphous apatites and hydroxyapatite (HA). The relative rates of 'ageing' ohserved by various authors are consonant with a reaction scheme leading to the formation of less and less soluble compounds. OCP and certain apatites seem to be particularly important among the transitory products formed since they store P in a soluble or partly soluble form. In a fertilized calcareous soil, only partial dissolution of calcium phosphates is possible in changing conditions of the environment.

2.3 Factors controlling solubility of phosphate in calcareous soils

- The presence of more soluble minerals of the calcite type (aragonite, monohydrate).
- Possibility of substitution of Ca in calcite by Mg.

- Existence of humic substances and the presence of Mg which inhibits the crystallization of calcite.
- The formation in solution of ionic carbonate complexes or molecular compounds
- Variation in CO_2 content of the medium.

Arvieu concludes as follows:

'This analysis of the mechanisms and factors of precipitation and dissolution of phosphate in calcareous soil shows that the concept of assimilable phosphate is physically ill-defined. If assimilable P is P in solution or capable of being dissolved, then all forms of phosphate present contribute according to their solubilities and their susceptibilities to dissolution under given conditions. From this point of view, OCP can be considered assimilable, HA not. But the situation with compounds formed by adsorption on $CaCO_3$ whose solubilities are intermediate between OCP and HA is unclear. In any case, a number of other factors relating to both phosphate and the medium can result in an apparent solubility which differs from that of the compounds actually present and it is therefore difficult to attribute a chemical identity to the P which may be dissolved.

'Alongside these general considerations, assimilable P has the characteristic of intensity: the potential of the phosphates present to maintain the concentration of P in the soil solution during periods of maximum uptake by the plant. This potential results essentially from the rates of dissolution and migration of phosphate ions, which is poorly understood and very complex in determination.

'Certainly plant behaviour demonstrates that a certain part of total P in a calcareous soil can be considered to be assimilable or at least more assimilable than the rest. But this fraction is physically ill-defined and it is quite evident that under such conditions the usual methods of extraction have only a conventional value.'

3. Determination of soil P status

Methods of analysis vary between countries and between laboratories. Some are so-called official methods in general use, of which several are adapted for particular soil types. Some methods are only used in research. All aim to measure that part of soil P which is relevant to crop nutrition and we can distinguish 4 groups of methods:

- Those based on chemical extractants
- Equilibration methods
  a) fixation capacity
  b) isotopic dilution
- Extraction by resins
- Biological methods

3.1 Chemical extractants

The widely used conventional methods are subject to two kinds of error. They aim to measure the content of exchangeable ions but they are never entirely satisfactory because the extractant used may extract some phosphate which is not actually available to plants (overestimate) or if a weaker reagent is used it may underestimate the assimilahle supply. According to their nature, these extractants dissolve variable proportions of the different forms of phosphate in the soil but *as the proportions of these different forms vary from one soil to another any particular method may be well-suited to certain soils while being less useful for others.*

3.2 Definition of P potential of soils *(Gachon [1966])*

'It is increasingly recognized that the P supplying potential of a soil depends on three main factors: the assimilable reserve, its electro-chemical potential and its mobility. It is also recognized that, despite its empirical basis, the isotopic dilution method is the most appropriate for evaluation of the assimilable reserve, that is the quantity of phosphate ions which can participate at any moment in supplying the P needs of the plant. Determination of labile P (L or E) thus measures the quantity factor.

'Among other things, the availability of phosphate reserves to plants depends upon their activation energy and the intensity of the flux which enables replenishment of solution P in the neighbourhood of the absorbing root from the reserve. Thus, leaving out of consideration morphological factors like soil structure and root ramification, which determine soil exploration these two factors depend closely on the fixation capacity of the soil which can be regarded as a *quality factor.* In fact, for a particular soil, assimilable reserve and fixation capacity are inversely related.'

Gachon's P potential is related to these two factors in the following way:

$$I_L = L \times \frac{L}{L+F} \quad \text{or} \quad I_E = E \times \frac{E}{E+F}$$

where L represents labile P and E exchangeable P and F the P in dissolved form needed to raise the P concentration in 0.01 M $CaCl_2$ to 2 mgl^{-1}, all being expressed in ppm of soil.

3.3 SASMA's views on the determination of fixation capacity

It is essential to know the fixation capacity of different groups of soils and, among others, the *World Phosphate Institute (IMPHOS)* has worked on Mediterranean soils. However, at *SASMA* we have had some surprises.

3.3.1 The procedure for determining P fixation capacity of Moroccan soils

Seven soil samples from various regions of Morocco were investigated. These showed low values for exchangeable P by the *Barbier-Morgan* method and relatively high or medium values for reserve P by *Dyer's* method; they were high in clay and calcium carbonate.

The method used was that current in France *(Gachon [1966]),* using double the usual quantities (*i.e.* 25g soil in 100 ml 0.01 M $CaCl_2$), in order to improve the homogeneity of the samples. Samples were shaken for two hours, rested overnight and shaken for a further two hours before filtering and measuring P in the extract. Five lots of each sample were then taken and to each was added sufficient P to bring the soil solution up to 2 mg P per litre. These were shaken for two hours then placed on one side at the ambient temperature. The lots were successively filtered after a further two hours shaking after 1, 11, 20, 40 and 60 days. The results are given in Table 1 and Figure 2.

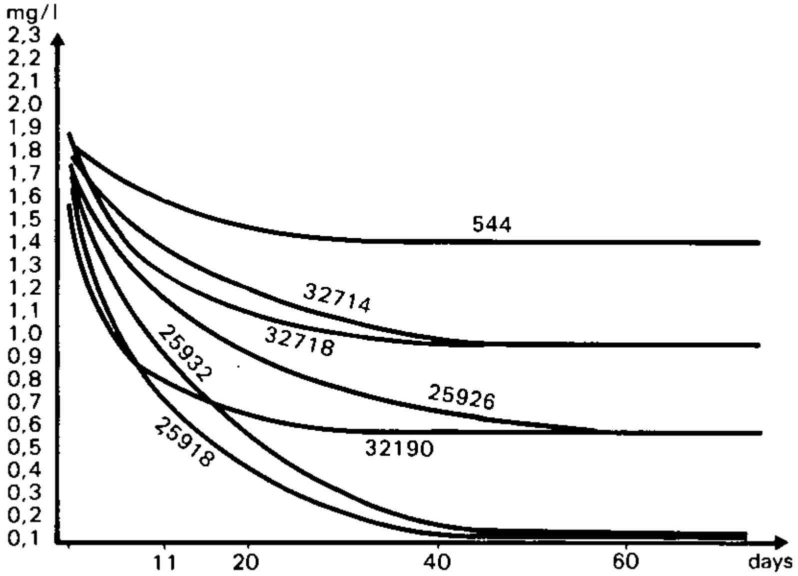

Fig. 2 P fixation capacities of 7 soils from different regions

Table 1. P fixation capacity (mg/lP)

Sample number	mg P added per 100 g solution	1st series	2nd series	3rd series	4th series	5th series
		1 day	11 days	20 days	40 days	60 days
32 714	4,5	2.05	1.31	1.30	1.08	1.00
32 718	4,5	2.17	1.40	1.20	1.00	1.06
25 926	5,5	2.00	1.20	1.00	0.68	0.60
25 932	5,5	1.98	1.00	0.64	0.04	0.03
544	6	2.11	1.94	1.68	1.60	1.60
25 918	6	1.92	0.78	0.44	0.04	0.02
32 190	7	1.80	1.02	0.66	0.68	0.70

25 g soil in 100 ml 0.01 M $CaCl_2$

This study shows that the standard period of contact between soil and solution is insufficient for some soil types. There is a further lowering of P in the solution after 11 days in every case. The maximum reduction was reached after 40 days under our conditions, there being no great difference between values for 40 and 60 days.

The lowering in P concentration after 40 days varied in accordance with soil type (nature of absorbant). Sample No. 544 lost only 24% of added P while at the other extreme sample No. 25 932 lost almost all the P added (98%). This latter sample came from an almond orchard near Meknes which is on a brown calcareous soil overlying an old soil on encrusted calcareous tuff. The 6 mg P added per 25 g soil in the investigation, all of which was required to satisfy the soil's fixation capacity is equivalent to 2.3 t/ha P_2O_5, assuming 30 cm depth and an apparent density of 1.4. The whole of this would be immobilized and non-exchangeable after 40 days.

4. Phosphate fertilizer advice for the arid and semi-arid areas

In any country, or even within a region, knowledge about soil phosphorus, upon which to base fertilizer advice, will be variable. In the first case we may know nothing about the forms of P in the soil, in the second case our knowledge may be fragmentary and, rarely, investigation by standard methods may be complete.

Where the situation is as described in case 1 above, advice has to be based on experience and practice in other countries and must therefore be somewhat generalized. The rates to be applied will be based upon crop removals. Advice will differ between acid and neutral or basic soils.

4.1 Acid soils

For *arable crops and vegetables,* maintenance dressings are applied to compensate for P removed in harvested produce, the rate being based on average yields for the area. Exchangeable P increases as soil moisture content increases, so it is advisable to increase the dressing somewhat in dry areas. Should, as is often the case in arid areas, yields be lower than the expectation, P uptake will be less than predicted and residual P will accumulate. If on the other hand the season is exceptionally wet, a supplementary P dressing in soluble form should be applied.

For *perennial crops* the rates to be applied are calculated from P removed in harvested produce, prunings and weeds or fodder fed to stock. Ground rock phosphate is suitable for perennial and the main arable crops as it is sufficiently rapidly solubilized on acid soils, though it is advisable to apply part of the P requirement in soluble form as a starter dose. For market garden crops, rock phosphate is not sufficiently rapidly available even at pH below 6, so superphosphate should be used.

Normally P fertilizer should be applied along with N and K. P should be applied to fruit trees at the end of the dormant period to be available at flowering and fruit setting.

4.2 Basic soils

If cations other than calcium dominate, P fertilizers high in calcium are suitable, for instance superphosphate 18%, but for calcium rich soils triple superphosphate is to be preferred. Ammonium phosphates are most suitable for winter application to

intensive crops when heavy rains intervene before tillering. The same considerations as for acid soils apply to the timing of P applications.
In order to minimize regression of phosphate in calcareous soils it is advisable to place the P fertilizer within the root zone rather than to broadcast over the whole area. P applications can be split in accordance with rainfall and the stage of crop development. For example half the phosphate for cereals should be applied as a top-dressing before tillering; a soluble form such as ammonium phosphate is suitable for this purpose. The crop's peak demand for P is between tillering and flowering.
Phosphate fertilizer efficiency can be improved by:
- Modifying pH
- Modifying temperature
- Improving microbiological activity
- Applying organic matter
- Soil aeration
- Moisture conservation

4.3 Advice in Morocco

The more complete the knowledge of the behaviour of phosphate in the soil the more perfect can be advice. Knowledge in Morocco is not complete but we have preliminary results upon which to base advice. Numerous advisory publications relating to the various crops are available but we shall confine ourselves here to the advice given by *SASMA*. Two points are fundamental: we have a range of soils from low to very high P fixation capacity: most of our soils are calcareous clays.

4.3.1 Analytical methods

SASMA uses the following methods for determining soil P status:
- Water soluble P by water extraction; soil/water ratio 1:5
- Exchangeable P: The *Morgan-Barbier* method is used with Na acetate at pH 4.8; soil/extractant ratio 1:2. Shaking for 30 minutes.
- Citric soluble P: This is *Dyer's* method with a soil/extractant ratio 1:10. Six hours shaking, rest overnight followed by 1 hour shaking.

4.3.2 Fruit trees

Application of P is based on the balance (application – removals)

4.3.2 Arable crops

P fertilizer application is based on the application of maintenance dressings taking into account as well as crop removal the regression of fertilizer P. There is no problem in estimating crop removal but our knowledge of the fixation capacity of soils is not precise. In some soils, even when their fixation capacity has been satisfied, they return to their original state after a month or six weeks and one is faced with the problem whether it is still necessary at this stage to saturate the fixation capacity and the

further problem as to whether this would be practicable or economic. Our practical solutions of these problems are as follows:
Where soil analysis shows satisfactory levels of exchangeable P and so-called reserve P we apply sufficient P to compensate for crop removal, using the fertilizer forms discussed above.
When exchangeable P is low but reserve P satisfactory we advise increasing the P dressing by 25–100% according to clay and calcium carbonate content. Where both exchangeable and reserve P are low we advise doubling the P dressing. At the same time we advise applying 30–50 kg/ha P_2O_5 over and above the maintenance dressing each year to build up the soil P level. We regard this as a long-term investment.

4.3.3 Market garden crops

Here also we use the balance method and we have set up norms for citric soluble P corrected as follows:
5% $CaCO_3 \times 90\%$
30% $CaCO_3 \times 70\%$
80% $CaCO_3 \times 53\%$, etc.

5. Conclusion

Advising on phosphate fertilizer usage is beset by problems. It is difficult to characterize the P status of a soil by conventional methods which have to be interpreted for individual soils. Crops vary in their ability to exploit soil P, especially the forms which are not considered assimilable. In the arid and semi-arid areas we have the additional difficulty caused by the irregularity of the rainfall which affects the dynamics of phosphorus in the soil and uptake by the plant.

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Potassium Dynamics in the Soils of Semi-arid and Arid Areas

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Summary

Differences in the amounts of soil moisture influence the speed of various reactions involved in K dynamics in soils. Soils of semi-arid and arid areas are relatively less weathered and hence potentially richer in K than comparable soils of humid areas. Soils which experience a period of drought preceding the crop season during which soil moisture is maintained at an adequate level should have a better supply of K. The movement of K to roots is also influenced by the amount of moisture in the soil during crop growth. Except in irrigated areas, the extent to which K additions may occur through irrigation water and composts is rather limited. External application of K is essential in soils having low supply of native K. Close correlation between exchangeable K and K uptake by plants exists only in soils of similar clay contents and uniform clay composition. More systematic work with bench mark soils is needed to delineate soils responsive to fertilizer K and to predict the developing needs.

1. Introduction

Potassium dynamics in the soils of semi-arid and arid areas is qualitatively similar to that in soils of humid areas but is quantitatively dissimilar owing to the low amounts of moisture in the soil. The equilibria among the forms of K in the soil and the forces acting upon them are schematically shown in Figure 1.

Differences in the quantities of moisture in the soil are likely to influence the speed of reactions involved in the following processes:

- Weathering of minerals
- Release and fixation of potassium
- Addition of potassium through water and organic residues
- Movement of potassium to the roots
- Movement of potassium within the soil profile

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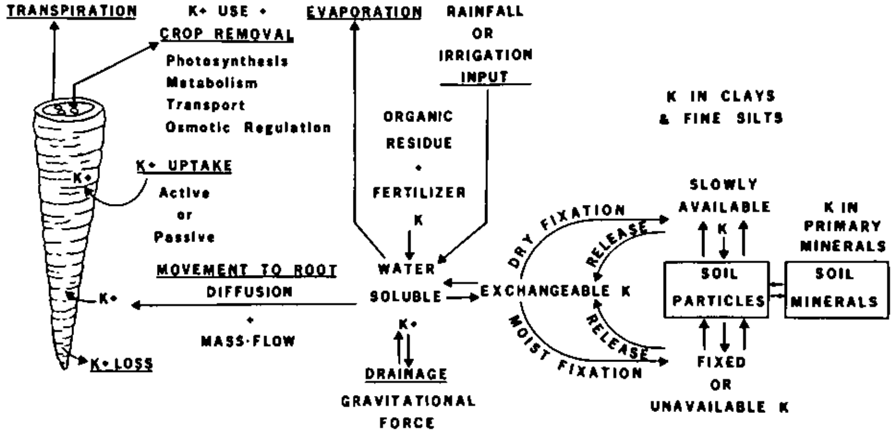

Fig. 1. Equilibria and forces acting on the different forms of K (adopted from *R.D. Munson [24]*).

2. Weathering of potassium bearing minerals

Soils contain a considerable supply of K in their various particle size fractions. *Plummer [27]* pointed out that relative availability of K contained in biotite, muscovite, orthoclase and microcline decreased in the order of their mention. *Dennison et al. [12]* suggested that secondary muscovite weathered more rapidly than the primary variety. This is perhaps due to particle size effect but may also be due in part to differences in disorder, occlusions, etc. *[34]*. Illite, usually dioctahedral, is considered an interstratification of mica and montmorillonite. Because of this and other types of disorder, the mica component may lose its K more readily than non-interstratified mica. Glauconite, a dioctahedral mica high in Fe^{2+}, apparently of marine origin and possibly considerable disorder *[11]* would be expected to weather rapidly in the environment of a well-drained soil.

Micas weather differentially through opening up of their interlayer region as also from their 'frayed edges'. Rate of K removal from freshly exposed crystals of K feldspars is much more rapid than from their highly weathered counterparts. Other things being equal the coarse particles eventually lose more K than the fine particles, although at an early stage of weathering the fine particles have been observed to release K at the most rapid rate *[23, 30]*. Thus, the release of K upon weathering of K-bearing minerals is conditioned not only by their abundance but also by their K content and stages of weathering or formation. *Reitemeier et al. [31]* have pointed out that a combination of fine-grained mica and montmorillonite promotes the maintenance of an adequate supply of exchangeable K; the former is a good source of K and the latter a high C.E.C. but a low fixing capacity mineral.

While composition, microstructure and bonding in the mineral are important factors, the nature and intensity of weathering may be influenced by the intensity of leaching as determined by the amount of water passing through the soil system.

Under laboratory conditions, carbonated water, which closely approximates the natural conditions of weathering was much more effective than ordinary water in release of K.
Apparently in soils of semi-arid and arid areas, the K-bearing minerals are relatively less weathered and are therefore potentially capable of releasing more K into the system. However, low moisture during the crop season may impose a limitation on the extent of actual release.

3. Release and fixation of potassium

It is generally held that the principal sources of K are illite and other 2:1 minerals containing mica-like zones, and that vermiculite is mainly responsible for fixation.
Laboratory studies *[2, 9, 37]* have indicated that drying causes release of K from non-exchangeable positions, at least in soils with small amounts of exchangeable K. Accordingly, plants that have been subjected to drying absorb much more K than those not subjected to drying. However, because soils, except for the few centimeters at the surface, do not normally (in the humid areas) dry to the extent necessary to cause release and subsoils alone have shown the principal response to drying *[17]*, practical significance of this observation remains to be examined for soils of semi-arid and arid areas.
Salmon [32] has examined the effect of drying and rewetting on release of non-exchangeable K from Rhodesian soils. Extracts from his data are reproduced in Table 1. These suggest that the long-term contribution by K reserves in some soils may be more than what is expressed by measurements obtained by cropping on soils which are not dried.

Table 1. Effect of drying and rewetting on release of non-exchangeable K from the Rhodesian soils *[32]*.

Soil site and local details		Exch. K (ppm)	K release (ppm)	
			moist	dried
2	Wiltshire PA (virgin soil)	148	5	3
5	Wiltshire PA (very good maize)	196	22	20
6	Chiduku TTL (fair maize)	23	4	5
8	Chiduku TTL (good maize)	165	34	59
10	Seki TTL (good maize)	56	1	14
11	Msengezi PA (good maize, sub-soil)	50	12	10
15	Mangwende TTL (variable maize, sub-soil)	91	42	69
16	Mangwende TTL (fair maize, sub-soil)	176	31	65
18	Chinamora TTL (fallow land)	48	9	9
22	Chiweshe TTL (good maize) On crest sub-soil	112	19	21
SE			± 5.2	

Potassium frequently gets fixed in the layer silicates in which it has a high selectivity with respect to divalent ions. Magnitude of the inter-layer charge determines the extent of K fixation *[4, 42]*. Some soil montmorillonites which have a high charge density and probably have wedge positions near mica-like zones have a greater capacity to fix K than do many specimen type montmorillonites *[35, 36]*. According to *Barshad [4]*, K ions in the ditrigonal holes of 2:1 layer silicates apparently are retained with different energies depending in part on the rotation and tilting of the tetrahedra about the ditrigonal holes. In addition to charge density, the configuration of the oxygen about exchange sites probably determines, partially at least, the observed differences in replaceability of fixed or native K in micas of the same layer charge. *Raman* and *Jackson [29]* demonstrated in electron microscope studies that mica surfaces have cracks and that the silicate layers at these cracks roll back in scroll-like fashion when the exchange sites are saturated with large hydrated cations and return to a flat morphology when again K saturated.
Potassium entrapment in the facing ditrigonal holes of expansible 2:1 layer silicates depends in part on the moisture content. When K is fixed, water molecules are excluded from the interlayer space and K^+ ions fit into them. Some minerals such as weathered micas and vermiculites fix K under moist as well as dry conditions whereas montmorillonites fix K only under dry conditions.

4. Addition of potassium through water and organic residues

The amount of K supplied to the soil through irrigation depends upon the quality of irrigation water and conditions of the soil. *Yoshida* and *Inada [44]* found that when K content of the soil was lower than 0.34 me K/100 g dried soil, irrigation water positively enriched the soil but when soil K was higher than this equilibrated value, K was leached down to the level of 0.34 me K/100 g. Also, the rate of adsorption of K by the soil decreased with the increase of exchangeable K.
The contribution of irrigation waters to K nutrition of crops depends upon the concentration in the irrigation water, information on which is rather scanty, and the volume of irrigation water used during the crop season. This contribution appears to be significant for preparing a balance sheet of K in soils.

Table 2. Estimated total annual production of potassium through organic wastes in the developing world *[39]*

Source	Million tonnes K	
	1971	1980
Human	2.61	3.25
Cattle	14.12	17.65
Farm compost	9.54	11.93
Urban compost	0.57	0.71
Urban sewage	0.86	1.08
Other*	11.35	14.19
Total	39.05	48.81

* Bone-meal, poultry litter, baghasse, sheep/goat litter, oil-cake, press mud.

Plants remove from soil substantial amounts of K, a considerable part of which is recycled back to the soil through manures and composts. According to an estimate by *FAO [39]* about 9.6 million t K_2O are contained in various types of organic materials added to the soil. According to one estimate (Table 2), total annual production of K_2O through organic wastes in the developing world amounted to 39 million t in 1971 and was expected to rise to 48.8 million t in 1980. Approximately 50 percent of the organic wastes are used even at present in agriculture. The extent to which K additions through organic wastes meet K nutritional requirements of plants depends upon the manner of disposal of various organic residues and farmyard manure.

5. Movement of potassium to the roots

Root interception, mass-flow and diffusion are the three mechanisms of movement of K to the plant roots. According to the work of *Barber et al. [3]*, diffusion is the major mechanism by which K reaches plant roots. Also, the significance of diffusion for K transport to plants increases with an increase in K requirement of the crops.
The rate of diffusion is influenced by the content of soil moisture and the amount of exchangeable K. As the effective volume of soil moisture decreases, the cross sectional area for K diffusion becomes smaller, the diffusion path to the roots becomes more tortuous owing to increase in air space; both factors tend to decrease the rate of K diffusion. Also, as the soil moisture content is reduced, the concentration of calcium, magnesium and potassium increases, but the concentration of calcium and magnesium increases faster than does the concentration of potassium. This results in a decreasing value of K/Ca + Mg with increasing soil moisture tension. According to *Jenne et al. [19]*, *Mederski* and *Wilson [22]* and *Branton et al. [8]*, plants with low moisture supply contain less K in their tissues. Whether K additions to the nutrient medium under such situations would induce larger moisture uptake by the stressed plants and help them to reduce transpirational losses has not been adequately investigated.

6. Movement of potassium within the soil profile

In arid and semi-arid areas, coarse textured soils alone may be particularly susceptible to losses of K through leaching. *Burns [10]* examined the distribution of added K in column studies on 3 soils – a coarse sand, a medium sand and a sandy loam. Mean displacements calculated from the difference between the initial and final distribution of K following the application of 100 kg K ha^{-1} were 1.6, 8.7 and 10.3 mm in the sandy loam, medium sand and coarse sand soils, respectively. Besides, the amount of residual K and the ionic composition of the soil solution also influenced the rate of leaching.
Intensity of rain appeared to be more important than the total amount of rain in leaching out K from the soil profile *[28]*. The arid and semi-arid areas which receive heavy monsoon showers may be subject to such periodical losses. *Singh* and *Sekhon [40]* observed that leaching loss of K was significant only when a rainy season crop

like maize was included in the cropping sequence. According to them, a balanced application of fertilizer increased K uptake by plants, reduced K saturation of the soil and thus K leaching down the profile. *Sparks et al. [41]* observed that downward movement of applied K could result in an accumulation of K in clayey sub-soil which could become available to plants unless root growth into the sub-soil was restricted by adverse chemical and physical properties. One may, therefore, generalize that losses of K by leaching from cropped fields are small except from soils which are sandy, poorly managed and receive rain of high intensity.

7. Crop response to potassium in soils of arid and semi-arid areas

As has been mentioned before, with low moisture in the soil, diffusion of K is slow and less K moves to the roots. At low moisture contents, plant roots absorb K mainly from their immediate vicinity. Increased amounts of K help to counteract the effects of reduced availability of native K. Adequate K enables the guard cells around the stomates to be more turgid so that the stomates open and close in response to rapidly changing transpiration conditions, thus reducing the transpira-

Table 3. Response of rainfed wheat to fertilizer potassium in some semi-arid tracts in India *[7]*

Soil	No. of Experiments	Response to indicated amount* of fertilizer K in kg grains/kg K_2O (kg K_2O per hectare)	
Mixed red and black		30	60
Satna (M.P.)	104	9.3	3.4
Sagar (M.P.)	20	10.6	5.8
Ujjain (M.P.)	20	3.9	2.2
Medium black			
Amravati (Maharashtra)	93	4.0	1.6
Nanded (Maharashtra)	40	4.1	2.4
Sangli (Maharashtra)	9	5.5	1.9

* 30 and 60 kg K_2O/ha was applied in addition to 60 kg N + 60 kg P_2O_5/ha and 90 kg N + 60 kg P_2O_5/ha, respectively.

Table 4. Changes in potassium levels in some Indian and Nigerian soils with and without potassium application during seven-eight years of continuous cropping *[1, 14]*.

Soil	Reduction in K-level (me/100 g)	
	Without K application	With K application
Typic Ustochrept (India)		
Ludhiana	0.18	0.10
Delhi	0.20	0.16
Oxic Paleustalf (Nigeria)	0.29	0.17

tion losses. Hence, although crop yields are relatively low in areas of low rainfall and, therefore, demands on native K also less, yet crops show considerable response to fertilizer K (Table 3). *Ghosh [14]* and *Adepetu et al. [1]* have described the changes in levels of soil K as a result of continuous cropping (Table 4).

8. Methods of soil analysis and predictability of crop response to potassium

The most popular method for estimation of K susceptible to absorption by plants is the K extracted by neutral normal ammonium acetate, which represents the sum of exchangeable and water soluble K. *Mackay* and *Russell [20]* observed very high correlation between exchangeable soil K values at the beginning of the experiments and the total yield of tops, without K. *Hunter* and *Pratt [18]* proposed extraction of soil with cold, dilute H_2SO_4 which removes about the same amount of K from most soils as does extraction with ammonium acetate. *Schachtschabel* and *Heinemann [33]* suggested determination of available K by extraction with 0.025 N $CaCl_2$. According to *Grimme* and *Németh [15]*, this extraction takes into consideration soil selectivity for K.

Wood and *DeTurk [43]* suggested extraction of soil with boiling normal HNO_3 which method has been used to estimate release of K from non-exchangeable forms. Data in Table 5 from *Jian-Chang et al. [16]* illustrate how low amounts of slowly available K, estimated by boiling in N HNO_3 for 10 minutes, are associated with large responses to K application. *Garman [13]* described a procedure to estimate K release rates by continuous leaching with dilute HCl. In the plot of cumulative K extracted against time (by a constant rate of leaching), exchangeable K is correlated with the initial linear portion of the curve with a steep-slope, and K release from non-exchangeable forms with the third part of the curve – a predominantly linear portion with a small slope. *Beckett [5, 6]* observed good correlation between K/Ca ratio and the K susceptible to absorption by plants. *Németh [25]* considered this association to be coincidental, owing to almost constant Ca values.

From a consideration of the dynamics of K in soils, it appears that neither the distribution of different forms of K in soils is well delineated, nor the rates of equilibra-

Table 5. Response of rice to K-fertilizer on soils containing different amounts of slowly available K *[16]* (pot experiment)

Slowly available K (mg/100 g)	No. of soils tested	Increase by K-dressing (%) 1st crop	2nd crop	3rd crop
8	6	236.5	*	*
8– 20	4	117.4	1870	*
20– 35	6	53.6	392	*
35– 50	5	15.8	98.0	631
50– 75	5	4.3	72.8	594
75–120	6	2.8	57.2	187
>120	3	0	10.6	39.6

* Indicates no growth in control treatment.

tion between those forms in different soils adequately examined. There is fair agreement, however, that close correlation between exchangeable K and K uptake by plants exists in soils of similar clay contents and uniform clay composition *[21, 26, 38]* and that methods capable of determining both the K concentration of the soil solution and buffering of the K concentration in the course of the growing period provide most significant correlations with K uptake. *Németh [25]* has proposed the Electro-Ultrafiltration method and discussed how a coordinated increase of voltage and temperature allows a better determination of nutrient reserves.

The determination of a reliable estimate of available K in soils is beset with two problems (i) there may be a lack of response to applied K on soils containing low or medium levels of exchangeable K, (ii) very considerable response to applied K may be obtained on soils that are very high or high in K.

It appears logical to do more systematic work with bench-mark soils where estimates of available K are periodically obtained, K dynamics in the soils is investigated, and yield responses to fertilizer K are measured in field experiments on a sufficient number of representative soils.

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Micronutrients in Arid and Semi-arid Areas: Levels in Soils and Plants and the Need for Fertilizers with Reference to Egypt

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Summary

The use of irrigation enabling improved higher yielding cultivars to be grown with increased usage of major element fertilizers has led to the emergence of micronutrient deficiency as a factor limiting yield. Factors affecting the availability of Zn, Mn, Fe and Cu are discussed. The relative value of soil and leaf analysis in diagnosis of micronutrient deficiency is discussed and their limitations exposed with reference to Egypt where micronutrient deficiencies are widespread, although analysis often indicates that deficiency would not be expected. Application of micronutrient sprays has resulted in appreciable increases in crop yield above the levels normally obtained in practice.

1. Introduction

The soils of the arid and semi-arid areas are of increasing agricultural importance but their inherent fertility is low. While micronutrient supply may not be a yield limiting factor in rain-fed crops because yields are limited by available water, irrigation imposes a strain on soil resources by enabling higher yielding cultivars to be grown and leading to a general intensification of agriculture with greatly increased offtakes of nutrients. The higher yields are supported by the use of NPK fertilizers while the use of farmyard manure is declining so that there is increasing concern that crop requirements for micronutrients may not be met. The micronutrient problem has in recent years received increasing attention both nationally and internationally *(Sillanpää [1982])* and in Egypt *(Naguib and El-Fouly [1974]; El-Fouly [1979])*. It is generally recognized that soil and leaf analyses are useful tools for diagnosing micronutrient deficiency while visual symptoms are also useful in the field. The micronutrient status of crops is also affected by agronomic practices.

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2. Micronutrients in soils

It is well known (Figure 1) that micronutrient availability is much affected by soil pH and that in alkaline soils, with which we are much concerned in Egypt, the availability of zinc, manganese, iron and copper is reduced. This paper concentrates on these four elements.

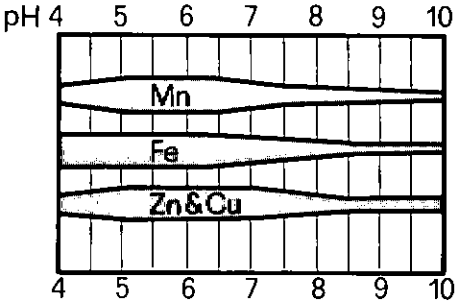

Fig. 1. Effect of soil pH on availability of nutrients.

2.1 Zinc

Zinc occurs in various forms in soils, in primary silicates, clay minerals, oxides and organic matter *(Amberger [1974a])*. In high pH soils, amounts of available Zn are low, Zn being precipitated as Zn(OH) and $CaZn(OH)_4$ *(Mortvedt and Cunningham [1971])*. Zn availability is low in calcareous soils presumably due to precipitation of zinc carbonate *(Kalbani et al. [1978])*. Soil texture, organic matter content, electrical conductivity and to a lesser extent CEC also affect its availability *(Sillanpää [1982])*. High P levels can lead to severe Zn deficiency. In the presence of high available phosphate, zinc might be partly precipitated as $Zn_3(PO_4)_2 \cdot 4H_2O$. While reactions between phosphate and zinc cannot be neglected *(Ellis [1977])*, the main reason for the unavailability of Zn under these conditions is likely to be physiological *(Hagen and Tucker [1982])*.

2.2 Manganese

It is widely accepted that manganese is taken up by plants in the divalent form (Mn^{++}) which is found in the soil solution or adsorbed on the exchange complex *(Anderson and Ohke [1977])*. Trivalent Mn occurs as unstable oxides or hydroxides and the fully oxidized form as stable oxides which are insoluble *(Hagen and Tucker [1982])*. Plant available Mn is also taken to be the so-called 'active Mn' which is the sum of the exchangeable and easily reducible forms or that fraction extracted with chelating agents *(Aubert and Pinta [1977]; Amberger [1974b])*. Clearly Mn availability is much affected by oxidation-reduction conditions in the soil and *Hagen and Tucker [1982]* concluded that Mn deficiency would occur in well aerated alkaline and calcareous soils which occur widely in arid and semi-arid regions. Soil texture, organic matter content and electrical conductivity also affect Mn availahility *(Anderson and Ohki [1977]; Sillanpää [1982])*.

2.3 Iron

Total iron content of soils is usually high but deficiencies occur through the effect of conditions which affect uptake by the plant. *Mortvedt et al. [1977]* discuss the forms in which iron occurs and conclude that it is ferrous iron which is available to the plant so that factors which affect the oxidation-reduction processes in the soil such as pH, soil aeration (drainage) and $CaCO_3$ content also affect iron availability. Iron availahility is thus reduced in arid and semi-arid soils of high pH rich in $CaCO_3$; in irrigated soils availability varies with soil aeration and the effectiveness of drainage. It is the free or active $CaCO_3$ which releases bicarbonate ions into the soil solution which decreases the solubility of iron *(Hagen and Tucker [1982])*. Soil texture and organic matter content also affect iron availahility *(Sillanpää [1982])*.

2.4 Copper

In arid climates, copper occurs as sulphate, chloride and carbonate which are soluble only under acid, oxidizing conditions *(Amberger [1974c])*. Availahle Cu occurs mainly in the clay fraction *(Khan [1979])* and irrigated sandy soils are likely to be low in available Cu. Increasing organic matter, rising texture index, increasing CEC and increasing electrical conductivity all increase availability of Cu *(Sillanpää [1982])*.

Table I. Major soil conditions affecting micronutrients availability in respect to alkaline soil in arid and semi-arid regions.

	Loss through leaching	Promoting availability	Promoting unavailability
Zinc	No problem	Microbial action – absorption on clay particles – medium soil texture.	High pH – phosphate – carbonate – fine and coarse soil texture – E.C.
Manganese	Mn^{++} from permeable poorly oxidized soils	High O.M. – high phosphorus content – fine soil texture.	High pH – highly oxidized soils – high E.C.
Iron	No problem	Microbial action – fine soil texture – high O.M.	High pH – wet soils high soluble phosphate – high calcium carbonate content.
Copper	In sandy over irrigated soils	Microbial action – fine soil texture – high cation exchange capacity – high E.C.	High pH – low organic matter content.

Modified according to data available after *Large* [1976]; *Sillanpää [1982]; El-Fouly et al. [unpublished data]*.

Table 2. Total and DTPA extractable micronutrient contents in different soils in Egypt (ppm)

		Nile clay (Nile mud)	Sandy soil
Zn	Total	348	52
	DTPA	4–18	0.3–0.9
Mn	Total	982	104
	DTPA	66–140	2–2.7
Fe	Total	18 364	4826
	DTPA	90–200	0.4–1.5
Cu	Total	198	50
	DTPA	7–18	0.4–0.6

Total contents *(Raafat et al [1981])*.

Table 3. Varying DTPA extractable, micronutrient contents with soil texture (Egyptian soils and pH over 7.5)

Texture	Zn	Mn	Fe	Cu
Nile clay	4–18	66–140	90–200	7–18
Clay loam (El-Minia) Nile valley	0.3–1.5	15–40	18–40	2–7
Clay loam (El-Menofia) Nile Delta	0.5–1.5	11–35	7–14	3–4
Silty loam El-Fayoum	1–2	6–7	6.0–6.5	0.4–0.7
Sand South Tahrir	0.3–0.9	2.0–2.7	0.4–1.5	0.4–0.6

Table 1 summarizes the factors affecting availability of Zn, Mn, Fe and Cu. Usually only a small fraction of the total micronutrient in a soil is available and Tables 2 and 3 give examples from Egyptian soils.

3. Determination of plant micronutrient requirements

Possible diagnostic methods are:
Measurement of available micronutrient content of soil and of other soil factors which influence availability,
Measurement of plant uptake (plant analysis),
Visual deficiency or toxicity symptoms.

3.1 Soil analysis

Numerous extractants, some designed to extract one specific element, others to extract more than one in one operation, have been tried, including salt solutions, acids, acid mixtures and chelating agents. Preference would obviously he given in routine analysis to an agent which extracts more than one element. At the start of the Egypto-German project on micronutrients and plant nutrition various methods were tried on a range of soils *(Hassanien et al. [1980])* and it was found that the DTPA metbod as developed by *Lindsay and Norvell [1969]* was the most suitable for extracting Zn, Mn, Fe and Cu in one operation. The method has also been used by *Wallace [1979]* in Lybia and *Sillanpää [1982]* for arid and semi-arid soils from various parts of the world. More recently, *Wolf [1982a]* has reported on a similar extractant.

Table 4. DTPA extracted micronutrients contents (ppm) in alluvial soils at different locations (0–30 cm) *(El-Fouly et al. [1983])*

	Assiut	Minia	Qaliubia	Monoufia	Dakahlia
Zn	1.9*	1.5**	1.3**	1.4**	2.1*
Mn	136	28*	4**	14**	31
Fe	42	21	10*	24	34
Cu	4.9	4.7	4.5	3.6	4.4

* Low
** Deficient

Table 5. DTPA extracted micronutrient contents (ppm) in sandy soils (0–30 cm). *(El-Fouly et al. [1983])*

	South Tahrir	Ismailia	Minia
Zn	1.7*	1.6*	1.5**
Mn	5.1**	10.5**	3.5**
Fe	3.6**	13.0	4.8**
Cu	1.7	3.0	1.0*

* Low
** Deficient

Table 6. DTPA extracted micronutrient contents (ppm) in calcareous soils (0–30 cm). *(El-Fouly et al. [1983])*

	Mariut	North Tahrir	Gianaclis	Nobaseed
Zn	3.3	2.9	2.8	1.2**
Mn	17.0**	16.0**	12.0**	2.8**
Fe	9.3*	10.3*	8.0*	7.1*
Cu	2.6	1.7	2.4	0.5**

* Low
** Deficient

Tables 4–6 give data obtained by this method for alluvial, sandy and calcareous Egyptian soils with indications of their status in relation to critical levels established after consultation of different authors *(El-Fouly et al. [1983])*. As mentioned above, the measurement of texture, organic matter, calcium carbonate content and pH as well as major element content can be of assistance in the interpretation of results.

3.2 Leaf analysis

Micronutrient uptake by the plant as indicated by leaf analysis is a good indicator of availability, the results being related to so-called 'critical values'. It is important that the methods used should be standardized if results are to be reproducible and used for comparative purposes. Samples must be taken at a defined stage of plant development which may vary from crop to crop and from a carefully defined part of the plant *(Bowen [1978])*. A full discussion of the use of leaf analysis in diagnosis has been published recently by *Wolf [1982b]*.

3.3 Interpretation of soil and leaf analysis

Where soil analysis indicates levels below those needed for maximum crop production interpretation is straightforward as it can be taken that there is a deficiency. However, if the values found are higher than the critical value this does not necessarily indicate sufficiency as there are many soil and environmental factors which affect uptake. Further, the accepted critical values may not be of universal application and may need varying according to soil type and crop. Even cultivars differ in their ability to take up micronutrients. *Mortvedt et al. [1972]* classified crops and cultivars according to their ability to take up iron.

Leaf analysis, on the other hand, does measure actual uptake by the plant and should therefore give an indication of actual availability. Critical values indicating sufficiency or deficiency have been established but these are, as yet, far from perfect as knowledge of varietal differences is incomplete. Uptake can vary greatly between cultivars *(Takker [1976])*. As an example, Table 7 shows micronutrient contents in two maize cultivars grown under identical conditions in Egypt; clearly the same critical value cannot apply to both. It has even been found *(Hagen and Tucker [1982])* that chlorotic plants showed higher Fe contents than normal plants.

Micronutrients occur in plants in different forms which differ as to physiological activity *(Fawzi and Bussler [1980]; Ghoneim and Bussler [1980])* so that total uptake could give a misleading indication of physiological activity. One must also take into account the dilution effect in interpreting results for vigorous, well grown plants can show micronutrient contents below those of stunted ones. It is necessary in interpretation to have a full knowledge of growing conditions.

Table 7. Comparison between the micronutrient contents of leaves of two maize varieties (ppm)

	Zn	Mn	Cu
Low yielding local variety	37	51	9
High yielding hybrid	123	83	22

3.4 Soil analysis vs. plant analysis

Sillanpää [1982] concluded in his global study that plant analysis is theoretically more reliable than soil analysis and he suggested that soil data should be corrected by reference to other soil data but, in Egypt, with alkaline soils varying little in pH, applying such corrections did not improve correlation between soil and plant analysis.

Table 8. Mn contents of soils of different locations and corn grown on them (ppm)

	Mariut	N. Tahrir	N. Nubaria
Soil	12*	7**	14*
Leaf	101	49	149

* Low
** Deficient

Table 9. Nutritional status of different crops (according to leaf analysis) grown on the same soil. Kafr El-Khadra-Loamy soil

	Soil analysis 0–30 cm	Leaf analysis		
		Maize	Clover	Wheat
Zn	Deficient	Intermediate	Low	Low
Mn	Low	Low/sufficient	Low	Deficient/Low
Fe	High	Intermediate	Intermediate	Intermediate
Cu	High	—	Intermediate	Intermediate

Table 10. Evaluation of nutritional status of wheat (soil and plant) 400 samples from 1000 fed. representing 100 000 fed. (acre) in Dakahlia (1981–1982)

		Percentage of samples				
		Deficient	Low	Intermed.	High	Very high
Zn	Plant	26.4	43.0	25.0	4.2	1.4
	Soil	46.0	27.0	24.3	2.7	0
Mn	Plant	21.4	29.3	49.3	0	0
	Soil	0	5.3	10.5	71.0	13.2
Fe	Plant	12.5	35.0	48.7	3.8	0
	Soil	0	17.7	14.7	32.3	35.3
Cu	Plant	0	6.1	43.2	49.2	1.5
	Soil	0	21.6	45.9	32.4	0

Table 8 concerning Mn content of maize from different places in Egypt shows that though soil values were considered low to deficient, leaf contents indicated sufficiency. Table 9 shows how different crops grown on the same soil react to varying soil micronutrient levels. Table 10 shows that wheat is relatively inefficient in making use of available Mn and Fe but can take up Cu in greater quantity than would be expected from soil analysis.

Sillanpää [1982] pointed out that Fe deficiency would not be expected to occur in Egypt and we would agree that results for soil and leaf Fe contents would support this view. However, under field conditions, almost all crops in Egypt can suffer from severe Fe deficiency, presumably because not all the iron found in the plant is physiologically active. Various methods have been tried for indicating the physiological status of micronutrients *(Fawzi and Bussler [1980]; Ghoneim and Bussler [1980])* but no practical routine method has been evolved.

3.5 Deficiency symptoms

As would be expected, since all the micronutrient detected in a plant by leaf analysis is not necessarily physiologically active, visual symptoms of deficiency do occur in plants which, according to analysis, contain sufficient of the relevant element. Field observation of deficiency symptoms is therefore important as shown by the case of iron in Egypt already discussed.

3.6 Agronomic practices

Agronomic practices greatly affect the interpretation of soil and leaf analysis and thus the need for micronutrient fertilizers *(Bergmann and Neubert [1976])*, major factors being:

- Cultivar,
- Availability of major soil nutrients, fertilizers applied and method of application; inter-element interactions,
- Water availability, soil aeration, waterlogging and irrigation method,
- Organic manures,
- Cropping intensity.

The example given in Table 8 illustrates this point. Normally when soil content is low or deficient it would be expected that leaf content would be similarly low, but, in this case, where the cultivar was unsuited to local conditions growth was severely limited and yield very low. Superficial consideration of leaf Mn content would indicate no need for Mn fertilizer but when a better variety was used with good agronomic conditions leaf Mn declined and clearly indicated the need for Mn fertilizer.

4. Effect of applying micronutrients

Wallace et al. [1978] found little indication of micronutrient deficiency in Egypt from leaf analysis but evidence has since accumulated that serious micronutrient prohlems do occur:

- Results throughout the course of the Egypto-German project *(El-Fouly et al. [1983]; Amberger [1982])*.
- Other information obtained locally *(Naguib and El-Fouly [1974])*.
- *Sillanpää's [1982]* study.
- The widespread observation of deficiency symptoms in all crops throughout the country and increasing from year to year.

Spray application of micronutrient compounds containing Zn, Mn, Fe in various ratios designed according to soil and leaf analysis and plant needs have given encouraging yield increases over average farmer's yields *(El-Fouly et al. [1983])* and Table 11 shows the range of increases obtained in various years and locations. Other groups have reported similar results in rice (using Zn, Fe and Mn) *(Mawardi et al. [1980]*, cotton with Zn, Mn and/or Fe *(Monged et al. [1980]; Farghal [1973]; Abu-Khadra and Zahran [1978])*.

Table 11. Yield increase on large scale application with micronutrients, over farmers average

Crop	Yield increase %
Citrus:	
Balady	10–20
Navel	12–20
Mango	14–20
Peaches	10–15
Pears	10–15
Potatoes	8–22
Groundnuts:	
Sandy soils	over 100
Alluvial soils	10–15
Maize	
High yielding varieties	11–30
Soybeans	20–30

Acknowledgement

Some of the data reported in this paper was collected from the unpublished internal reports of the Egypto-German Project *Micronutrients and Plant Nutrition Problems in Egypt*, carried out under the leadership of Prof. Dr. *A. Amberger*, Director, Institute for Plant Nutrition, TU-Munich FRG. The project was executed by the *National Research Centre (NRC)*, Cairo; and financially supported by the *German Agency for Technical Cooperation (GTZ)* and the *Egyptian Academy of Scientific Research and Technology (ASRT)*.

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Co-ordinator's Report on the 2nd Session

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Nutrient Dynamics in Arid and Semi-Arid Areas

In arid and semi-arid climates evaporation is by definition in most periods of the year higher than precipitation. Under rainfed conditions water is in many cases the limiting growth factor. This refers equally to the amount and distribution of water and has many implications for crop production:

At low soil moisture regimes the rate of nutrient release from soil particles as well as the rate of nutrient transport to the root is decreased. Depletion of the rhizosphere in water leads to increases in air space, and nutrient transport is restricted within the thin films of soil matrix.

The prevalent upward movement of water brings about an accumulation of ions and salts in the topsoil. High pH values associated with lower P and micronutrient availability are the consequence. Similarly, ion balances are disturbed and the ratios of K: (Ca + Mg) or K:Na are generally low.

Nevertheless, erratic rainfall can cause some nutrient losses by leaching. As *Chiang et al.* have pointed out in their paper on 'Soil nitrogen mineralization and nitrification under Moroccan conditions,' the topsoil can contain about 30 ppm inorganic N in a dry winter season, being roughly comparable to 90 kg N/ha. If, however, after the summer drought light rainfalls occur these will induce mineralization leading to a NO_3-flush which is subject to being leached hy the heavier rains in the winter.

From an agronomic point of view nutrient requirements of crops adapted to such climates and nutrient availability in the soils including fertilizer needs can be determined empirically by short and long-term field experiments. Although they have the great advantage of integrating all climatic factors, soil conditions and hushandry techniques with the genetic yield potential of the crop in mind, the variability of yields between fields, regions and seasons is so high that more sophisticated approaches in describing the effects and interactions of growth factors are needed.

Session 2 therefore emphasized the nutrient dynamics in arid and semi-arid soils. In the main paper on 'Nutrient mobility, root growth and root-induced changes in the rhizosphere as factors of nutrient availability in soils of semi-arid and arid areas,' *Marschner* first explained mass-flow and diffusion as transport processes for

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nutrients from the bulk soil through the rhizosphere to the root surface. The contribution of each to the nutrient supply is quite variable depending upon transpiration, species and soil moisture. For P and K the concentration in the soil solution is rather low. Therefore diffusion is the most important mechanism for supplying both these macronutrients. Diffusion can be stimulated by building a sufficiently high concentration gradient between bulk soil and root surface. This could be achieved by higher fertilizer inputs. But the plant itself contributes to such a concentration gradient by extending roots and root hairs. Thus the rhizospheric soil is much more depleted for nutrients than the bulk soil. Recent data show that K concentration at the root surface can be as low as 2–3 μM and that the depletion zone for P corresponds with the length of root hairs. Extent and distance of nutrient depletion within the rhizosphere depend of course upon soil texture, the P- or K-buffer capacity of the soil and the root system of the crop. In addition roots are not only sites of nutrient absorption, they also influence the rhizospheric environment. Crop species with a preferential cation uptake lower the pH in the rhizosphere in the same way as can be achieved by NH_4^+ – as compared to NO_3-supply. In calcareous soils this pH decrease will improve P availability. Adaptations to poor soils can also be achieved by exudation of organic molecules, mucigels, 'proteoid roots' and mycorrhizal infection whereby unavailable plant nutrients can be mobilized directly or through microbial activity.
Low soil moisture in surface soils of semi-arid and arid areas also implies that the contribution of subsoil to the nutrition of crops might be higher than in humid areas. Data by *Harmsen* and *Shepherd* on nitrogen and phosphorus in North Syrian soils showed 1 ppm available P in a soil depth up to 1.50 m and results by *Ghanem et al.* from a research project on Moroccan soils gave between 16 and 140 ppm exchangeable K in 80–100 cm depth. This would support such a statement. Support, however, is no proof and only detailed research will bring us further in quantifying the nutrient supply from the subsoil.

The enumeration of soil and crop characteristics affecting nutrient dynamics and nutrient availability raises doubts as to the value of conventional soil testing as a basis for fertilizer recommendations.
But extension officers need at least soil analysis as a tool in their important work. Nutrients occur in the soil generally in three pools: the soil solution, the labile pool and the reserve pool. Sharp separations between these pools cannot be made due to the many transitory states of soil nutrients according to soil chemistry, physics and mineralogy. Consequently more than one method must be used, and also the time factor in nutrient desorption should be taken into consideration if a better description of the actual as well as of the potential availability of a nutrient is required.
For phosphorus this seems to be done routinely in Morocco according to *Squalli* and *Nadir* who discussed the phosphate dynamics in arid and semi-arid soils. The available P is determined by water extraction, the labile P by using Na-acetate as an extractant (pH 4.8, *Morgan-Barbier* method) and the reserve P by 1% citric acid – *Dyer)*. If labile P and reserve P are both low a double maintenance P fertilizer recommendation is given. In this way the soil P level is built up continuously until the extent of P-fixation – which can be equivalent to 2.3 t P_2O_5/ ha – has reached a level which can be tolerated.

Several extractants have also been worked out for the analysis of exchangeable and non-exchangeable K as *Sekhon* has pointed out in his paper on potassium dynamics. So far, however, only NH_4-acetate is used routinely and the data are interpreted in relation to clay content and sometimes types of clay.
The equally complex nature of nitrogen in the soil is very difficult to describe. *Chiang et al.* are using incubation experiments and simulation models in order to quantify the amount of mineralizable nitrogen and the rate of mineralization. Only the future will show if computers will bring us a step forward in making recommendations for nitrogen more reliable.
There are also serious problems in plant production in the arid and semi-arid areas in the sector of micronutrients (*El-Fouly:* 'Micronutrients in arid and semi-arid areas: levels in soils and plants and need for fertilizers'). pH values around 8 cause low availability of Fe, Mn, Cu and Zn. Soil analysis has been shown to be inferior to leaf analysis, which also has some limitations, and soil application to be inferior to foliar sprays of micronutrients, nowadays primarily in the form of chelates.

In summary it can be said, that the principles of nutrient dynamics are independent of the climatic region. The intensity of nutrient release and nutrient transport to the root, however, is lower in the arid and semi-arid regions. Under rainfed agriculture, crops with a large and deep root system with root hairs seem to be the best adapted.

Chairman of the 3rd Session

Prof. Dr. *Dj. B. Jelenič*, Faculty of Agriculture, University of Belgrade/Yugoslavia; member of the Scientific Board of the International Potash Institute

3rd Session

Rainfed Farming Systems

Nutrient Balances in Rainfed Farming Systems in Arid and Semi-Arid Regions

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Summary

Following a general discussion of the practical difficulties in measuring the various terms of the nutrient balance in rainfed systems, examples are given from two typical rotations: cotton – sorghum and millet – groundnut. The results show that in order to arrive at a meaningful assessment of the development of fertility it is necessary to take into account most of the terms in the balance and particularly net mineralization, replenishment of the available pool from the mineral reserve, leaching, loss of N by volatilization and additions from the atmosphere. The balances show that the maintenance of soil fertility in these regions depends upon the control of their organic matter and nitrogen status, adjustment of potassium fertilizer application to the rotation taking into account additions of manures and fertilizers and maintenance of the calcium and magnesium status which are much affected by leaching.

1. Introduction

The world is faced by the problems of population growth, malnutrition and underdevelopment. In a recent analysis of the position, the *World Bank [1980]* concludes that, while there may be no direct connection between the natural resources of a country and its economic situation, it is no mere coincidence that most of the poor countries lie within the tropics and, furthermore that a great number of the most disadvantaged of the world's people inhabit the arid and semi-arid regions of Africa and Asia. These regions, the least well endowed with natural resources, have been undergoing a change in recent years. Whether these areas are in dry tropical Africa *(Tourte* and *Moomaw [1977]*, in Latin America *(Sanchez [1976])* or in Asia *(Kanwar)*, the problems of agriculture have taken on a new meaning because, under increasing demographic pressure, the 'old equilibrium' – population/natural soil fertility/food prodution – upon which traditional subsistence farming was based is being increasingly disturbed. The necessary change from subsistence farming, formerly stable and satisfactory in most respects, to a more intensive agriculture entails significant stress. Ecological disequilibrium is not slow to manifest itself in the physically and biologically unstable arid and semi-arid tropics; this is a part of the inheritance of such areas *Charreau [1972])*. Several lines of research have now been

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proposed to test cropping systems which, while being suited to the constraints of the physical and human environment, would result in increased production through better exploitation of the natural resources; the principal constraint is water *(Krantz* and *Kampen [1978])*.

Nevertheless, as *Greenland [1970]* says, no agricultural system can be considered stable or satisfactory unless it ensures the maintenance or improvement of soil fertility. Thus we must be careful not to advocate systems which, though they may be highly productive and profitable in the short term, in the medium or long term result in mineral imbalance. Intensive systems can easily give rise to such problems. While there is no point in striving for indefinite enrichment of the soil, there can be no possible advantage in systematically running down soil fertility *(Barbier [1968])*.

The acceptance of such views calls for a knowledge of the gains and losses of each plant nutrient imposed by the system. While such balances are easy to establish for intensive farming in temperate climates, largely because fertilizers are widely used and crops are homogenous, it is far otherwise for rainfed cropping in the arid and semi-arid areas, apart from the difficulties of evaluating these balances under the variable conditions of soil, climate and cropping characteristic of the arid areas; aspects of balance which would be considered of minor importance in other areas are of more than negligible importance. For these reasons it is appropriate that we should review existing knowledge of these matters in the dry tropical areas of Africa and other parts of the world as regards the extent of nutrient gains and losses in the main rainfed farming systems of such areas and should study the fertility trends in soils which result.

2. Nutrient balances – general considerations

Before specifying the nature and size of the terms ('incomes' or credit and 'expenditure' or debit) of the balance of each nutrient, we have to define clearly at what point the balance should be struck.

2.1 Agricultural systems and nutrient balance (after *Frissel [1978]*)

The cropping system is only a part of the whole system of agriculture. In *Frissel*'s model there are three basic constituents: soil, plant, animal. The dynamics of nutrients within any agricultural system depend not only on these three basic factors but also upon external conditions (energy input, water, etc.). The nutrient balance can be calculated on an overall basis or for each of the constituents of the whole. The object of studying the balances is to find out what effects over time they have on the soil. For this purpose it is necessary to consider soil nutrient supply as being made up of three pools:

- Pool A – nutrients available to plants
- Pool B – nutrients associated with soil organic matter
- Pool C – the mineral reserves of the soil.

A complete study of nutrient balance must take account of the effects on these three of inputs and losses in the light of external factors and internal fluxes by which they are re-distributed. Figure 1 is adapted from *Frissel*'s scheme.

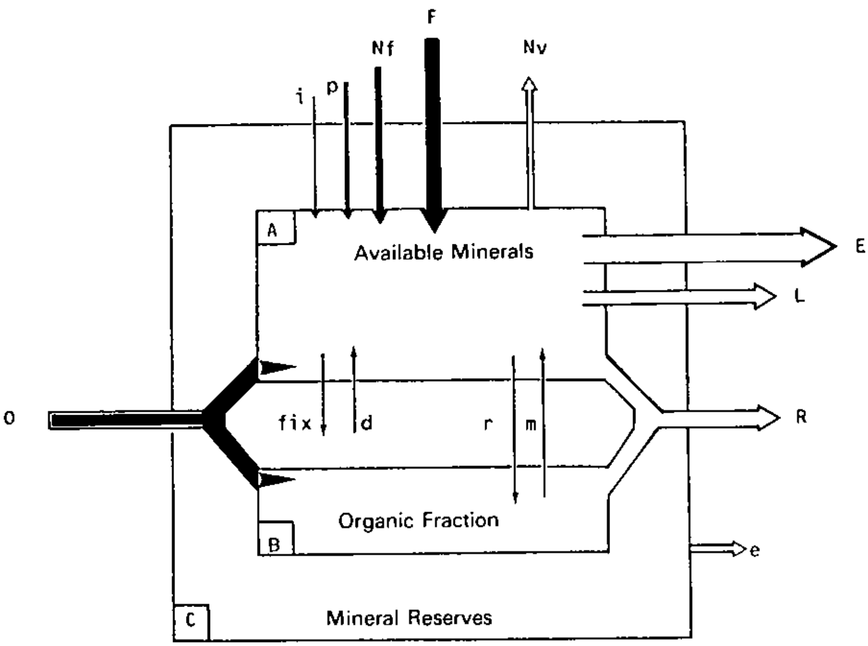

Fig. 1. Schematic representation of nutrient flux in the soil

Income
F Fertilizer application
O Organic additions (crop residues, farmyard manure, compost, etc.)
i Irrigation and flood water
p Rainfall and dust
Nf Biological fixation of N_2

Expenditure
E Nutrient removal in crop
L Leaching losses
R Erosion and run-off
e Wind erosion
Nv Volatilization of N (denitrification, volat. of NH_3)

Internal flux
d enrichment by alteration and dissolution of soil minerals
fix irreversible fixation (P and K)
m mineralization of organic matter
r reorganization

The algebraic sum of the inputs and removals should indicate whether soil fertility is being maintained, improved or degraded. There are two difficulties in calculating the balance: correct measurement of each term of the balance for each nutrient on the one hand and the réconciliation of the values thus found with analysis for nutrient and organic matter content of the soil before and after cropping on the other. There is a difference of several orders of magnitude between the fluxes (tens of kg/ha) and soil stocks (tonnes per hectare) which makes this reconciliation very delicate and, further, as we shall show, our knowledge of soil science and plant nutrition is often insufficient to enable us to say with any precision what properly belongs in each of the pools A, B and C.

2.2 Nutrient additions

2.2.1 Fertilizers (F)

This term in the balance should pose no great problem, but so far as concerns information obtained, we often find that though the quantities of N, P and K applied are accurately known there is a lack of knowledge about the secondary elements with which they are associated. In this connection it should be pointed out that in recent years the growing use of high analysis complex fertilizers based on ammonium phosphate and KCl has resulted in a decrease in the amounts of calcium and sulphur applied. Further, since the fertilizers used in these countries come from various origins, depending on market conditions, bilateral aid, etc., they are not of constant and known composition. In any case, with the exception of Egypt, where agriculture, thanks to plentiful irrigation is intensive, fertilizer usage in the arid and semi-arid areas is on a very low level (Table 1)

Table 1. Total consumption of fertilizer ($N + P_2O_5 + K_2O$) in kg/ha of agricultural land *(FAO statistics [1979])*

	$N + P_2O_5 + K_2O$ (kg/ha)		$N + P_2O_5 + K_2O$ (kg/ha)
Algeria	4.0	Brazil	16.1
Morocco	11.0	India	27.6
Tunisia	8.0	Europe	141.7
Egypt	212.1	Africa	1.5
Cameroun	2.2	Latin America	9.7
Upper Volta	0.9		
Niger	0.2		
Senegal	2.7		

2.2.2 Organic manures and residues (O)

Additions by this route are extremely variable in both quantity and quality. Though there are many references to the nutrient content of these materials, which are useful (*e.g.* FAO Bulletins Nos 27 and 43) the variability of crop residues, faeces, manures, etc., is emphasised for example by *Richard [1976]* who found the following values for manures in the cotton-growing zone of Mali:

Table 2. Mineral content of farmyard manure in the cotton zone of Mali

	% in dry matter		
Element	Average	Standard error	Extreme values
N	1.18	0.64	0 –2.05
P_2O_5	0.74	0.35	0.31–1.45
K_2O	1.83	1.17	0.31–5.02
S	0.15	0.06	0.05–0.23
CaO	1.24	0.59	0.28–2.73
MgO	0.69	0.36	0.18–1.33

Gigou [1982] points out that the savannah grasses of North Cameroun usually have very low nutrient contents (0.11% N) and are consequently of little manurial value. However, the main problem with these residues is not so much their quality as their limited availability. In a survey over 3 seasons (1978–80) workers at *CNRA* Bambey found that the quantities available for use as manure were negligible or, at best, very little.

Further south in less dry areas, somewhat more is available but its use is hampered by lack of transport on the farms.

It can only be concluded, in agreement with many writers *(e.g.* FAO Bulletins already cited) that, while organic residues are not negligible as sources of nutrients (and their utilization in biogas production further increases their value, *Sedogo [1981])* their practical impact in the nutrient balance of cultivated soils unhappily remains very limited in arid and semi-arid zones.

Table 3. Availability of crop residues in central Senegal (after *Allard et al. [1983])*

Zone	Crop	Straw t/ha	Collected %	Use	Availability
N groundnut area	Groundnut	0.7–1.0	100	Animals	Nil
	Millet	1.0–2.0	50–100	Domestic + animals	Nil
	Fallow	0.4–3.0	50–100	Domestic + animals	Nil
S groundnut area	Groundnut	0.7–1.7	100	Animals + sale	Nil
	Millet	1.7–3.0	10– 15	Domestic	1.0–2.5
	Fallow	0.4–3.0	10– 15	Domestic	0.2–2.5

2.2.3 Additions from the atmosphere (p)

These have been the subject of many studies, particularly in Australia *(Wetselaar et al. [1963]; Briner et al. [1977])* and West Africa *(Jones [1972]; Roose [1980]; Piéri [1982]),* whose findings are summarized in Table 4.

Generally speaking, these additions appear to depend upon proximity to the sea or to industrial complexes *(e.g.* cement works in Senegal) whose fumes can be carried several hundred kilometres by the prevailing winds. Some authors *(Wetselaar [1963])* consider that the wind, by picking up dusts in certain areas and depositing them in rainfall in others, effects territorial redistribution. While the amounts of

Table 4. Nutrient additions by rainfall

Country	Site (rainfall mm)	Nutrients, kg/ha per year N	Ca	Mg	Na	K	P	Si	Cl	SO_4
Australia (Victoria) (** Wetselaar [1963]* and *Briner [1977]*)	24 900	1*	3.7	2.1	20.7	5.1	5.9	20.5	25.4	15.8
Nigeria (Samaru) (*Jones [1972]*)	Samaru (1218.5)	4.6								
Ivory Coast (Kor.) (*Roose [1980]*)	Korhogo (1350)	12.2	25.7	1.4	2	4.1	1.3	4.4	4.1	13.5
Haute Volta (Saria) (*Roose [1980]*)	Saria (860)	5.4	18.4	2.7	1	3.4	2.1	2.6	2.8	13.8
Senegal (*Piéri [1982]*)	Bambey, Nioro Sefa, Djibelor 1+2 (av. 836)	0.5	17.1	2.7	10.9	4.1	1.3	Tr	17.2	13.9

nitrogen involved are very variable it is true to say that the amounts of K, Mg and P are always very small (except for cases of contamination by the spreading of P fertilizers noted by *Briner).* It is quite surprising that additions of calcium are far from negligible in West Africa being of the same order as crop removal by the main cereals in dry areas.

2.3 Nutrient offtakes

2.3.1 Nutrient uptake by crops (E)

Several recent results appertaining to millet, sorghum, maize, upland rice cotton, groundnut and soya are summarised in the appendix. These figures demonstrate that the values are so variable that mean values are of little practical significance. This is usually true for crop removals of N and K and in the case of cereals for Ca and Mg which can vary according to location and conditions by a factor of 3 (in kg/ha per tonne product harvested). For this reason, most authors give a mean value with the range *(Jones [1976]; Arrivets [1976]).* While crop variety has some effect on uptakes it does not seem to be very important.

N'Diaye [1978] in Senegal showed that there was a good relationship between total uptake and crop yield of millet and groundnuts on peasant farms. For 27 plots of millet whose yields varied from 100 to 1700 kg/ha grain, there was a correlation ($r = +0.8$) between N, P and K uptake and total produce harvested. The same was found for 25 groundnut crops and this result agrees well with IRHO findings *(Gillier [1964, 1966]).* However, such agreement is far from being general, notably with cotton as demonstrated by *IRCT* in Cameroun *(Déat et al. [1976]).*

In the areas where cotton is grown, water availability varies greatly from year to year and even from place to place in the same field in the same year so that the relationship between yield of harvested product and total biomass produced is extremely variable (from 1971 to 1974 the proportion varied between 18.0 and 63.7%). *Arrivets*

Table 5. Correlation between cotton yield and nutrient removal by the above-ground parts of cotton. Maroua Cameroun 1972.

	N	S	P	K	Ca	Mg
r	0.30	0.46	0.35	0.13	–0.04	0.05
r at probability 0.05			0.632			

[1976] comparing two sites (A) a deep soil and (B) a soil on the ferruginous crust with low moisture capacity found the following: at A 3300 kg/ha grain with a grain/straw ratio of 31% and at B 630 kg/ha grain with a grain/straw ratio of only 12%. Great differences are also found in nutrient content of harvested produce according to seasonal conditions and in lesser degree to chemical analysis of the soil. Tables 6 and 7 illustrate the well-known effects of fertilizer and manurial treatment on the analysis of straw and grain.

Table 6. Effect of K fertilizer on yield and percent K in millet straw *(Piéri [1982])*

Fertilization, kg/year	0	NP	NPK_{30}	NPK_{60}	NPK_{90}
Yield, kg/ha grains	1064	2031	2444	2524	2486
straw	3211	4665	6694	7349	7956
K% in harvested straw	1.75	1.00	1.52	2.13	2.45

Table 7. Effect of fertilizers and manure on millet yield and leaf N, P and K contents at harvest *(Arrivets [1976])*

Fertilization, kg/year	0	NP moderate (50–24–0)	NP heavy (100–50–0)	NP moderate + 5 t ha^{-1} $year^{-1}$ manure*
Yield, kg/ha grains	138	870	900	1 800
kg ha^{-1} straw	1300	5400	4000	10 500
N% in leaves	0.59	0.46	0.71	0.69
P% in leaves	0.068	0.052	0.104	0.130
K% in leaves	0.362	0.321	0.359	0.421

* equivalent NPK = 35–17–75

The main difficulty in estimating nutrient removal in rain grown grops in arid and semi-arid areas lies in estimating dry matter production per hectare. *Gigou [1976]* in Cameroun found that sorghum yield of dry matter (and mineral content of harvested parts) within a field followed a normal distribution and calculated the number of samples required to give an estimate of nutrient offtake within 20%; these are shown in Table 8.

Déat et al. [1976] gave higher figures for sorghum and cotton in Tchad (Bebedja) but the crops were particularly variable.

In any case, whatever the precautions taken, estimates of nutrient offtake are likely to be subject to high errors and notably so for potassium (30 to nearly 40%).

Table 8. Number of sorghum clumps for an estimate of nutrient removal within 20% *(Gigou [1976])*

	N	P	K	Ca	Mg	S	Dry matter
Coefficient of variation, %	41.5	54.2	37.8	33.0	39.1	41.9	38.1
n 20%	17	29	14	11	15	18	15

Finally we should not lose sight of the fact that the nutrient content of above-ground parts of the crop at harvest represent only a part of the total nutrients taken up during the course of growth; they take no account of the amounts immobilized in roots (for sorghum, 11%, 33%, 5%, 4% and 12% of the total N, P, K, Ca and Mg respectively mobilized at harvest according to *Arrivets [1976]);* neither do they include the quantities taken up before harvest and redistributed back to the soil by leaf senescence and root exudation. *Siband [1981]* in his analysis of growth and mineral nutrition of *Pennisetum typhoides* found the following losses between the period of maximum uptake and harvest: dry matter 15.8%, N 36.7%, P 15.8% and K 30.8%.

2.3.2 Losses through surface run-off and erosion (R)

It is often thought that these losses are small in arid areas. In fact such losses are far from negligible and can be catastrophic if soil preparation is inappropriate *(Charreau [1969]). Roose [1981]* pointed out that the rains in West Africa are 3 to 60 times as violent as in temperate regions and that losses can average between the following limits:

C	80–1900	kg/ha/yr
N	15– 80	
P	3– 30	
K	10– 55	
Ca	15– 70	
Mg	10– 35	

Most of these losses occur in the solid form on the soil surface as illustrated by the following example for a fertilized sorghum crop at Saria (Upper Volta):

	K kg/ha	Ca	Mg
By solid erosion	38.2	6.1	6.9
By run-off	8.6	8.4	2.4
By drainage	0.6	0.7	2.7

These values, however, apply to a shallow encrusted soil where run-off is high (30% of total rainfall) and with poor drainage (21 mm out of 826 mm total annual rainfall). Conditions are very different on more permeable soils or where anti-erosion techniques as advocated by *ICRISAT (Kampen [1974])* are practiced.

While soil erosion can be the cause of ecological catastrophies, its importance from the point of view of nutrient economy in the soil should not be exaggerated *(Nye* and *Greenland [1960])*. On the other hand losses of organic matter in run-off can be very high, the C content of the transported fine material can be up to 4 times that of the soil from which it originated *(Piéri [1967])*.

2.3.3 Leaching losses (L)

If these losses are usually negligible in arid areas, this is not always the case in semi-arid zones and particularly on the sandy soils which cover several million hectares of Sudan-Sahelian Africa. Between 1969 and 1974, *IRAT [1975]* measured leaching losses in lysimeter experiments for cultivated soils of Upper Volta and Senegal as follows

N: 5 to 15 kg/ha/yr.
CaO: 40 kg/ha/yr.
MgO: 10 to 25 kg/ha/yr.
K_2O: 10 kg/ha/yr.

Ca and Mg are the cations which are usually strongly leached, K losses are on a smaller scale. This contrasts with the behaviour of ferralitic soils or andosols (Madagascar and Cameroun) which cannot hold K. Leaching losses can vary greatly according to soil, water conditions, fertilizer usage and type of crop as indicated in Table 9.

Table 9. Loss of minerals by leaching under crops in Senegal *(Piéri [1982])* in Cameroun *(Gigou [1982])* and on the Ivory Coast *(Chabalier [1983])*

Place (Country)	Annual rainfall, mm	Crop	Drainage mm	Losses, kg/ha/year N	CaO	MgO	K_2O	P_2O_5
Bambey (Senegal)	507 (1981)	Millet	9.5	0.3	0.8	0.4	0.3	Tr
		Groundnut	100.6	25.1	54.1	13.6	5.2	Tr
Maroua (Cameroun)	705 (1975)	Sorghum	2	Tr	0.1	0.1	Tr	Tr
	683 (1977)	Cotton	83	2.1	43.7	12.3	1.7	Tr
Bouaké (Ivory Coast)	633 (1981)	Maize	210	6.1	36.4	26.2	2.4	Tr
	532 (1981)	Cotton	260	7.1	18.0	6.6	2.0	Tr

Movement of calcium and magnesium to depth is largely determined by the anionic composition of the soil solution, particularly nitrate but also chloride and sulphate *(Ritchey et al. [1978]; Pieri [1979])* it is otherwise for potassium, the movement of which depends on the clay mineral composition of the soil layers through which the solution passes rather than on the composition of the latter *(Munson et al. [1963]; Sattarkhan [1981])*.

Most of these measurements of leaching losses were made in lysimeters and their practical significance may be open to question especially as related to semi-arid zones with frequent alternation of moist and dry regimes which affect the movement of soil water (and the nutrients contained therein). Further criticisms of the lysimeter method are its high cost and the fact that it cannot take into account spatial variation in the field. As in the case of estimating crop uptakes it is necessary to take into account the nature of the distribution laws of the parameters studied often log-normal and to arrive at an estimate of the density of sampling which would be required to give values representative of field conditions. *Vachaud et al. [1982]* did a study of this kind in Senegal. They showed that losses were very variable (13 to 90 mm of drainage to depth and 2 to 70 kg/ha loss of N) and that water flux should be measured at 10 points and mineral content of the soil solution at 30 points to give a measure of leaching losses within 20%.

2.4 Elements in the nitrogen balance in soil

The nitrogen balance of soils is a more complex matter due to the dynamic behaviour of this element in farming systems. To establish the balance it is necessary at least to take into account on the one hand additions via biological fixation and from the atmosphere and, on the other, gaseous losses to the atmosphere. We shall briefly review the information at present available and its quantitative significance in tropical semi-arid areas.

2.4.1 Symbiotic fixation (Nf)

The quantity of N fixed by a given legume on a given site varies greatly according to environmental conditions and, so far as concerns arid and semi-arid zones, on water supply to the crop. *Ganry* and *Wey* (cited in *Wetselaar* and *Ganry [1982]*) for different legumes grown in Senegal give the following percentages of total N uptake for N by symbiotic fixation (Nf):
- 20 to 70% for one groundnut cultivar
- 0 to 58% for one soyabean cultivar

Table 10. Effect of rainfall on N fixation by legumes *(Ganry* and *Wey* in *Wetselaar [1982])*

Rainfall	Crop	Yield, kg/ha (kg/ha N mobilized)	% N in aerial parts coming from fixation	soil	fertilizer
Sufficient*	Soya	2315 (189 N)	55	40	5
	Groundnut	1420 (74 N)	66	32	2
Poor**	Soya	835 (68 N)	58	38	4
	Groundnut	1126 (59 N)	21	75	4

* Rainfall sufficient for adequate supply to plant
** Insufficient rainfall and bad distribution

the variation being due to incidence of dry periods, the amount of mineral N in the soil and/or the presence of effective strains of *Rhizobium*.
It is interesting to note that in the case of groundnut (Table 10) while inadequate rainfall reduces yield by only 21%, symbiotic fixation (Nf) is reduced by almost 70%; in the latter case the crop obtains 75% of its N requirement from soil mineral N and organic matter which as a result are run down. Wetselaar (1967) showed clearly that the effect of symbiotic fixation in raising soil N content is often over-estimated.

2.4.2 Non-symbiotic N fixation (Nf)*

Recent work *(Dart et al. [1982]; Boddey* and *Dobereiner [1982])* has renewed interest in this field of research. While there is no question that this process does take place, either under controlled conditions or in the field, it is still difficult to estimate its practical importance as is evidenced by the tremendous variation in the figures mentioned by specialist workers (from a few kg to 40 kg/ha N per year). In practice, the contribution in rain-fed cropping in the arid and semi-arid areas is probably negligible.

2.4.3 Losses of N by volatilization (Nv)

Such losses take place by two routes: denitrification and volatilization of ammonia. Losses by denitrification are usually considered to be of lesser importance *(Greenland [1962]; Chabalier [1976])*.
Losses by volatilization can be very considerable when N fertilizer is applied to the soil surface of sandy soils. *Ganry et al. [1982]* in Senegal found loss of 45.7% of urea N applied with ploughed-in straw. On alkaline soil in the *Gezira Musa [1968]* recorded loss of 35% N given as ammonium sulphate and similar results were obtained by *Abdelgawad* and *Matar [1979]* in Libya. However, incorporation of the fertilizer at a depth of a few centimetres reduces the loss to a very low level.
The general conclusion is that in arid and semi-arid areas N losses by denitrification and volatilization vary but, provided fertilizer is correctly applied, they are usually quite small. In contrast, in the traditional extensive and semi-intensive systems practised in these areas, losses of N (and S) in the periodic burning of crop residues are appreciable (10–20 kg/ha N per year) and should be taken into account in working out the N balance.

2.5 Accuracy of nutrient balances

The discussion above of the relative importance of the various terms in the balance and the difficulty of their evaluation makes it clear that it would be pointless to be too precise in our statements. Up to now we have not considered the internal fluxes – dissolution (d) of soil minerals and the converse, fixation or regression of elements like P and K, nor the consequences of the nitrogen cycle in the soil.
Little is known about the dissolution of minerals but it is generally thought to be negligible in arid and semi-arid conditions, a point to which we shall return later. Potassium fixation is not very important in these soils in which kaolinitic minerals and iron sesquioxides dominate in the exchange complex.

Phosphorus is strongly fixed in tropical soils rich in sesquioxides, mainly it is true in the humid zones. Cases of regression of soluble P are known in the arid zone and in alkaline soils, notably in countries on the south of the Mediterranean *(Baruni [1979])*.
As for the nitrogen cycle, most authors say that there is a peak in the mineralization of soil organic matter at the beginning of the rains *(Blondel [1971])* of which the intensity and timing are very variable *Gigou [1982])*. The inverse process of immobilization of N (r) is less understood. *Ganry [1979]* has measured this in a very sandy soil; 16–20% of 150 kg/ha N applied as urea was immobilized in the soil organic matter in the first year while 34% was recovered in the crop.
These observations support the view that we should not rely too much on the accuracy of mineral balances since we do not know enough to measure them precisely. However, they are sufficient to show up the more obvious imbalances that may result within a farming system and the factors in the balance that are the chief causes. It seems more important to appreciate the variability in the factors contributing to the balance than to measure them with great accuracy in a particular situation. We have shown that variations in nutrient uptake and removal by crops and leaching losses can be extremely variable, consequently detailed work on a particular site may give precise results but the extent to whicb such results apply even to the local area, let alone to a whole region is doubtful.

3. Nutrient balances in arid and semi-arid zones

There is a great deal of variation in farming systems practised in these areas, depending on climate and soil. However, if we consider Sahelian and Sudano-sahelian Africa and the semi-arid zone of the Indian sub-continent, most farming systems are based on typical crop associations (crops associated either in space or time). Thus the rotation cotton-sorghum (or cotton-maize) appears to be typical of semi-arid zones where farming is being intensified and the rotation millet-groundnut is characteristic of millions of hectares in the arid tropics. We shall therefore concentrate attention on these two types of rotation, examining the consequences in terms of soil mineral and organic matter status. We shall only consider successions of sole crops because, so far as we know, there is a lack of information on nutrient balances relating to mixed cropping *(Kassam et al. [1973])*.

3.1 Systems based on the cotton-sorghum rotation

These have been investigated in various African countries by *IRCT*. Though all the terms in these balances have not been fully evaluated they are, nevertheless, quite eloquent and at least show up the consequences of applying fertilizers with regard only to the needs of the cash crop without taking the succeeding crop into account. For example, on the fertile soil of the Bebedja (Tchad) station 12 years under 4 different cropping systems (Table 11) resulted in the apparent balances given in the table (fertilizer applied [F] – Crop removals [E]).
The balances are mostly negative and the consequences in the soil as revealed by soil analysis can be seen in the second part of the table. The levels of organic matter and

Table 11. Approximate nutrient balances in 4 crop sequences and effects in soil (Bebedja, *IRCT [1980]*)

Crop sequence (no. of years)	Approx. mineral balance ($kg\ ha^{-1}$) N	S	P_2O_5	K_2O	CaO	MgO	Soil analysis (0–20 cm) MO %	N ‰	K ech. me/100 g	P_2O_5 ass ppm
A Continuous cotton no fertilizer (12 years)	−296	− 22	−141	−272	−103	− 70	1.15	0.47	0.18	523
B Continuous cotton with NSB* (12 years)	+242	+374	−245	−459	−169	−121	1.19	0.50	0.17	514
C Cotton NSB* – sorghum (12 years)	− 67	+169	−253	−538	−219	−162	1.17	0.48	0.18	580
D Cotton NSB* – sorghum (4) fallow (4 years)	− 56	− 24	−109	−234	− 96	− 71	1.49	0.62	0.22	613

* NSB: 60 N, 12, 2B (kg/ha)

nitrogen in the soil are affected mainly by the intensity of cropping (*cf.* columns C and D) rather than by the apparent N balance: though the latter are similar (−67 and −56 kg/ha), the soil under treatment C has provided 448 kg/ha N (140 ppm N) more than that under D. The apparent N balances are evidently much underestimated by taking account only the terms F and E.

A similar experiment on continuous cotton on a less fertile soil at the same place has shown that leaching losses alone were as much as 39 kg/ha N, 67 kg/ha K_2O, 77 kg/ha CaO and 19 kg/ha MgO. Taking account of the terms F, E and L it was shown that a rotation of type B rapidly exhausted this rather infertile soil (assuming no internal flux to redistribute the nutrients): exchangeable K would last 4 years only, exchangeable Ca and Mg and assimilable P 30 years.

Mineral balances for a type C rotation receiving fertilizers and farmyard manure have been worked out by *Gigou [1982]*. After four years on a soil derived from river alluvium in north Cameroun (Maroua soil with 10% clay, 0.7% organic matter, 2–5 me/100 g exch. Ca and 0.15 me/100 g exch. K) the nutrient balances derived from F (fertilizers), O (return of 10 t/ha sorghum straw every other year [treatment F_5]), E (removals by cotton and sorghum), L (leaching measured in lysimeters 80 cm deep) were as listed in Table 12.

Every year the best yields were obtained on treatment F_3 (over 4 t/ha sorghum and 1.7–3.2 t/ha seed cotton) and the poorest on treatment F2 (2 t/ha sorghum and 1.2–2.2 t/ha seed cotton). The overall apparent N balance was positive in every case but this did not, in spite of all precautions) show up in soil analysis except on the plots where straw had been returned:

Total N % treatment F_2 = 0.033 (1973), 0.030 (1977)
Total N % treatment F_3 = 0.033 (1973), 0.031 (1977)
Total N % treatment F_5 = 0.03 (1973), 0.39 (1979)

Table 12. Nutrient balances after 4 years under cotton – sorghum (Maroua, Cameroun 1974–1977)

Term in balance*	N			P_2O_5			K_2O			CaO			MgO		
	F_2	F_3	F_5	F_2	F_3	F_5	F_2	F_3	F_5	F_2	F_3	F_5	F_2	F_3	F_5
E	−140	−268	−168	−91	−148	−112	−258	−499	−403	−76	−130	−102	−52	−87	−62
L	−18	−27	−22	−Tr	−Tr	−Tr	−7.4	−7.1	−6.8	−103	−104	−131	−14	−29	−32
F	+200	+400	+111	+270	+270	+270	+300	+300	+300	150	150	150	0	0	0
0	0	0		0	0	+45	0	0	+393	0	0	+74	0	0	+51
Balance kg ha^{-1}	+42	+105	+103	+179	+122	+203	+35	−206	+283	−29	−84	−9	−65	−115	−43

* See Figure 1

Fertilizer treatments: N fert. $\begin{cases} F_2 = 50 \text{ kg ha}^{-1} \text{ year}^{-1} \text{ N urea} \\ F_3 = 100 \text{ kg ha}^{-1} \text{ year}^{-1} \text{ N urea} \\ F_5 = 50 \text{ kg ha}^{-1} \text{ year}^{-1} \text{ N urea + straw 10 t/ha} \end{cases}$

PK supplement cotton: 45 P_2O_5, 60 K_2O (TSP, KCl), Sorghum: 90 P_2O_5, 90 K_2O

Table 13. Nutrient balances under millet – groundnut rotation *(Tourte [1971],* Senegal)

Crop	Yield kg/ha			Term of balance	N			P_2O_5			K_2O			CaO		
	0*	tl	TL		o	tl	TL	0	tl	TL	0	tl	TL	0	tl	TL
Groundnut	950	1090	1149	E	105	−129	−132	−22	−28	−30	−51	−62	−64	−39	−47	−47
Millet	430	700	1020	F	0	+51	+64	0	48	190	0	+40	+110	0	45	245
Groundnut	960	1170	1070	Balance	−105	−78	−68	−22	+20	+160	−51	−22	+46	−39	−2	+198
				no groundnut	(−8)	(−8)	(+29)									

* 0: no fertilizer

tl: 150 kg/ha 6:10:10 on groundnut, 14:7:7 on millet

TL: 500 kg/ha rock phosphate plus supplementary NSK on all crops

The author thinks that there must have been losses of N by volatilization.
The P balance was positive due to large applications of triple superphosphate (600 kg/ha in 4 years) which also maintained the Ca balance when all the sorghum straw was returned. It should be noted that had ammonium phosphate been used as is increasingly the practice, the Ca and Mg balances would have been strongly negative.
Study of the terms of the K balance in Table 12 show that the K balance depends primarily on the removals in sorghum (about 180 kg/ha K_2O per year, while cotton removed 65/kg/ha). The calcium and magnesium balances are mainly determined by leaching losses.
Leaching losses occur mainly under cotton when percolation is high (19% of annual rainfall or 145 mm per annum); the corresponding figure for sorghum is only about 1%. On the average, leaching losses under cotton are annually 11.2, 3.2 and 48.3 kg/ha N, K_2O and Cao while under sorghum N and K losses are negligible and CaO loss less than 2 kg/ha. These results point to the value of the cotton-sorghum rotation not just from the the point of view of productivity but also for maintaining soil fertility.
Improved cultivars of the traditional cereals *(e.g.* sorghum IRAT 55) are efficient traps for water and nutrients while cotton is a cash crop which can reap large profits for the farmer and at the same time serve as an indicator of change in soil fertility, notably potassium which is taken up by cereals and other traditional crops. *Braud [1981]* illustrates this point in comparing two 4 year rotations: yam – cotton – sorghum – sorghum and groundnut – cotton – sorghum – sorghum. In the 6th year, the former yielded 945 kg/ha seed cotton on a soil with 0.065 me/100 g exch. K and the latter 1250 kg/ha on a soil with 0.092 me/100 g exch. K.
The fact that many farmers in India and some in Africa grow these two crops in association can hardly be the result of chance though other reasons (pest and disease) may be advanced as a reason for the practice.

3.2 Systems based on the millet – groundnut rotation

Much work has been done on these rotations in Senegal. *Tourte [1971]* following up earlier work *[1964]* compared intensive (TL) systems with animal traction, improved varieties and generous fertilizer treatment, with a less intensive system (tl) without animal traction and with lower rates of fertilizer and with a rotation receiving no fertilizer (0) (Table 13 and found that only the intensive system could maintain soil fertility.
The above partial balances were amplified in interesting work by *Sarr [1981]* on a rotation begun in 1963 at Nioro du Rip (central Senegal) with the rotation fallow – groundnut – sorghum – groundnut and progressively modified from 1972 to maize – cotton – sorghum – groundnut. After 17 years the nutrient balances were as in Table 14. These took account of fertilizers (F), return of residues (0) and N fixed by groundnut (Nf), which was estimated to amount to 60% of N uptake by the crop, and crop removal (E).
Contrary to the preceding work the N balance was always strongly negative (a loss of 20–30 kg/ha N per year) and the K balance was positive only if the cereal straw

Table 14. Estimated nutrient balance after 17 years of a 4 year rotation (Senegal 1963–1979, *Sarr [1981]*)

Terms in balance	N			P_2O_5			K_2O			CaO		
	0*	1	2	0	1	2	0	1	2	0	1	2
E	−746	−1731	−1669	−178	−379	−484	−411	−1095	−1467	−273	−480	−510
F+Nf+O	+252	+ 956	+1338	0	+438	+769	0	+1353	+1252	+364	+571	+483
Balance	−494	− 415	− 331	−178	+ 59	+285	−412	+ 285	− 215	+ 96	+ 91	− 27

* 0 = Without fertilizer
1 = Standard recommendation for NPK + return of cereal straw
2 = As above + supplementary P and supplementary N on cereals

Table 15. Change in soil stocks of total N, assimilable P_2O_5 and exchangeable K and Ca after 17 years cropping in Senegal (after *Sarr [1981]*)

	N			P_2O_5			K_2O			CaO		
	0	1	2	0	1	2	0	1	2	0	1	2
Balance soil	−1320	−1200	−1674	+10	+55	+110	+12	+44	+78	−571	−1438	−1620

was incorporated after harvest. These balances can be compared with the details of nutrient and organic matter content of the soils in Appendix II. Losses or gains in nutrients to a depth of 30 cm in comparison with a soil maintained under fallow for 17 years are listed in Table 15.
Comparison of the two tables (14 and 15) suggests the following:
- The soil N balance seems to be 3 to 5 times more in deficit as would be expected because much organic matter has been mineralized (50% of the stock has vanished, *cf.* App. II). Even if there are reservations as to how far the border area under fallow was truly representative, the situation should cause concern and it is not unique in the Soudano-Sahelian region. *Sedogo [1981]* in Upper Volta found that 19 years cropping decreased soil organic matter by 30% and total N by 10%. Unquestionably, nitrogen losses in such a system have been underestimated and it would be interesting to know the reason.
- The P and K balances show that the methods of soil analysis used (assimilable P and exchangeable K) are poor indicators of the nutrient status of sandy soils. In the absence of manure or return of straw the balance (E–F) shows that the soil is being exhausted but there is little change in soil exchangeable K content. True, errors are involved in estimating E but it seems that the stability of the exchangeable K content must be due to redistribution within the soil. Actually, if we use extraction with boiling HNO_3, there is better agreement between the apparent balance and soil K content *(Piéri [1982])*.
- Soil Ca balance is strongly negative, though this would not be expected from the apparent balance (F–E). As we pointed out above, this balance depends largely on leaching loss which is no taken into account in table 14.

From these examples it is clear that knowledge of the terms E, F, O and Nf alone does not enable us to make a complete balance. Internal fluxes in the soil – net mineralization (m–r) and the balance between liberation and immobilization of K and P (d–fix) play a determinant role in sandy soils of the arid and semi-arid regions. Similarly losses through leaching (L) and those connected with the nitrogen cycle are important in the N balance and those of Ca and Mg.
Table 16 is an example of N balance under millet – groundnut obtained by using labelled N(^{15}N) *(Ganry* in *Wetselaar* and *Ganry [1982])*.

Table 16. N balance in groundnut – millet system in semi-arid conditions (Bambey, Senegal, *Ganry [1982]*)

Gains (kg/ha)		Removals (kg/ha)	
– Atmosphere	Tr	– In millet (net)	−33
– Fertilizer to millet	+80	– In groundnut	−109
– Fertilizer to groundnut	+15	– Denitrification and volatilization	−50
– Symbiotic fixation (Nf)	+82	– Soil N (2 years)	− 8
		– Organic residues (2 years)	−28
		– Fertilizer N (2 years)	−20
		– Leaching (2 years)	
Net balance:	−71		

In this investigation the balance was much affected by volatilization losses (Nv) which were particularly high. Table 17 shows calculation of the balance for a large scale field experiment also at Bambey *(Piéri [1981])*.

It was possible in this study to take into account spatial variability notably water and mineral flux *(Vachaud et al. [1982])*. All the balances, except for P are strongly negative. Supposing that groundnut obtains 75% of its N via symbiotic fixation we

Table 17. Terms of the balance of 3 years rotation (Bambey 1979–1981)

1) Leaching losses in 3 years

Year	Rainfall (mm)	Crop	Drainage	Leaching losses kg/ha				
				N	CaO	MgO	K_2O	P_2O_5
1979	351	Groundnut	30.9	14.8	25.9	10.7	1.1	3
1980	346	Millet	18.7	5.0	4.2	2.1	0.9	3
1981	507	Millet	9.5	0.3	0.8	0.4	0.3	3
Total	204	$Gr+M_1+M_2$	58.1	20.1	30.9	13.2	2.3	3

2) Crop removals

Year	Crop	Yield kg/ha		Removals kg/ha				
		Grain or unshelled nuts	Straw	N	CaO	MgO	K_2O	P_2O_5
1979	Groundnut	899	1663	85.4	20.9	12.7	30.6	16.7
1980	Millet	2209	5851	83.0	33.8	71.0	98.9	24.6
1981	Millet	1818	4169	63.2	23.7	47.7	72.8	19.2
Total	$Gr+M_1+M_2$	–	–	231.6	78.4	131.4	202.3	60.5

3) Nutrient additions kg/ha

Source of additions	N	CaO	MgO	K_2O	P_2O_5
Fertilizer and symbiotic fixation					
1979: 150 kg/ha of 8–18–27	12+Nf	0	0	40.5	27
1980: 150 kg/ha of 10–21–21 + 2× 150 kg/ha sulphate of ammonia	75	1.5	0	31.5	31.5
1981: 150 kg/ha of 10–21–21 + 2×50 kg/ha urea	60	1.5	0	31.5	31.5
Total	147+Nf	3.0	0	103.5	90.0
Additions from atmosphere: 1204 mm of rainfall in 3 years	1	41.5	10.4	10.4	2.6
General total	148+Nf	44.5	10.4	113.9	92.6
Overall balance of succession groundnut–millet–millet (1979–81)	−103.7+ fixed N	−64.8	−134.2	−90.7	+32.1

arrive at a deficit of 15 kg/ha N per year which supports *Wetselaar's [1967]* reservations about soil N enrichment by legumes. The experiment confirmed the close connection between losses of nitrate and calcium – their concentrations in the soil solution move in parallel (Figure 2).

The K balance reflects removal of K by millet.

To conclude, the nutrient balances of the two types of rotation discussed show similarities, notably in the losses of Ca and Mg by leaching under crops other than cereals. Balances of N and organic matter appear rather more problematic in arid and semi-arid than in temperate zones.

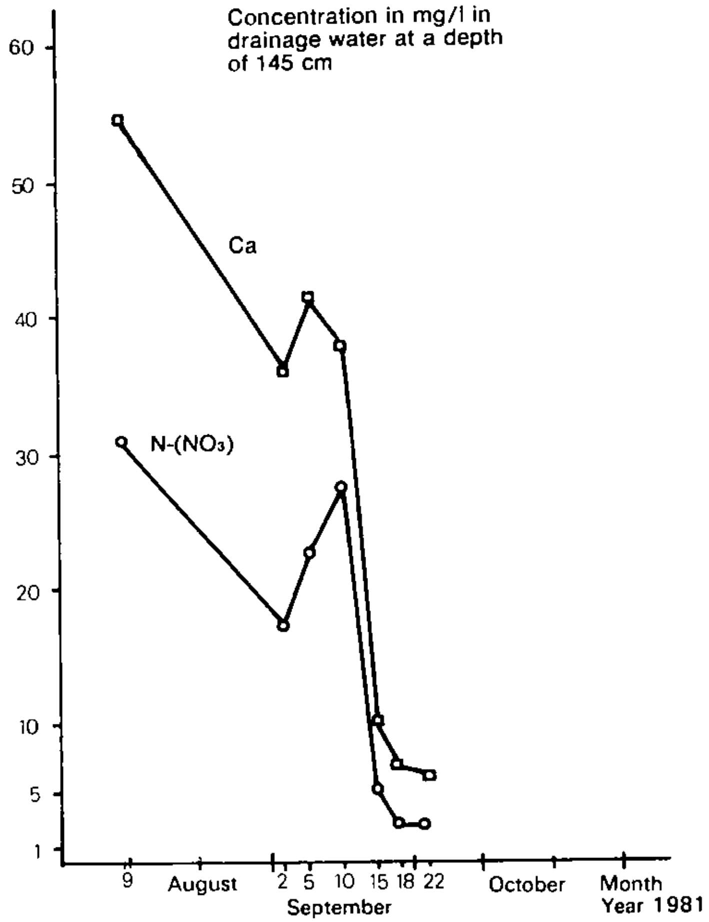

Fig.2. Seasonal variation in composition of soil solution (Bambey *[1981]*)

4. Agronomic consequences and conclusions

Study of the nutrient balance under rotations of cotton with sorghum and millet with groundnut lead to important conclusions on the maintenance of fertility in arid and semi-arid soils.

4.1 Nitrogen balance

Far from being determined by the algebraic sum (F–E) this balance seems to be largely determined by net mineralization (m–r) of soil organic matter, by volatilization (Nv) and leaching (L) while additions from the atmosphere may be considered negligible. Fixation of atmospheric N by legumes such as groundnut is not as great in arid and semi-arid areas as it was thought to be. Losses of N by leaching under legumes are large on account of the rapid mineralisation of organic matter and the carrying into the subsoil of nitrate which is not taken up by the crop. While in the case of the cotton – sorghum rotation it seems possible to maintain levels of soil organic matter by returning organic residues (cereal straw) and applying N fertilizer, it is otherwise under more arid conditions.

The Senegal results of Tables 14 and 15 show that the ploughing-in of cereal straw and N fertilizer cannot maintain the N level in the soil because of the rapid mineralization of organic matter of high C/N ratio in these sandy soils and in this climate. The only way is to apply well-rotted organic matter with N fertilizer *(Ganry et al. [1978])*.

It should be pointed out that the semi-intensive millet-groundnut system of Tables 14 and 15 is no more damaging to the N balance than is the traditional system (0) and it increases groundnut yield by 28% (1970 *vs.* 1540 kg/ha), doubles the yield of seed cotton (1012 *vs.* 582 kg/ha) triples sorghum (2264 *vs.* 844 kg/ha) and increases maize yield by nearly ten times (2820 *vs.* 325 kg/ha) *(Sarr [1978])*.

Finally it is very important to follow closely the recommendations on method of applying N fertilizer; volatilization losses are very high when it is applied to the surface, whatever the soil pH.

4.2 Ca and Mg balance

This is always determined by leaching. Leaching losses are not very heavy under vigorous traditional cereals, like the millets and African sorghums; it is otherwise under cotton or groundnut (or maize). These losses are proportional to the nitrate load soil solution (Figure 2). The nitrate concentration reflects partly N fertilizer application but, even more, the mineralization of organic matter which is intense at the beginning of the rainy season *(cf.* 2.5) liberating much nitrate at a time when demand by the crop is minimal. There is considerable practical and theoretical interest in intercropping 'draining' crops with traditional cereals to optimize the use of available water and nutrients, a system which is practised in some types of traditional farming. It is very important to maintain the Ca and Mg status of these soils. While additions from the atmosphere (of calcium) are not negligible, fertilizer recommendations should take into account the need for Ca and Mg the soils are not naturally well provided (alkaline Mediterranean soils, calcareous alluvium, etc.). The use of rock phosphates as a source of P adds to the calcium supply and it can be recommended provided the P solubility is sufficient to supply the needs of crops. We should not forget that the amount of Ca left in the soil is equivalent to the P taken up by the crop *(Jones [1976])* and it might be supposed, from this point of view, that single superphosphate, triples and calcareous rock phosphates are equally good per unit P_2O_5.

4.3 Potassium balance

In all the cases studied, the dominant factor has been offtake in the crop, more particularly in that part which is not marketed or eaten. Additions from the atmosphere and leaching losses are alike negligible.
The maintenance of the K status of soils then depends on the return of as large a part as possible of crop residues and the application of K fertilizer in accordance with the needs of the rotation. The need for both has been explained and illustrated by *Poulain* (1 in FAO Soils Bulletin No. 43). K should preferably be applied to the non-cereal crop of the rotation on account of the tendency of the gramineae to take up K in excess of their requirements (luxury consumption) *(Piéri [1982])*. Leaching losses of K are negligible so that it is better to apply a heavy dressing to the groundnut; any excess over crop requirement will be retained in the soil and will be available to the following crop.
In connection with the return of crop residues it has to be born in mind that their proper incorporation requires a source of energy lacking in traditional farming; either animal or tractor powered implements. Much remains to be done in this area.
Finally the monitoring of soil K status in arid and semi-arid areas should not rely on the measurement of exchangeable K content but should take into account changes in the available reserves. Nitric acid extraction is proposed for these predominantly sandy soils.

4.4 Phosphorus balance

Maintenance of the P balance is less of a problem. Strongly P fixing soils which are very rare in arid and semi-arid areas and alkaline soils in which chemical regression is known to occur may give problems but, in general, there is no problem in maintaining the P status of semi-arid and arid soils if P fertilizer is applied in sufficient quantity to replace crop removals.
In conclusion it can be said that the calculation of nutrient balances is not without difficulty but can be very useful for arid and semi-arid areas. Comparison of the calculated balances with soil nutrient stocks as indicated by soil analysis shows that it is necessary to take into account most of the factors which affect it in order that they may be of value in predicting changes in soil nutrient status. Unless internal flux in the soil, mineralization of organic matter, the equilibrium between reserve and available fractions, leaching, losses by volatilization, additions from the atmosphere are taken into account as well as additions in fertilizers and manures and removals in harvested produce, indications can be misleading.

Some of the difficulties have been overcome and though there remain some imperfections in the balance method (losses by erosion and run-off have been little studied under field conditions) it does show up that apart from the need to look after the supply of N and to maintain organic matter status there is a need to maintain the K balance by returning residues and applying K fertilizer and that the need to keep a watch on losses of calcium and magnesium through leaching has usually been under estimated.

Appendix I

Uptake and removal of nutrients by rain-grown crops

Total uptake by crop and removal in harvested produce per tonne harvested produce. Removals in parentheses.

Country (author)	Variety (rainfall mm)	Yield kg/ha Straw	Yield kg/ha Grain	Uptake and (removal) per t produce harvested N	P_2O_5	K_2O	CaO	MgO	S
Millet									
Niger *(Bertrand [1972])*	Local (638)	5125	1785	49.6 (20.4)	10.0 (5.4)	73.7 (5.2)	12.2 (0.3)	16.8 (1.8)	11.2 (1.9)
Nigeria *(Jones [1976])*	Local (1120)	4516	2428						
Mali *(Traore [1974])*	Local (700)	5220	1516	29.7 (18.0)	9.9 (6.6)	56.1 (5.6)	12.2 (0.4)	14.3 (2.0)	2.4 (1.0)
Senegal *(Siband [1981])*	Souna III (391 mm+ 30 irrigation)	8458	3310	49.8	24.2	90.6	–	–	–
Senegal *(N'Diaye [1978])*	Local	–	950	39.9	17.6	70.3	14.6	15.8	–
Sorghum									
Cameroun *(Gigou [1976])*	IRAT 55 (800)	7700	4600	20 (13)	11.5 (8)	30 (5)	8 (0.5)	7 (2.4)	3.7 (1.6)
Upper Volta *(Arrivets [1976])*	S 29 (826)	8460	1500	35 (16.5)	13.7 (5.9)	43.2 (3.6)	11.2 (0.3)	13.3 (2.0)	–
Senegal *(Jacquinot [1964])*	Congossane (450)	8700	2300	34	7	17	14	22	–

Maize									
Mali *(Traore [1974])*	Local (1100)	4870	3458	27.7 (15.0)	6.6 (4.9)	25.9 (6.4)	8.4 (0.8)	7.5 (1.7)	1.7 (0.9)
Ivory Coast *(Chabalier [1982])*	Hybrid CJB (1100)	4000	3000	34 (19)	10.6 (6.7)	42 (6)	6.2 (0.8)	5.8 (2.2)	–
Senegal *(Cisse [1980])*	Local (750)	4088	2354	26.1	6.5	29.6	11.2	10.0	–
Nigeria *(Jones [1976])*	Local (1120)	6562	3637	–	–	23.2 (4.8)	6.8 (0.1)	5.1 (0.1)	–
Upland rice									
Senegal *(Siband [1972])*	Ikong Pao (1100)	2555	2078	24.4 (9.0)	8.1 (3.4)	51.6 (4.6)			
Ivory Coast *(Chabalier [1976])*	Igüapecateto (1121)	2000	1400	34.3 (17.1)	10.3 (6.9)	37.8 (3.6)			
Cotton Results from IRCT *(Déat et al. [1976])*									
		Cotton	Seed						
Cameroun (1972)	BJA 592	–	2148	38.4 (17.2)	17.0 (8.0)	50.2 (9.0)	22.2 (1.7)	10.5 (3.1)	5.9 (4.3)
Cameroun (1974)	3372	–	2623	25.4 (18.3)	12.9 (8.4)	40.3 (9.2)	8.6 (2.7)	5.6 (3.3)	3.3 (1.1)
Ivory Coast (1973)	4402	–	1675	36.2 (22.5)	11.1 (8.2)	34.3 (11.7)	15.4 (2.6)	8.3 (3.3)	–
Benin (1973–74)	Various	–	1244	30.0 (16.6)	22.1 (14.2)	30.3 (6.2)	16.9 (1.2)	8.5 (3.1)	3.4 (1.4)

Groundnut

Senegal, North *(Gillier [1964])*	Local (416)	950	1540	45.7 (38.0)	5.0 (4.2)	15.1 (7.3)	8.2 (1.6)	6.3 (2.3)	–
Senegal, Center *(Pouzet [1974])*	28–206 (738)	2300	2445	52.4 (37.5)	9.3 (6.7)	18.8 (8.6)	9.9 (0.6)	12.8 (3.1)	3.7 (2.1)
Senegal, South *(Bockelee, Morvan)*	Various	1334	1835	47.2 (34.2)	8.5 (6.5)	16.4 (7.8)	11.6 (1.1)	12.0 (1.6)	–
Niger *(Bertrand [1972])*	Local	3875	2350	66.8 (38.9)	10.7 (6.6)	41.4 (8.5)	19.5 (0.5)	15.8 (2.4)	5.1 (2.0)
United States *(Collins, Morris)*	–	4480	2230	70.1 (30.5)	12.2 (6.9)	51.7 (10.4)	29.6 (1.9)	15.2 (2.6)	–

Soyabean

Senegal *(Larcher [1983])*	44A–73 (1200)	2232	1618	81.6 (67.4)	15.4 (12.6)	36.3 (22.2)	25.1 (4.3)	20.5 (4.6)	4.0 (2.8)
Madagascar *(Arrivets [1982])*	Davis	3230	3160	69.6 (61.3)	16.4 (13.9)	40.5 (27.9)	33.4 (9.0)	10.8 (4.9)	–
United States *(Ollrogge [1978])*	–	4800	4000	90	19.4	37	31	15	7

Appendix II

Development of soil characteristics after 17 years cropping in Senegal *(Sarr [1981])*

	Fallow area	Analyses 1972			Analyses 1980		
Horizon 0–15 cm		0	1	2	0	1	2
Total C %	7.5	4.8	5.1	4.8	3.2	3.01	2.7
Total N %	0.6	0.34	0.36	0.35	0.31	0.32	0.24
Ca me/100 g	2.78	1.2	1.3	1.7	1.82	1.0	1.06
Mg me/100 g	0.63	0.6	0.6	0.5	0.30	0.11	0.14
K me/100 g	0.08	0.06	0.07	0.09	0.06	0.07	0.06
T me/100 g	3.83	2.8	2.8	3.0	1.91	1.64	1.55
P_2O_5 total	30				75	100	37
P_2O_5 ass	8				10	25	35
	Fallow area	Analyses 1972			Analyses 1980		
Horizon 15–30 cm		0	1	2	0	1	2
Total C %	4.7	3.4	4	3.5	2.4	2.6	2.3
Total N %	0.52	0.27	0.32	0.31	0.26	0.30	0.18
Ca me/100 g	1.71	1.2	1.4	1.8	1.82	1.35	1.02
Mg me/100 g	0.46	0.4	0.5	0.6	0.22	0.17	0.13
K me/100 g	0.03	0.03	0.03	0.06	0.04	0.08	0.12
T me/100 g	2.21	3.0	3.0	3.0	1.98	1.91	1.72
P_2O_5 total	71				83	93	113
P_2O_5 ass	7				9	13	26

0: without fertilizer, superficial cultivation

1: 150 kg/ha 6:20:10 to groundnut to 1974 then 150 kg/ha 8:18:27
150 kg/ha 14:7:7 to sorghum to 1974 then 150 kg/ha 8:14:8 + 100 kg/ha urea

2: 500 kg/ha Taiba rock phosphate in 1963
Fertilizer for groundnut as in (1)
Fertilizer for sorghum changed in 1975 to 150 kg/ha 10:21:21 + 150 kg/ha urea

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Experimental Bases of Dry Farming Techniques in Arid and Semi-Arid Zones

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Summary

Discussion of the effects of rainfall and its distribution on crop yield is followed by description of the effects of climatic factors on yield of wheat and its components drawn from a field survey of wheat crops leading to the conclusion that we should aim for an ear number at flowering appropriate to local conditions (water availability in the spring). There follows a discussion of the choice of cultural methods which may be adopted to improve plant establishment and water supply to the growing crop. Though sowing should not be unduly delayed it is advisable to ensure that the seedbed is sufficiently moist to support the survival of young seedlings. Cultivation methods should be such as to encourage the penetration of rain and to promote the development of a root system which explores the soil to depth. Water loss can be reduced by adequate weed control. The use of a cultivated fallow to increase water storage appears problematical.

1. Introduction

The distinguishing feature of crop production in the so-called 'arid'** areas is that the principal constraint on yield is water supply to the crop. Potential evapotranspiration is substantially constant from site to site and from year to year *(Arnon [1972])*, but rainfall is erratic and it is this which determines crop yield. The realization of this simple fact is not sufficient to form a basis for deciding on a dry farming cropping system. The fact that within an area of uniform climate and in the same year there is great variation in yield must have some explanation; it is necessary to analyze in detail the relationships between crop development and the physical environment; this should enable us so to arrange things as to favour crop performance. This analysis is the subject of the first part of this paper from which, in the second

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** The definition of this word – and hence of the areas to which the description applies – varies between authors: simple weather indices (mean annual rainfall) for some *(Meigs [1962])* or certain aspects of the utilization of the area may be taken into account *(Papy et al. [1981])*. This point is not discussed here and we shall be content only to give the background information necessary for the understanding of the examples given.

part we proceed to discuss the choice of suitable techniques for use in practice. Our discussion will be limited to one example taken from work carried out in the upland plains of Algeria *(Manichon* and *Sebillotte [1975]; Manichon* and *Badufle [1977]; Leval [1978]).*

2. Crop behaviour and the objectives of cultural practices

The upland plain area of Algeria is characterized by:
- an autumn with great variability in the date when the rain returns following a hot summer with negligible rainfall;
- a damp winter when temperature is low (enough to arrest crop growth);
- a spring in which the temperature rises very rapidly and with very irregular rainfall.

In the absence of irrigation it is impossible to grow spring sown crops in this area where the crops grown are winter cereals and lentils. There are 4 climatic zones in the area distinguished by the rainfall (Table 1). The effects of the rainfall gradient from south to north are reinforced by the nature of the soils (poor water storage in the south, better in the north). We shall study the effects of this variability on the relationship between rainfall and crop yield and then the relations between yield and its components. From this we shall draw conclusions on the cultural practices to be recommended to ensure regular yields and to improve them.

Table 1. Correlations between rainfall and yield (High Plains, Algeria).

	Total Rainfall extremes (mm)	medium	Autumn (Oct–Dec)	Winter (Jan–Mar)	Spring (Apr–Jun)
North	400 to 650	500	115 to 220	85 to 255	120 to 210
Centre	360 to 610	450	90 to 225	80 to 240	70 to 180
South-East	340 to 580	400	85 to 210	85 to 230	65 to 170
South	300 to 550	350	80 to 215	80 to 230	30 to 150
Wheat					
T. aestivum Siete-Cerros	0.59*		–0.09 NS	0.50*	0.74*** (Y = 0.09 R – 2.4)
T. aestivum Mahon-Demias	0.23 NS		–0.21 NS	0.20 NS	0.54* (Y = 0.03 R + 2.8)
T. durum Mohammed B. Bachir	0.71**		–0.20 NS	0.69**	0.90*** (Y = 0.04 R + 1.9)
Barley (local)	0.18 NS		–0.53*	0.31 NS	0.64** (Y = 0.06 R + 0.5)
Lentil (local)	0.41 NS		–0.10 NS	0.30 NS	0.63** (Y = 0.01 R + 0.4)

Y: Yield (q/ha) R: Spring rainfall (mm)
Levels of significance (N = 16) * 5%, ** 1%, *** 0.1%

2.1 Rainfall and yield

The correlations presented in Table 1 are based on mean yields over 4 years for the stated crops. It appears that:

- Total annual rainfall accounts for only a small part of the variation in yield, but yields of all crops are closely connected with spring rainfall; this is the factor that shows the greatest variation between regions. Although the mean yields conceal much variation between sites (and of rainfall) it does seem that rainfall distribution is more important than total precipitation. Several authors have found the same, notably *Papy [1979]* in Morocco who found very high correlations between yield of hard wheat and barley and rainfall over specific periods in spring and also that excessive autumn rain adversely affected germination (superficial crusts and temporary anoxia) *(Papy et al. [1981])*.
- The crops do not all behave in the same way; yields of hard wheat and wheat *cv* Siete Cerros seem to be more climate-dependant than those of wheat *cv* Mahon-Demias, barley and lentils. This has two important consequences:
- optimization of the overall production of a region requires the choice of species and varieties adapted to local environment and this is especially important in a dry year.
- more attention must be paid to cultural methods for the more sensitive crops in which yield variation and progress possibilities are the greatest. This must be taken into account in the choosing of cultural methods and the timing of operations, since the different crops compete for the available labour.

It would be unwise to draw more conclusions from these results. Other aspects are discussed in the following paragraphs using data for Siete Cerros.

2.2 Yield and yield components – Siete Cerros

The study of the behaviour of a plant population under given conditions can be approached in various ways *(Masle-Meynard [1982])*: study of morphogenesis, or of competition within the population, or the analysis of yield components, which latter is the chosen method here using field data for one year from the northern and southern zones. Spring rainfall was particularly high (150 mm in the south, 210 mm in the north). In each area, the plots chosen were from fields which had been in fallow or under lentils in the preceding year, and where cultural operations, and their timing, were similar. Typically, sites in the north were sloping, on clay soil with good moisture storage (100–150 mm) those in the south were on calcareous loamy clay low in moisture storage (50–100 mm).

The variables measured (on 5 samples each 1 m^2 per plot) were: yield (Y), 1000 grain weight (WG/NG) and number of ears per m^2 (NE). Using the breakdown of yield proposed by *Boiffin et al. [1976]* and *Sebillotte [1980]* grain per m^2 (NG) was calculated as was number of grains per ear (NG/NE). Rather than considering these variables separately in succession we have used multivariate analysis (analysis of principal components) and the results are presented graphically in Figure 1. The variable 'Y' and certain plots (very weedy, or deep sub-soiling) were excluded from the analysis and their positions on the diagram calculated *a posteriori*. Each point represents the mean of the samples from one plot.

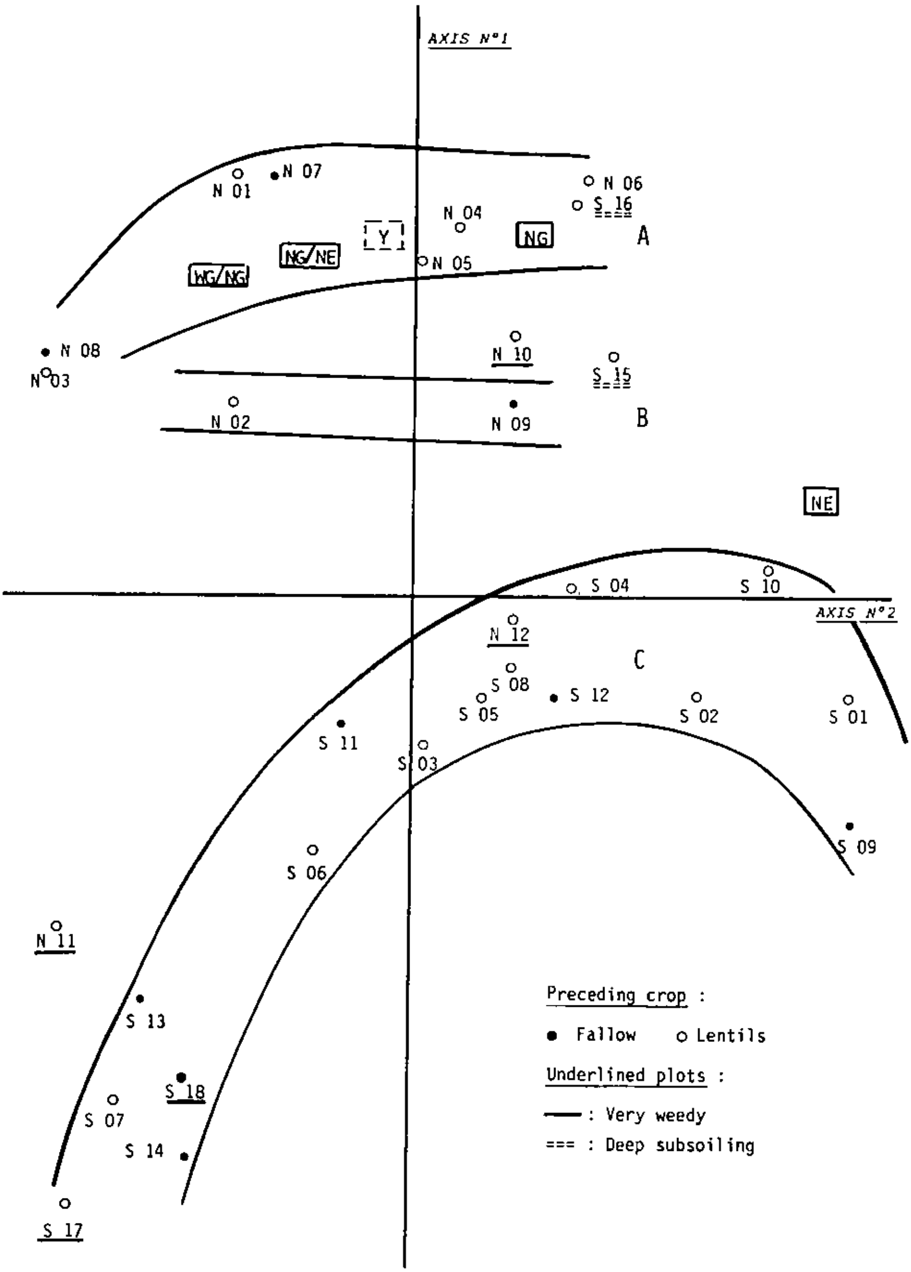

Fig.1. Principal component analysis on components of yield (Siete-Cerros)

Table 2. Schematic changes in yield and components as number of ears/unit area increases.

Groups $NE \cdot m^{-2}$	A 200 to 370	B 200 to 350	C 160 to 380
Y ($g \cdot m^{-2}$)	180 ● 250/270	≃180	50 ▼ ≃100 ● 80
$NG \cdot m^{-2}$ (0.10^{-3})	60 ● 80/85	55/60	25 ● 50/55
NG/NE	≃30 ● 23	30 18	15/17 ● 13
WG/NG (mg)	30/32	≃30	18/22 ● 15

▼: NE≃250, ●: NE ≃300

Axis No 1 (computed value: 64.5%) is set by NG, NG/NE and WG/NG (values of correlations: 0.96, 0.92 and 0.82 respectively): in fact it represents the variable 'Y'. Axis No. 2 (value 29.5%) is set by NE (correlation 0.92) the only criterion among those examined for which the range of variation in the north and south was virtually identical. The two zones contrast, on the other hand, as regards yield and the other components, notably WG/NE. One can distinguish three types of behaviour by wheat as NE increases and these are illustrated schematically in Table 2.

Groups A and B comprise plots in the northern zone which are substantially the same as regards moisture reserve but the depth of root penetration in N_{02} and N_{09} (group B) was limited by a plough pan. Group C comprises the plots in the south with low moisture reserves. It is remarkable that in 2 cases out of 3 (Figure 1) plots severely infested by weeds in the north behaved similarly to those of Group C; conversely plots in the south which had been sub-soiled to a good depth (destruction of the calcareous crust) allowing an increase in rooting depth and improved water storage, behaved similarly to the northern group.

The following interpretation is proposed:

- In either zone there are plots where yield is limited by ear number (lack of dry matter at the end of winter and at shooting depressing NG) *(Masle-Meynard [1980]; Sebillotte et al. [1978]*.
- Above a certain value for NE, differing according to the group, yield reaches a plateau (A, B) or decreases (C), increase in NG being limited by an inverse variation in NG/NE. In the absence *a priori* of some other limiting factor, it seems that water availability at flowering is the differentiating factor. This is supported by the fact the sub-soiled plots of the south fall into groups A or B. In C it is the quantity of water which is limiting; in B as compared with A it is the availability of the water (a function of root exploration).
- The shrivelling which is general in the south (C) (and for N_{11} and N_{12} badly infested by weeds) is not explained by accidents of the climate (absence of sirocco

and high temperatures) but by water supply during grain filling *(Sebillotte [1980])*.

This analysis suggests that there should he two aims:

- To achieve an ear number at flowering which does not restrict grain number.
- To make the most of the ear number by improving water availability in the spring.

It seems that the optimum ear number for the south is 250 to 300 and for the north 300 to 350. If water availability could be improved it would be possible to aim for a higher number in the north.

3. Cultural methods and their effects on cereal yield

Cultural methods affect crop environment rather than the crop itself. Crop behaviour is the result of interactions between the physical, chemical and biological conditions of the site and climate, and the importance of these has been discussed above. The choice of cultural method is made more difficult by year to year variations in climate even as regards actions which affect the plant population directly (seed rate for example). It is with the interactions that we are principally concerned. It is not enough simply to analyze successively and independently the possible effects of different methods (crop succession, cultivation method, fertilizer use, weeding . . .). This is why we prefer to start from the two considerations mentioned above, presenting for each the main sources of variation of the parameters responsible and discussing the practical consequences.

3.1 Control of ear number

Ear number at flowering depends upon germination and tillering. Tillering is generally weak (the median value in the investigation discussed above was 1.2). This seems to result from the temperature regime but may also be caused by loss of plant through the winter. Nitrogen does not seem to increase tillering significantly though it increases NG/NE when moisture is not too limiting *(Manichon* and *Lebris [1979])*. It seems therefore that germination is decisive. This is affected by germination capacity and characteristics of sowing. We shall confine ourselves to the latter point which is especially delicate.

3.1.1 Causes of variation in germination

Field enquiries have shown *(Bourgeois [1975]; Leval [1977])* that germination percentage in the North African cereal areas is frequently below 50%. Three things are responsible for this: seed bed structure, depth of sowing and rainfall after sowing *(Fenech* and *Papy [1977])*. If the latter is high, germination depends less on seed bed condition and depth of sowing except on slaked soils and for seed sown too deep. Otherwise, if there is a dry period after sowing or poor rainfall, these factors are important but in different ways according to whether the soil was initially moist or dry. In Table 3 we show some typical cases.

Table 3. Emergence percentage (T) in relation to climate post-drilling and initial humidity of seed-bed.

Humidity of seed-bed at date of drilling	Climate post-drilling	
	No rain	Little rain
Dry	No germination before rain occurs. Date of emergence late. T depends on amount of subsequent rain.	Germination and death of superficial seeds. T is depressed. Other seeds do not germinate until subsequent rain occurs.
Damp	Germination depends on the position of seed/position of self-mulch profile. T is depressed if seeds are above self-mulch (depending subsequent rain).	T is high (if subsequent rain is high).

– *Dry seedbed.* Lack of rain after sowing retards germination and this can penalize final yield (backward crops are more susceptible to spring drought). If rainfall following sowing is slight and followed by a dry period, only seed in the moist surface layer germinates, if moisture is above critical value, depending on texture *(Bruckler [1979]);* the seedlings die almost immediately being unable to find sufficient moisture to support growth *(Arnon [1972]).* This risk is increased by shallow sowing as in broadcasting or when the drill is improperly adjusted.
– *Damp seedbed.* Drying out of the seedbed, under given conditions of evaporation, depends on seedbed structure *(Boiffin et al. [1980]);* the coarser it is the more it contains cavities and the deeper the desiccation front. The position of the seed in relation to this limit determines the possibility for germination. With shallow sowing and poor post-sowing rain, the danger of loss is great.

3.1.2 Consequences for the choice of techniques

The preceding clearly indicates that it is desirable to wait until the profile is thoroughly moistened – at least to the working depth – before sowing, suggesting a date for sowing when the risks of light rainfall followed by drought are reduced though they are never negligible *(Leval [1978]).* It is necessary to study the autumn rainfall pattern in order to evaluate the risks. Usually, however, because of the area to be sown and limited labour availability it is not so much a case of waiting till it is fit to sow as of minimizing the risks incurred when sowing *must* be done, by adapting cultural methods. Sowing cannot be too much delayed due to the risk of losing in spring everything which has been gained in autumn. Late sowing is also detrimental when autumn is very wet (see the negative correlations in Table 1). Our strategy for sowing is:
a) For early sowing under dry conditions, select fields with the minimum risk of weed infestation, the earlier sowing is done the more important this is *(Manichon* and *Lebris [1979]).* Seedbed preparation in the dry does not destroy weeds and weed seeds germinate along with the wheat. The weed risk depends on the previous crop

Table 4. Influence of previous crop on weeds in wheat (*Manichon* and *Lebris*, 1979).

Previous crop	Cultivation techniques in previous crop	Weeds in wheat (comparative densities)
Fallow	– Early disc-ploughing (January)	
	+ Cover crop April	ε
	+ Cover crop February	*
	– Late disc-ploughing (April)	
	+ Cover crop June	**
Lentil	Early harrowing (April)	*
	Late harrowing (June)	**
Forage	Early harvesting (June)	*
	Late harvesting (July)	***

Table 5. Possible effects of cultivated fallow (High Plains, Algeria).

Climatic zone	Soil	Positive effects [1]) on:		
		Weeds destruction	Soil structure	Water balance
North	Heavy Clay	***	*** [2])	***
South	Sandy Loam	**	*	0

[1]) If correctly cultivated
[2]) Seed-bed: A risk exists of creating plough-pans

and its treatment (Table 4). The number of fields suitable for early sowing depends upon the rotation and usually they are less numerous the greater the potential of the area.

Select also those fields where seedbed preparation is easy, those of light texture which do not hold together in dry conditions, where a sufficiently fine seedbed can be quickly made without the need for heavy implements. Fields cultivated in the preceding spring (fallow) or soils which break down easily under alternate wetting and drying are also suitable (Table 5).

b) Manage later sown fields so as to:

- control weeds by repeated cultivation of the surface after the first rain;
- avoid practices which make seedbed preparation more difficult such as deep cultivation of heavy land which creates large clods *(Fenech* and *Papy [1977])*.

Clearly, in order to get satisfactory results in all fields and to correct adverse conditions *(e.g.* by rolling), one must have the means at one's disposal. It is also necessary to observe the behaviour of each individual field and adapt methods accordingly.

3.2 Water supply in spring

The reduction of drought stress in crops when rainfall is insufficient demands a well developed root system which thoroughly explores the soil so as to make use of the water present therein. It is also necessary that sufficient water should be available in the soil.

3.2.1 Causes of variation in the quantity of soil water and its availability in spring

Water availability: root penetration is controlled by mechanical resistance of the soil *(Maertens [1964])* and this depends on structure and water status. Early germinating seed is penalized if the soil is moistened only superficially (cessation of root growth at depth); whatever the date of sowing, deficiencies in soil structure often limit access by roots to stored water.
Water storage capacity: Available water capacity depends on soil type, texture and depth of root penetration. It can be improved by breaking up the plough pan or the calcareous crust (if soil structure below allows root penetration).
Water status at the beginning of spring: For a given value of available water capacity, change in soil water content between sowing and early spring is given by:

$$\Delta S = aR - ET - D$$

where S = water stored, R = rainfall, ET = evapotranspiration and D = drainage, a is the infiltration coefficient of rain.

- *Drainage* can be considered negligible in land under crop *(Dutil [1962]* except when AWC is low.
- *Evapotranspiration.* This is low in winter but rapidly increases as temperature rises in spring. Under given climatic conditions, the rate of water consumption depends on the density of the crop cover. We have seen the depressive effect of too high a number of ears per unit area *(cf.* 2.2): too generous fertilizer use causing excessive growth of foliage can have a similar effect *(Viets [1965]).* Finally, weeds can compete for water with the crop.
- *Infiltration coefficient.* This varies with the gradient of the slope and with structure on the surface and at depth. Plough pans hamper the penetration of water to depth in winter (absence of clefts) and aggravates water erosion.

3.2.2 Consequences for the choice of techniques

Two things are essential:

- *To encourage a dense and deep root system.* This calls, in the first place for the improvement of soil structure: subsoiling (increasing the depth of soil that can be exploited), annual cultivations. It must be pointed out that disc implements often have a bad effect especially when used on wet soil (late autumn work, winter cultivation of fallows).
- *Need for weed control* which has already been mentioned (3.1.2) in connection with the dates of sowing and cultivation. One should not rely too heavily on chemical control which is often too costly (grass killers) in relation to expected crop yield.

However, these two points relate only to the access to and utilization by the crop of the stock of soil water and up to now we have reviewed only the factors which influence this so far as the current crop is concerned.
The possibility of increasing this stock by using a fallow before the wheat crop is often discussed *(Pendleton [1965]; Sims [1977],* among others). *Sebillotte [1976]* suggested an investigation method for the effect of fallow based on water balance during fallow. In the case of a bare fallow for 15 months preceding wheat in the high plains of Algeria, or under similar climatic conditions, the result depends on two factors:

- Available water capacity which for a given rainfall determines drainage losses. *Dutil [1962]* working in the Batna region of Algeria (rainfall ahout 400 mm) found negligible percolation on clay soil with a high reserve of water and found that it was not always possihle to replenish to field capacity during the course of the fallow; in contrast on loamy sands, drainage accounted for one quarter of total rainfall. *Yankovitch [1956]* in Tunis found that water drained to a great depth, hut this was with a higher rainfall (500 mm). Part of the nitrogen mineralized in the fallow may thus he removed from the rooting zone of the following crop.
- Cultivation techniques used during the fallow and their effects on the infiltration of rainfall and on drying of the soil. Date of ploughing is particularly important: if early (at the heginning of the wet season) it appreciahly increases infiltration (above all on sloping fields) and destroys weeds thus reducing evapotranspiration *(Leval [1978])*. If late it increases desiccation of the soil *(Perrier [1973])*. As much for the sake of weed control as of limiting evaporation from bare soil (forming of a mulch) it is necessary to follow ploughing with superficial cultivations in spring before weed development proceeds too far.

It can be concluded that bare fallowing will only increase water storage if the soil's available water capacity is relatively high and that the main concern is with autumn conditions (favourable conditions for root development) rather than with spring (except in the case of a dry winter). Finally the constraints on the realization of this effect have to be recognized. The results in Figure 1, which on the whole show that fallowing had no appreciable effect on wheat yield, suggest that the required conditions seldom apply in practice.

4. Conclusion

We have chosen to base our discussion mainly on one example from which certain conclusions may be drawn about the possibility of improving cereal growing. The attainment of increased yield of a given crop and variety depends upon the removal as far as possible of limiting factors in the field. This requires annually a series of decisions based on the initial state of the field and on forecasts of their development. It requires appropriate treatment of the preceding crop whose effects can be many and variable according to physical conditions. Table 5 shows the possible effects of a cultivated fallow. It is interesting that the fallow gives the best results in the potentially most productive climatic zone where it is most difficult to be eliminated. Thus, in the south crop, production might be increased by increasing the area under crop at the expense of the fallow which now occupies half the rotation, but, here, one is faced with the problem of food supply for the herds to which the fallow makes a significant contribution. Paradoxically in the more favourable conditions of the north, improvement depends on better management of the fallow (especially as regards date of ploughing) the area under fallow can be decreased only if more equipment for cultivation is available.

Finally, it is clear that in these areas which suffer under natural constraints, high competence of the farmers and references adapted to the uncertain conditions have to exist for the advancement of agriculture.

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Crop Response to Nitrogen and Phosphorus in Rainfed Agriculture

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Summary

Agronomic trials conducted in Northwest Syria indicate that a considerable potential exists to increase yields of barley through the use of nitrogen and phosphorus fertilizers. Crop response to applied fertilizers is discussed in terms of climatic factors, such as amount and distribution of rainfall, soil factors, such as the availability of nitrogen and phosphorus, and crop factors.

1. Introduction

In the Mediterranean environment crop yields under dry farming conditions are generally assumed to be limited by available moisture. Crop yields decline with decreasing annual precipitation, and much of the variability in yields between seasons can be explained by variability in amount and distribution of rainfall. However, there is a strong interaction between soil moisture and nutrients available to the plant, and in many instances actual crop production appears to be limited by the availability of soil nutrients rather than by available moisture. In fact, the responses to fertilizers observed at many locations in the Mediterranean countries *(FAO [4])*, show that available moisture was not the major constraint to actual crop production at these locations.

Many of the soils in the Mediterranean environment are deficient in nutrients *(FAO [4], Sillanpää [18], Jackson [13])*, and application of fertilizers under these conditions may increase the tolerance of the crop to adverse environmental conditions, such as cold or drought, and increase the water-use efficiency of the crop *(Viets [20])*, resulting in increased crop yields. However, many factors other than the soil nutrient status, may affect the response of field crops to applied fertilizers. Among these are climatic factors, such as amount and distribution of rainfall, and temperatures during the season, and other factors, such as crop management, varietal differences between crops, the effect of crop rotations, fertilizer management, residual effects of fertilizers, land management, weeds, pests and diseases. If these factors are not considered in fertilizer response trials, it is difficult to draw conclusions and to generalize the results of such trials.

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It is the objective of this paper to discuss some results of fertilizer research done in Northwest Syria by the *International Center for Agricultural Research in the Dry Areas (ICARDA)*. The emphasis will be on responses of cereal crops to nitrogen and phosphorus fertilizers, under low rainfall conditions (200–600 mm/year). Some of the factors that affect crop responses to applied fertilizers will be discussed.

2. Description of agronomic trials and experimental sites

As part of *ICARDA*'s research programme on the agronomy of cereal crops, a series of field trials were conducted for three years at five experimental sites in Northwest Syria.

2.1 Description of agronomic trials

The major objective of the trials reported here was to study the effect of seed rate, nitrogen and phosphorus fertilizers, on the productivity of barley crops grown under rainfed conditions in Northwest Syria. The trials were laid down in a modified central factorial design at five sites in Northwest Syria, covering a range of climatic and soil conditions. Factors considered in the trials included seed rate (30–150 kg/ha), nitrogen (0–120 kg N/ha) and phosphorus fertilizer (0–120 kg P_2O_5/ha), where the ranges are given in parenthesis. One cultivar of barley (Beecher) was selected for the trials at all sites. Nitrogen fertilizer was applied as ammonium nitrate (33% N), up to 20 kg N/ha at planting, drilled with the seed, and the remainder topdressed at the start of stem elongation (late February to early March). Phosphorus fertilizer was applied as triple superphosphate (46% P_2O_5), drilled with the seed at planting. Management of the trials was kept as uniform as possible across different locations. Weeds were controlled, and pests and diseases were not significant factors in the trials.

2.2 Description of experimental sites

The trials were conducted at five experimental sites in Northwest Syria (Table 1): at *ICARDA*'s main experiment station (Tel Hadya), and at two wetter sites (Kafr Antoon and Jindiress), and two drier sites (Breda and Khanasser). Each site was divided into four equal-sized blocks (2.5 ha each) and managed according to a rotational system representative for the area in which the site was located. At the two drier sites, the barley experiments were preceded by a year of fallow, and at Tel Hadya and the two wetter sites, the barley experiments followed a year of winter fallow – summer crop (sesame or water melons). All experimental sites were on deep soils, and on nearly flat land.

Table 1. Seasonal rainfall (from October to crop maturity) at experimental sites. Long-term averages for the whole season (October to June inclusive) are for the approximate period 1960–1980.

Site		Rainfall (mm)			Long-term Average	
Name	Abbre-viation	1979/80	1980/81	1981/82	Mean	Range
Jindiress	JD	377	456	343	479	290–720
Kafr Antoon	KAF	392	430	312	444	250–700
Tel Hayda	TH	414	347	393	342	180–420
Brida	BR	256	274	276	278	75–430
Khanasser	KH	263	242	253	215	98–390

2.2.1 Climate and growing conditions

The climate in Northwest Syria is cool subtropical with winter rainfall *(Kassam [15])*. Figure 1 summarizes some information on the climatic conditions at two locations in Northwest Syria: Aleppo and Azaz. Climatic conditions at Tel Hadya are assumed to be similar to those at Aleppo, whereas Azaz would be more representative for the wetter sites, in particular Kafr Antoon.

The long-term rainfall data in Table 1 were taken from meteorological stations nearest to the sites, and are assumed to be approximately representative for the experimental sites. From the start of the agronomic trials in 1979, rainfall and other meteorological data have been recorded at the experimental sites.

In the 1979/80 season precipitation was above the estimated long-term average at the drier sites and Tel Hadya. Rainfall distribution was favourable at all sites, and heavy rains fell prior to anthesis (end of March). In the 1980/81 season rainfall was close to the estimated long-term averages at all sites. In the 1981/82 season rainfall was below average at the wetter sites, but above average at the drier sites and Tel Hadya.

Minimum temperatures in winter (December, January) were low in all three seasons, and frost damage was observed in cereal crops. The 1981/82 season was particularly unfavourable with heavy frosts in February, coupled with inadequate rainfall.

Germination date depended on the start of the rains, and ranged from early November to late December. Crops normally matured in early May. The site of Kafr Antoon was characterized by a longer growing season because of lower mean temperatures.

2.2.2 Soil conditions

Soils at the experimental sites have been classified according to the *USDA [19]* and *FAO-Unesco [5]* systems of soil classification *(Buringh P.:* Personal communication, 1980; *ICARDA [10])*. They covered a range of soil types representative for Northwest Syria. Soils at all sites were calcareous and heavy, the texture ranging from clay at the wetter sites, to clay loam and loam at the drier sites (Tables 2 and 3).

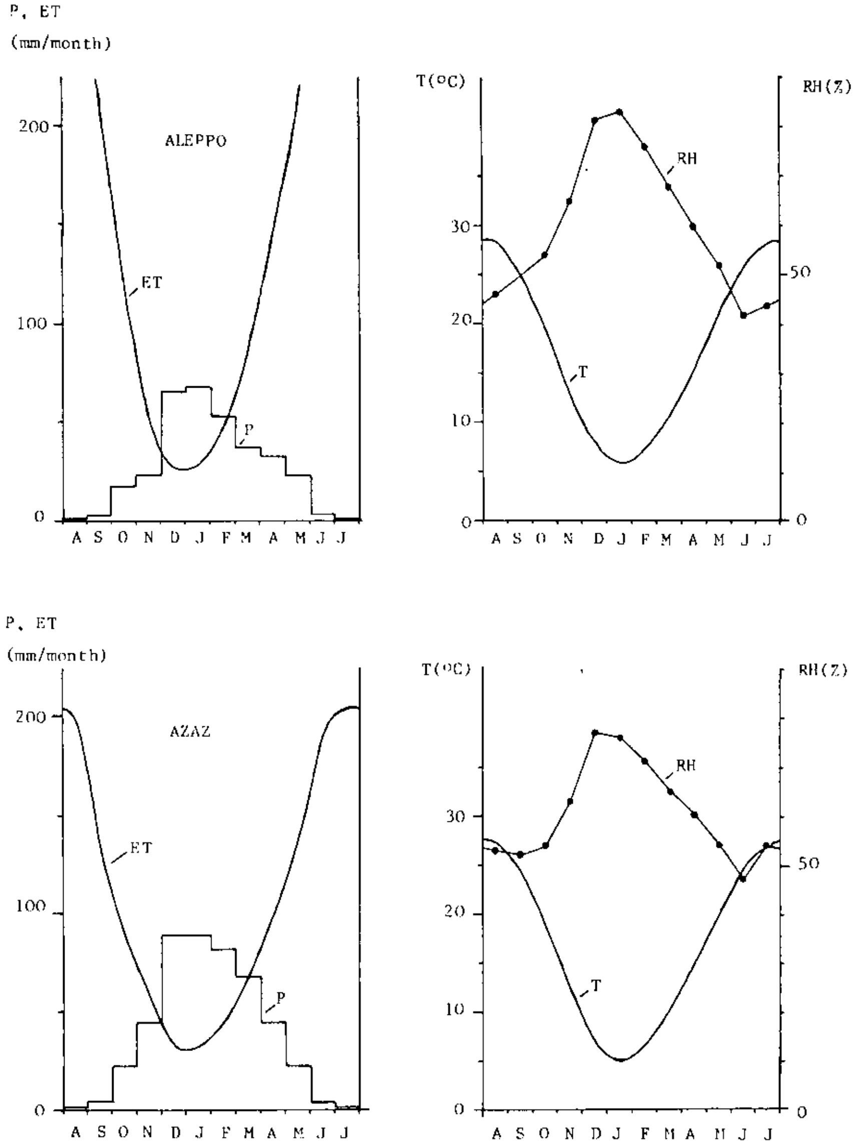

Fig.1. Average monthly precipitation (P; mm/month), potential evapo-transpiration, estimated from the Penman formula (ET; mm/month), mean temperature (T; °C), and mean relative humidity (RH; %) for two locations in Northern Syria: Aleppo (altitude 392 m) and Azaz (555 m). Data from: FAO Agroclimatic Data Bank *(Arar A:* personal communication, 1981).

Table 2. Classification of soils at experimental sites.

Site	Texture	Classification
Jindiress	Clay	Palexerollic Chromoxerert *(USDA)* Chromic Vertisol *(FAO)*
Kafr Antoon	Clay	Palexerollic Chromoxerert *(USDA)* Chromic Vertisol *(FAO)*
Tel Hadya	Clay	Chromoxerertic Rhodoxeralf *(USDA)* Vertic (calcic) Luvisol *(FAO)* Calcic Rhodoxeralf *(USDA)* Chromic (calcic) Luvisol *(FAO)*
Brida	Clay Loam (top) to Silty Clay (at depth)	Typic Calciorthid *(USDA)* Calcic Xerosol *(FAO)*
Khanasser	Loam (top) to Clay Loam (at depth)	Typic Calciorthid *(USDA)* Clacic Xerosol *(FAO)*

Organic carbon and total nitrogen contents were low, and available-phosphorus contents were in the low to medium range.

The mineral-nitrogen contents, determined at planting 1980, ranged from low (Jindiress and Kafr Antoon), to medium (Tel Hadya and Breda), to high (Khanasser). The assessment of the mineral-nitrogen status of soils in terms of plant-available nitrogen is based on expected yields *(i.e.*, nitrogen requirements) at the experimental sites, and assumes that nitrate-nitrogen in the soil at planting is the major source of plant-available nitrogen during the growing season. The latter assumption is supported by a study on the dynamics of mineral nitrogen in soils at the experimental sites, which indicated that nitrate-nitrogen in these soils was not subject to extensive losses *(e.g.*, leaching or denitrification), and that nitrification of ammonium-nitrogen mineralized during the growing season was not a major source of plant-available nitrogen *(Harmsen [9])*. These conclusions are preliminary, however, and more research on the dynamics of mineral nitrogen as related to cropping systems and crop management, soil and climatic conditions, is in process.

3. Results and discussion

Results of the trials have been reported elsewhere *(ICARDA [10, 11, 12])*, for each season separately. Because of the central composite factorial design of the trials, actual yield data were available for a limited number of treatments only. From these yield data regression equations covering the full range of seed rate, nitrogen and phosphorus fertilizer, can be derived and crop yields of other treatments can be predicted (Section 3.9).

The objective of this paper is to compare responses to nitrogen and phosphorus fertilizers over the five sites and three growing seasons, based on actual yield data. To this end, four treatments were selected (Table 4), for which actual yield data were available for all sites and seasons. Fertilizer rates of 60 kg/ha (P_2O_5 or N) and a seed rate of 90 kg/ha correspond to the middle levels in the treatment matrix of the agronomic trial.

Table 3. Data on soils at experimental sites: mechanical analysis (hydrometer), lime equivalent (titration), pH (1:1 soil-water suspension), organic carbon (Walkley-Black), total nitrogen *(Kjeldhal)*, available phosphorus *(Olsen)*, and mineral nitrogen *(Bremner)*.

Site	Soil Depth (cm)	Mechanical Analysis (% w/w)			Lime Equivalent (% w/w)	pH	Organic Carbon (% w/w)	Total Nitrogen (ppm)	Available Phosphorus* (ppm)	Mineral Nitrogen** (ppm)	
		2 mm–50 μ	50–2 μ	<2 μ						NH_4–N	NO_3–N
JD	0– 20	3.8	32.5	60.8	20.2	8.0	0.65	601	3.37	4.2	5.4
	20– 40	3.8	32.5	61.0	20.6	8.0	0.49	515	1.60	4.1	3.2
	40– 60	4.0	33.3	60.8	21.3	8.0	0.43	451	1.00	3.1	2.5
	60– 90	3.8	32.7	61.8	21.6	8.0	0.37	395	0.98	3.7	1.8
	90–120	3.9	32.3	61.8	22.0	8.1	0.33	290	0.92	3.6	1.3
	120–150	7.5	32.9	60.3	–	8.1	–	234	0.84	3.1	0.7
KAF	0– 20	5.1	29.9	61.8	10.8	8.0	0.49	512	3.22	3.4	6.4
	20– 40	5.6	31.6	62.0	11.3	8.0	0.43	441	1.59	3.0	4.2
	40– 60	5.6	31.6	62.0	11.8	8.0	0.37	378	0.91	4.6	2.7
	60– 90	5.6	31.8	61.8	12.7	8.0	0.32	339	0.87	3.7	2.9
	90–120	5.8	32.0	61.0	14.7	8.0	0.29	290	0.90	3.1	2.9
	120–150	15.1	33.6	48.5	–	8.1	–	193	0.84	3.2	3.3
TH	0– 20	6.5	37.3	55.0	24.9	8.1	0.39	530	6.88	10.7	21.8
	20– 40	6.8	36.9	55.0	26.4	8.1	0.33	441	2.92	6.6	11.5
	40– 60	5.8	35.8	57.0	26.5	8.1	0.29	382	1.06	4.7	2.4
	60– 90	6.5	37.1	56.5	26.9	8.1	0.27	322	0.75	3.1	3.4
	90–120	5.8	37.7	58.0	26.5	8.1	0.21	255	0.46	3.1	2.3
	120–150	3.9	38.0	59.5	–	8.1	–	217	0.62	3.5	1.7
BR	0– 20	24.5	42.4	28.8	33.7	8.3	0.63	647	3.48	2.6	7.8
	20– 40	18.6	38.7	38.0	37.1	8.4	0.35	386	2.20	2.6	2.7
	40– 60	12.8	39.5	43.5	48.5	8.5	0.25	281	1.68	3.3	4.2
	60– 90	15.1	38.7	41.3	47.4	8.5	0.19	207	1.49	2.3	4.1
	90–120	17.3	39.2	40.0	37.5	8.3	0.13	161	1.49	2.5	6.8
	120–150	16.4	40.7	40.3	–	8.0	–	100	1.29	2.1	9.9
KH	0– 20	26.2	44.3	23.5	38.6	8.2	0.74	817	5.13	6.1	34.7
	20– 40	23.1	41.6	29.8	41.8	8.2	0.45	522	2.41	4.3	17.0
	40– 60	19.8	40.0	36.3	44.9	8.2	0.23	303	1.96	3.2	16.8
	60– 90	–	–	–	41.7	8.0	0.16	183	1.94	2.7	27.6
	90–120	–	–	–	32.1	8.1	0.12	132	1.68	2.9	49.7

* Mean values for the 1980/81 growing season

** Determined at planting 1980

Table 4. Factors in the analysis of variance.

Factor	No. of Levels	Treatments
Replicates	2	–
Sites	5	JD, KAF, TH, BR, KH
Years	3	1979/80, 1980/81, 1981/82
Nitrogen	2	N_0(0 kg N/ha) and N_1(60 kg N/ha)
Phosphorus	2	P_0(0 kg P_2O_5/ha) and P_1(60 kg P_2O_5/ha)

3.1 Statistical analysis

Factors considered in the analysis of variance are summarized in Table 4. Variables in the analysis of variance were grain yield (GY), harvest index (HI), and total amount of above-ground dry matter, or dry matter yield (DMY). The latter was calculated from grain yield and harvest index, according to DMY=GY/HI.
The analysis of variance assumes homogeneity of errors across years and sites. For a preliminary analysis, this was considered to be adequate *(Cochran* and *Cox [2])*. Third order interactions were found to he small and these components were pooled with the error term in the analysis of variance. Standard errors for comparing differences between treatment means were calculated in the conventional way, using the error mean square for the pooled components.

3.2 Significant components

Components with significant F-values are presented in Table 5, for grain yield and dry matter yield, listed in approximate order of significance. Site was the factor which had the most significant influence on yield, followed by nitrogen, year, and phosphorus. The site × year and site × N interactions were also highly significant, but F-values for N × P and site × P interactions were close to the tabulated significance levels and should be viewed with caution.

Table 5. F-values for significant components from the analysis of variance.

Component	F-values	
	Grain Yield	Dry Matter Yield
Site	186.8***	184.5***
N	46.4***	53.9***
Year	43.3***	21.8***
P	10.7**	16.0***
Site × Year	8.0***	9.7***
Site × N	6.4***	5.4***
N × P	4.2*	5.9*
Site × P	2.6*	1.7^{NS}

*** 0.1%; ** 1%; * 5%; ^{NS} Not significant at 5% level.

3.3 Effects of site, nitrogen, and phosphorus

The main effects of N and P on grain yields, averaged over three years, are shown in Table 6 for the five experimental sites. Only grain yields are presented because dry matter yield responses were generally similar, reflecting that fertilizer treatments had little effect on harvest index (see Section 3.7).

Yield responses to nitrogen tended to be larger at the higher-rainfall sites, while responses to phosphorus tended to be larger at the lower-rainfall sites.

Yield responses to nitrogen largely reflected the available-nitrogen status of soils at the experimental sites. Figure 2 summarizes some information on labile nitrogen, which is the sum total of plant-nitrogen (cropped plots), and nitrate- and ammonium-nitrogen in soil (all plots). The amounts of mineral-nitrogen were calculated for different depths at the experimental sites, corresponding to the approximate depths of penetration of moisture at these sites. Below these depths the amounts of ammonium- and nitrate-nitrogen did not change significantly during the growing season, and therefore it was assumed that mineral-nitrogen below the approximate depths of penetration of moisture was not available to the crop during the growing season.

Mineral-nitrogen contents varied considerably between plots (even within plots) and between fields. Therefore, the data presented in Figure 2 have to be interpreted with caution. Some trends, however, can be distinguished. At Khanasser, the driest site, nitrate contents in soils were high to very high. The difference between cropped and fallowed plots, sampled at harvest 1980 (Figure 2), reflected spatial variability. At all sampling occasions there were significant amounts of nitrate left in the top 60 cm of the soil (both cropped and fallowed plots), and therefore a crop response to nitrogen fertilizer would not be expected at this site. At Breda, the second-driest site, there was virtually no nitrate-nitrogen left in the soil at harvest 1980, indicating that crops in unfertilized plots may have been deficient in nitrogen during the first growing season. During the second and third growing seasons, the situation was different (see Section 3.4). At Tel Hadya, some nitrate-nitrogen was left in the soil at harvest (no significant response to nitrogen), but at Kafr Antoon and Jindiress, virtually all nitrate-nitrogen was taken up by the crop at harvest (significant

Table 6. Main effects of N and P on grain yield (t/ha), averaged over three years. All yields are expressed as oven dry weights. Least significant difference for the site × N and site × P interactions (5% level) = 0.4 t/ha. The mean rainfall represents the average for three seasons (from October to crop maturity).

Site	N_0	N_1	ΔN	P_0	P_1	ΔP	Mean Rainfall (mm)
JD	2.2	3.3	1.1***	2.7	2.8	0.1	392
KAF	3.6	4.2	0.6***	3.9	3.8	−0.1	378
TH	3.6	3.9	0.3	3.6	3.8	0.2	385
BR	1.5	1.9	0.4*	1.5	1.9	0.4*	269
KH	1.4	1.4	0	1.1	1.7	0.6***	253

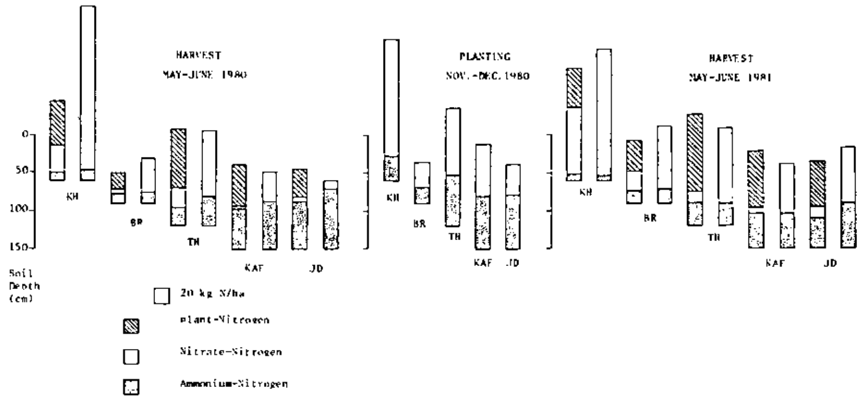

Fig.2. Labile nitrogen at five experimental sites, in fallow plots and cropped (barley) plots, at three sampling occasions during 1980/81. The positioning of the bars indicates that the amount of mineral nitrogen in the soil was calculated for the 0–60 cm layer at Khanasser, 0–90 cm at Breda, 0–120 cm at Tel Hadya, and 0–150 cm at Kafr Antoon and Jindiress.

responses to nitrogen). The nitrate-nitrogen in soils in cropped plots at Jindiress at harvest 1981, may have been due to nitrification of ammonium-nitrogen during May 1981, after the crop had ceased to take up nitrogen from the soil.

The ratio of nitrate- to ammonium-nitrogen tended to increase with decreasing rainfall (Figure 2). This may reflect the lower clay contents, and hence the lower cation-exchange capacities of the soils, but may also be due to the generally drier conditions (better aeration) at the drier sites.

Significant amounts of nitrate-nitrogen were conserved in soils in fallowed plots (Figure 2). The increase in nitrate-nitrogen in fallowed plots over cropped plots at harvest 1980 ranged from 6 (Jindiress) to 60 kg N/ha (Tel Hadya), with an average of 35 kg N/ha for four sites (excluding Khanasser). These values are in the same range as values given by *French [7]*, who reported a mean increase in nitrate-nitrogen of 36 kg N/ha for five locations in South Australia.

Yield responses to phosphorus were significant at the drier sites, but at the wetter sites there seemed to be little or no response to phosphorus. The available-phosphorus status of soils at all sites was in the low (below 5 ppm) to medium (5–10 ppm) range (Table 3). This would suggest that crops may require a higher level of available soil phosphorus under dry conditions, and critical soil test levels may need to be reassessed according to soil moisture conditions. Most of the phosphorus recovered by the soil test is in the form of adsorbed phosphorus or in the form of easily soluble compounds. Since the crop takes up most of its phosphorus from solution, the kinetics of desorption and dissolution, and of diffusion, play an important part in the phosphorus nutrition of crops. Hence, an interaction between the soil moisture status, and the availability of phosphorus to the crop would be expected.

3.4 Effect of year

Table 7 shows the effect of year on grain yield responses to nitrogen and phosphorus. The site × year interaction was large for the response to nitrogen at Breda in the 1979/80 season (1.1 t/ha grain), but there was no response in subsequent seasons.

Table 7. Main effects of N and P on grain yields (t/ha) for each site and year. Least significant difference for the Site × Year interaction (5% level) = 0.8 t/ha.

Year:	1979/80			1980/81			1981/82		
Site	N_0	N_1	ΔN	N_0	N_1	ΔN	N_0	N_1	ΔN
JD	2.1	3.3	1.2***	2.6	3.7	1.1***	1.8	2.9	1.1***
KAF	3.5	3.9	0.4	4.1	5.0	0.9***	3.0	3.6	0.6*
TH	3.6	4.1	0.5	4.0	4.1	0.1	3.0	3.6	0.6*
BR	1.2	2.3	1.1***	1.8	1.8	0	1.5	1.5	0
KH	2.4	2.3	–0.1	1.4	1.3	–0.1	0.4	0.7	0.3
Site	P_0	P_1	ΔP	P_0	P_1	ΔP	P_0	P_1	ΔP
JD	2.9	2.5	–0.4	2.8	3.5	0.7*	2.3	2.4	0.1
KAF	3.9	3.6	–0.3	4.7	4.4	–0.3	3.3	3.4	0.1
TH	3.7	3.9	0.2	3.9	4.2	0.3	3.3	3.3	0
BR	1.6	2.0	0.4	1.5	2.1	0.6*	1.4	1.6	0.2
KH	1.8	2.9	1.1***	1.1	1.6	0.5	0.4	0.7	0.3

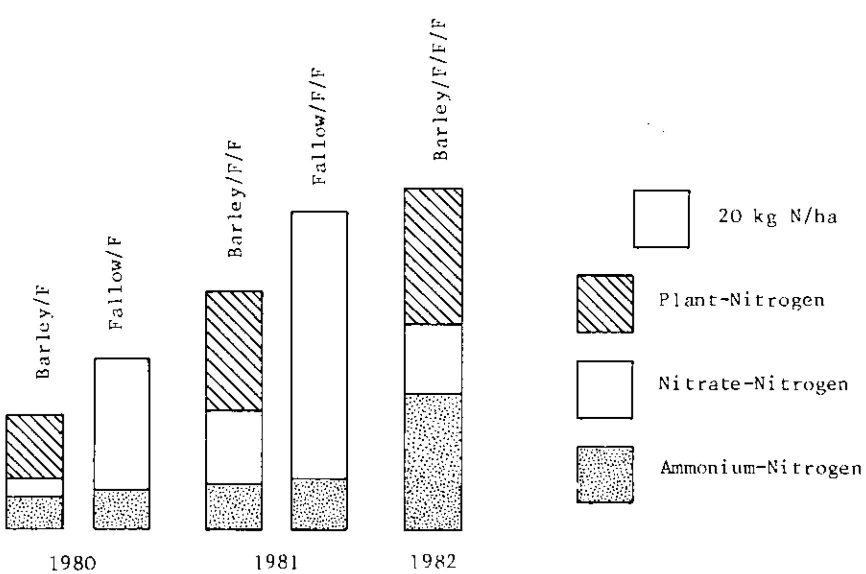

Fig. 3. Labile nitrogen at Breda in fallow plots and cropped (harley) plots, following one year (F), two years (F/F) and three years of fallow (F/F/F).

The 1979/80 season differed from the other seasons in that rainfall distribution was more favourable around anthesis, but the main reason for the response to nitrogen in that season was probably the lower available-nitrogen status of the soil during the first season. The first year (1979/80) of barley experiments followed one year of fallow, the second year (1980/81) followed two, and the third year (1981/82) three years of fallow. This resulted in a gradual build-up of mineral nitrogen in the soils (Figure 3).

The response to phosphorus at Khanasser was large in the 1979/80 season, but comparatively small in the 1981/82 season. Conditions were less favourable for growth in the 1981/82 season, as indicated in Section 2.2.1. Also, poor emergence in fertilized plots at Khanasser may have contributed to low yields in the 1981/82 season.

3.5 Rainfall-yield relationship

Amount and distribution of rainfall are major factors in determining crop yields under rainfed conditions. Table 5 shows that site and year were among the most significant components in the analysis of variance. If nutrients are not limiting crop production, one would expect yields to increase with increasing rainfall. A regres-

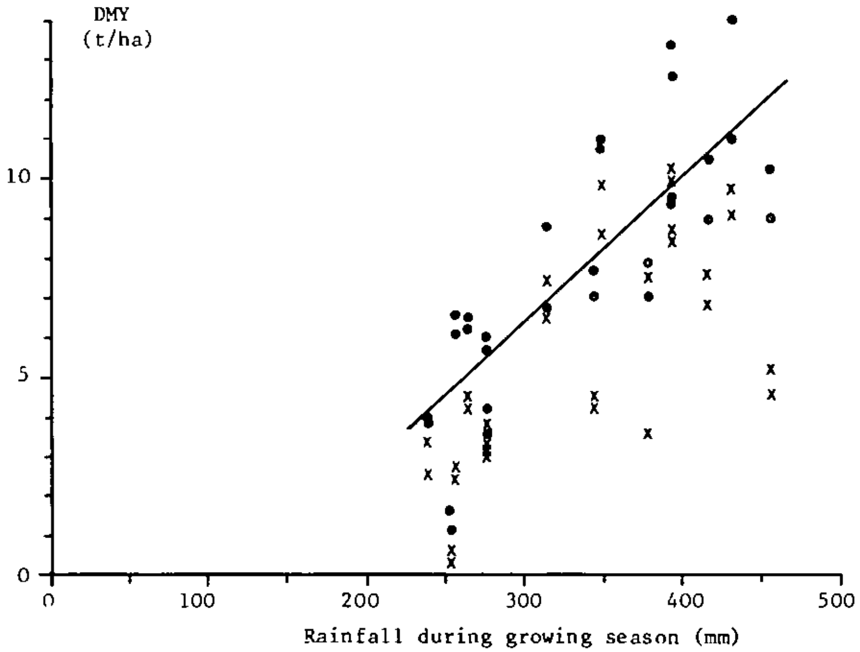

Fig. 4. Dry matter yields (DMY) of Beecher barley in unfertilized (×) and fertilized (●) plots (60 kg N/ha, 60 kg P_2O_5/ha) at all sites during three seasons, plotted against rainfall during the growing season. The straight line represents the regression equation of yields of fertilized plots on seasonal rainfall.

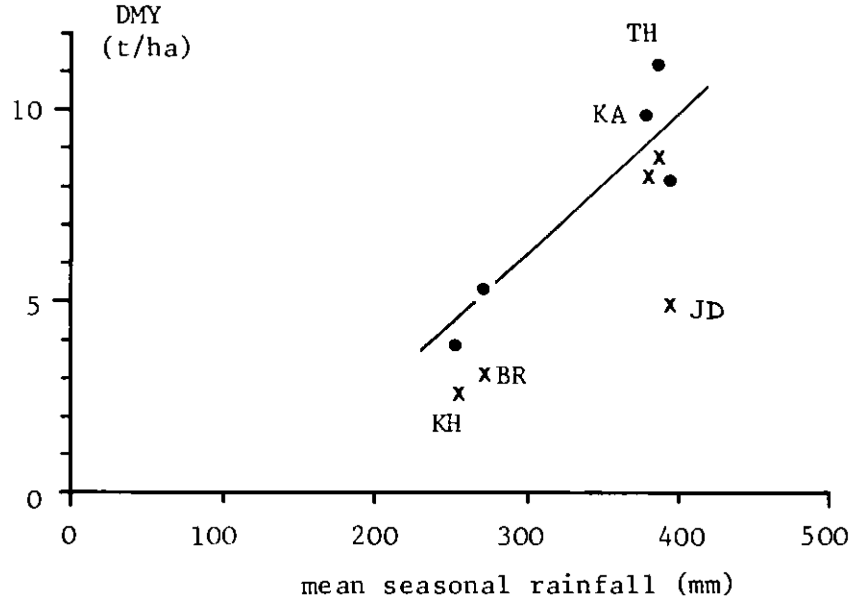

Fig. 5. Dry matter yields of fertilized (●) and unfertilized (×) Beecher barley, averaged over replicates and seasons, plotted against mean seasonal rainfall. The straight line represents the regression equation of individual plot yields of fertilized barley on seasonal rainfall.

Fig. 6. Dry matter yields of fertilized (open bars) and unfertilized (shaded bars) Beecher barley at three experimental sites during three seasons: 1979/80 (1), 1980/81 (2) and 1981/82 (3).

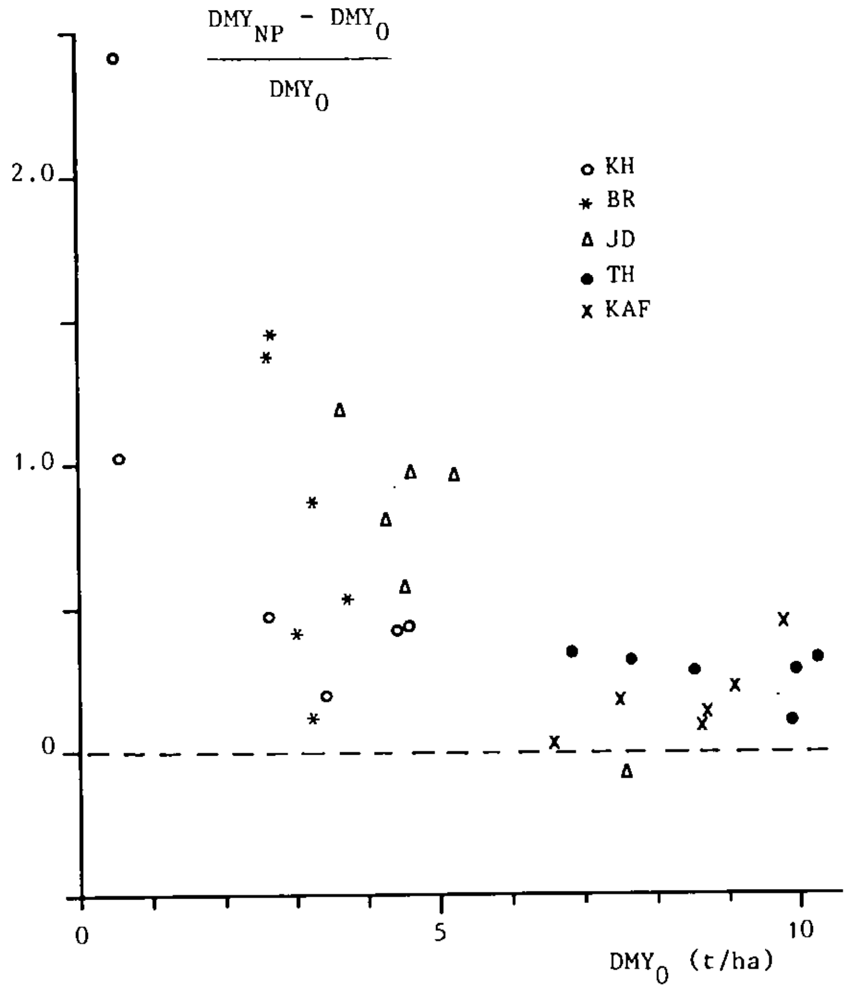

Fig. 7. Relative increase in dry matter yield of Beecher barley in fertilized plots (NP) relative to unfertilized plots (0), plotted as a function of dry matter yields in unfertilized plots (DMY_0.

sion of dry matter yields of fertilized plots (60 kg N/ha and 60 kg P_2O_5/ha) on total amounts of rainfall during the growing season (October to crop maturity) results in the following regression equation:

DMY_{NP} (t/ha) = $-4.66 + 0.037 \times$ Rainfall (mm)

where: $n = 30$ (number of observations), $r^2 = 0.65$ (coefficient of variation), and $F = 299.7$. Hence, dry matter yields tended to increase by about 3.7 t/ha per 100 mm of rainfall, for the range of rainfall conditions covered by the experiments (200–500 mm/year).

Figure 4 shows that seasonal rainfall was an important factor in determining yields of fertilized barley crops. The relationship could probably be improved (the scatter reduced), if rainfall distribution and the effectiveness of the rainfall were considered in the analysis. Yields of unfertilized barley tended to be lower than those of fertilized barley. This is further illustrated in Figure 5, which shows that Jindiress, Breda and Khanasser could be considered as low-fertility sites, whereas Kafr Antoon and Tel Hadya were higher in soil fertility. It may be concluded that at low-fertility sites (*i.e.* low in available nutrients) yields of unfertilized crops were limited by available nutrients rather than available moisture. This conclusion does not imply that yields of unfertilized crops at low-fertility sites would not vary between seasons. Figure 6 shows the effect of season on yields of fertilized (N and P) and unfertilized crops at three sites. At Khanasser, yields of all crops declined, reflecting the deteriorating growing conditions (rainfall distribution, temperature) during the three years the trial was conducted. At Breda, the increase in yields of unfertilized crops probably reflected the increased soil fertility (see Section 3.4) at this site, whereas at Jindiress, yields of unfertilized crops tended to decrease slightly.

In a season with above-average rainfall, and a favourable rainfall distribution, the effective availability of nutrients is likely to increase, even under conditions of low fertility. Moisture penetrates deeper into the soil, thus increasing the volume of soil accessible for the rooting system. An early start of the rains may lengthen the growing season and create more favourable conditions for early vegetative growth, also because average temperatures are higher in November than in December or January. A better root development and a higher microbiological activity in the soil may result in an increased availability of soil nutrients. Late rains allow the crop to take up nutrients from the surface horizon, where nutrient availability (in particular phosphorus) is generally higher than in sub-surface horizons.

The relative yield responses to fertilizer application tended to increase with decreasing yield levels of unfertilized crops (Figure 7). This could have important consequences, because it would imply that there would be a considerable potential for increasing yields, even in low-rainfall areas, where at present fertilizers are not commonly applied.

3.6 N × P interactions

N × P interactions were generally not significant (see Table 8). This was to be expected, since there were few cases when there was a significant response to both nitrogen and phosphorus at the same site (Table 7). In cases where larger interactions were apparent, these usually resulted because of the negative effect of one nutrient in the absence of the other nutrient.

Phosphorus application tended to decrease yield in the absence of applied nitrogen, but this observation requires verification. Nitrogen application in the absence of applied phosphorus tended to decrease yields at the drier sites. This was probably associated with delayed maturity, which resulted in less favourable climatic conditions for grain filling, and consequently in lower grain yields. Application of phos-

Table 8. The increase in grain yield response to N (t/ha), due to the addition of P, or vice versa (N × P interaction), for each site and year.

Site	Year			Mean
	1979/80	1980/81	1981/82	
JD	0.7	0	0.7	0.5
KAF	1.1	0.7	0.6	0.8*
TH	−0.7	−0.6	0.6	−0.2
BR	0.4	0.1	−0.4	0
KH	1.1	0.4	−0.3	0.4

LSD for the N × P interaction in one year = 1.1 t/ha (5% level).
LSD for the N × P interaction for mean of three years = 0.6 t/ha (5% level).

phorus when the nitrogen supply to the crop was adequate, resulted in advanced anthesis, by as much as two weeks *(cf. Jackson [13])*, which may have resulted in more favourable climatic conditions during grain-filling.

The tendency for negative N × P interactions at Tel Hadya in the 1979/80 and 1980/81 seasons was probably caused by lodging, which was observed to be more serious at higher levels of fertilizer application. Lodging occurred at the three wetter sites in the 1979/80 and 1980/81 seasons, and may have restricted the magnitude of yield responses to fertilizer application.

3.7 Harvest index and dry matter yields

In Syria, barley is an important source of feed for livestock; green-stage grazing of the crop is commonly practised, and the value of the straw may actually exceed the value of the grain *(ICARDA [12])*. Thus, levels of vegetative growth and final dry matter yields should be considered in assessing crop response to fertilizers.

A summary of harvest index values for the trials is presented in Table 9. Harvest index was hardly affected by fertilizer treatment (0.43 ± 0.01). Hence, dry matter yield responses to fertilizer were similar to those for grain yield. However, site had a significant effect on harvest index, and there were significant site × year interactions.

Harvest index was highest at the driest site, Khanasser, and lowest at Tel Hadya. The gradual onset of water stress at the driest site, from before anthesis, may have resulted in a balance between pre-anthesis and post-anthesis levels of growth. At Tel Hadya, a more sudden onset of stress probably occurred, particularly in the 1981/82 season (when harvest index was low), as the trial was conducted on a shallower soil than in the previous two seasons.

In general, fertilizer application increased levels of winter growth. Relative differences in the level of winter growth achieved between fertilized and unfertilized crops, were generally maintained until maturity *(Shepherd K.D.:* Ph. D. Thesis, University of Reading [in preparation]) One factor that contributed to this was the advanced development of fertilized crops. This frequently resulted in fertilized crops utilizing no more water in evapotranspiration, than unfertilized crops by the time of anthesis, despite the improved growth attained with fertilizer application.

This pattern may not occur under different climatic or soil conditions (*e.g.*, warmer winters, or shallower soils), when excessive early growth can lead to premature exhaustion of available water by the crop, which may result in reduced grain yields and lower harvest indices (*Fischer [6]*).

Table 9. Analysis of harvest indices.

(a) F-values of significant components

Component	F-values
Site	50.9***
Site × Year	15.6***
Year	7.8***
N	5.2*
P	4.8*

(b) Harvest index for each site and year, averaged over N and P levels

Site	1979/80	1980/81	1981/82	Mean of three years
JD	0.44	0.43	0.43	0.43
KAF	0.44	0.45	0.47	0.45
TH	0.44	0.41	0.32	0.39
BR	0.42	0.39	0.40	0.40
KH	0.47	0.44	0.50	0.47

LSD for comparing any two sites (5% level) = 0.01.
LSD for the site × year interaction (5% level) = 0.03.

3.8 Economic analysis

Application of fertilizer is only of economic interest to a farmer if the additional income from the increased yield exceeds the costs associated with the application of fertilizer. The increase in expenses to the farmer include the cost of the fertilizer, labor for application, and increased harvesting costs for labor, equipment, transport, bags, etc.
During the 1981/82 season the fertilizer and crop prices were as follows (Syrian Liras SL per kg):

	Zone 1	Zone 4
Ammonium nitrate (33% N)	0.82	0.91
Triple superphosphate (46% P_2O_5)	1.05	1.10
Barley straw	0.47	0.75
Barley grain	0.85	1.20

Zone 1 is the highest rainfall zone and zone 4 the lowest rainfall zone.

The application of 60 kg N/ha or 60 kg P_2O_5/ha was profitable to the farmer in the 1981/82 season if the increase in grain yield due to application of fertilizer exceeded 0.10 (N) or 0.11 (P) t/ha at Khanasser, 0.12 (N) or 0.13 (P) t/ha at Brida and Tel Hadya, and 0.14 (N) or 0.15 (P) t/ha at Kafr Antoon and Jindiress. Hence, the mini-

mum yield increase requirements for fertilizer application to be profitable to the farmer tended to increase from Khanasser (zone 4) to Kafr Antoon and Jindiress (zone 1). This is because the relative increase in the price of barley from zone 1 to zone 4 exceeded the increase in the cost of fertilizer from high to low rainfall zones. In addition, the cost of labor tended to decrease from zone 1 to zone 4.
Therefore, in all situations where significant reponses were recorded (Table 7) the application of fertilizer (at 1981/82 prices) was highly profitable to the farmer, the additional income ranging from about 600 to 2000 SL/ha. Averaged over three seasons, the application of nitrogen fertilizer was most profitable at Jindiress and Kafr Antoon, and of phosphorus fertilizer at Khanasser and Brida.

3.9 Fertilizer response functions and fertilizer use efficiencies

The results of fertilizer trials are generally reported as fertilizer response functions, *i.e.* mathematical models relating yield to fertilizer or nutrient application rates *(Colwell [3])*. Response functions such as the Mitscherlich equation *(Mengel and Kirkby [17]* p. 235) are based on the assumption that only one growth factor changes, while all others remain constant. The Mitscherlich equation, however, does not allow for a decrease in yield at high levels of applied fertilizer. For example, high rates of applied nitrogen fertilizer may decrease yields due to lodging of the crop or 'haying off', *i.e.* decreased harvest indices because of water stress during the latter part of the growing season. Similarly, the Mitscherlich equation does not describe an increasing yield response with increasing rates of applied fertilizer, such as may be the case with phosphorus or potassium applied to fixing soils. In these cases yield responses to fertilizers may be described by quadratic or higher order equations. The fact that economists can easily calculate optimum rates of profitability from quadratic equations, may have contributed to their widespread use *(Kafkafi [14])*.
The results of the agronomic trials discussed in the previous sections, have been reported elsewhere *(ICARDA [10, 11, 12])* in the form of quadratic regression equations. The regression model used, included linear and quadratic effects, and linear interactions between the independent variables.
For Jindiress (1980/81) the following regression equation was obtained *(ICARDA [11])*, after linear transformations of S, N and P:

$$\begin{aligned} GY(S,N,P) = 2510 &+ 2.33\ S + 10.67^{**}N + 14.67^{**}P \\ &+ 0.01\ SN - 0.01\ SP - 0.01\ NP \\ &- 0.01\ S^2 - 0.01\ N^2 - 0.07\ P^2 \end{aligned}$$

where GY is grain yield of Beecher barley (kg grain/ha), S is seed rate (kg seed/ha), N is nitrogen fertilizer (kg N/ha) and P is phosphorus fertilizer (kg P_2O_5/ha). The asterisks (**) indicate that these coefficients were significantly different from zero at the 1% level. For the middle seed rate of 90 kg/ha, the regression equation reduces to:

$$\begin{aligned} GY(90,N,P) = 2639 &+ 11.57\ N + 13.77\ P - 0.01\ NP \\ &- 0.01\ N^2 - 0.07\ P^2 \end{aligned}$$

This equation represents the response surface of grain yields (at S = 90 kg/ha) to applied nitrogen and phosphorus fertilizers in the ranges of 0–120 kg N/ha and

0–120 kg P_2O_5/ha. The response curves of grain yield to one nutrient at a constant level of the other nutrient can easily be derived from this equation. The shape of the response curves can be evaluated by taking the partial derivatives:

$$\left(\frac{\delta GY}{\delta N}\right)_{S=90,\ P=P_c} = 11.57 - 0.01\ P_c - 0.14\ N$$

for nitrogen, and:

$$\left(\frac{\delta GY}{\delta P}\right)_{S=90,\ N=N_c} = 13.77\ P - 0.01\ N_c - 0.14\ P$$

for phosphorus. The notations P_c and N_c denote that P and N assume constant values. It follows from the partial derivatives that the response curves for nitrogen did not reach a maximum in the range of 0–120 kg N/ha, whereas the response curves for phosphorus reached a maximum between 90 and 100 kg P_2O_5/ha.

The partial derivatives of the response curves are a measure for the efficiency with which applied fertilizer nutrients are converted into grain yield, and may therefore be referred to as 'fertilizer use efficiencies' *(Harmsen [8])*. It follows that the fertilizer use efficiency (FUE) changes with the level of applied fertilizer. In the above example, the nitrogen use efficiency decreased from a maximum value of 11.57 at N = 0 and P_2O_5 = 0 to a minimum of 7.97 kg grain/kg nitrogen at N = 120 and P_2O_5 = 120 kg/ha. Hence the crop still responded to the application of nitrogen fertilizer, even at the highest levels of N and P applied. The phosphorus use efficiency decreased from 13.77 at N = 0 and P_2O_5 = 0 to –4.23 kg grain/kg P_2O_5 at N = 120 and P_2O_5 = 120 kg/ha. Hence the application of phosphorus fertilizer was profitable only up to rates of 70–80 kg P_2O_5/ha (see Section 3.8).

The above definition of fertilizer use efficiency requires knowledge of the fertilizer response curve. If this relationship is not known, the fertilizer use efficiency can be estimated from:

$$FUE = \frac{GY_2 - GY_1}{F_2 - F_1} = \frac{\Delta GY}{\Delta F}$$

where GY_2 and GY_1 denote the grain yields (kg/ha) at rates of F_2 and F_1 kg of fertilizer nutrient applied per ha, respectively. If F approaches zero, FUE approaches the partial derivative of the fertilizer response curve at a given rate of fertilizer applied. In this form, FUE can also be estimated from experiments in which only two rates of fertilizer application are considered. It has to be borne in mind, that in this case FUE is an approximation, which becomes less accurate the larger the interval F_1 to F_2.

The main effects of N and P on grain yields, listed in Tables 6 and 7, are essentially fertilizer use efficiencies, *i.e.* increases in grain yield (t/ha) per 60 kg of one nutrient applied per ha, averaged over two levels of the other nutrient (0 and 60 kg/ha). Main effects, therefore, are linear approximations and cannot be used to predict yield responses at intermediate (or higher) rates of fertilizer application. An analysis of the regression equations reported elsewhere *(ICARDA [10, 11, 12])* shows that almost none of the response curves reached an extreme value (maximum or minimum) at rates of fertilizer application below 60 kg/ha. Therefore, the main effects reported in Tables 6 and 7 represent the trends in grain yield responses quite well in the lower ranges of fertilizer application (0–60 kg/ha), and they provide a basis for comparison of fertilizer responses between sites and seasons. An analysis of the full set of regression equations, although certainly worthwhile, is beyond the scope of the present paper.

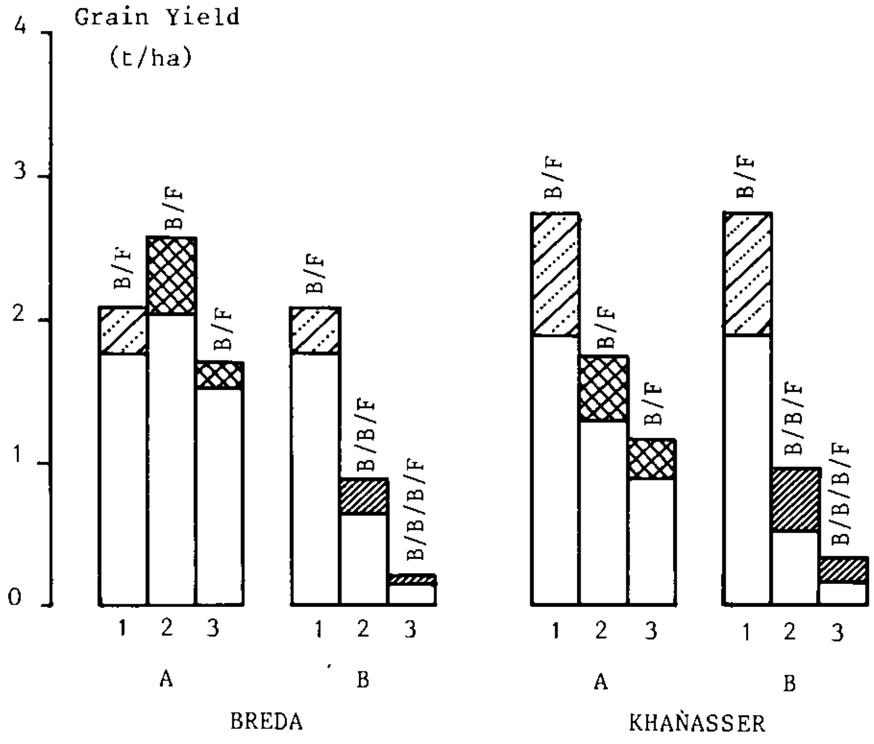

Fig.8. A) Grain yield response to 60 kg P_2O_5/ha (shaded part of the bars), in barley (Beecher) grown after fallow (B/F), during 3 seasons (A1, A2, A3) at two experimental sites. B) Grain yield response to 60 kg P_2O_5/ha, applied in the first year, in barley grown after barley in the second (B/B/F) and third year (B/B/B/F).
All crops received 20 kg N/ha at planting.

4. Residual effect of fertilizers

In an evaluation of the role of fertilizers in rainfed agriculture in low-rainfall areas, residual effects would have to be considered. The more so, because apparent recovery fractions *(Harmsen [8])* are quite often lower than in higher rainfall areas, but losses of nutrients from the soil-crop system are generally limited.

For example, apparent recovery fractions for nitrogen fertilizers at Breda experimental site were in the range of 20–50%, depending on factors such as the nutrient status of the soil, and rainfall distribution. Nitrogen-balance studies*, using N-15 labeled fertilizers, showed that 80–95% of the applied nitrogen was recovered in the soil-crop system, about one half in the crop and half in the soil.

Hence, significant amounts of nitrogen were left in the soil by the end of the growing season.

Apparent recovery fractions for phosphorus fertilizers at Breda and Khanasser were rather low, *e.g.*, 3–7% during the 1979/80 season, even though yield response to applied phosphorus was highly significant at Khanasser. Figure 8 shows that the residual effect of phosphorus, applied in the first season (1979/80), on subsequent barley crops (1980/81 and 1981/82), was of considerable importance. For example, at Khanasser the direct response to applied phosphorus during the second growing season (A2, barley after fallow) was equal in magnitude (0.44 t/ha GY) to the response to phosphorus applied during the first season on the subsequent barley crop (B2). Figure 8 further shows the effect of season on yield levels of barley grown after fallow (part A), and the decline in yield of barley grown after barley (part B).

5. Effect of crop rotation

Crop rotational practices may have a pronounced effect on yield levels of crops, and on yield responses to applied fertilizers. Important two-course rotations in the rainfed barley-producing area of Syria are barley/fallow and barley/barley. It has been observed at several locations in Syria that yields decline if barley is grown continuously. Whether the beneficial effect of fallow on yields of cereal crops is due to moisture conservation, increased nutrient availability, or to other factors, is not yet established. *Loizides [16]* suggested that the poor yields obtained in wheat/wheat rotations could be due to the presence of undecomposed crop residues at planting time, which would have an adverse effect on the emergence and early growth of wheat.

Wheat grown after fallow responded more strongly to applied nitrogen, than wheat grown after wheat (Figure 9). In addition, grain yields of wheat grown after fallow were about twice as high as yields of wheat grown after wheat. Such a strong decline in yields is not always observed, when cereal crops are grown continuously. For example, in rotational trials conducted at Cyprus *(CARI [1])*, barley yields in a barley/barley rotation were not different from those in a barley/fallow rotation, provided sufficient fertilizer was applied to the crop.

* Conducted in collaboration with the *International Fertilizer Development Center*, Muscle Shoals, USA

Tables 7 and 8 show that in the first season at Breda (after one year of fallow) there was a significant response to nitrogen, as well as a response to phosphorus, but no significant N × P interaction. In contrast, in a field that had been cropped with barley during the previous two seasons, little or no yield response was observed when either nitrogen or phosphorus were applied, but a strong yield response (more than 75% increase in yield) was observed when both nutrients were applied at levels of 90 kg/ha (N and P_2O_5, respectively), indicating that there was a N × P interaction in this trial (Figure 10). In the trial reported in Section 3, conducted at the same site during the same season, but in a field that had been fallowed for three years, no response to applied nitrogen was observed, an insignificant response to phosphorus,

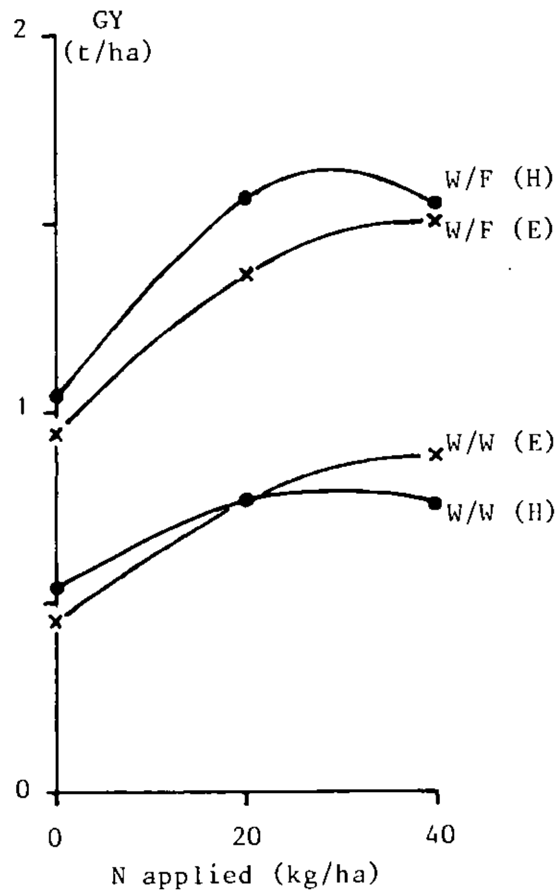

Fig.9. Grain yield responses of wheat grown after wheat (W/W) and after fallow (W/F) to applied nitrogen, at Ezraa (E) and Himo (H) experimental sites, averaged over three growing seasons (1965/66–1967/68). All crops received 40–45 kg P_2O_5/ha.

and an insignificant (negative) N × P interaction. The barley yield levels shown in Figure 10 (following barley) are well below those reported in Table 7 (after fallow), reflecting the effect of rotation on yield levels of cereal crops at this site.

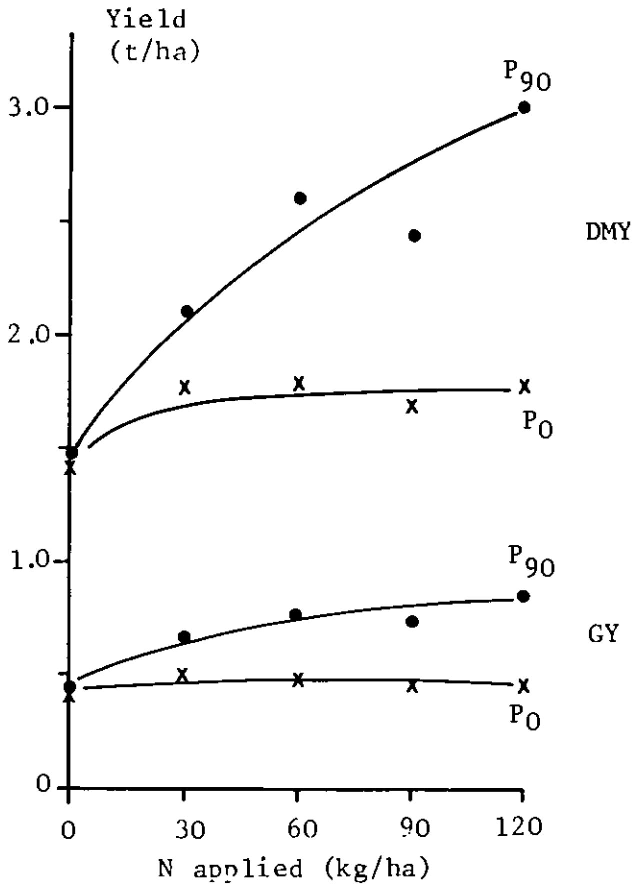

Fig. 10. Mean response of grain yield (GY) and dry matter yield (DMY) of four cereal varieties to applied nitrogen, at zero applied phosphorus (P_0) and at 90 kg P_2O_5/ha (P_{90}).

6. Varietal effects

All results discussed in Section 3. pertained to one variety of barley (Beecher). Cereal varieties may differ considerably in their response to applied fertilizers, however, and results obtained for one variety cannot be assumed to apply to other varieties without comparative agronomic research.

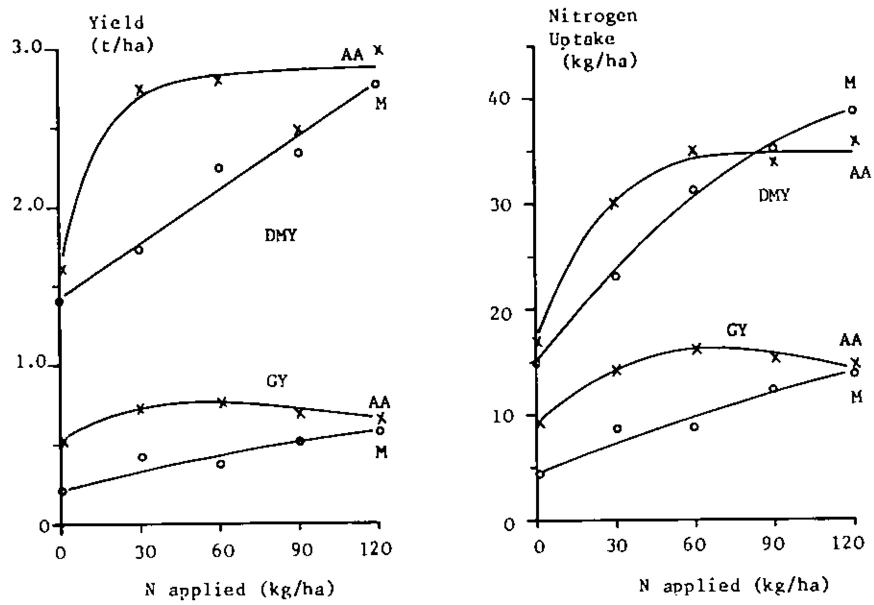

Fig. 11. Response of grain yield (GY) and dry matter yield (DMY) of two barley varieties, Arabic Abiad (AA) and Martin (M), to applied nitrogen (left). Amount of nitrogen taken up by the grain and the above-ground dry matter of two barley varieties, as a function of applied nitrogen (right).

To illustrate this point, some results of a variety × nitrogen × phosphorus trial, which was conducted during the 1981/82 season at the Breda experimental site will be presented *(Anderson, W.K.:* Unpublished data *[1982]).* The trial followed two years of uniform barley crops, and the soil was low in available phosphorus and nitrogen. Figure 11 shows the yield responses of two barley varieties to applied nitrogen, averaged over two levels of applied phosphorus. The response curve of Arabic Abiad, a local variety, was quite different from that of Martin, an improved variety. Arabic Abiad responded very strongly to the first 30 kg of N applied, but little thereafter, while yields of Martin continued to increase with increasing amounts of nitrogen applied. The contrasting response curves of Arabic Abiad and Martin, shown in Figure 11, have been observed during several seasons in similar experiments *(Anderson W.K.:* Personal communication *[1983]).* In a trial in the same field as the one described here, it was observed that the yield response of Beecher barley was similar to that of Martin, up to 60 kg N/ha, the highest nitrogen-level in that trial.

Figure 12 shows the grain yield response of four cereal varieties to applied nitrogen at zero applied phosphorus. There was little response to applied nitrogen, presumably because of the low available-phosphorus status of the soil. Yields of Arabic Abiad were similar to those of Arvand, a drought-tolerant breadwheat variety, and considerably higher than those of Martin or Sahl, a durum wheat variety.

These results illustrate that cereal varieties may differ considerably in their yield potential under adverse conditions (low available moisture and nutrients), and in their yield response to applied fertilizers. It is important to consider these factors if new varieties are to be introduced, or fertilizer recommendations are to be made for rainfed agricultural systems.

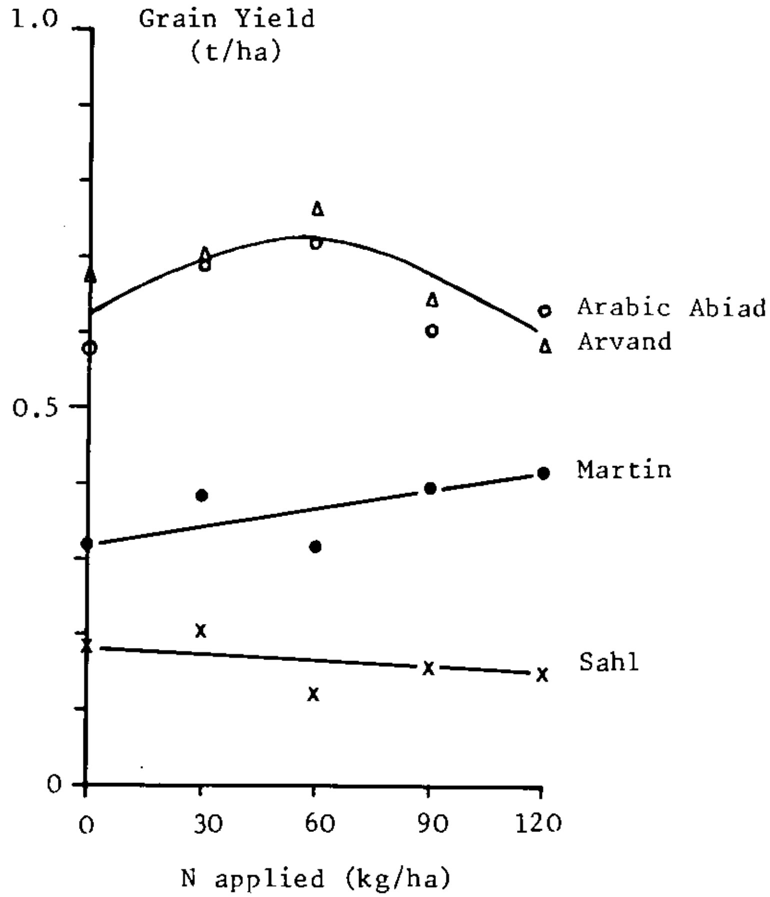

Fig. 12. Response of grain yield of Arabic Abiad (barley), Arvand (breadwheat), Martin (barley) and Sahl (durum wheat) to applied nitrogen at zero applied phosphorus.

Acknowledgement

The research reported in this paper was conducted as part of a UNDP/ ICARDA Global Project on *'Increasing the fixation of soil nitrogen and the efficiency of soil water use in rainfed agricultural systems in the countries of North Africa and Western Asia'* (GLO/78/003) sponsored by the *United Nations Development Programme*, New York.
A large number of FSP staff have been involved in the research described in this paper. Their contribution to the work in the field, the laboratories, and in the office, is gratefully acknowledged.

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The Relation between Root Development and Mineral Nutrition of the Sugar Beet Crop: its Importance for Fertilizer Placement

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Summary

The development of the root-system of sugar beet during growth and its distribution in the soil is described and discussed. The concept of root area index, reflecting colonization of the soil by the roots is introduced. It was possible to establish a linear relationship between root length and root surface and the total uptakes of nitrogen, phosphorus and potassium, and also, taking account of the dynamic character of root development to compare the rates of root growth and nutrient uptake.

1. Introduction

Since the introduction of fertilizers, agronomists have tended to the view that nutrient supply and water supply are the two main factors limiting crop growth. Nevertheless, even in countries with well developed agriculture, where fertilizers are widely used and irrigation and drainage are available, the gap between potential yield and the yield realized in practice remains large. It is only during the past twenty years or so that agricultural research has become increasingly concerned with the 'black box' in the soil beneath the plant and the part played by development of the roots in yield formation.

Root behaviour is of particular significance in the study of soil-plant relationships since it is via the roots that plants obtain their supplies of nutrients and water. Better knowledge on their behaviour is a *conditio sine qua non* for better understanding of plant nutrition problems. In order that nutrients may be available to the plant they must come into contact with the roots by the three routes of mass-flow, diffusion and root elongation. A knowledge of root length and root surface area and the distance between roots is therefore of great importance to our understanding of the plant's potential for nutrient and water uptake.

Many Moroccan soils in the main agricultural areas of Saïs, Gharb, Zaërs, Tadla, Haouz, Doukkala and Chaouia, are characterized by P deficiency *(Thomann [1952], Michel et al. [1967], Bouzoubaa et al. [1979])* and its correction is difficult *(Michel*

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and *Bouzoubaa [1970], Squalli* and *Bouzoubaa [1979])*. A technique which should he useful in these soils is placement, but if this is to be effective it is necessary to have a knowledge of root development. This is the underlying objective of this study.

2. Materials and methods

The study has embraced the investigation of the course of root development over time and the course of nutrient uptake by the plant.
The crop under study was sugar beet *(cv.* Desprez Mono E) grown on a clayloam soil in the Gharb plain at a density of 80 000 plants per hectare after thinning. Characteristics of the soil are shown in Table 1.
The crop received 60 kg/ha N at sowing, 60 kg after 69 days and 60 kg after 130 days (total 180 kg/ha N); 120 kg/ha P_2O_5 and 60 kg/ha K_2O. Sampling was done 6 times: 72, 87, 115, 128, 150 and 171 days after sowing.
Soil analysis: Soil samples were taken from all horizons from the trenches opened to expose the roots. P was determined by *Olsen*'s method and exchangeable K by extraction with N ammonium acetate.
Plant studies: The aerial parts of the plant were cut before digging the trenches and analyzed for N, P and K content. We measured the following values by taking 20 samples at each depth (representing a total soil volume of 4 dm^3) freeing the roots from soil by the wet method *(Maertens* and *Chopart [1977]):*

- Total length of roots by *Newman's [1966]* method using a 'light box' to count the intersections
- Surface area of the root from the diametric area *(Bonzon et al. [1969], Maertens* and *Chopart [1977])*.

Table 1. Soil characteristics

Mechanical analysis			Chemical analysis					Moisture by weight	
Clay %	Loam %	Sand %	pH	Total $CaCO_3$ %	O.M. %	P_2O_5 %	K_2O %	$H_pF_{4.2}$ %	Field capacity %
27.5	28	20.3	8.25	21.8	2.3	0.049	0.291	15	30

3. Results and discussion

3.1 Growth of aerial parts and storage root

Before discussing the development of the feeding roots and the uptake of N, P and K we shall devote some space to discussion of the production of dry matter during the course of crop growth. Figure 1 shows the development of dry matter production in terms both of total dry matter and storage root dry matter. Dry matter accumulation assumes large proportions only from the 100th day, corresponding with the development of the storage root. Between the 100th and 171st day (date of last sampling) dry matter production is almost a linear function of time at a mean rate of about 350 kg/ha/day.

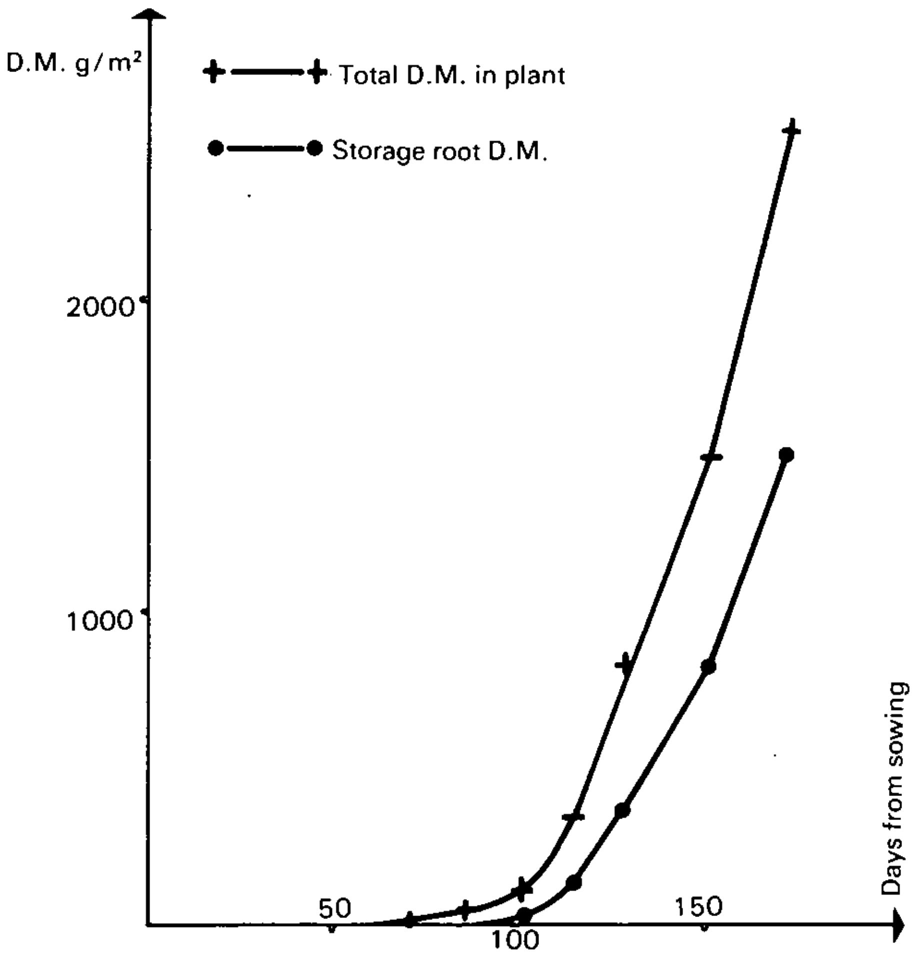

Fig. 1. Dry matter accumulation in relation to time.

The curve for dry matter accumulation by the storage root shows its dominance in total dry matter production by the whole plant, especially towards the end of growth. Root yield after 200 days was 96.3 t/ha with a sugar content of 14% corresponding to 13.5 t/ha sugar; yields from good farms in the area average 60 t/ha roots (Figure 1).

3.2 Growth and development of root system

Tables 2 and 3 illustrate the root profiles expressed as root length (metres of root underlying/m^2 of soil surface) and as root surface area (m^2 under/m^2 surface) at different stages of growth of the crop. These tables show that root development proceeds without abatement up to the last date of sampling.

Table 2. Root length, m per m² of soil surface

Depth (cm)	Days from sowing					
	72	87	115	128	150	171
0– 15	387	633	619.5	840	826.5	1605
15– 30	99	172.5	318	343.5	412.5	532.5
30– 45		61.5	258	331.5	261	393
45– 60			126	190.5	232.5	252
60– 90			222	213	204	315
90–120				84	144	309
120–150					246	432
150–200						535
Total	486	867	1543.5	2002.5	2326.5	4403.5

Table 3. Root surface area – m²/m² soil surface

Depth (cm)	Days from sowing					
	72	87	115	128	150	171
0– 15	1.1385	1.3710	1.6500	2.4150	2.8725	4.6050
15– 30	0.1680	0.4575	0.8775	1.1325	·1.7175	1.5900
30– 45		0.1290	0.7560	0.9960	1.0800	1.3800
45– 60			0.3600	0.5805	0.9930	0.7590
60– 90			0.6210	0.5490	0.5850	0.8760
90–120				0.2010	0.4500	0.9870
120–150					0.7680	1.3140
150–200						1.7900
Total	1.306	1.957	4.264	5.874	8.466	13.3010

We found that root development is always abundant in the surface soil; 50–60% in the top 30 cm of soil and 65–80% in the 0–45 cm band. This agrees with the generally accepted view that most crops colonize the surface soil intensively *(Mengel* and *Barber [1974], Allmaras et al. [1975], Stanley* and *Barber [1975], Maertens* and *Bosc [1981])*.

While colonization of the surface layers plays a predominant role in plant nutrition, the presence of roots in the deeper layers is of the greatest importance in ensuring water supply to the crop during periods of drought *(Maertens et al. [1974], Blanchet et al. [1974])*. This is well illustrated in our experiment at the last sampling date, when the moisture status of the surface soil approached wilting point (16% moisture by weight) while moisture content at over 1.5 m depth exceeded 26%. The crop showed no signs of drought stress, since doubtless it obtained water from depth where, at this time 20% of the total root system was situated.

Table 2 illustrates the tremendous capacity of the beet root system for elongation both near the soil surface and at depth: between day 150 and day 170 the roots extended by 99 m/m²/day – almost 1000 km/day/ha! The sugar beet has a great capacity of soil exploration allowing it to obtain easily its nutrient requirements by progressively exploiting fresh environments.

3.3. Uptake of N, P and K

Figure 2 shows the pattern of uptake of N, P and K during growth of the crop. These are typical sigmoid curves but show some differences from day 150 when N and K continue to be taken up at a high rate but P uptake is on a plateau. This change closely follows the second application of N fertilizer at day 130. It is conceivable that the cause is ion antagonism between NO_3^- and PO_4^{--} *Heller [1969])*.

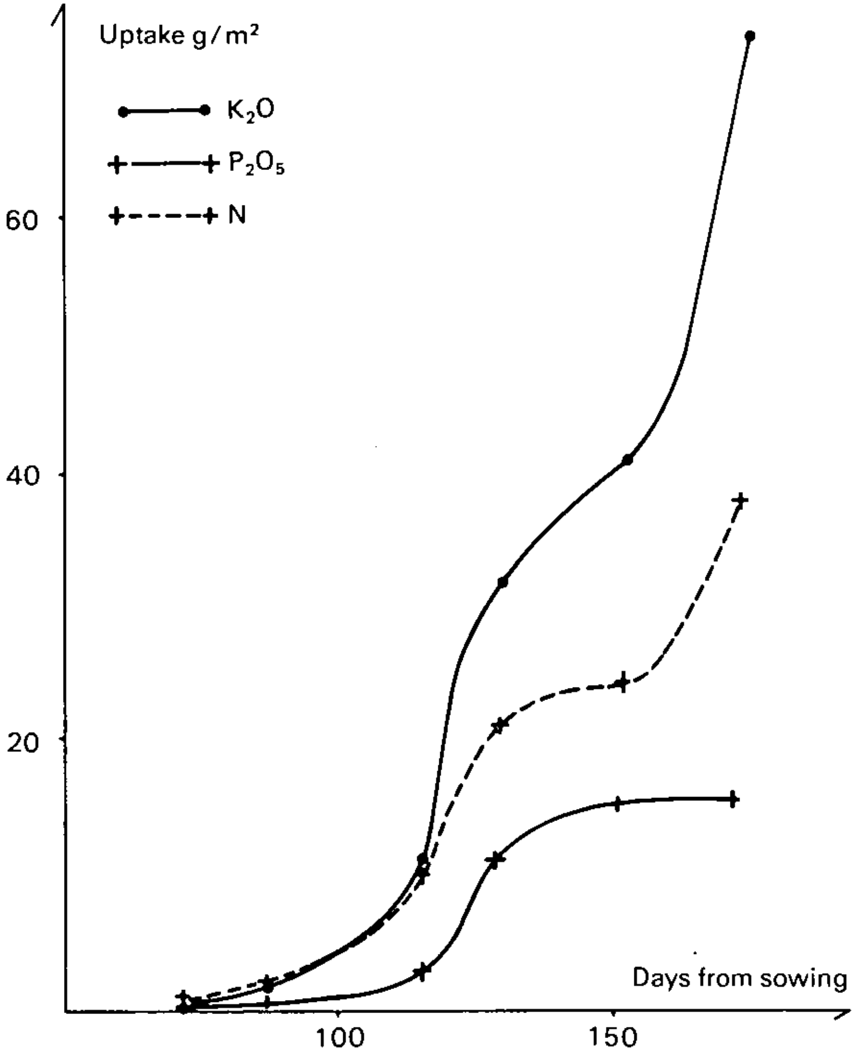

Fig. 2. N, P_2O_5 and K_2O uptake during growth.

3.4. Relation between nutrient uptake and root development

First, we wanted to known whether there exist relations between the synthetic root characteristics and the uptake of N, P and K.
Figure 3 (a and b) and Table 4 show that there is a close relationship between the uptake of N, P and K and root length or root area of sugar beet. Nutrient uptake closely follows root development.
Comparing Figures 3 and 4 it is seen that periods of rapid root development correspond with periods of active nutrient uptake, except for phosphorus after day 150. This agrees with earlier results for phosphorus uptake by cotton *(Khasawneh* and *Copeland [1975])* and by maize *(Schenk* and *Barbier [1979]);* and for potassium uptake by tomato *(Bosc* and *Maertens [1981]).*
As a second step we wanted establish the relation between the kinetics of N, P, K uptake and that of the rate of root growth.
The relationship between rate of uptake of N, P and K and rate of root growth is illustrated diagrammatically in Figure 5. From this it appears that nutrient uptake is a function of root development though there is an exception to this rule in the case of phosphorus, uptake of which declines after the last application of N fertilizer, though root growth continues unabated.
This result, obtained in a field experiment confirms the findings of *Bosc's [1981]* pot experiment for uptake of P and K.

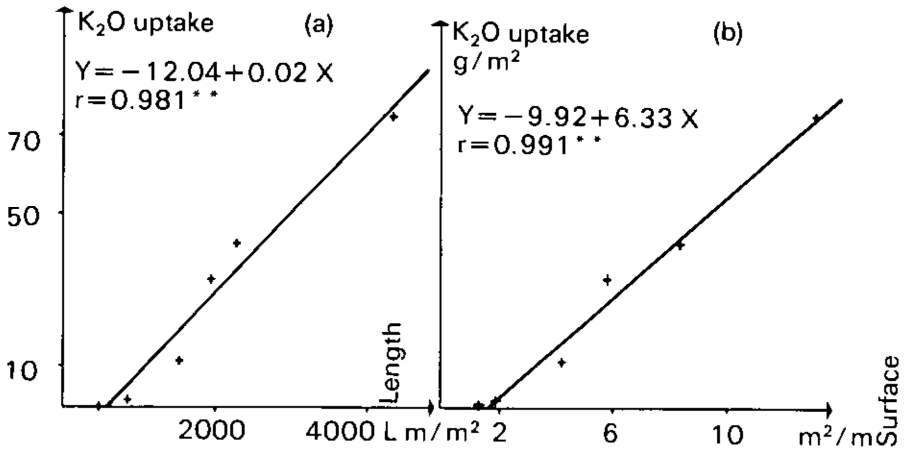

Fig. 3. Relationship between K uptake and root length (a) and root surface area (b).

Table 4. Correlation of nutrient uptake with root development

Uptake	Root length	Root surface area
N	Y=0.01X−3.57 R=0.971 (H.S)	Y=3.27X−2.56 R=0.985 (H.S)
P	Y=0.0048X−1.36 R=0.872 (S)	Y=1.57X−1.28 R=0.923 (H.S)

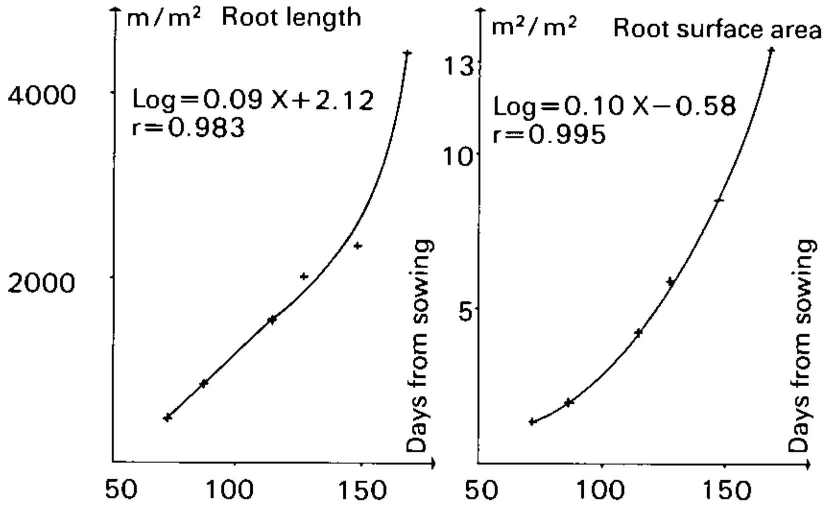

Fig. 4. Root development by sugar beet in relation to time.

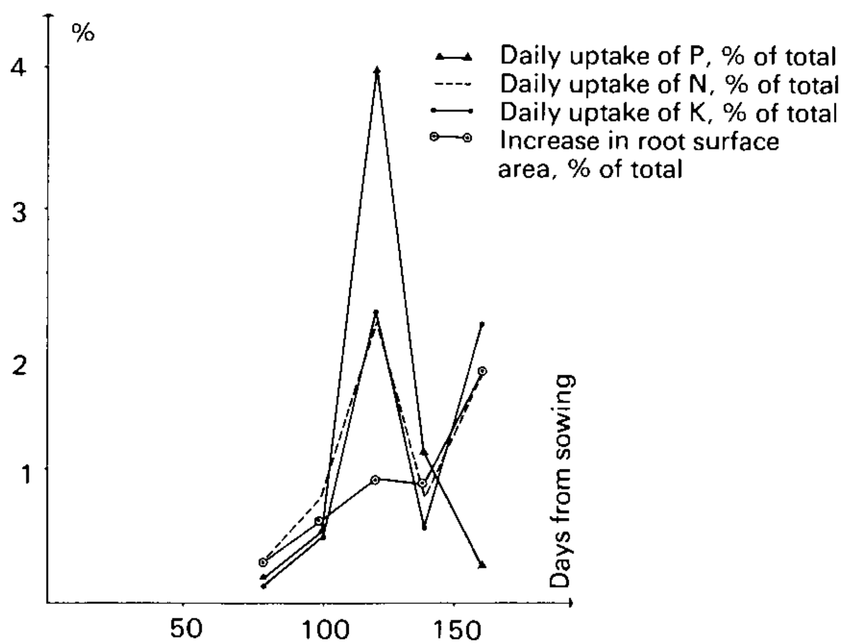

Fig. 5. Root surface area and uptake of N, P and K: ▲——▲ Daily uptake of P, % of total; --- Daily uptake of N, % of total; ●——● Daily uptake of K, % of total; O——O Increase in root surface area, % of total.

3. Conclusions

Several interesting conclusions can be drawn from this investigation:

- The root system of sugar beet is well developed and can attain a total length of 1000 km/ha/day to a depth of 2 m. The practical result of this is that the plant is continually offered a fresh environment, thus facilitating satisfaction of its nutrient requirements.
- The development of the root system at depths of 2 m or more plays an important part in assuring water supply to the crop, conferring better toleration of drought conditions than that shown by shallower rooting crops.
- We have introduced the concept of root area index, analogous to leaf area index (LAI) and this attained a value of 13.3 several days before harvest.
- Nutrient uptake at various stages of growth is related to root length and root surface area.
- The rate of nutrient uptake, upon which depends satisfaction of nutrient requirements, closely follows growth of root surface area.
- The development of the root system, successively exploiting different zones of the soil gives rise to some doubts as to the value of conventional soil sampling and analysis in relation to any particular nutrient. Root development depends on a number of factors, either physical or mechanical soil properties, as well as nutrient supply. If root growth is limited by such physical barriers, nutrient supply in the soil needs to be at a higher level than is needed in soils where root development is unrestricted.
- This work has improved understanding of root development and of factors in the root environment which affect crop development and should lead to improvements in the techniques of fertilizer application, particularly as regards placement.

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Nitrogen, Phosphate, Potassium and Management of Arid and Semi-Arid Soils of Morocco (Preliminary results of a large scale research project)

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1. Introduction

Considerable fertilizer research has been done in Morocco over the past few decades on irrigated crops and on rain-fed crops in the more favourable areas not subject to the extreme drought conditions of the arid and semi-arid zones. It is only in the past few years that a research programme has been mounted for areas where the rainfall is between 200 and 400 mm per annum (Figure 1). The work is being done under the aegis of *Aridoculture Project No 608-0736* under the terms of a contract (AID C 1606) between the *Government of Morocco, AID* and the *Middle American International Agriculture Consortium,* concluded in February 1980.

The objective of the programme is to improve cereal and forage production through: plant breeding (wheat and barley), improvement of cultural methods (fertilizers, water economy, etc.) and the analysis of socio-economic constraints.

This paper deals only with that part of the programme concerned with the testing of nitrogen, phosphate and potash fertilizers and the investigation of the effects of cultivation methods on water economy and which is under the charge of the *INRA Research Station,* Rabat.

Past research on fertilizer use and water economy has produced few data which are applicable to the arid and semi-arid zones, consequently it has not been possible to establish any rational basis for fertilizer use or to achieve optimum use of the very limited rainfall. We lack information on nutrient dynamics in the soil, on crop fertilizer requirements (nutrient uptakes), required forms of fertilizer and of how these are related to soil nutrient status, while little is known about cultural methods which could conserve the maximum of water to support crop growth.

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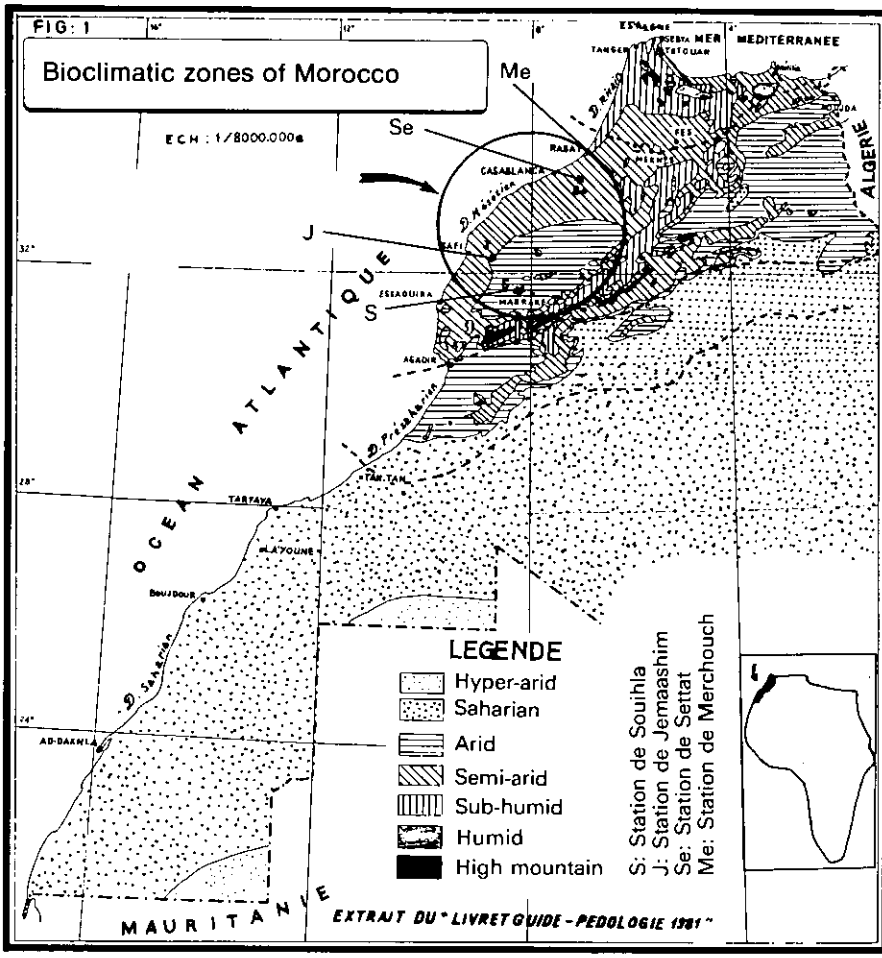

Fig. 1. The climates of Morocco (Extract from: Livret Guide-Pédologie 1981).

The fertilizer recommendations (Table 1) which formed a working basis for the 1960s in a country where fertilizer use was not general show great variation between and within regions and it is evident that there is a need to examine more carefully the fertilizer requirements of the various crops and their varieties in each region of the country.

The problem is particularly severe in the arid and semi-arid zones (Figure 1) where water supply is always a limiting factor and risks associated with climate (frequency and irregular distribution of rainfall, high temperature, etc.) are high and a severe limitation on the realization of the genetic potential of crops, even of those varieties bred for, or adapted to, Moroccan conditions. In general terms, past experiments on INRA stations: Merchouch (Zaer); Afourer (Tadla); Souihla (Haouz); Sidi Kacem

Table 1. Fertilizer recommendations for cereals. Extract from the document 'Fertilizer recommendations for the principal crops of Morocco', Central station for Crop Improvement. INRA, May 1980.

Climatic zone	Crop	Cultivar	Nitrogen			P_2O_5	K_2O
			kg/ha	timing	form	kg/ha	
Semi-arid 250–200 mm	Wheat	908; 27/77; Nesma; 5–70–11; Potam; Cocorit; Haj-Mouline	20–40 40–80	sowing sowing	Urea or sulphate of ammonia	20–40	0–30
	Barley	905	30–60	sowing	Urea or ammonium nitrate	0–40	0–30
Favourable areas >400 mm	Wheat	Nesma; Potam; Cocorit, and Haj-Mouline	60–100	½ sowing ½ tillering	Urea or ammonium nitrate	40–80	30–50
	Barley	905; Briggs; 111	40–80	⅔ sowing ⅓ tillering	Urea or ammonium nitrate	40–80	30–50
Irrigated	Wheat	Nesma; Haj-Mouline; 5–70–11; Potam; Cocorit; 5–70–9	50–100	⅓ sowing ⅓ tillering ⅓ shooting	Urea or sulphate of ammonia or ammonium nitrate	40–80	40–60
	Barley	071; 905; Briggs; II and III	50–100	½ sowing ½ tillering	ammonium nitrate	40–80	30–60

(Gharb); have shown no effect of phosphate, either direct on wheat or residual, on succeeding crops, or between maintenance and heavier dressings *(Michel et al. [1])*. There have been no significant effects of potash. There is a lack of information on the water economy of these soils or on the effect of cultivation methods on the availability of water.

Long term fertilizer experiments have now (1980) been established at three stations representative of the climatic gradient from north to south (Figures 1 and 2).

These experiments aim to test how far earlier results can be extrapolated to the arid and semi-arid areas and to investigate how the major nutrients behave in these soils. We wish to find the reason for past poor responses to phosphate and potash and eventually to determine the optimum fertilizer rates corresponding to optimum yields of cereals (wheat and barley). The suitability of various cultivation methods (type of machine, depth of working) is also under examination. Long-term fertilizer experiments and cultivation experiments were commenced in 1980 at Souihla, Jemaa Shim and Settat, représentative of arid and semi-arid conditions in West Morocco (Table 2, Figures 1 and 2) and, additionally, a factorial NPK experiment was laid down in 1981 at Merchouch.

2. Materials and methods

2.1 Climate and Soils

a) Climate. The arid and semi-arid zones under study are characterized by a dry period (P<2T) of from 3 to 6 months or more (Figure 2), by extreme variation in annual precipitation and by a high rate of evapotranspiration particularly during the growing season so that the growing of crops is subject to considerable risk. The data in Table 2 show how aridity increases from north to south of the area covered by the project, *i.e.* from Merchouch in the Zaërs to Souihla in Central Haouz (Table 2).

Table 2. Experimental sites

Climate	Souilha Arid	Jemaa Shim arid – semi-arid	Settat semi-arid	Merchouch semi-arid
Mean annual rainfall mm	490	318	392	479
Mean annual evapotranspiration mm	1015	768	849	951
Water deficit mm	525	450	457	472
Mean annual temperature	19.3	15	17.5	17.6
Soil type (FAO)	Typic yermosol	Chromic vertisol	Petrocalcic xerosol	Vertic luvisol

b) Soils. The soils on which the experiments were sited are representative of the four areas: Zaërs, Chaouia, Abda and Central Haouz.

b.1) Souihla (Central Haouz).
The soils are found on flat areas and on recent Quaternary alluvium, subject to intense sheet erosion. The water regime is extremely arid and the temperature regime is of the thermic type according to *Newhall's (1975)* model. *Tavernier* and *van Wambeke [1974]).*
The soil is a Yermosol (Fluventic Torriorthent) with a light texture to over 1.5 m depth, overlying loamy clay palaeosols (probably Soltanian). From the agricultural point of view the soils are poorly structured, dominated by sand and silt and liable to capping though permeable. Capping is a serious constraint at germination and shooting. As seen from Appendix 2 the soils are:

- very low in organic matter (scarcely 1% total organic matter in surface soil), with a low C/N ratio expressing intense mineralization.
- Quite high in $CaCO_3$ (active $CaCO_3$ 1.0 to 1.7%); low in total N (less than 0.1%), very high in total K but on the low side in exchangeable K (*cf.* trials of K fertilizer); sufficiently high in total P but poor in available P (*cf.* phosphate fertilizer experiments).

The surface soils are slightly saline (ESP = about 10%); have high pH throughout the profile; dominant cations calcium and magnesium; average free iron content; poor structural stability (Is>4).

b.2) Jemaa Shim (Abda)
The soils are of two types: Chromic Vertisol (Typic Chromoxerent) and Petrocalcic Xerosol (Petrocalcic Palexeroll). The experiments were on vertisols on a slight slope

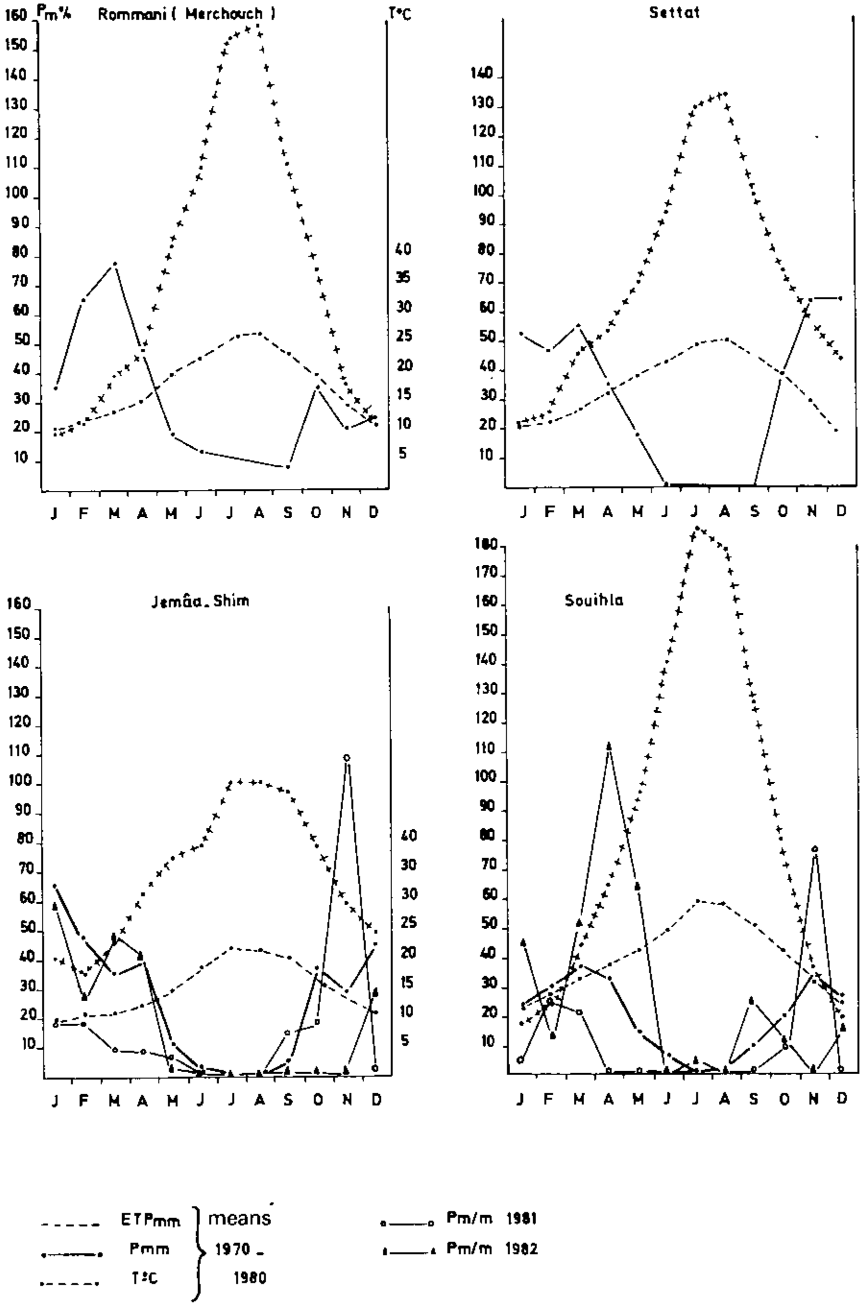

Fig. 2. Ombrothermic diagrams for the experimental stations.

or level ground overlying Senomien calcareous rock. Analytical characteristics of these heavy (45–48% clay) soils are given in Appendix 3. Their organic matter content is medium and the C/N ratio (about 10) is favourable; CEC is high and the main cations calcium and magnesium; basic reaction (pH around 8.2) total K high, available K low to medium; total P high but available P very low; structural stability average to good (Is below 2).

b.3) Settat

The soils are found on slopes, average (6%) on secondary Senomian limestone. Water regime xeric and temperature regime thermic *(Newhall, op. cit.)*. External drainage good, internal poor.

These are Petrocalcic Xerosols (Vertic Petrocalcic Palexeroll), shallow and limited by a hard discontinuous calcareous crust overlying a soft crust, well structured but with some variation in structure resulting from the movement of clays of the smectite group. There are wide fissures and slickensides at the base of the A horizon. Their main characteristics are listed in Appendix 4. Texture heavy clay (55–66% clay) low in calcium in the surface but rich in active calcium carhonate from 30 cm down (29%). High in organic matter (3,5%) and with a good C/N ratio ($\cong$10). Basic reaction (pH 8.2–8.4) and the dominant cation is calcium. Exchange capacity is correspondingly high and the dominant clay mineral is smectite. The soils are rich in total K but quite low in available P and K.

b.4) Merchouch (Zaërs)

Several soil types are found on this station (Xerosols, Vertisols, Luvisols, etc.). The experiments were on gentle slopes on Miocene mollasse with a more or less stony covering. Water regime intermediate between xeric and aquic (Soil Taxonomy *[1975]*) and temperature regime thermic. The soil is Vertic Luvisol (Vertic Ochraqualf) with analytical characteristics shown in Appendix 5. Texture favourable (clay-silt-sand) becoming clayey at depth (less permeable). Calcium content is low; organic matter content medium (1.6%) and the C/N ratio favourable (10.5); average CEC (20–30 me %) mainly saturated with Ca; total K average, available K rather low and available P very low.

2.2 Crops

The long-term fertilizer and cultivation experiments grew hard wheat *cv.* Cocorit, soft wheat *cv.* Nesma, barley *cv.* 905 and forage peas or oat-vetch hay grown in 2-year rotations, either cereal – legume or cereal – cereal. Mean yields given by the chosen cultivars are:

	at Khemisset (rain grown) t/ha	at Marrakesh (irrigated) t/ha
Cocorit	1.27	5.65
Nesma	3.65	5.33
	at Boulaouane	
905	1.57	3.52

Seed rates were: 80 kg/ha for the wheats and barley, 70 kg/ha for oats and 50 kg/ha for vetch.

2.3 Management

The cultivation experiments received uniform dressings of 40 kg/ha P_2O_5 and K_2O as triple superphosphate and sulphate or muriate of potash plus 40 kg/ha N as sulphate of ammonia or urea at Jemaa Shim and Settat and 60 kg/ha N at Souihla. 60 kg/ha P_2O_5 was applied to long-term potash experiments. Crops were sown at the end of November in 1980 and at the beginning of December in 1981. In both seasons, crops were sometimes affected by aphids, gall midges oidium and septoria. Very high temperatures were experienced in 1980–1981 and there was severe drought at all centres in 1980–1981 and at Souihla and Jemaa Shim in 1981–1982 when crops either failed or gave extremely low yields.
The factorial NPK experiment, started at Merchouch in 1981 grew soft wheat (Nesma).
All the experiments were laid out in randomized blocks with four replications.

2.4 Experimental treatments

2.4.1 Cultivation experiments

13 cultivation treatments: minimum tillage, and combinations of 3 depths of cultivation – superficial to 15 cm (P_1), medium, to 25–30 cm (P_2) and deep to 40 cm (P_3) – with disc plough (I_1), mouldboard plough (I_2), chisel (I_3) and cultivator (I_4) were compared with and without mulching. Because of the extreme drought conditions, measurements concerned with soil water regime and soil structure commenced only at the end of the 1981–1982 season, so that only yield data are available at this stage. The treatments were simplified in the second season by omitting the mulching treatment and abandoning deep cultivation at Settat.

2.4.2 Form of nitrogen fertilizer

Treatments were: Control (no N fertilizer), farmyard manure at 40 t/ha (Nf) sulphate of ammonia (Nsa) and ammonium nitrate (Na) each at 40 kg/ha N. All were tested with and without mulch (2 t/ha straw). The second aim of the experiment was to investigate the mineralization of soil N and its influence on yield. Total N was determined by the Kjeldahl method, mineral N by the distillation method of *Chang* and *Bremner [1965]*.

2.4.3 Phosphate experiments

These tested the effect of increasing dressings of P (0, 60, 120, 240 and 480 kg/ha P_2O_5) on yield of cereals. They were also used to study in the field effects on the forms of assimilable phosphate in the soil, using the 10 methods of extraction listed in Table 6 and Figure 4.

2.4.4 Potash Experiments

The effects of increasing dressings (0, 30, 60, 120, 180 kg/ha K_2O) on cereal yield and soil potassium status were examined. Soil analysis (exchangeable and water-soluble K) was carried out before the treatments were applied and after harvest. A complete potassium balance (fixation, retrogression, and liberation in relation to K application, crop removal and leaching) can be established only after several seasons.

2.4.5 Factorial experiment

Factorial combinations of N at 0, 40 and 80 kg/ba, P at 0, 80 and 120 kg/ha P_2O_5 and potassium at 0, 30 and 60 kg/ha K_2O were tested for their effect on the yield of soft wheat.

3. Preliminary results and discussion

Even had the weather experienced since laying down the experiments been normal, it would be early days to attempt an evaluation of results. Many of the experimental crops in both 1980–1981 and 1981–1982 were subject to exceptional drought and very high temperature resulting in complete or virtual crop failure and tolerable yields were obtained only in 1981–1982 and only at Settat and Merchouch so that meaningful discussion of results must of necessity be confined to these.

3.1 Cultivation experiments

Mean yields for hard wheat of 0.7, 2.7 and 4.2 quintals per hectare at Souihla, Settat and Jemaa Shim respectively and similarly low yields of soft wheat and barley in 1980–1981 and very low yields at Souilha in 1981–1982 really only indicate complete or virtual crop failure due to the extreme drought. Though the analysis of variance does reveal some apparently significant differences between treatments, these cannot be taken to indicate any definite effects. There were indications of a slight superiority of deep cultivation with chisel plough or cultivator and of a positive effect of mulching. However, the latter provisional finding is of doubtful practical significance since the availability of straw and litter is very limited in these areas and the

Table 3. Cultivation experiment Settat 1981–1982. Yields (t/ha) of hard wheat

Treatment			
Minimum cultivation		3.37	
Shallow	Disc	2.74	
	Mouldboard	3.54	
	Chisel	3.39	coeff. variation 17.3%
Medium	Disc	3.39	
	Mouldboard	3.42	
	Chisel	2.88	

needs of livestock are paramount. In 1981–1982, yields at Settat were satisfactory (Table 3) averaging 3.35 t/ha but none of the treatment effects were significant, possibly because of the residual effects of extreme water deficit in the previous season.

3.2 Form of nitrogen fertilizer

3.2.1 Crop yield

Extreme drought caused very poor yields or crop failure at all centres in 1980–1981 and at Souihla and Jemaa Shim in 1981–1982. Fair crops averaging about 1.5, 3.6 and 2.4 t/ha for soft wheat, hard wheat and barley were obtained at Settat in 1981 to 1982: treatment means for these crops are given in Table 4. Neither farmyard manure at 40 t/ha nor either of the nitrogen fertilizers increased yields.

Table 4. Nitrogen fertilizer experiment Settat 1981–1982. Grain yields – t/ha

Treatment	Soft wheat Nesma	Hard wheat Cocorit	Barley 905
Without mulch			
Control	1.61	4.13	2.26
FYM 40 t/ha	1.83	4.08	2.33
Amm. sulphate 40 kg N/ha	1.55	3.53	2.15
Amm. nitrate 40 kg N/ha	1.73	3.30	2.20
Mean	1.63	3.76	2.23
With mulch			
Control	1.57	3.62	2.41
FYM 40 t/ha	1.49	2.94	2.75
Amm. sulphate 40 kg N/ha	1.37	3.73	2.40
Amm. nitrate 40 kg N/ha	1.37	3.40	2.45
Mean	1.43	3.42	2.51

3.2.2 Soil nitrogen

Soil mineral N, especially nitrate, was increased by manure and both N fertilizers, nitrate levels in the soil increasing in the order control, farmyard manure, sulphate of ammonia, ammonium nitrate (Figure 3).

It was not possible to identify any relationship between mineralization of N and the activity of soil micro-organisms, specifically nitrifying bacteria, through the course of the two seasons. The increase in soil nitrate appeared to be due to low uptake of N by crops and negligible loss by leaching. It is hoped that the monitoring of soil nitrate and ammonium N in the future will assist in the formulation of advice on the forms and rates of N fertilizer which should be used.

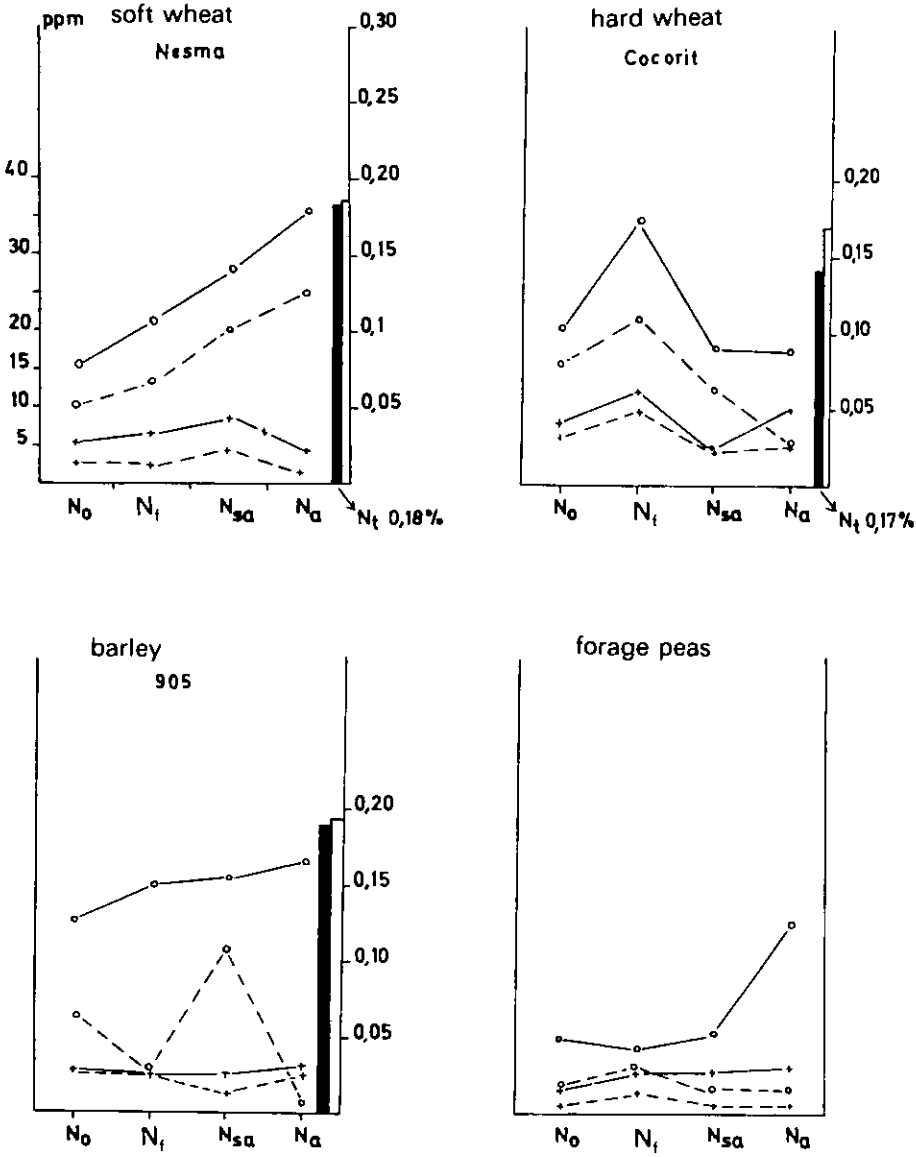

Fig. 3. Effects of N fertilizers on soil mineral N content (Settat)
1981–◧–1982 N_t total nitrogen
—o—o—— NO_3 after harvest
---o---o--- NO_3 after sowing
—+—+—— NH_4 after harvest
---+---+--- NH_4 after sowing

3.3 Phosphate experiments

3.3.1 Crop yield

There were no significant effects of P fertilizer on yield in either of these very dry years. The only experiment to give tolerable yields was at Settat in 1981–1982 (Table 5) all crops at Jemaa Shim and Souihla gave 0.25 t/ha or less.

Table 5. Phosphate experiment Settat 1981–1982. (Grain yields t/ha)

Treatment	Soft wheat Nesma	Hard wheat Cocorit	Barley 905
No phosphate	3.12	2.70	failed
60 kg/ha P_2O_5	3.18	2.68	failed
120 kg/ha P_2O_5	3.28	3.61	failed
240 kg/ha P_2O_5	3.17	2.62	failed
480 kg/ha P_2O_5	2.60	3.01	failed
c.v.	13.7%	14.6%	

Table 6. Matrix of correlation coefficients given by various methods of analysis for soil P

	Y_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
X_1	0.09	0.12	0.24	0.32	–0.88	*0.97*	*0.98*	*0.96*	*0.99*
P_2	*0.91*	–	0.40	–0.40	–0.17	0.05	0.23	0.25	0.23
P_3	0.05	–	–	0.60	–0.31	0.38	0.14	0.40	0.25
P_4	–0.42	–	–	–	–0.64	0.52	0.21	0.50	0.31
P_5	–0.01	–	–	–	–	*–0.92*	–0.86	*–0.95*	*–0.89*
P_6	–0.05	–	–	–	–	–	0.91	0.97	0.95
P_7	0.25	–	–	–	–	–	–	0.94	0.99
P_8	0.12	–	–	–	–	–	–	–	0.97
P_9	0.90	–	–	–	–	–	–	–	–

X_1: increasing rates of P_2O_5 (0, 60, 120, 240 and 480 kg P_2O_5/ha)
Y: yield
P_2: *Bray* method
P_3: *Mitchiguina* method
P_4: *Saunders'* method
P_5: Arrenius method
P_6: P–Al, P_7: P–Fe, P_8: P–Ca, P_9: PH_2O — *Chang* and *Jackson* method

3.3.2 Soil phosphate

In general, application of P fertilizer increased the content of assimilable P in all the soils (Figure 4). The slightly calcareous sandy soils of Souihla (torrifluvents), the typical vertisol of Jemaa Shim and the encrusted clayey soil of Settat are characterized by low potential P-fertility as indicated by low contents of available P by any of the usual methods of extraction *(Olsen, Bray, Joret-Hébert)*. Acid *(Arrenius, Egnér-Domingo)* and strongly basic *(Saunders)* extractants extract more P, giving values similar to those by *Chang* and *Jackson's* method which gives high values for the forms of bound P (P-Fe, P-Al and P-Ca).

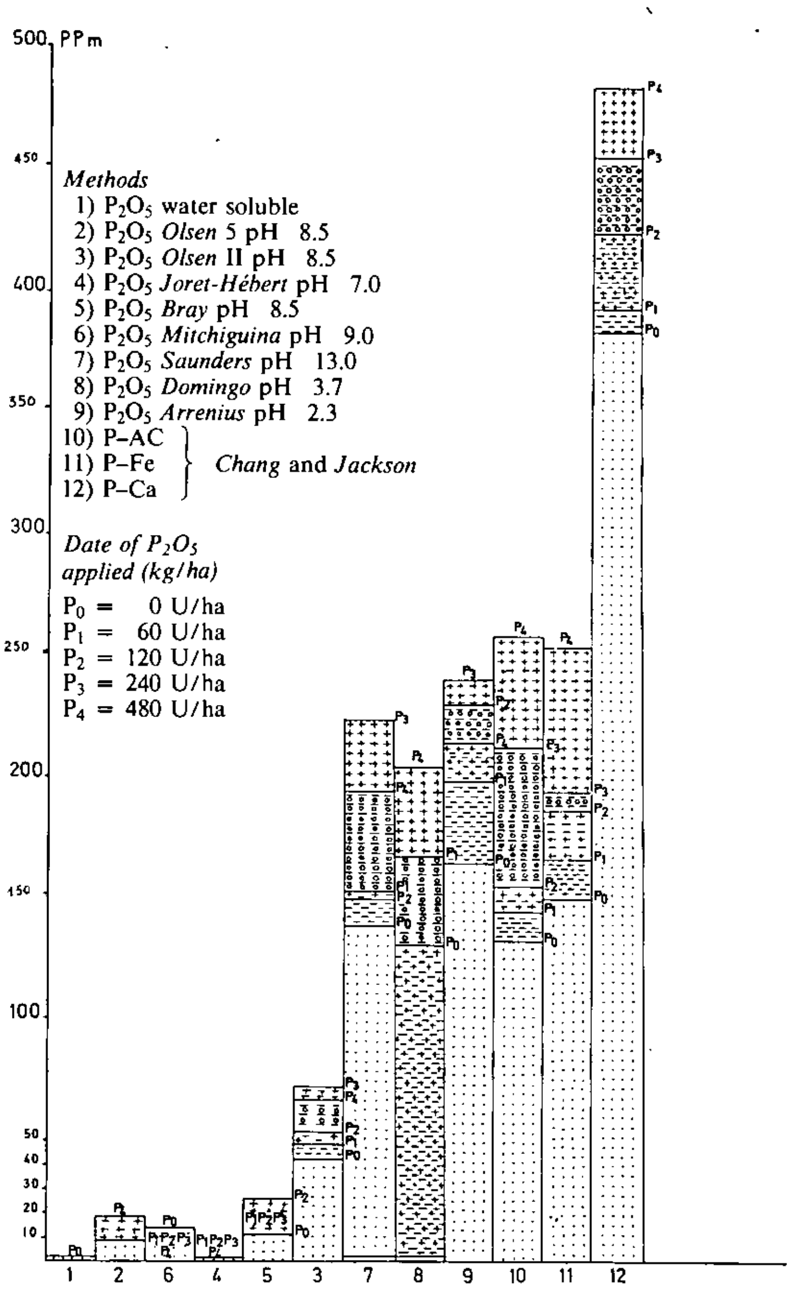

Fig. 4. Effect of P fertilizer treatment on assimilable soil phosphorus (at Settat). Crop: hard wheat (cocorit)

The analysis of the soils before and after application of P fertilizer indicates the following:
1) A slight increase in assimilable P as determined with acid (pH 2–3.7) and strongly basic (pH 13) extractants. The differences between the values given by the 10 methods were significant for all soil types and depths of sampling.
2) Soil P values given by either of the *Olsen* methods were poorly related to rate of P fertilizer applied and yield. *Bray's* method gave good correlation with yield ($r = +0.91$) but this result should be confirmed by investigation of a greater number of samples.
3) The contents of bound P (P-Ca, P-Fe, P-Al) were well correlated ($r = +0.96$–0.99) with the rate of P fertilizer applied (Table 6). This reflects both addition of P as fertilizer and low crop uptake caused by drought. These fractions account for five times the available P content and almost 20% of total P.
The problem of determining what may be called 'assimilable' P in the more or less calcareous sandy and clayey soils of the Moroccan arid and semi-arid regions is a difficult one. Under these arid conditions, the pool of labile P consists mainly of phosphate ions in solution. Potentially soluble P bound to Fe, Ca (exchangeable or active $CaCO_3$) or Al is only difficultly 'available' on account of the dryness of the soil, frequently drier than pF 2.5. It may appear that, if P fertilizer 'has made no impression' on these soils *(Bouzoubaa, Michel, Dardari)* this is because they are already high in bound P, especially P-Ca.

3.4 Potash experiments

3.4.1 Yields

All crops were either failures or gave extremely low yields except at Settat in 1981 to 1982 where moderate yields of barley and poor yields of wheat were recorded (Table 7). The experimental errors were very high and it is not possible to draw any conclusions regarding the effects of K fertilizers on crop yield.

Table 7. Potash experiment Settat 1981–1982. (Grain yields t/ha)

Treatment	Soft wheat Nesma	Hard wheat Cocorit	Barley 905
No potash	1.49	1.48	2.47
30 kg/ha K_2O	1.52	1.48	2.07
60 kg/ha K_2O	1.35	1.56	2.20
120 kg/ha K_2O	1.22	1.99	2.11
180 kg/ha K_2O	1.63	1.70	2.28
c.v.	32%	34%	32%

3.4.2 Soil potassium

The application of K fertilizer increased the levels of exchangeable K in all the experimental soils (Table 8). It is thought that the Jemaa Shim soil is sufficiently well-supplied with K and that application of K fertilizer here would not be justified. At the other sites, applying K fertilizer has raised the soil K status from 'low' to 'satisfactory'.

Table 8. Effect of K fertilizer on contents of water soluble and exchangeable K in soils

Initial values	Treat-ments (kg K_2O/ha)	Hard wheat (Cocorit)		Soft wheat (Nesma)		Barley 905	
		Ks	K^+me/100 g	Ks	K^+me/100 g	Ks	K^+/me 100 g
Settat							
A = 60.3%	0	80	0.46	12	0.44	8	0.34
CEC = 61me/100 g	30	12	0.59	13	0.46	9	0.36
pH = 8.3	60	16	0.57	13	0.47	10	0.38
pFK_H = 23%	120	12	0.53	16	0.57	12	0.42
pFK_S = 38%	180	12	0.61	24	0.68	16	0.48
Shim							
A = 47.6%	0	16	0.74	16	0.74	12	0.84
CEC = 44me/100 g	30	20	0.82	20	0.84	36	0.72
pH = 8.1	60	17	0.70	24	0.91	24	0.76
pFK_H = 24%	120	44	0.99	32	0.99	56	0.93
pFK_S = 37%	180	20	0.89	56	1.41	40	0.87
Souihla							
A = 14.3%	0	51	0.61	41	0.51	42	0.72
CEC = 18.5me/100 g	30	62	0.66	45	0.51	37	0.72
pH = 8.10	60	71	0.64	57	0.62	50	0.81
pFK_H = 12%	120	82	0.72	50	0.71	152	0.91
pFK_S = 15%	180	45	0.84	84	0.74	261	0.94

Ks : K soluble in water
pFK_S : dry fixation capacity
pFK_H : wet fixation capacity
K^+ : exchangeable K

3.5 NPK factorial experiment

Merchouch, where this experiment was sited in 1981–1982 has a more favourable climate than the other sites. It is in the Zaërs region and the climate is semi-arid but with cool winters, annual rainfall of about 480 mm, mean annual temperature 17.6 °C and annual water deficit of 472 mm. The yields obtained (Table 9) were considered satisfactory for the area and gave some definite indications. Grain yield and number of ears were significantly increased by N fertilizer and there was a significant positive N × K interaction. It is clear from Table 9 that N fertilizer increased yield appreciably only when potash fertilizer was applied and it would appear that the testing of higher rates of N than those applied in the experiment might well be justified since there was no falling off in response to increasing dressings of N. Though application of phosphate did not improve yield on this very low phosphate soil it did improve establishment. The effect of heavier P dressings will be investigated in the future.
In the light of these preliminary results it is intended to simplify the experiments by applying a uniform potash dressing of 40 kg/ha K_2O and studying the combined effects of nitrogen and phosphate in more detail.

Table 9. Factorial experiment on soft wheat (Nesma) at Merchouch 1981–1982. Two-way table (N × P), (N × K) and (P × K) t/ha grain

	P_0	P_{80}	P_{120}	Mean	K_0	K_{30}	K_{60}
N_0	3.46	3.30	3.60	3.45	3.47	3.51	3.37
N_1	3.53	3.51	3.65	3.56	3.49	3.69	3.52
N_2	3.66	3.93	3.81	3.80	3.62	3.90	3.89
Mean	3.55	3.58	3.69	3.61	3.53	3.70	3.59
	P_0	P_{80}	P_{120}				
K_0	3.51	3.56	3.51				
K_1	3.57	3.72	3.80				
K_2	3.57	3.47	3.75				

4. General conclusions

The early years of this investigation have been much affected by severe drought and the responses to fertilizer were therefore much less than might have been expected. No firm conclusions upon which to base fertilizer recommendations can yet be drawn and, clearly, the work must be continued for several years before it will be possible to make any recommendations.

Taking account of the extreme drought experienced, it would seem that the preliminary results indicate:

1) The benefits of mulching, though this could not be widely practised because of the shortage of mulching materials in mixed farming areas (due to high price of straw: 1 kg wheat straw = 1 Dh; 1 kg grain = 1.20 Dh).

2) A slight beneficial effect of deep cultivation with chisel plough or cultivator.

3) A positive effect of N fertilizer as well as a positive and significant N:K interaction in the more favourable area (Merchouch).

4) An effect of PK fertilization in improving the potential fertility of the soils though in these calcareous soils phosphate application brings about enrichment of bound P (P-Ca, P-Al, P-Fe) rather than of 'available' P and there is a need for further investigation of methods for P determination which relate well to crop yield.

The first results obtained have suggested some changes of the experimental programme by:

a) Establishment of long-term experiments for K-depletion in semi-arid and arid zones in order to verify the effect of potassium on soils rich in available K.

b) Abandonment of the cultivar Nesma at Souihla since it is not sufficiently drought resistant.

c) Abandonment of the mulching treatment since it is not practicable in mixed farming areas.

d) Combining the NPK fertilizer experiments with a test of cultivation treatments (three implements at three depths) with study of the water economy of the soils, temperature conditions, and structural stability.

5. References

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Appendix 1. Analytical methods

1) Phosphorus

– *Assimilable phosphorus*

1.1 *Olsen,* in: *Jackson M.L.:* Soil Chemical Analysis; Prentigi Hall, 1958
1.2 Modified *Olsen,* in: *Alban L.A., Jackson M.L. et al.:* Agr. J. *56* (1964)
1.3 *Joret-Hébert,* in: *Joret C.* and *Hébert J.:* Ann. Agron. No. 2 (1955)
1.4 *Bray,* in: *Jackson M.L.:* Soil Chemical Analysis, Prentigi Hall, 1958
1.5 *Arrenius,* in: *Piper C.S.:* Soil and Plant Analysis, 1950
1.6 Al-method *(Domingo),* in: *Egnér H., Domingo W.R. et al.:* Lantbrukshögskolan Ann. *26,* 1960
1.7 *Mitchiguina,* in: *Peterburgski A.V.:* Moskwa Praktik. Agron. (1963)
1.8 *Saunders,* in: *Saunders R.H.:* Soil Sci. No. 82 (1956)
1.9 Forms of phosphorus, in: *Jackson M.L.:* Soil Sci. No. 84 (1957)
1.10 P-Ca
1.11 P-Al } in: *Jackson M.L.:* Soil Sci. No. 84 (1957)
1.12 P-Fe
1.13 Total phosphorus, in: *Pinto M.:* Masson & Cie, vol. 2, 1971

2) Nitrogen

2.1 Total N, in: *Jackson M.L.* (1958); *Black et al. (1965)*
2.2 Mineral N, in: *Black C.A. et al.* (1956)
2.2.1 Ammonium: extraction with KCl; analysis with MgO
2.2.2 Nitrate: extraction with KCl; analysis with *Dewarda's* alloy

3) Potassium

3.1 Total K: alkaline fusion, in: *Pinto M.* (1977)
3.2 Exch. K: NH_4 acetate 1 N, pH = 7, in: *Jackson, M.L.* (1958)
3.3 Water soluble K, in: *Richards,* Soil Sci. No. 51 (1941)

4) Other methods

– EC and CEC: NH_4 acetate, pH 7.0
– pF; in: *Richards,* Soil Sci. No. 51 (1941)
– pH: potentiometry
– carbon in: *Walkley* and *Black:* Methods of Analysis, Soils, agron. J. No. 9 (1965)
– Density: picnometry

Appendix 2. Soil analysis – Souihla

Depth	Mechanical analysis %				$CaCO_3$		Organic matter				Density
cm	<2 μ	2–50 μ	50–200 μ	200–2000 μ	Total %	Active ‰	Ct %	Nt %	MO %	C/N	Ra
0– 10	14.3	31.6	40.2	2.7	6.4	17.5	0.59	0.80	1.02	7.3	2.1
10– 20	16.3	36.8	39.8	2.0	7.4	17.5	0.56	0.08	0.96	7.0	2.2
20– 40	12.8	35.3	41.5	1.2	6.5	17.0	0.37	0.05	0.64	7.4	2.5
40– 60	12.3	51.0	27.8	0.8	9.0	13.5	0.06	0.04	0.10	1.0	2.5
60– 80	8.1	16.3	33.1	37.2	6.8	10.0	0.31	0.05	0.53	7.7	2.8
80– 95	5.1	18.3	30.7	38.2	6.8	13.7	0.21	0.03	0.36	7.0	–
95–100	8.2	28.6	25.6	28.2	7.9	12.5	0.12	0.02	0.21	6.0	2.7
100–115	2.0	6.1	22.0	59.0	7.3	3.7	0.13	0.04	0.22	3.2	–
115–146	7.1	26.4	42.5	16.6	8.1	13.7	0.34	0.02	0.59	17.0	2.8
146–190	26.2	50.3	12.6	2.1	4.1	13.7	0.16	0.02	0.27	8.0	2.8

Depth	pH		Exch. cations (EC) me/100 g				CEC	K_2O ‰		P_2O_5 ‰		Fe_2O_3 %	
cm	H_2O	KCl	Ca^{++}	Mg^{++}	K^+	Na^+	me/100 g	Total	Assim.	Total	Assim.	Total	Free
0– 10	8.1	7.4	5.2	3.5	0.33	1.04	10.2	5.84	0.105	1.88	0.029	5.6	2.0
10– 20	8.2	7.5	5.9	3.0	0.26	0.65	9.9	7.38	0.105	1.96	0	5.6	2.0
20– 40	8.3	7.6	4.4	4.0	0.17	0.75	9.4	6.24	0.069	1.72	0	5.2	2.0
40– 60	8.3	7.5	6.0	4.0	0.13	0.88	11.1	6.82	0.050	1.81	0	5.9	2.1
60– 80	8.2	7.7	8.0	3.0	0.13	0.93	7.1	4.39	0.057	1.65	0	4.7	1.6
80– 95	8.7	7.9	3.8	2.2	0.13	0.38	6.6	2.35	0.046	1.56	0	4.3	1.1
95–100	8.8	7.8	3.5	5.1	0.13	0.45	9.1	4.21	0.055	1.42	0	4.2	1.4
100–115	8.7	8.0	1.8	1.8	0.06	0.18	3.9	5.03	0.023	1.41	0	4.8	2.6
115–146	8.6	7.8	4.2	3.3	0.14	0.28	8.0	11.11	0.025	2.03	0	4.7	2.3
146–190	8.6	7.7	7.2	6.0	0.53	0.68	14.4	–	0.233	–	0	5.8	2.4

Mineralogy: Kaolinite + illite + quartz + feldspars

Appendix 3. Soil analysis – Jemaa Shim

Depth	Mechanical analysis %				$CaCO_3$		Organic matter				Physical constants		
cm	<2 μ	2–50 μ	50–200 μ	200–2000 μ	Total %	Active ‰	Ct %	Nt %	MO %	C/N	Rd	pF 2.5	pF 4.2
0– 20	47.6	16.2	26.8	11.5	0.50	25.6	0.90	0.09	1.57	10.0	2.58	29.7	16.6
20– 40	45.6	17.4	26.0	11.3	0.90	21.7	0.76	0.09	1.31	10.0	2.54	31.8	17.7
40– 60	38.2	22.9	25.1	12.0	2.10	31.3	0.76	0.10	1.31	7.6	2.57	39.7	19.8
60– 80	44.8	15.6	24.6	11.8	2.88	38.1	0.57	0.09	0.98	6.3	2.59	43.5	21.0
80–100	48.2	14.1	23.4	11.3	4.20	54.1	0.39	0.07	0.67	5.6	2.56	46.7	21.3
100–120	37.3	19.5	22.9	10.9	4.30	35.5	0.37	0.06	0.64	6.2	2.56	49.2	–
120–140	39.0	20.1	23.0	10.3	3.70	23.2	0.34	0.04	0.58	8.5	2.55	41.1	21.3
140–170	39.0	22.2	21.6	18.3	3.70	10.9	0.24	0.04	0.42	6.0	–	–	–
170–220	44.6	38.5	15.5	5.0	1.40	9.5	0.16	0.03	0.32	6.0	–	–	20.2

Depth	pH		Exch. cations (EC) me/100 g				CEC	K_2O ‰		P_2O_5 ‰		Fe_2O_3 %	
cm	H_2O	KCl	Ca^{++}	Mg^{++}	Na^+	K^+	me/100 g	Total	Assim.	Total	Assim.	Total	Free
0– 20	8.1	7.2	33.1	7.3	0.4	1.10	42.1	6.31	0.223	1.85	0.070	4.25	0.89
20– 40	8.2	7.1	35.9	6.5	0.5	0.53	43.4	10.58	0.343	2.01	0.021	4.26	0.89
40– 60	8.4	7.2	31.5	8.7	0.7	0.40	41.3	6.04	0.184	2.00	0	4.16	0.89
60– 80	8.5	7.0	28.1	10.3	1.4	0.38	40.3	5.83	0.180	2.01	0	4.16	0.87
80–100	8.2	7.3	25.1	10.0	3.0	0.35	38.4	5.39	0.160	2.28	0	4.04	0.89
100–120	8.4	7.2	24.8	11.2	3.4	0.34	39.8	6.46	0.170	2.56	0	4.29	0.89
120–140	8.4	7.3	24.2	11.2	4.1	0.46	39.4	6.68	0.200	2.50	0	4.24	0.85
140–170	8.4	7.3	23.5	12.2	4.5	0.51	41.0	6.31	0.220	2.97	0.049	3.52	0.90
170–220	8.3	7.2	18.3	9.4	4.2	0.74	32.6	10.58	0.342	–	0	5.20	0.89

Mineralogy: Montmorillonite dominant, kaolinite little, quartz

Appendix 4. Soil analysis – Settat

Depth cm	Fraction >2 mm	Mechanical analysis %					$CaCO_3$		Organic matter				Physical constants		
		<2 µ	2–20 µ	20–50 µ	50–200 µ	200–2000 µ	Total %	Active ‰	Ct %	Nt %	MO %	C/N	Rd	pF 2.5	pF 4.2
Ap 0–10	4.7	60.3	5.8	11.1	13.7	2.0	3.5	2.93	2.07	0.22	3.58	9.4	2.34	28.29	15.35
A_{II}–33	0.9	57.6	8.6	10.6	13.6	2.1	4.2	2.93	1.93	0.22	3.32	8.7	2.38	30.18	16.86
B_{caI}–45	crust	–	–	–	–	–	92.0	–	–	–	–	–	2.37	30.57	16.58
B_{2ca}>45	0.2	–	–	–	–	–	85.9	14.14	0.32	0.04	0.54	8	–	–	–

Depth	pH		Exch. cations (EC) me/100 g				CEC	K_2O ‰	P_2O_5 ‰	Fe_2O_3 %	
cm	H_2O	KCl	Ca^{++}	Mg^{++}	K^+	Na^+	me/100 g	Assim.	Total	Free	Total
Ap 0–10	8.30	7.20	56.06	4.24	0.56	0.41	61.27	0.261	0.047	2.23	5.26
A_{II}–33	8.40	7.20	57.62	3.20	0.20	0.30	62.44	0.142	0.002	2.33	5.11
B_{caI}–45	–	–	–	–	–	–	–	–	–	–	–
B_{2ca}>45	8.70	8.25	4.24	4.97	0.04	0.12	6.37	0.057	0	0.21	0.58

Appendix 5. Soil analysis – Merchouch

Depth cm	Fractions >2 mm	Mechanical analysis %				$CaCO_3$		Organic matter			
		<2 μ	2–50 μ	50–200 μ	200–2000 μ	Total %	Active ‰	Ct %	Nt %	MO %	C/N
0– 20	4.9	33.8	26.2	32.3	9.4	0.3	0	0.94	0.09	1.62	10.4
20– 35	4.0	31.7	27.9	32.4	10.7	0.3	0	0.94	0.10	1.62	9.4
35– 80	21.2	37.8	17.8	21.0	21.0	0.5	0	0.36	0.06	0.62	6.0
80–130	2.6	53.8	17.0	18.7	7.3	0.5	0	0.21	0.04	0.36	5.3

Depth	pH		Exch. cations (EC) me/100 g				CEC	P_2O_5 ‰	K_2O ‰		Fe_2O_3 %	
cm	H_2O	KCl	Ca^{++}	Mg^{++}	Na^+	K^+	me/100 g	Assim	Total	Assim	Free	Total
0– 20	5.65	4.70	11.20	4.34	0.17	0.52	19.93	0.073	4.3	0.254	1.99	5.00
20– 35	5.75	4.75	12.18	4.10	0.28	0.55	20.51	0.061	4.3	0.141	2.10	4.91
35– 80	6.55	5.40	14.06	4.75	0.32	0.21	27.06	0.061	5.4	0.104	2.52	7.69
80–130	6.95	5.70	17.57	6.66	1.15	0.26	29.02	0	5.6	0.120	2.32	7.06

Mineralogy: Settat: Montmorillonite dominant, kaolinite very low, quartz and calcite, feldspars
Merchouch: Illite and kaolinite dominant, interstratified and smectites at depth

Coordinator's Report on the 3rd Session

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Rainfed Farming Systems

Rather than discussing in detail all the papers and the discussions which made up the third working session, I will confine myself to the main impressions I received and try to summarise the present status of research in this field.

C. Piéri opened the session with an excellent main paper which clearly showed the practical difficulties of measuring the various terms of the nutrient balance in rainfed farming systems. He described results from two typical crop rotations – cotton, sorghum and millet, groundnut – and these showed that in order to arrive at a meaningful assessment of the development of fertility it is necessary to take into account most of the terms which contribute to the balance and to give special attention to net mineralisation, replenishment of the labile pool from mineral reserves, leaching, loss of nitrogen by volatilisation and additions from the atmosphere. He showed that the maintenance of soil fertility in these regions depends upon the control of their organic matter and nitrogen status, adjustment of potassium fertilizer application to the needs of crops in the rotation, taking into account additions of manures and fertilizers; it is important to maintain the calcium and magnesium status which are much affected by leaching. The study of nutrient balance under different crop rotations can lead to important conclusions on the maintenance of fertility under arid and semi-arid conditions.

H. Manichon had studied the effects of rainfall distribution on crop yield in arid and semi-arid regions. He discussed cultural methods designed to improve crop establishment and the supply of water to the growing crop. His results showed clearly that, though sowing should not be unduly delayed, it is advisable to ensure that the seedbed is sufficiently moist to support the survival of young seedlings. Cultivations for wheat should be such as to encourage the penetration of rain into the soil and to promote the development of a root system which explores the soil to depth. Adequate weed control reduces water loss. The use of a cultivated fallow to increase stored water is problematical.

Harmsen and Shepherd's paper, presented by *K. Harmsen* described agronomic trials in northwest Syria which showed that there is a considerable potential for yield increase in barley through the use of nitrogen and phosphate fertilizers. Crop response was discussed in relation to climatic factors, amount and distribution of rainfall and temperature during the growing season and in relation to soil P supply and crop characteristics.

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M. Agbani has studied the development of the root system of sugar beet during growth. He used the concept of root area index to describe colonisation of the soil by roots and established a linear relationship between root length and root surface and total uptakes of nitrogen, phosphorus and potassium; he compared the rates of root growth and nutrient uptake.
Finally, *H. Ghanem* discussed preliminary results from a large-scale researcb project in the arid and semi-arid regions of Morocco. Results to date have been adversely affected by exceptional drought and it is too early to draw any conclusions but this is a most comprehensive research project of great importance to the future of agricultural development in Morocco and further progress will be watched with great interest.

Chairman of the 4th Session

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4th Session

Irrigated Farming Systems

Short and Long-Term Effects of Irrigation on the Fertility and Productivity of Soils

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Summary

The effects of irrigation on the fertility and productivity of soils are reviewed. Models have been developed to describe nutrient movement and distribution in soils as affected by soil water status, but the spatial and temporal variations in soil parameters limit the use of deterministic models and this is giving way to stochastic approaches. Irrigation increases the efficiency of fertilizer use by facilitating the transport of nutrients to roots and by increasing the crop demand for nutrients. The method of irrigation can affect the efficiency of fertilizer use, particularly the methods that allow almost continuous nutrient application. Salinity is considered a major threat to the long-term preservation of irrigated agriculture. Other effects of irrigation on soil properties are briefly reviewed. It is concluded that water management and conservation practices that optimize irrigation water use are the key to achieve high efficiency of nutrient utilization and to counteract the detrimental effects of irrigation on soil produtivity.

1. Introduction and background

For a long time, irrigation has been the most important way of increasing food production in the arid and semi-arid zones. More recently, irrigation has been used in sub-humid areas with the objective of stabilizing food production against occasional drought. Proposals are now being made *(Tanner* and *Sinclair [74])* for new irrigation developments in areas with abundant rainfall such as the Eastern United States on the theoretical basis that crop water use efficiency is higher under the small vapor pressure deficits of humid climates.

The primary and traditional objective of irrigation is to provide the crop with adequate water supply throughout the growing season. Irrigation significantly increases crop yields in areas of insufficient rainfall where water is the most limiting factor for crop production. *Boyer [12]* reports that water stress limits crop productivity more than any other environmental factor, thus the importance of irrigation cannot be overemphasized. However, rather than viewing irrigation as a means of removing the water constraint on crop production, it may be more desirable to consider that

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irrigation allows the achievement of crop yields which approach the potential productivity of a given environment. In the irrigated areas of the arid and semi-arid zones, the conditions of high radiation – the driving force for photosynthesis – favorable temperatures, and adequate water and nutrient supply, all combine to provide ideal environmental conditions for very high levels of crop production. Too often, however, the high potential productivity of irrigated lands is not realized. Failures associated with irrigation development can be attributed to various reasons which can be classified into three major groups.

First, providing adequate water supply does not by itself realize the yield potential of an environment. Other factors such as nutrient supply, appropriate cultivars and plant populations, and weed control among many others, then become limiting for crop production. Therefore, it shoult be emphasized that, without a complete and appropriate package of agronomic measures, the full benefit of irrigation development is not achieved. When the system is considered as a whole and most of the constraints for crop production are removed with adequate management practices, crop yields of the irrigated arid and semi-arid zones are the highest of the world and approach the theoretical potential limits. *(Loomis* and *Gerakis [45]).*

The second group of problems affecting irrigated crop production is related to the effects of irrigation on the environment. The extensive development of irrigation after the Second World War has been followed in the last decade by an increasing awareness and concern over the environmental damage associated with irrigation. It has long been known that poor irrigation management can produce irreversible damage to soil productivity, to the point that civilizations declined because of the salinity problems associated with irrigation *(Jacobsen* and *Adams [42]).* Salinity and other effects of irrigation on the environment related to soil erosion and groundwater pollution will be reviewed here.

Finally, there is a third area of concern that influences crop production of irrigated lands. A number of problems of socio-economic nature which will not be considered here, are frequently responsible for the observed lack of success of many irrigation projects. Among them, insufficient education of the irrigators is most important.

The application of irrigation water to the land, brings about many changes in the properties of the soil which may have serious implications on its productivity. Table 1 lists some important effects of irrigation on soil productivity. Most of the changes require a number of years to take place and thus they are generally considered long-term. Among them, salinity is perhaps the most important in the arid and semi-arid zones. It should be noted that the effects listed in Table 1 are not necessarily detrimental to crop production and that, in most cases, they can be eliminated by sound

Table 1. Effects of irrigation on soil productivity

Soil properties			Other effects
Physical	Chemical	Other	
1. Infiltration rate 2. Hydr. conductivity 3. Structure 4. Texture	1. Nutrient supply 2. Salinity 3. Ion toxicity	1. Erosion 2. Topography	1. Climate change 2. Water pollution

water management practices. The effects can also be classified into those affecting a given irrigated field such as a reduction in infiltration rate as compared to the changes that could affect downstream users such as impaired quality of irrigation return flows.

Earlier reviews *(Hagan, Haise* and *Edminster [35]; FAO/UNESCO [26])* have addressed the many effects of irrigation on soil productivity. The effects of irrigation on soil nutrients and fertility will be emphasized here while only brief reviews will be presented on other effects.

2. Irrigation effects on nutrient supply and soil fertility

As soon as the water constraint on crop production is removed by irrigation, the crop mineral nutrient requirements become critical. The lack of crop response to adequate fertilization often observed under dryland conditions *(Black [10])* gives way under irrigated conditions to substantial increases in crop yields as fertilizer nutrients are added to the soil. Two features characterize the responses to the application of fertilizers under irrigation as illustrated in Figure 1 for the case of nitrogen. First, an irrigation schedule designed to meet the crop evapotranspiration (ET) losses, results in increased uptake of soil mineral nitrogen as compared to a water deficit situation (Figure 1). Second, as fertilizer N is added, N uptake increases much more dramatically in the case of the fully irrigated corn crop whereas in the drier treatment, doubling the rate of fertilizer N application hardly changed N uptake. Obviously full irrigation results in more complete recovery of the applied fertilizer and higher efficiency of fertilizer nutrient utilization. The two effects discussed above may be explained by exploring the relation between soil water and nutrient movement and utilization in soils.

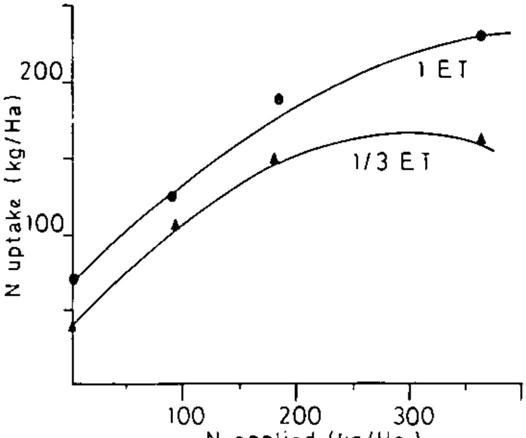

Fig. 1 Relations between applied fertilizer N and N uptake for a corn crop under full and deficit irrigation (1/3 ET). Data taken from Broadbent and Carlton *(Nielsen* and *MacDonald [57])*.

2.1 Nutrient movement and uptake in soils as affected by soil water status

The complexities involved in describing the movement of solutes and their distribution in the soil profile, has led to the use of simplified systems such as soil columns to study these processes. Among all nutrients, nitrogen in its nitrate form has been the most studied, both because of its mobility as a non-absorbed solute and because of the concerns about nitrate pollution which have been raised over the last decade (*Nielsen* and *MacDonald [57]*).

Predicting the movement of nitrate in soils is complicated by the transformation processes (mineralization and immobilization; nitrification and nitrate reduction; and denitrification) which take place simultaneously with plant uptake. In lahoratory columns packed with uniform soil, it has been possible to describe accurately the movement and distribution of nitrate in the soil profile as a function of time, by solving the equation of continuity for solute transport with appropriate initial and boundary conditions. An example of the excellent agreement between the theory and experimental evidence of nitrate movement is shown in Figure 2 taken from *Rolston* and *Mariño [68]* who included the denitrification process in their model. Figure 2 also illustrates the theoretical pattern of nitrate fertilizer movement in field soils with the peak concentration being displaced with depth as a function of time and the distribution spreading over a larger depth due to diffusion and hydrodynamic dispersion.

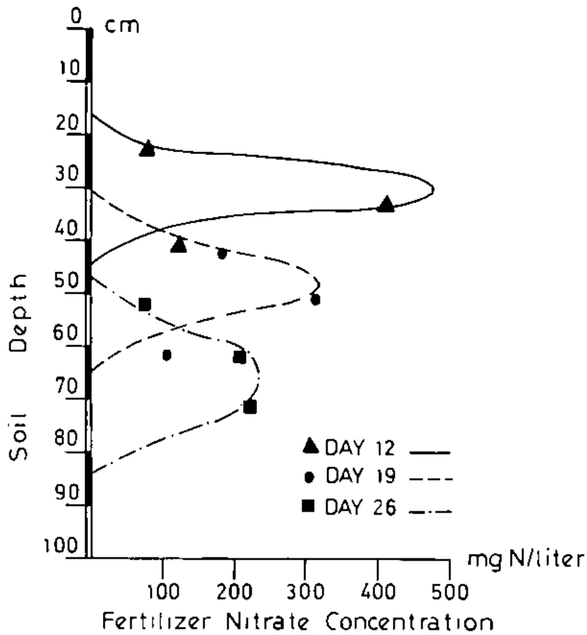

Fig. 2 Concentration of fertilizer NO_3^- as a function of soil depth for three times after application of a NO_3^- pulse to a column of Yolo loam soil maintained at a soil matric potential of -0.02 bar. The curves were calculated using an equation describing NO_3^- transport with denitrification. (After *Rolston* and *Mariño [68]*).

The dynamics of nitrogen transformations in the field combined witb the lack of steady state conditions for water movement in the profile and with crop uptake, make the description and simulation of nitrogen behavior under field conditions a very difficult task. However, the large body of experimental work carried out over the last 15 years, has generated enough information on the various processes so that complete simulation models are now available *(e.g., Tillotson* and *Wagenet [75]). Tanji [73]* in a thorough review of the modeling efforts on soil nitrogen, has evaluated a number of simulation models currently available. Only a few models have been checked against independent experimental data showing fair agreement between predicted and measured values *(Tanji [73]).* This should be encouraging considering the complexity of the system being simulated and suggests that the theory used for model development is basically sound. However, one limitation of the simulation models mentioned above is the large number of parameters which must be known for a given situation. *Rose et al. [70]* have proposed the use of a simplified model to describe solute movement based on mass conservation of water and solute as an alternative to more complex models. Their approach requires only knowledge of field capacity and follows a simple accounting procedure to determine the mean depth of penetration of a solute such as Cl^- which is not taken up, adsorbed or transformed within the root zone. This model has been applied to the movement of NO_3^- and has shown fair agreement with two independent sets of data taken from the literature *(Rose et al. [70]).* Further testing and refinement of such simplified models is needed to predict the effects of irrigation on nutrient movement in soils.
All models discussed above are deterministic in nature and their usefulness to describe and manage nutrient behavior in soils depends on how well their parameters represent the whole area under consideration. Since *Nielsen, Biggar* and *Ehr [55]* showed that there was substantial spatial variability in the soil water properties of a uniform field, soil scientists have become more aware of the spatial and temporal variations in soil parameters. New approaches are being developed to describe better such variations in a useful manner with stochastic analyses playing an important role *(Vieira, Nielsen* and *Biggar [80]). Nielsen, Biggar* and *Wierenga [56]* recently reviewed both the deterministic and stochastic approaches describing N transport processes in soils. They suggested that geostatistical analyses provide much more information about overall system behavior than deterministic analyses, although they require a greater number of observations and therefore cost more.
Nutrient uptake by root systems in soils depends on the transport of ions to the root surfaces and on the interception of ions by growing roots. Two basic mechanisms participate in the transport of nutrients to root surfaces; molecular diffusion and convective transport also called mass flow *(Nye [58]).* Tbe relative importance of each mechanism depends on the nutrient under consideration. The transpirational flow of water to the roots carries ions in solution and, for some nutrients, this supply is adequate for maximum plant growth. For some less mobile nutrients, mass flow transport is not sufficient to meet the shoot demand. In such cases, molecular diffusion, following steep concentration gradients from the soil to the root, plays a major role in supplying nutrients to the roots. In addition to the two transport mechanisms, nutrients may be taken up by root interception as growing roots extend into the soil. Table 2 shows the relative importance of the three mechanisms in the supply of the nutrients needed for a 9 to 10 t/ha corn crop typical of irrigated conditions.

Table 2. Relative importance of nutrient supply mechanisms to corn roots (adapted from *Barber* and *Olson [7]; Barber [6]).*

Nutrient	Mass flow (%)	Diffusion (%)	Root interception (%)
N	95–100	0– 5	–
P	0– 5	90–95	2–4
K	15– 20	80–85	2–4
Mg	100 *	–	**
Ca	100 *	–	**

* Supply by mass flow significantly exceeds the uptake requirements
** Root interception could supply a substantial proportion of these nutrients.

Mass flow could then deliver the total needs of N, Ca, Mg and S while substantial transport by diffusion is needed to meet the uptake requirements of P and K and some micronutrients. Root interception plays a minor role due to the small soil volume (0.1 to 1% at the most) permeated by the root system *(Barber [6])*. The differences shown in Table 2 are basically due to the different mobilities of the various ions in the soil as evidenced by their diffusion coefficients. Typical values for the diffusion coefficients of nutrients in soils are summarized by *Barber [6]* who indicates that the diffusion coefficient for NO_3^- is approximately three orders of magnitude greater than that of $H_2PO_4^-$ and nearly two orders of magnitude greater than that of K^+.

It should be noted that, as pointed out by *Nye* and *Tinker [59]*, diffusion and mass flow occur simultaneously and both processes interact in the movement of ions to roots. *Nye* and *Tinker [59]* reviewed the theoretical approaches developed to characterize the simultaneous transport of solutes by diffusion and convection and stated that current models are appropiate to describe the flux of ions to roots. *Caasen* and *Barber [15]* applied a convection-diffusion model to K uptake from the soil and found reasonable agreement between calculated and measured uptake. However, *Phillips et al. [63]* found significant discrepancies when using a similar approach to predict NO_3^- uptake under field conditions probably because of the uncertainties in some of the assumptions made in their model.

Soil water levels play a very important role in nutrient availability as emphasized in earlier reviews *(e.g., Viets [81]; Newbould [54])*. Figure 3, drawn from classical data of *Russell* and *Newbould [72]* give evidence of the close association between soil water content in the 0 to 5 cm depth and the proportion of Ca uptake extracted from that layer. Recently, *O'Toole* and *Baldia [62]* have shown excellent correlation between nutrient uptake and transpiration in rice subjected to water deficits. *Mengel* and *Braunschweig [52]* found that K uptake by young corn plants was maximum at a soil water potential of -0.1 bar and declined as soil water potential decreased. *Loué [46]* reviewed several experiments where K uptake was enhanced by irrigation. How does soil water influence nutrient uptake? *Nye* and *Tinker [59]* list eight effects that soil moisture could have on nutrient uptake by single roots. From their review it can be concluded that the improvement of soil water status by irrigation increases the nutrient demand as the shoot growth rate is greatly accelerated upon relief of water stress conditions *(Hsiao [39])*. Furthermore, the enhanced transpiration under irrigated conditions increases convective transport to the roots resulting in

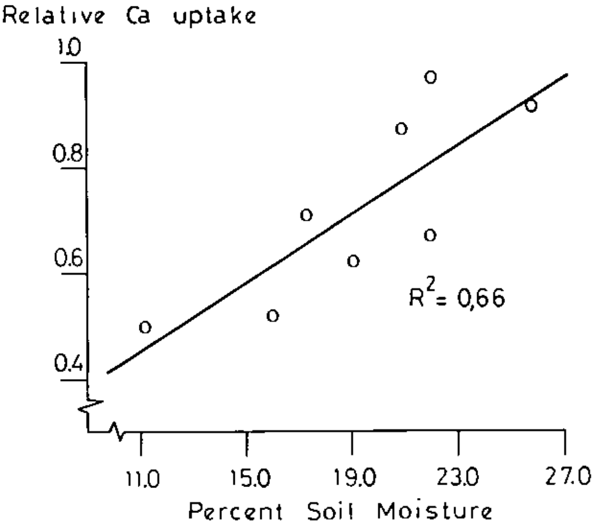

Fig. 3 Regression between soil moisture in the 0 to 5-cm depth and uptake of Ca in the same layer relative to total Ca uptake. Drawn from data taken from *Russell* and *Newbould [72]*.

greater movement of nutrients by mass flow. Irrigation also affects the diffusion coefficient of ions in the soil by reducing the tortuosity and increasing the cross-sectional area for nutrient movement in the soil *(Barber [6])*. Other effects of reduced soil water levels include an increase in the solution concentration of non-absorbed nutrients and that of exchangeable cations such as Ca and Mg, which tend to reduce the concentration of adsorbed anions like phosphate *(Nye* and *Tinker [59])*. In addition, root shrinkage due to water stress *(Huck, Klepper* and *Taylor [41])*, further restricts the movement of ions at the soil-root interface.

In view of the various cbanges mentioned above, it appears that a prediction of the patterns of nutrient uptake as affected by soil water status is a difficult task. *Dunham* and *Nye* (as cited by *Nye* and *Tinker [59])* measured the uptake of several ions in a simplified system under three levels of water supply. As the soil water potential increased from −25 bar to near zero, the mass flow to the roots, the root absorbing power and the diffusivity of chloride all increased, resulting in greater uptake of this ion. Reduced plant demand was shown to limit the uptake of P under low soil water potential. However, a much smaller reduction in K uptake was observed in dry soil and was attributed by *Dunham* and *Nye* to a reduction in the diffusion coefficient.

Under field conditions, soil water deficits may not induce nutrient deficiencies. The data collected by *Verasan* and *Phillips [79]* in corn and *Eck* and *Musick [24]* in sorghum indicate that the decrease in nutrient uptake is commensurate with the reduction in dry matter production. Furthermore, from the data of *Eck* and *Musick [24]* it can be inferred that the content of N and K per unit dry matter increased under water stress and that total Ca and Mg uptake was unaffected by water stress. The latter could be predicted by the expected increases in the concentration of exchangeable cations in the soil solution discussed above.

It can be concluded that, as suggested by *Pitman [64]*, the shoot demand plays a critical role in controlling nutrient uptake under water stress conditions. Therefore, when water stress is relieved by irrigation, the improvement in crop growth promotes concomitant increases in nutrient uptake through feedback controls. At the same time high soil water potentials facilitate the transport of the additional nutrients required. Whether the additional supply is capable of meeting the shoot demand remains in question. In addition to the quantities of fertilizers applied under irrigation, nutrient transport and uptake will depend on the patterns of root development in relation to nutrient availability in the various zones of the soil profile and on the pattern of fertilizer movement as affected by the method of irrigation and by the water management practices.

2.2 Effects of irrigation on root growth, water and nutrient uptake

The pattern of root development in soils generally follows an exponential function with maximum root length density, L_v (cm root/cm^3 soil) near the surface *(Gerwitz* and *Page [33])*. This type of pattern may well respond to the usual concentrations of nutrients encountered at the soil surface layers rather than being required for water uptake. It has been shown *(Acevedo [1]; Fereres [28])* that L_v values between 1 and 2 cm/cm^3 are sufficient to extract subsoil water down to about -15 bar soil water potential under dryland conditions.
It has long been known *(e.g. Troughton [76])* that root growth is less affected by water stress than is shoot growth. Thus irrigation, by promoting shoot growth, reduces the relative importance of roots as a carbohydrate sink. Mild water stress has little or no effect on root biomass but does change the pattern of root distribution in the soil. Figure 4 presents the root density as a function of depth for a sorghum crop near the end of the season for two treatments, one of which was irrigated at weekly intervals, the other not being irrigated. While rooting depth was similar in both treatments, there was more root proliferation from the surface layers in the irrigated treatment while higher L_v values in the subsoil were observed in the unirrigated treatment (Figure 4). Similar changes in root weight distribution with depth in irrigated and unirrigated soybean, corn and sorghum crops have been reported *(Mayaki, Stone* and *Teare [49])*.
While, contrary to common belief, rooting depths of unirrigated and irrigated crops are usually similar, water uptake patterns are very different with important consequences for nutrient uptake. *Hsiao et al [40]* presented the water uptake patterns of an unirrigated corn crop grown in the same location as the sorghum crop of Figure 4. Maximum root water extraction rates calculated as the sink term of the equation of continuity *(Rose* and *Stern [71])* occurred deeper in the soil profile as time went on and the upper layers were depleted. As nutrients are generally concentrated in the upper layers, nutrient supply to dryland crops in the latter part of the season may be even more limiting than water supply. Displacement of fertilizer nutrients deeper in the profile should assure adequate supply to dryland crops. The importance of deep placement of nutrients when water uptake takes place in the subsoil has been demostrated by *Newbould [54]* for perennial rye-grass production. Under a deficient water regime, dry matter production was doubled when nitrogen

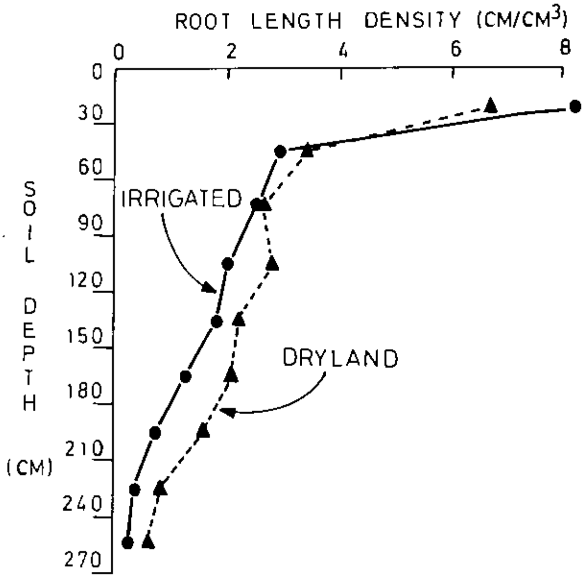

Fig. 4 Root length density as a function of depth for grain sorghum grown on Yolo loam soil under a frequently irrigated and an unirrigated treatment. Samples were taken at the end of the 1973 season (After *Fereres [28]).*

was placed at the 45-cm depth as compared to surface placement. It was also shown that the deep nitrogen application enhanced the extraction of phosphate and calcium placed at the 45 and 60-cm depths.

The plasticity of root growth in response to the soil microenvironment is substantial *(Carson [16]). Drew* and *Saker [21]* have shown that significant root proliferation occurs in response to localized placement of phosphate and this may explain why L_v values near the surface are so high. An interesting question refers to the activity of roots placed in dry soil layers following irrigation. Figure 5 presents the results of an experiment performed with grain sorghum which was first irrigated 55 days after planting. At that time, maximum water uptake rates were taking place at the 105 and 135-cm depths with negligible uptake in the surface layers. Four days after irrigation, the water uptake pattern had shifted dramatically with the greatest uptake rate taking place in the 0 to 30-cm layer (Figure 5). Concurrent measurements of L_v showed an increase of over 20% in the L_v values at the 0 to 15 cm and 15 to 30 cm depths over a period of six days *(Fereres [28]).* This would indicate that renewed root growth was at least partly responsible for the shift in the water uptake pattern. However, new root growth may not be necessary for some water uptake as it has been shown *(Fereres et al. [30])* that orange trees which had not been irrigated for over six months in the Arizona desert, took up water and presumably solutes within a few hours of irrigation.

The changes in the patterns of water uptake described above must influence significantly the nutrient uptake patterns. *Al-Ithawi, Deibert* and *Olson [2]* have shown for

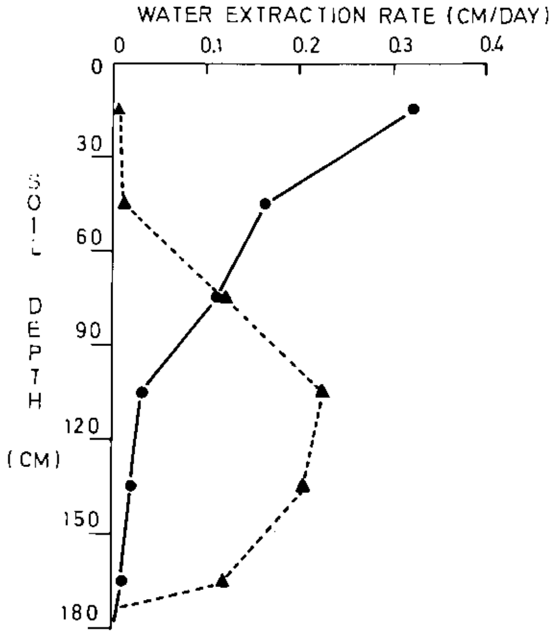

Fig. 5 Water extraction rate as a function of soil depth for grain sorghum. The dotted line represents the pattern of water extraction two days before the first irrigation was applied 55 days after planting. The solid line shows the water uptake pattern four days after the irrigation. For experimental details see *Fereres [28]*.

soybeans that the proportion of P uptake derived from fertilizer placed near the surface (22.5 cm) was greatest under their best irrigated treatment. They also demonstrated that appropriate water and nitrogen management for maximum grain yield enhanced the uptake of P, K, Ca, Mg, Fe and Ca compared to deficit irrigation treatments.

In summary, irrigation management in terms of timing of application and depth of water plays a critical role in determining the availability of soil and fertilizer nutrients to crops. In addition, the method of irrigation could influence the fertilizer requirements and the techniques used for fertilizer application.

2.3 Influence of the irrigation method on nutrient movement, distribution and uptake

2.3.1 Surface irrigation

Shaping land for surface irrigation normally includes some degree of land leveling. Often the considerable earth moving needed results in uncovering the subsoil in some areas. Care must be taken not only in restoring the original fertility to those areas but to apply fertilizers in the amounts indicated by soil and plant tests. Yields are frequently depressed in the first years following irrigation development because of mineral nutrient limitations. It has been shown *(Reuss* and *Campbell [67]; Eck, Hauser* and *Ford [23]* and *Eck [22])* that it is usually possible to restore full productivity to recently leveled lands if the fertilization rates meet the requirements of the less fertile subsoils of the semi-arid zones. In one field experiment *(Eck, Hauser* and *Ford [23])* where 40-cm soil cuts were made, yields were reduced by about 20% below those of the control in spite of heavy fertilization. When restoring soil fertility to leveled lands, heavy applications of K and P fertilizers are usually recommended because these nutrients are normally mostly concentrated in the top-soil. In any case, fertilizer recommendations should be based on yield response in field experiments and on soil test levels conducted on fertilizer application treatments giving maximum yields.

Among surface irrigation techniques basic differences in relation to fertilization exist between furrow and flood irrigation, in particular with respect to nitrogen fertilization. Bands of nitrate fertilizer applied to beds and placed above the water level in the furrows, are not as easily leached out of the root zone as nitrate fertilizer applied under flood or sprinkler irrigation. This is shown in Figure 6 where the NO_3^- fertilizer content of the 0 to 30-cm layer is compared under equally fertilized furrow and sprinkler irrigation treatments *(Onken et al. [60])*. Almost three times more water had to be applied under furrow irrigation to leach the nitrate fertilizer out of the surface layer. *Kemper, Olsen* and *Hodgdon [43]* found that the spatial relationships between the water level in the furrow and the depth of the nitrate band were critical. If the water level was closer to the fertilizer band than 5 cm in a sandy soil or

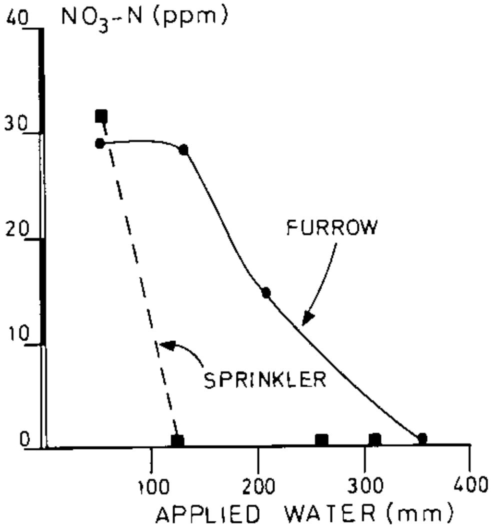

Fig. 6 Concentration of NO_3^- in the 0- to 30-cm layer as a function of the applied water under sprinkler and furrow irrigation. The data was read from complex three dimensional graphs presented by *Onken et al. [60]*.

10 cm in a clay soil, irrigation water displaced most of the fertilizer out of the bed which was then leached with the downward movement of water *(Kemper, Olsen* and *Hodgdon [43])*.

When the N fertilizer is not leached from the bed it is possible to have high efficiency of fertilizer use under furrow irrigation. *Miller et al. [53]* found that applications of N through a drip system did not increase tomato yield or the fertilizer use efficiency over a single application by furrow irrigation. However, the accumulation of nitrate in the surface soil under furrow irrigation is not always desirable. Fall rains may leach nitrate into the root zone of sugar beet at a time when some nitrate deficiency is beneficial for maximum sugar yield and quality *(Hills, Sailsbery* and *Ulrich [37])*.

Poor irrigation management under surface irrigation often results in the development of a perched water table which may affect nutrient uptake. Nitrogen deficiency due to enhanced denitrification rates is a commonly observed response *(e.g. Meek et al. [51])* while P, K, Zn, Ca and B deficiencies have been reported for corn *(Lal* and *Taylor [44])*. The latter authors detected an increase in the uptake of Al, Fe, Ma and Mo probably because the reducing conditions increased the solubility of the ions mentioned.

2.3.2 Sprinkler irrigation

Viets [82] reviewed early experiments in Utah where sprinkler irrigation was compared to furrow irrigation in relation to the fertilizer requirements for maximum yields. His conclusions indicate that no advantages were observed when the water supply regimes to the crop were comparable under both methods. Under sprinkler irrigation, it becomes very convenient to apply the fertilizer with the irrigation water. Mechanized sprinkler systems recently developed, are capable of applying fertilizers at short time intervals to match the crop nutrient demands. This technique results in very high potential efficiency of fertilizer application. The technique of split applications of nitrogen fertilizer applied with the irrigation water, has become very popular with the use of center pivots in light soils where leaching of nitrate represents the major loss of N-fertilizers *(Watts* and *Martin [83])*. Split applications of nitrogen fertilizers under sprinkler irrigation are not always beneficial. *Christensen* and *Killorn [18]* failed to detect either a positive wheat and barley yield response or an increase in fertilizer efficiency when N applications were split between seeding and flowering compared to one application at seeding on a fine-textured soil.

Nitrate leaching is not the only potential loss when nitrogen fertilizers are applied through the irrigation system. Ammonia volatilization losses may be substantial when fertilizer solutions containing ammonia are applied through the sprinkler systems *(Henderson, Bianchi* and *Doneen [36])*. The magnitude of the losses depends on the pH of the fertilizer solution with values of pH below 7.5 producing negligible losses. Ammonia volatilization may also be significant if it is applied dissolved in water by surface irrigation. In a detailed study conducted under furrow irrigation *Denmead, Freney* and *Simpson [20]* found that 7% of the N applied with the irrigation was volatilized per hour when the crop was about 1 m tall, while only 1% per hour was lost in a tall crop (2.5 m). This difference was due to the attenuation of wind in the tall crop which resulted in a much lower turbulent diffusion coefficient for ammonia. Volatilization losses resulted in very irregular distribution of N fertilizer along the furrow with an 84% decrease in the N content of the irrigation water for the short crop and a 59% reduction for the tall crop between the beginning and the end of the furrow 400 m long *(Denmead, Freney* and *Simpson [20])*.

2.3.3 *Drip irrigation*

The precise control of applied water by drip irrigation makes possible also uniform application of nutrients through the irrigation system. Such possibility, which also exists for mechanized sprinkler systems, becomes imperative under drip irrigation where the localized wetting patterns may present limitations to nutrient uptake. *Rolston et al. [69]* have summarized aspects of nutrient movement and application under drip irrigation. A notable characteristic of localized nutrient application by drip, is the substantial dispersion in the soil of less mobile nutrients such as ammonium or phosphate much greater than under other irrigation methods *(Rolston et al. [69])*. Phosphorus has been found to have considerable mobility when applied through a drip system because of saturation of the soil reaction sites near the point of application *(Rauschkolb et al. [65])*. An application of orthophosphate at a rate of 39 kg of P/ha through drip, moved the fertilizer about 30 cm into a clay loam soil. This is about 5 to 10 times more than it will move if uniformly distributed over the surface soil *(Rauschkolb et al. [65])*. Potassium is commonly applied through drip systems because clogging of the system has not been a problem with any of the common sources of potassium. *Uriu, Carlson* and *Henderson [77])* found that seasonal movement of K in the soil was as much as 70 cm vertically when applied at a rate of 4 kg of potassium sulphate per tree via drip irrigation.

Drip irrigation is often used on marginal soils which are very poor in nutrients and have very low water holding capacity. Such situations demand considerable attention to supplying adequate amounts of N, P, K and most micronutrients through the drip system and approach a solution culture situation. Nitrogen fertilization is particularly important as the soil solution must be above a critical level at all times while leaching losses must be kept to a minimum. In a drip irrigation experiment on sand dunes, *Bar Yosef [8]* obtained very high tomato yields by maintaining the N concentration in the soil solution around 110 ppm of N by daily fertilization.

Two recent reports explore aspects of fertilization under drip irrigation not previously studied. *Bacon* and *Davey [3, 4]* investigated the dynamics of phosphate and mineral nitrogen availability in stratified sandy clay loam soil under drip irrigation. In such soil, phosphate release in a circle of 30-cm radius from the outlet occurred during the 8 to 12 hour irrigation increasing the concentration of phosphate by about 63% above preirrigation levels. The higher phosphate concentration lasted 6 to 23 hours after the end of irrigation. Both native and fertilizer phosphate were subjected to cyclic releases becoming more available, thus the authors suggest that the requirements for P fertilization may be lowered under drip irrigation. Three-day irrigation cycles also demonstrated that nitrate decreased in the wetted zone during the irrigation – probably through denitrification – but ammonium increased simultaneously. However, the ammonium not removed by the crop was immobilized very rapidly after the irrigation. Consequently the time available for nitrification and subsequent leaching and denitrification was reduced.

Frequent applications of nitrogen through drip system must improve the efficiency of N fertilization. A recent report by *Feigin, Letey* and *Jarrell [27]* compared N application in the irrigation water to preplant application of both ammonium sulphate and a slow release fertilizer for celery under drip irrigation. While higher yields and N uptake resulted from continuous applications of N in the irrigation water as compared to preplant applications at similar rates, it is interesting to note that the crop recovered only 40 to 60% of the applied N in the various continuous application treatments *(Feigin, Letey* and *Jarrel [27])*. The soil where the experiment was conducted had essentially no available nitrogen (the unfertilized crop extracted 9 kg of N/ ha). Therefore, the remainder of the nitrogen must have been leached or remained in the root zone. This indicates that to obtain the maximum yields characteristic of some vegetable crops, relatively low efficiency of fertilizer N must be accepted even under careful and continuous N applications through drip irrigation.

Root systems of drip-irrigated crops are often considered to be confined to the zone wetted by the emitters but perennial plants in areas of appreciable rainfall develop roots throughout the soil of the normal root zone. Once the soil outside the irrigated zone is totally depleted of available water, the root system remains dormant in dry soil but ready to resume water and nutrient uptake in the event of a rainfall (see Figure 5). Natural stratification of soil nutrients may induce mineral deficiencies under localized irrigation. In some soils of the Sacramento Valley of California, most of the available K exists in the 0 to 5 cm surface layer and frequent irrigation by the sprinkler method results in greater K uptake and higher prune yields than under drip irrigation *(T.A. Aldrich,* personal communication). Application of K through the drip irrigation system or directly under the emitter corrected K deficiencies in such situations *(K. Uriu,* personal communication).

3. Irrigation effects on soil productivity

Many of the effects of irrigation on soil productivity listed on Table 1 not only affect crop production at the individual farm level, but may also have significant impacts on the water resources of the basin. Figure 7 presents in diagrammatic form the effects of irrigation on the quality of the return flows. Salinity, nitrate pollution, sediments and, to a lesser extent, phosphorus and pesticides are all detrimental to downstream water users and threaten irrigation agriculture in many areas of the world. Their effects on soil productivity are briefly reviewed below.

3.1 Salinity

All irrigation waters contain salts. Such salts become concentrated in the soil solution through the evapotranspiration process and accumulate in the crop root zone. This is the origin of the salinity problem in irrigated agriculture, a problem which affects over one third of all irrigated lands around the world *(Mass* and *Hoffman [47])*. Salinity is normally a long-term process as few irrigation waters contain enough salts to salinize a soil in a single irrigation season. Evidently, soluble salts in the soil solution may be leached out of the root zone and rainfall and excess irrigation water normally eliminate salt accumulation. However, poor irrigation manage-

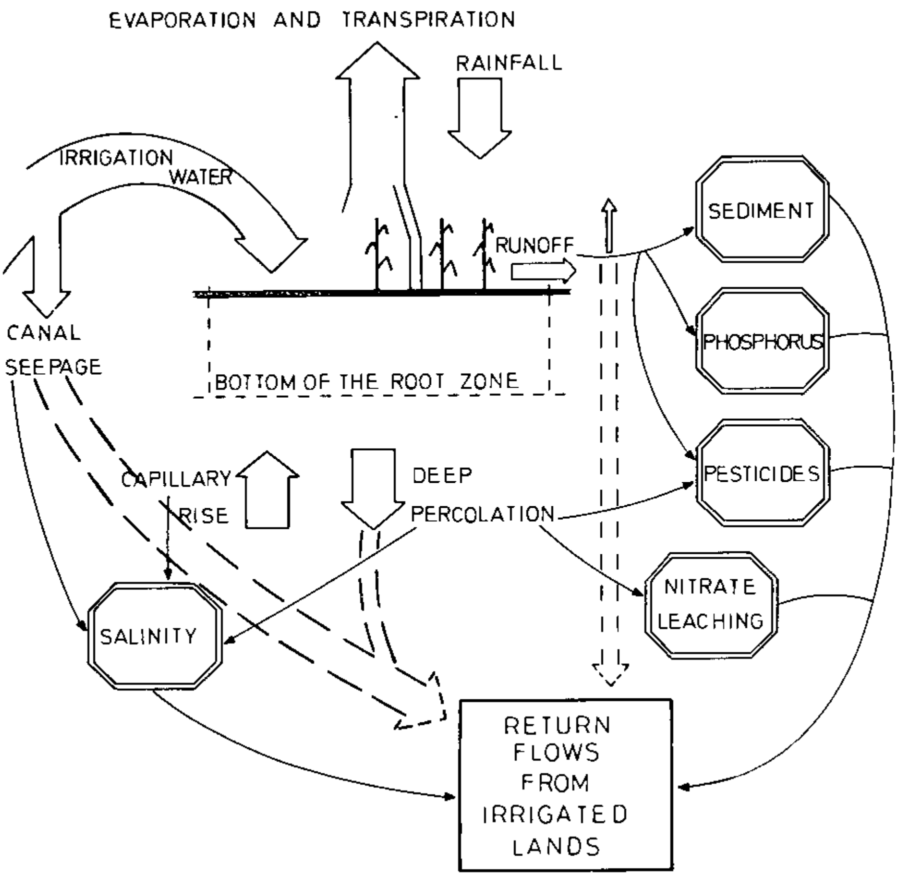

Fig. 7 The water balance of a field under irrigation showing the processes which contribute to the water quality degradation of irrigation return flows.

ment often creates a drainage problem which prevents salt leaching. Thus, most on-farm salinity problems on normal soils are the result of development of perched water tables which eventually become salinized.

Even when on-farm drainage is effective, it must be recognized that irrigation contributes salts to the return flows as shown in Figure 7. Such contributions affect the water quality downstream and increase the salinity hazard to other users. Numerous cases of water quality degradation in irrigation return flows have been identified; perhaps one of the better known is tbe case of the Colorado River as it affects both the United States of America and Mexico. In this case, even though the degradation of the water quality of irrigation return flows is considered a slow process, salt content of the Colorado River water delivered to Mexico nearly doubled from 1960 to 1962 following the development of a 30 000 ha irrigation project in Arizona *(Holburt [38]). Bower [11]* presented a 30-year study of the effects of irrigation on the

quality of drainage waters in the Rio Grande of the Western U.S. which shows that normally water quality degradation of irrigation return flows is a slow process.
Salinity in irrigated agriculture is a problem of such magnitude that new approaches are needed to deal with it. A reduction of the classical requirements for salt leaching as defined by the *U.S. Salinity Laboratory Staff [78]* has been proposed by *Bernstein* and *Francois [9]*. Their concept of minimum leaching states that salts may be accumulated near the bottom of the root zone without being harmful since water extraction of frequently irrigated crops takes place in the surface layers (see Figure 5).
Epstein [25] argued that breeding salt tolerant crop plants is a viable alternative to the usually expensive measures for salt control. His work with barley, wheat and tomatoes demonstrated substantial genetic variability with respect to salt tolerance and breeding programmes should yield appropriate cultivars to be used on salt-affected soils. It is doubtful that this will be a permanent solution for irrigated agriculture in the arid and semi-arid zones where the rate of salinization in the absence of drainage would be extremely fast.

3.2 Soil physical properties

The long-term use of irrigation water also affects the infiltration rate and the soil hydraulic conductivity *(Aragües,* this volume). Since drainage is essential for salt leaching, these effects tend to counteract water management measures for salinity control. The presence of sodium and the total salt concentration are important factors in determining the long term effects of the irrigation water on the water-transmission properties of soils *(Oster* and *Schover [61])*.
Sodium disperses clay particles and separates soil aggregates having more significant effects at the soil surface. This, together with the mechanical effects of irrigation on the surface, clogs most pores reducing greatly the infiltration rate of the soil. Low electrolyte concentration in the irrigation water also disperses clays and reduces soil permeability. In both cases, application of gypsum has beneficial effects.
Hadas and *Frenkel [35]* studied the infiltration rates of two fields that had been irrigated for two and eight years with sodic-saline waters. Infiltration rates of plots treated with gypsum were higher than in the controls for both fields. Long-term use of the water (8 years) did not decrease the intake rate of the soil below that observed after two years of irrigation. Actually, differences in surface crust structure resulted in a somewhat greater infiltration rate in the plot which was irrigated for eight years.
Soil structure may also be negatively affected by the mechanical effects of flood irrigation on some soils. *Mathieu [48]* described substantial changes in porosity and aggregate size in flood-irrigated areas of North-East Morocco due to the irrigation method used, the leaching of clay particles and to tillage practices. Unfortunately, the effects of such changes on the water-transmission properties of the soil were not reported.

3.3 Soil erosion

Water flowing over the land may cause erosion, thus surface irrigation is the method that presents most potential erosion problems. Erosion of irrigated land has been recognized as a detrimental effect of irrigation on soil productivity for many years. *Mech* and *Smith [50]* reviewed earlier investigations conducted by Israelsen and co-workers who recognized that excessive erosion was a serious threat to the perpetuation of irrigation agriculture.

Several factors influence the amount of erosion although the slope in the direction of irrigation and the stream size used are most critical. Among surface irrigation methods most of the erosion studies have been conducted under furrow irrigation. *Mech* and *Smith [50]* cite earlier work that estimated seasonal soil between 60 and 120 t/ha under the typical furrow irrigation systems of 1940 with an extreme case of a soil loss of 50 t/ha during a single irrigation on a 7% slope.

Carter and *Bondurant [17]* reviewed the technology available to reduce erosion and sediment loss from irrigated lands and concluded that sufficient technology is available to minimize the erosion hazard although it is not widely used. Furrow irrigation on slopes exceeding one percent generally results in some erosion which can be controlled on slopes up to two percent by adjusting the stream size *(Carter* and *Bondurant [17])*. The maximum non-erosive stream size in furrow irrigation may be calculated using the following empirical relationship:

$$q = \frac{0.63}{s}$$

where q is the discharge per furrow in l/s, and s is the percent slope.

Erosion also occurs under pressurized irrigation systems when the rate of water application exceeds the infiltration rate of the soil resulting in ponding and runoff. Significant erosion is not unusual in the case of center-pivots where the application rates near the end of the line approach 30 mm/h.

Associated to sediments, soil phosphorus and adsorbed pesticides are transported whenever erosion occurs. The addition of phosphorus improves the quality of irrigation return flows if they constitute part of the water supply of downstream users. *Balba [5]* estimated that building the Asswan dam in Egypt reduced the P content of the irrigation water derived from the Nile river by about 5000 t/year. There is little information about the presence of pesticides in irrigation return flows. *Wauchope [84]* reviewed the considerable body of literature on pesticide content of runoff from agricultural fields in the humid zones and concluded that for most pesticides total losses do not exceed 0.5% of the amounts applied.

3.4 Climate change

Climatic changes effected by large irrigation developments have been considered an advantage in the arid and semi-arid zones. Outside the large advective conditions encountered in the boundaries of irrigated areas *(Davenport* and *Hudson [19])* the studies conducted so far indicate only modest changes in both temperature and humidity. The study of *Fowler* and *Helvey [31]* indicated a minimal decrease in air temperature caused by irrigation development of the Columbia Basin in the U.S.A. *Fritschen* and *Nixon [32]* measured less than 2 °C decrease in air temperature due to irrigation development in the Joaquin Valley of California. *Burman et al. [14]* detected a reduction in August mean air temperature of 3 °C in the middle of a large irrigation area in the Western United States as compared to the neighbouring desert. However, even these small temperature effects combine with decreases in vapor pressure deficits and wind to reduce the evaporative power of the atmosphere as one moves from the edges to the centre of large irrigation developments such as the Gezira area in Sudan *(Davenport* and *Hudson [19])*. While the changes discussed above will have little or no effect on crop and soil productivity they need to be considered from the water management and environmental viewpoints.

4. Preserving the long-term productivity of irrigated agriculture

A number of irrigation effects on the soil environment have been discussed above. It has been shown that soil fertility management must be intimately tied to water management, nitrogen management in particular. N leaching losses depend directly on the magnitude of deep percolation *(Tanji [73])*. The relatively few cases where nitrate pollution has become a hazard to groundwater quality, are related to heavy fertilization rates and excessive application of irrigation water typical of vegetable crops. Deep percolation may be controlled by modifying the irrigation system to improve distribution uniformity and by avoiding irrigating too frequently or with an excessive irrigation depth.

For irrigation agriculture to be permanent, the salinity problem must be controlled. Here again, uniform water distribution and appropiate irrigation scheduling programmes can maintain harmful salts below the major portion of the crop root zone. Interim measures such as salt tolerant varieties may alleviate the problem in cases where detrimental effects of irrigation water on the soil structure delay infiltration and internal drainage. Eventually, excess salts must be leached out of the crop root zone and some degradation of the water quality of irrigation return flows is unavoidable to control the major threat to irrigation agriculture. However, water conservation programmes can minimize the deterioration of the quality of irrigation return flows *(e.g. Holburt [38])*.

Improving water control at the farm is also needed to reduce sediment loss and degradation of soil productivity by erosion. Runoff can be eliminated or re-used by installing tailwater recovery systems. Sediment retention basins can be used to recycle sediment and associated nutrients from irrigated farms.

It appears that improved water management and conservation practices are the key to preserve the long-term productivity of irrigation agriculture. In many developed countries technology already exists *(e.g. Fereres [29])* for very precise irrigation water management. Adapting such technology and developing new, appropriate water management practices are the only permanent solutions that developing countries have to counteract the detrimental effects of irrigation on soil productivity.

Acknowledgement

I wish to thank Ms. *C. Gimenez* for her valuable assistance and Mr. *F. Insúa* for drafting the figures in the text.

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Interactions Between Water and Phosphate and Potash Fertilizers

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Summary

The phosphorus and potassium requirements of citrus fruit are relatively high but soil conditions and restricted root colonisation may limit the availability and uptake of soil nutrients. Two methods of overcoming this difficulty have been investigated:
1) *With micro-irrigation:* application by fertigation or by placement in a furrow parallel to the dripping ramp where the soil is moist. This improves the mobilities of P and K and enriches the soil where the roots are concentrated resulting in an increase in uptake reflected in enhanced leaf nutrient levels. Improved fertilizer efficiency points to economy in rates of fertilizer applied.
2) *With macro-irrigation:* application of fertilizers by placement in the zone receiving water. This improves the mobility of P and especially of K (up to a depth of 60 cm). Effects on P mobility and uptake are less and levels of leaf P cannot be considered satisfactory.

Introduction

The efficiency of maintenance fertilizer dressings applied to satisfy the nutrient demands of a crop and to achieve optimum yield depends on several factors: nutrient status of the soil and its physico-chemical characteristics; the extent of root proliferation; soil aeration which affects root development; rate and composition of fertilizer dressing; satisfaction of the crop's demand for water and the method of irrigation. Where the first mentioned is limiting one can consider the application of supplementary fertilizer as a corrective treatment, but in practice, and for obvious reasons of economy, this is not always practicable.
No appreciable improvement in the following three factors is possible without regular applications of organic manures and improved soil management. This suggests that the most practicable course will be by:
- Calculation of the maintenance dressing in relation to possible limiting factors (P fixation capacity, CEC as concerns potassium).
- Applying fertilizer in such a way as to minimise these limiting factors, *i.e.* by placement.
- Devising a method of irrigation which will optimise water supply to the crop and which will bring nutrient ions near to sites of active root absorption.

In this paper we consider two possibilities: micro-irrigation with partial fertigation and macro-(furrow)irrigation with placement of fertilizer in the furrows.

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1. Micro-irrigation

An experiment to compare different irrigation systems, sprinkler (control), drip and micro-irrigation applied in relation to water deficit (Bas-Rhône system) was laid down in 1977/78. The annual fertilizer dressings are as follows:

N 80–250 kg/ha

P_2O_5 70– 80 kg/ha

K_2O 100–250 kg/ha

(In comparison, SASMA's routine fertilizer recommendations – also given in Table 1 – suggest the following dressing (in kg/ha): N: 150–200, P_2O_5: 50–90, K_2O: 150–220.)

The fertilizers to be applied each year were calculated by the balance method taking into account:

- Nutrient removals in fruit, prunings and weeds in the years when they were removed (a cause of considerable year-to-year variation).
- Soil and leaf analysis.
- Estimated losses by retrogression, fixation, leaching and volatilisation.

Table 1. Particulars of the experiments

	Date laid down	Planned duration (years)	Soil type		Annual fertilizer application (kg/ha)		
			Clay %	Carbonates %	N	P_2O_5	K_2O
Micro-irrigation	1978	10	25	5	80–250	70–80	100–250
Macro-irrigation	1980	10	25	10	250	140–350	170–400
Routine SASMA recommendations					150–200	50–90	150–220

+ FYM = 10–20 t/ha

Fertilizers were applied in two ways: by applying in a shallow furrow opened along the irrigation line in the case of farmyard manure and triple superphosphate or in the irrigation water via a diluter (potassium given as potassium nitrate). In the control (sprinkler) treatment, farmyard manure and fertilizers, were broadcast on the soil surface within the canopies of the trees. For 24 years before the experiment was laid down fertilizers had been broadcast on the surface and irrigation was by gravity.

Assuming that soil conditions were substantially uniform at the outset we have studied the trends under each treatment by soil and leaf analysis.

1.1 Nutrient distribution in the soil

Soil samples for analysis were taken in 1982, 4 years after laying down the experiment on various dates during the month of application and 2 months later, in April, at increasing depths beneath the points where water was applied. These investigations were concerned only with the migration of nutrients to depth. The results of these analyses are given in Tables 2–4 and in Figures 1 and 2. Further samples were taken from the drip irrigation treatment only 4 months after the first sampling, in June, on lines at right angles to the irrigation lines in order to study the lateral movement of nutrients as well as their vertical distribution. The results of these later analyses are given in Tables 5 and 6.

Table 2. Distribution of soil P & K to depth; 1:5 water extract, February 1982

Depth (cm)	P ppm			K ppm		
	Sprinkler	Drip	B. Rhône	Sprinkler	Drip	B. Rhône
20	4.80	95.80	79.00	107.00	612.60	755
40	1.60	28.10	50.30	64.00	374.50	855
60	0.60	8.80	19.60	49.80	202.30	688
80	0.30	2.30	5.50	36.30	96.00	270
100	0.30	1.80	1.70	34.50	55.60	143

Table 3. Distribution of soil P & K to depth; *Dyer & Morgan* methods, February 1982

Depth (cm)	P Dyer ppm			P Morgan ppm			K Morgan ppm		
	Sprinkler	Drip	B. Rhône	Sprinkler	Drip	B. Rhône	Sprinkler	Drip	B. Rhône
20	600.37	1690.94	2711.92	38.92	196.25	301.87	278.00	873.32	2160.00
40	398.07	507.94	745.56	11.73	64.55	126.27	202.60	623.66	1120.00
60	440.36	375.66	417.80	9.34	27.81	51.72	154.60	400.66	954.00
80	598.76	271.76	361.88	5.00	8.25	21.73	113.34	210.00	452.66
100	337.90	285.58	289.20	2.28	9.13	5.43	113.00	144.66	488.00

Table 4. Distribution of soil P & K to depth; 1:5 water extract, April 1982

Depth (cm)	P ppm			K ppm		
	Sprinkler	Drip	B. Rhône	Sprinkler	Drip	B. Rhône
20	7.20	36.00	96.00	160.00	230.00	650.00
40	2.90	23.50	59.50	150.00	350.00	315.00
60	2.00	9.50	36.00	97.50	225.00	250.00
80	0.60	15.60	42.50	40.50	210.00	235.00
100	0.70	9.30	27.00	37.00	123.00	250.00

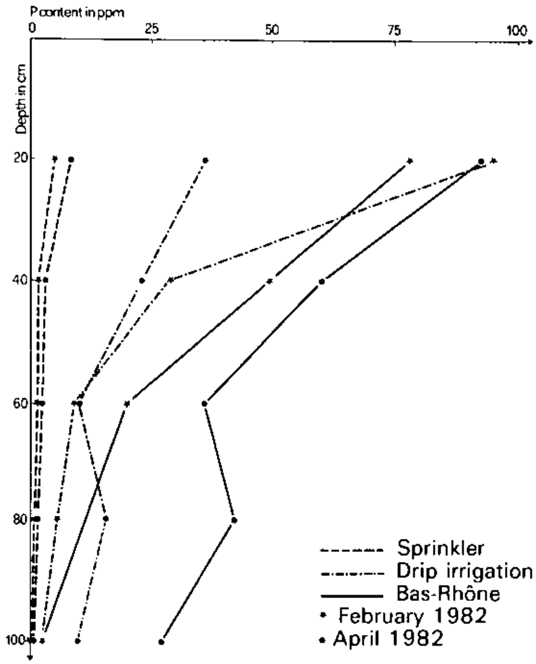

Fig. 1.
Vertical distribution
of P (extract ⅕)
in the soil.

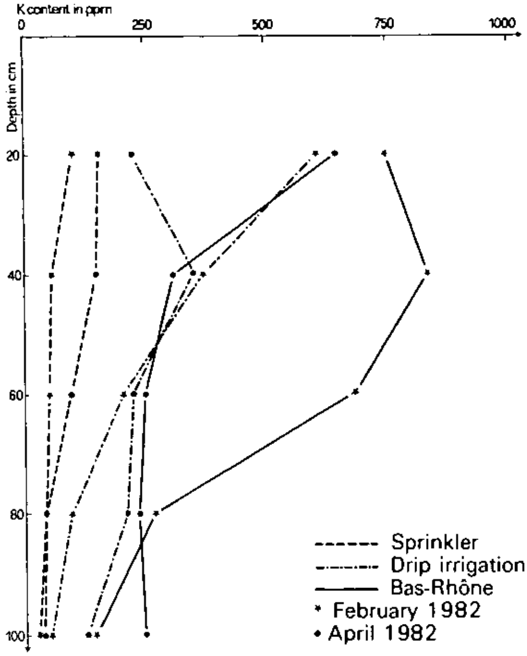

Fig. 2.
Vertical distribution of K (extract ⅕) in the soil.

Table 5. Vertical and lateral distribution of soil K (ppm); 1:5 water extract; drip irrigation, June 1982

	0	20	40	60	80	100	120	140	160	180	200	L cm
0	165.0											
20	132.0											
40	96.0	118.5										
60	109.5	99.0										
80	103.5	91.5	67.5	64.5	69.0	88.5	87.0	82.5	81.0	84.0	91.5	
100	87.0	64.5	69.0	70.5	81.0	88.5	90.0	84.0	85.5	91.5	100.5	
120	70.5	57.0	66.0	63.0	67.5	85.5	72.0	78.0	87.0	99.0	100.5	
140	81.0	109.5	100.5	112.5	130.5	124.5	160.0	111.0	117.0	155.0	170.0	
160	114.0	106.5	120.0	135.0	133.0	138.0	135.0	145.5	138.0	190.0	180.0	
V cm												

Table 6. Vertical and lateral distribution of soil P (ppm); 1:5 water extract; drip irrigation, June 1982

	0	20	40	60	80	100	120	140	160	180	200	V cm
0	0.67											
20	1.1											
40	8.1	2.0										
60	1.0	2.0										
80	0.8	3.1	1.4	0.8	0.8	0.7	0.8	1.0	1.4	0.5	0.7	
100	0.5	0.5	1.5	3.2	3.7	0.6	0.5	0.6	1.4	0.5	0.5	
120	0.5	trace	trace	trace	1.2	0.8	1.1	0.5	0.4	0.7	0.4	
140	0.6	0.6	0.6	0.7	0.4	0.9	0.9	0.3	0.4	0.3	0.5	
160	1.1	0.4	0.8	0.8	0.4	0.5	1.2	0.6	0.3	0.3	0.4	
V cm												

The earlier samples showed that under the control treatment nutrient levels were medium to medium high for the upper 20 cm of soil beneath which they fell off rapidly to low or very low. Very much higher levels have been obtained under drip irrigation and these extended to a depth of 60 cm; they attained levels which would be considered excessive especially in the surface layers. Below 60 cm P levels became low and K levels moderate but they remained higher than under sprinkler. Still higher levels were found under the Bas-Rhône irrigation treatment and K levels continued high to very high well below 60 cm. P contents were satisfactory at a depth of 80 cm but poor at deeper levels. Two months later (in April) the Bas-Rhône treatment retained its superiority over normal drip irrigation which, in turn, was much superior to sprinkler irrigation. It is regretted that there was insufficient sampling in June to compare the different irrigation treatments. By this date nutrient levels, particularly for phosphate had declined in the enriched zone of the soil. As concerns phosphorus, levels which would be considered satisfactory were found only in a pocket of radius no more than 20 cm around the point of application and to a depth of 40–50 cm. For K on the other hand, levels were high in all samples within a radius of 2 m and to a depth of over 1 m. Even so higher levels were found on the surface.

The results can be summarised as follows:
Four years after laying down the experiment soil P and K levels were increased on all treatments with P and K application.
During the period of fertilizer application there were large differences in P and K levels recorded under the different irrigation treatments
- Though broadcasting of PK fertilizer with sprinkler irrigation improved soil P and K status the improvement was less than that in the other treatments. The difference was particularly striking in water extracts.
- Placement of fertilizer with micro-irrigation was much more effective in improving soil P and K status. The best results were obtained by micro-irrigation in mini-furrows filled with water.
- In the case of P, analysis by *Dyer*'s method showed differences in P level only to a depth of 40 cm. On the other hand extraction with *Morgan*'s reagent or in water showed differences to a depth of 80 or even 100 cm, reflecting differences in P availability.
- The mobilities and availabilities of P and K beneath the points of application reflect the rate of application per unit surface (*i.e.* the degree of placement), the water status (rate and frequency of irrigation) and the method of irrigation.
- 4 months after application, the P and K levels declined from the very high levels recorded earlier due to P fixation and buffering of K by the CEC.
- The result of the latter was to equalise nutrient levels throughout the volume of soil moistened by the irrigation treatment, the eventual K levels being indicative of sufficiency while P levels were only low to moderate.

1.2 Effects on leaf nutrient content

Leaf analysis was carried out every year from 1978.
In 1978 at the start of the experiment P levels were moderate between 0.09 and 0.12% in dry matter. Deficiency levels of K (below 1% K in D.M.) were recorded on 3 plots out of 21. By 1979 on the plots with placed fertilizer P levels became satisfactory (0.12–0.18% P in D.M.) K levels below 1% were recorded on 3 plots, the rest showing 1.08 to 2.04% K in D.M. which could be considered very satisfactory.
Various difficulties were experienced in management of the experiment in the two following years (1980 and 1981) resulting in over-irrigation with the soil at moisture levels above field capacity which adversely affected root development with resulting decline in leaf P and K contents. This applied to the sprinkler (control) treatment as well as to micro-irrigation.

1.3 Conclusion

Placement of PK fertilizer in conjunction with micro-irrigation considerably improves the mobility of P and K in the soil. Improvement was particularly noticeable during and immediately after application of fertilizer. Fractionation of fertilizer dressing and thus quasi-continuous application in the irrigation water can maintain assimilable P and K more or less permanently at satisfactory levels.

2. Macro-irrigation

The experiment is sited in a citrus orchard in the Gharb on soil with 25–28% clay, 15–20% silt and 10% carbonates and compared 3 methods of fertilizer application: surface application in a narrow band, placement in a wide channel (30 cm) and placement by applicator at 25–30 cm depth.

The rates of fertilizers applied are shown below:

N 80–250 kg/ha
P_2O_5 70– 80 kg/ha
K_2O 100–250 kg/ha

(In comparison, SASMA's routine fertilizer recommendations – also given in Table 1 – suggest the following dressing (in kg/ha): N: 150–200, P_2O_5: 50–90, K_2O: 150–220.)

From April to mid-July irrigation was via a wide central channel coinciding with the trench in which fertilizer had been placed and the line along which fertilizer had been placed at depth and on the appropriate plots central to the area over which fertilizer had been broadcast. After this irrigation was via 3 channels overlapping the fertilizer application zone.

Soil analysis was carried out before the experiment was laid down and samples for analysis were taken annually at varying depths and distances from the point of fertilizer application. The discussion which follows is based on results of analysis 3 years after laying down (Table 7). At this stage only preliminary conclusions can be drawn. These can be summarised as follows.

Vertical movement of nutrients

Placement of P and K fertilizers or surface application in a narrow band in the zone where irrigation water is applied improves the phosphate status of the soil to a depth of 30 cm and the potassium status to a depth of 50 cm. This improvement is obtained by concentrating the fertilizer in a limited zone thus counteracting P fixation and increasing the K saturation of the CEC in a limited volume of soil which also benefits from irrigation. The improvement in reserve P is accompanied by an improvement in availahility thanks to the furrow irrigation which maintains soil moisture content and maintains aeration.

Lateral movement

There is enrichment in P and K at the depth of application to at least 40 cm from the line of application due to lateral movement in the irrigation water.

Root activity is increased preponderantly in the volume of soil affected by the irrigation channels and this volume of soil is partly coinciding with the zone enriched in P and K to the extent that P fixation is largely reduced and the K saturation of the CEC markedly improved. Nutrient availability is therefore much improved in this zone hence the nutrient needs of the tree are satisfied. Concentration of fertilizers in this manner largely overcomes the problems of fixation.

3. General conclusions

The soils under discussion are characterised by high P and K fixation capacities and conventional broadcast application of fertilizers to the whole surface of the orchard or even in broad bands cannot be recommended. The problem can be overcome by concentrating (by placement) the fertilizer in the zone of the soil which is affected by irrigation and where root activity is at its maximum. The principle applies both for

Table 7. Furrow irrigation: vertical and lateral distribution of soil P and K for 3 methods of fertilizer application (contents in ppm)

Depth (cm)	Analyt. method	Distance from line of fertilizer application: 0 to 40 cm			40 to 70 cm			70 to 100 cm			100 to 130 cm		
		Broad-cast	Appli-cation in furrow	Place-ment by appli-cator	Broad-cast	Appli-cation in furrow	Place-ment by appli-cator	Broad-cast	Appli-cation in furrow	Place-ment by appli-cator	Broad-cast	Appli-cation in furrow	Place-ment by appli-cator
10	P Dyer	1029	1940	876	445	1286	907	279	658	920	222	828	684
	P Morg.	32.6	54.8	31.9	6.2	39.1	31.9	2.2	13	31.9	1.2	22.8	35.2
	K Morg.	348	450	426	318	390	372	378	330	344	366	330	420
20	P Dyer	1844	2385	1068	318	318	231	139	157	222	131	170	222
	P Morg.	73.7	45.6	86	3.2	4.9	1.6	0.26	0.52	1.95	0.13	0.39	1.95
	K Morg.	414	740	1020	330	552	546	366	354	432	318	300	564
30	P Dyer	584	432	1251	170	153	266	131	140	166	126	140	161
	P Morg.	20.9	5.5	31.3	1.37	0.52	6.9	0.33	0.33	0.46	0.13	0.33	0.52
	K Morg.	620	760	1480	426	528	600	360	306	492	240	246	438
50	P Dyer	113	126	170	109	117	140	113	118	140	113	113	140
	P Morg.	0.13	0.26	0.65	0.26	0.06	0.65	0.13	0.06	0.46	0.13	0.13	0.46
	K Morg.	740	546	940	360	396	740	318	158	396	50	62	396
60	P Dyer	118	144	126									
	P Morg.	0.06	0.06	0.13									
	K Morg.	422	158	258									

gravity irrigation through channels and for micro-irrigation. Under micro-irrigation fertilizer application should be by repeated small doses or by metering through the irrigation system in order to maintain soil nutrient supply at a satisfactory level in the long term.

The Quality and Availability of Water Used in Irrigation Systems

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Summary

Irrigation is undoubtedly one of the most important agricultural practices developed by man. The extension and intensification of irrigated agriculture and/or the lack of proper water management have frequently led to the degradation of water quality, which is now decreasing the agricultural productivity of many areas of the world.
The need for sound irrigation water quality criteria and evaluations, as well as the implementation of alternative actions for the control or alleviation of water quality deterioration are therefore basic goals of today's agriculture.
This paper summarizes the more general water quality classifications, discusses their salinity, sodicity, specific ion and fertility-salinity criteria and stresses the need for an in-depth conceptual knowledge of their advantages and limitations.

1. Introduction

It is almost impossible to set general criteria for irrigation water quality; the suitability of existing water classification schemes can be accepted only as indicating potential use, due to the number of variables affecting them (crop, soil, climate, irrigation management problems, etc.).
Despite these limitations, there are three parameters generally accepted as basic criteria for the assessment of the quality of an irrigation water: total salt concentration ('salinity hazard'), sodium concentration or sodium adsorption ratio ('sodicity hazard') and specific ion concentration ('specific ion hazard'). Also, the interaction between soil fertility and salinity ('fertility-salinity hazard') is another important consideration for maximizing crop production in arid and semi-arid areas.

2. Salinity hazard

The main effect of salinity on plant growth is osmotic; that is, wben the osmotic potential (OP) of the soil solution decreases without a corresponding decrease in the root water potential, the gradient for water flow from soil to root is reduced. If the

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root resistance remains unchanged, the result is a restricted water uptake by roots and, therefore, a reduction in crop growth.
However, in many cases the reduced soil osmotic potential induces a similar reduction in the leaf osmotic potential ('osmotic adjustment'; *Bernstein [4]*), keeping the gradient unchanged up to certain levels.
Various salinity criteria have been established for estimating soil solution concentration (actual osmotic potential) from that of irrigation water. Thus, *Doneen [14]* considered 'effective salinity' as being made up by only chloride salts, thus assuming a quantitative precipitation of the less soluble salts (carbonates and sulphates) in the soil profile, whereas *Eaton [16]* considered only the precipitation of carbonates and half of the sulphates, defining 'potential salinity' as being made up hy the rest of the non-precipitated salts. Finally, others *(U.S.S.L. [28])* assumed that none of the salts precipitate, and used the electrical conductivity (EC) of the irrigation water as a criterion for salinity.
The use of EC as a criterion for salinity hazard seems to be reasonable because, despite the fact that single-salt solutions produce different osmotic pressures *(Bernstein [5])*, the osmotic potential and electrical conductivity of 'normal' mixed-salt solutions are well related *(U.S.S.L. [28])*.

$$OP\ (\mathrm{bar}) = -0.36\ EC\ (\mathrm{mmhos/cm})$$

It should be emphasized, however, that this criterion assumes that all salts in irrigation water remain dissolved in the soil, which may not be true for some waters and/or some management practices (low leaching fractions, LF). On the other hand, EC is an indirect measure of charged electrolytes *only* and therefore may underestimate the osmotic potential of waters forming neutral ion pairs. In that sense, *Rhoades [24]* discusses in detail some important factors that must be considered in assessing the suitability of waters for irrigation.
Despite these minor limitations, EC is the actual standard parameter for most water salinity classifications.
The most often cited and used general classification is that proposed by the *U.S. Salinity Laboratory* in 1954 *(U.S.S.L. [28])*, which divides waters into four categories, from low ($0.1 < EC$ [mmhos/cm at 25 °C] < 0.25) to very high ($EC > 2.25$) salinities.
The *U.C. Committee of Consultants, Cooperative Extension (U.C.C.C. [27])* considered those levels to be conservative, and proposed a new classification in 1974 with a range between low ($EC < 0.75$) and very high ($EC > 3.0$) salinities. Based on these studies, *Ayers [2]* specifies the potential salinity hazards of using saline waters dividing the waters into three categories (Table 1). This classification has been published by *FAO*, 'Irrigation and Drainage Paper No. 29' *(Ayers* and *Westcot [3])*, and can be considered as the most up-to-date water quality criterion for irrigation.
From the point of view of crops, it seems obvious that these classifications give only potential uses, since there is approximately a tenfold range in salt tolerance of crops. Thus, *Maas* and *Hoffman [19]* concluded from an extensive review of salt tolerance data that relative crop yield (Y) is affected by salinity according to the equation

$$Y = 100 - B(EC_e - A)$$

Table 1. Guidelines for interpretation of water quality for irrigation

Problem and related constituent	Water quality guidelines		
	No problem	Increasing problems	Severe problems
Salinity[a]			
EC of irrigation water (mmhos/cm)	<0.75	0.75–3.0	>3.0
Permeability			
EC of irrigation water (mmhos/cm)	>0.5	<0.5	<0.2
adj. SAR[b]	<6.0	6.0–9.0	>9.0
Specific ion toxicity[c]			
ROOT absorption			
Sodium (evaluated by adj. SAR)	<3	3.0–9.0	>9.0
Chloride (me/l)	<4	4.0–10	>10
(mg/l or ppm)	<142	142–355	>355
Boron (mg/l or ppm)	<0.5	0.5–2.0	2.0–10.0
FOLIAR absorption[d] (sprinklers)			
Sodium (me/l)	<3.0	>3.0	–
(mg/l or ppm)	<69	>69	–
Chloride (me/l)	<3.0	>3.0	–
(mg/l or ppm)	<106	>106	–
Miscellaneous[e]			
NH_4-N and NO_3-N for sensitive crops			
(mg/l or ppm)	<5	5–30	>30
HCO_3 (only with overhead sprinklers)			
(me/l)	<1.5	1.5–8.5	>8.5
(mg/l)	<90	90–520	>520
pH		normal range =6.5–8.4	–

[a] Assumes water for crop plus needed water for leaching requirement (LR) will be applied. Crops vary in tolerance to salinity.
[b] *adj. SAR (Adjusted Sodium Adsorption Ratio)* is calculated from a modified equation developed by U.S. Salinity Laboratory to include added effects of precipitation or dissolution of calcium in soils and related to $CO_3 + HCO_3$ concentrations.
[c] Most tree crops and woody ornamentals are sensitive to sodium and chloride (use values shown). Most annual crops are not sensitive.
[d] Leaf areas wet by sprinklers (rotating heads) may shown leaf burn due to sodium or chloride absorption under low-humidity high-evaporation conditions. (Evaporation increases ion concentration in water films on leaves between rotations of sprinkler heads).
[e] Excess N may affect production or quality of certain crops, *e.g.*, sugar beet, citrus, avocados, apricot, and grapes. HCO_3 with overhead sprinkler irrigation may cause a white carbonate deposit to form on fruit and leaves.

where A = the threshold salinity (mmhos/cm), B = percent yield decrease per unit salinity increase, and EC_e = electrical conductivity of saturation extract.
Based on that information, *Ayers* and *Westcot [3]* published a crop salt tolerance table in which the conversion from soil salinity (EC_e) to comparable irrigation water salinity (EC_{iw}) assumes a leaching fraction in the range of 15–20% (that is, EC_{iw}

$3 = EC_e$). Other important assumptions are that yields are closely related to the average salinity of the root zone, and that water uptake is normally much higher from the upper root zone (40–30–20–10% extraction pattern).

Finally, *Bresler et al. [10]* present extended crop salt tolerance tables giving threshold salinity and productivity decrease as a percentage of normal yield for each increase in EC_e. Those tables, with 125 crops listed, can be useful in selecting crops or determining expected yield losses for a given crop under anticipated salinity conditions.

Another important problem is that low salinity waters tend to decrease the soil hydraulic conductivity because of the dispersion of finer soil particles, filling of pore spaces and/or sealing of the soil surface.

These aspects have been neglected in most water quality classifications, although the problem has long been recognized *(Quirk* and *Schofield [22])*.

Ayers [2] points out in his classification (Table 1) that waters of $EC < 0.2$ mmhos/cm often result in soil permeability problems, and that the lower the EC, the greater is the potential problem.

Although a quantification of this potential hazard needs still some clarification, different authors *(Oster* and *Schroer [21], Shainberg et al. [25], Agassi et al. [1])* have pointed out some basic aspects of the problem in recent years.

3. Sodicity hazard

The negative effects of an excessive amount of soil exchangeable sodium (ESP) on soil permeability and soil structure have long been recognized *(U.S.S.L. [28])*; in evaluating the suitability of waters for irrigation an important consideration is therefore the extent to which ESP will increase in the soil by adsorption of sodium from these waters.

Any suitable evaluation of the potential sodicity hazard of an irrigation water must then relate some property of the irrigation water to the ESP that will result in the soil from use of that water.

Although some early attempts *(Wilcox [31])* used the soluble sodium percentage as a parameter for sodium hazard, the sodium adsorption ratio of a water ($SAR_{iw} = Na/[(Ca + Mg)/2]^{1/2}$, where all concentrations are expressed in meq/l) has been the most widely used criterion for sodicity hazard.

However, it is important to understand that this SAR_{iw} may be used as a measure of sodicity hazard only if it can be related to the resultant SAR of the equilibrated soil water (SAR_{sw}). The quantification of this relation and the demonstration of its general validity have been major limitations in the assessment of the sodicity hazard of irrigation waters in the past *(Rhoades [24])*.

The *U.S. Salinity Laboratory [28]* published a widely used sodium classification diagram in which the waters are divided into four SAR categories in such a way that, for a given SAR, the sodium hazard increases as salinity increases. From a permeability point of view, this is just the opposite of what is actually known (high salinities [partially] compensate for the negative effects of sodicity on permeability) and therefore this classification cannot be recommended.

Due to the fact that some irrigation waters dissolve calcium from calcareous (and/or

gypsiferous) soils (decreasing therefore the sodium hazard) whereas others tend to precipitate $CaCO_3$ (and/or gypsum) increasing the sodium hazard, several authors have used different parameters trying to predict this potential reaction.
Thus, *Eaton [15]* developed the 'residual sodium carbonate' and *Doneen [14]* the 'permeability index' parameters, without too much success.
A reasonable compromise for predicting $CaCO_3$ precipitation is the use of the so-called 'Langelier saturation index', first applied to soils by *Bower et al. [8]*. The 'adjusted SAR' (SAR_{adj}) is then derived from the expression *(Rhoades [24])*

$$SAR_{adj} = SAR_{iw}[1 + (8.4 - pH_c)]$$

where pH_c is the calculated pH that would exist if the water in question was equilibrated with solid-phase $CaCO_3$ (see *Ayers* and *Westcot [3]* for examples of calculation).
According to *Rhoades [24]*, the above equation can be used to predict surface-soil ESP, whereas a modified equation including a mineral weathering correction factor and the leaching fraction is used to estimate the ESP that will develop deeper in the soil profile.
Based on these criteria, *Ayers [2]* has used the SAR_{adj} concept on his classification of sodicity hazard, and has considered that waters with $SAR_{adj} < 6$ do not have permeability problems, whereas waters with $SAR_{adj} > 9$ show severe permeability problems (Table 1).
More recently, the adjusted SAR concept has been questioned by some authors: *Bingham et al. [7]* found considerably better agreement with experimental soil ESP values when using SAR_{adj} values based on free-ion concentrations; *Miyamoto [20]* argues that the SAR_{adj} is only valid if HCO_3 and Ca irrigation water concentrations are similar, and concludes that the HCO_3 effect on sodicity is much lower than was thought earlier. He calculates the amount of $CaCO_3$ precipitating in the soil from the activity equations governing the chemistry of the $CaCO_3 - CO_2 - H_2O$ system; in his equation, *Suárez [26]* takes the leaching fraction, the CO_2 partial pressure of the soil atmosphere and the $CaCO_3$ over- or undersaturated conditions of the irrigation water into account, and calculates the SAR for surface soil and for drainage waters.
Although the latter evaluations seem to give better results than the SAR_{adj}, they require (small) computer facilities and some knowledge of chemistry because of the relative complexity of their calculations.
Finally, *Cass* and *Sumner [12]* have recently presented an empirical sodium stability model for quantitative evaluation of the relationship between irrigation water quality, soil structural stability and crop response to salinity. Although conceptually promising, its verification is still lacking and its practical application is questionable due to its relative complexity.
From all these considerations it may be concluded that the sodicity criteria are still not well clarified, and that additional research is needed to elucidate the key parameters affecting the physical characteristics of the soil and the corresponding development of a simple, applicable, water quality classification scheme.
It could be said that at present the empirical approach is probably the most reasonable way to evaluate the sodicity hazard of a given water on the structural deterioration of a given soil.

4. Specific ion hazard

Specific ion effects are twofold: an excess of specific elements (toxicity effect) and an induced deficiency of nutrient elements. In general, the effects of specific ions are numerous and not well understood; also, plant species and even varieties within a given species may differ in tolerance to specific ions.

In Table 1 *(Ayers [2])* the well known sodium and chloride toxicities from root absorption and foliar absorption, and the boron toxicity from root absorption are presented.

Although not all crops are equally sensitive to these toxicities, most tree crops and other woody perennial type plants show reduced yields and crop failure.

Also, in Table 1 some miscellaneous problems, such as excess N, and HCO_3 with overhead sprinklers, are presented. In this respect, it should be noted that as overhead, rotating sprinklers for irrigation expand to larger areas and to more diversified crops, foliar salt absorption and subsequent crop damage are becoming an increasingly important problem.

In relation to the induced deficiency, *Bernstein et al. [6]* have demonstrated that increases in Na and Ca in the solution decrease the concentration of K and Mg in the leaves, and *Khalil et al. [18]* and *Devitt et al. [13]* have suggested that additional K might be required in saline soils to counteract the competitive effect of Na and Ca.

It should be noted that the literature on specific ion effects is rather large and its review outside the scope of this work. Although *Ayers* and *Westcot [3]* summarize some of these effects in easy-to-read tables, readers interested in more specific aspects of this subject should refer to the extensive work of *L. Bernstein, E.V. Maas, L.E. Francois, W.C. Cooper, F.T. Bingham, A. Poljakoff-Mayber,* and others.

5. Fertility-salinity hazard

Although the literature on the effect of fertilizing crops under saline conditions appears to be contradictory, it suggests that, in most cases, moderate levels of soil salinity can be compensated for by increased fertilization *(Jurinak* and *Wagenet [17])*.

On the other hand, if fertilization is excessively high or the fertilizer is applied hy a method that localizes it in high concentrations in a small volume of soil, severe osmotic effects may result in injury to plants.

This injury may be quantified by the salt index parameter *(Rader et al. [23])*, defined as 'the ratio of the increase in osmotic potential produced by a fertilizer to that produced by the same weight of sodium nitrate, multiplied by 100'.

In general, chloride salts have very high salt indices (because of their high solubilities), phosphorus fertilizers have low salt indices (low solubilities) and nitrogen fertilizers vary in their effect depending on the combined factors of chemical solubilities and soil pH effects.

It should also be noted that this osmotic effect is higher in sandy than in clayey soils because of its usual lower soil water content *(Jurinak* and *Wagenet [17])*.

From a nitrogen fertilizer viewpoint, it has been shown *(Westerman* and *Tucker*

Table 2. Principal physical, chemical, and biological contributors to clogging of trickle systems

A. Physical: suspended solids	B. Chemical: precipitation	C. Biological: bacteria and algae
1. Organic a) Aquatic plants (phytoplankton/algae) b) Aquatic animals (zooplankton) c) Bacteria 2. Inorganic a) Sand b) Silt c) Clay	1. Calcium or magnesium carbonate 2. Calcium sulphate 3. Heavy metal hydroxides, oxides, carbonates, silicates, and sulphides 4. Fertilizers a) Phosphate b) Aqueous ammonia c) Iron, zinc, copper, manganese	1. Filaments 2. Slimes 3. Microbial depositions a) Iron b) Sulfur c) Manganese

Table 3. System for classifying irrigation waters used in trickle systems

Arbitrary rating	Physical	Chemical* (max. mg/l)		Biological
	Suspended solids (max. mg/l)	Dissolved** solids	Iron and/or manganese	Bacteria*** populations (max. no./ml)
0	< 10	< 100	<0.1	< 100
1	20	200	0.2	1 000
2	30	300	0.3	2 000
3	40	400	0.4	3 000
4	50	500	0.5	4 000
5	60	600	0.6	5 000
6	80	800	0.7	10 000
7	100	1000	0.8	20 000
8	120	1200	0.9	30 000
9	140	1400	1.0	40 000
10	>160	>1600	>1.1	>50 000

* Tentative chemical classification is based on the highest rating for either dissolved solids, soluble iron, or manganese.
** If water pH is 7.5 or greater, rating is increased by 2.
*** If water is known to contain an abundant reproductive snail population, rating is increased by 4. Bacteria populations do reflect increased algae and microbial nutrients.

[30]) that fertilizers requiring nitrification to become plant available (urea, ammonium salts . . .) are negatively affected by soil salinity, as is the nitrogen fixation or conversion of atmospheric nitrogen to organic nitrogen *(Vincent [29])*.
The interaction effects of fertilizer and salinity on crop parameters are rather complex and somewhat contradictory, and cannot be extrapolated beyond the conditions of the parent study from which they were developed. A discussion of these

aspects is outside the scope of this paper, but readers interested in this subject are referred to the up-to-date work of *Jurinak* and *Wagenet [17]*.
Finally, in relation to the fertility-salinity hazard, a particular problem in trickle/drip irrigation systems is emitter clogging. To avoid it, chemicals (fertilizers) applied through drip systems must be highly soluble and must not react with each other to form a precipitate.
The main problem with nitrogen fertilizers is microbial growth and subsequent clogging of emitters. This microbial growth is promoted if nitrogen solution remains in the irrigation lines between irrigations, so flushing of the lines after fertilizer application is recommended.
With phosphorus fertilizers, their reaction with calcium to form an insoluble precipitate can clog emitters. Acidification of the stock solution prevents this precipitation without causing any adverse effects in the soil.
On the other hand, any of the common sources of potassium may be used in drip systems without clogging problems, although for chloride sensitive crops the KCl form should be avoided *(Branson et al. [9])*.
From a more general point of view, Table 2 presents the main contributors to clogging of trickle systems, and Table 3 shows a water quality classification system used by *Bucks et al. [11]* to evaluate surface irrigation water for trickle systems.
The numerical rating selected in this classification for the physical, chemical and biological composition is arbitrary but it gives a basis for comparing different types of water. Each of the three factors is given a rating from zero to ten. A combined value of '0–0–0' or, alternatively, the sum of the three factors being ten or less means a good quality water. If the sum amounts to ten to twenty, it indicates some problems and twenty to thirty or a combined value of '10–10–10' means waters of poor quality (severe hazard).
Although – as pointed out by the authors – this classification is tentative, it shows the main water quality parameters affecting trickle systems and can, with further research and validation, be a practical tool for predicting problems associated to its use.

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The Response of Rice Varieties to Applied Fertilizer in the Semi-Arid Zone in West Africa with Special Reference to Richard Toll (Senegal) and Mopti (Mali)

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Summary

The response of rice varieties to various N-levels is discussed, applied in addition to a uniform rate of 60 kg/ha, each of P_2O_5 and K_2O. Split N-application favoured grain yield in both vertisols and hydromorphic soils and substantial profit was achieved particularly with variety Jaya with N-application in the form of urea. On hydromorphic soil, later flooding during the reproductive stage of the rice plant was conducive to greater mineralization and nitrogen availability, whereas on vertisol flooding during the vegetative stage was the best stimulant for mineralization. Addition of compost decreased NH_4 and N-concentration in the soil during the early growth stages, but a gradual increase in concentration occurred during the middle and later growth stages in vertisols under continuous flooding. The water requirement and nitrogen efficiency index for dry season rice in vertisol and hydromorphic soils have been calculated. On vertisols, continuous flooding generated higher income which rose with increasing dose of N. Water requirement on vertisols is very high. In hydromorphic soils, substantial increase in income could be realized with higher doses of N and alternative field capacity at the vegetative stage followed by flooding at the reproductive stage. The high fixing power of these soils was responsible for the non response to P-application.

1. Introduction

In this paper, we present the results of fertilizer trials conducted at the *WARDA Special Research Project* at Richard Toll/Fanaye, Senegal (irrigated rice) and Mopti, Mali (deep water/floating rice). In these experiments, nitrogen was tested at various levels in combination with phosphorus and potassium; P + K were applied at a uniform rate of 60 kg/ha as triple superphosphate and muriate of potash. The above two stations fall in the semi-arid zone of the *WARDA* region.

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2. Ecological description

In the following the authors give a short description of the rice ecologies of the two research stations.

2.1 Rainfall and cropping season

Figure 1 shows the rainfall distribution in the *WARDA* region. The annual rainfall at Richard Toll/Senegal (irrigated rice) and Mopti, Mali (deep flooded/floating rice) varies between 300 and 600 mm respectively (Figure 2). The rainy season starts any time between May and June, reaches a peak between July and August and thereafter shows a steady decline. With irrigation, three crops of rice are taken within a year at Richard Toll as follows:

a) wet season crop: July–October;
b) cold season crop: November–February;
c) hot season crop: February–June.

On the other hand, at Mopti, only one crop of rice is grown under deep water/floating conditions between July and December. At Mopti, land is prepared and seed sown directly at the start of the wet season. Before the arrival of flood water from the Niger River in September, rice is grown mainly under rainfed conditions.

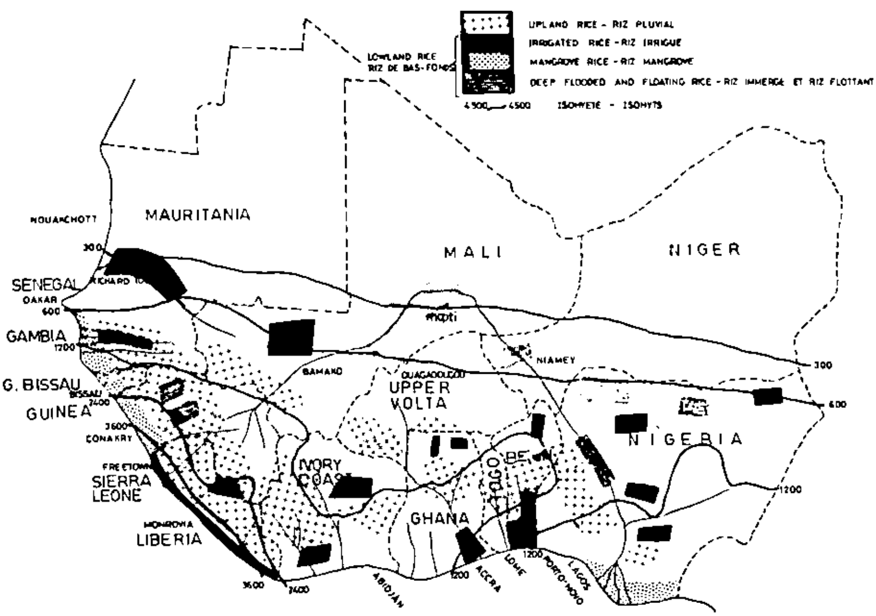

Fig. 1. Categories of rice cultivation and rainfall distribution (preliminary)

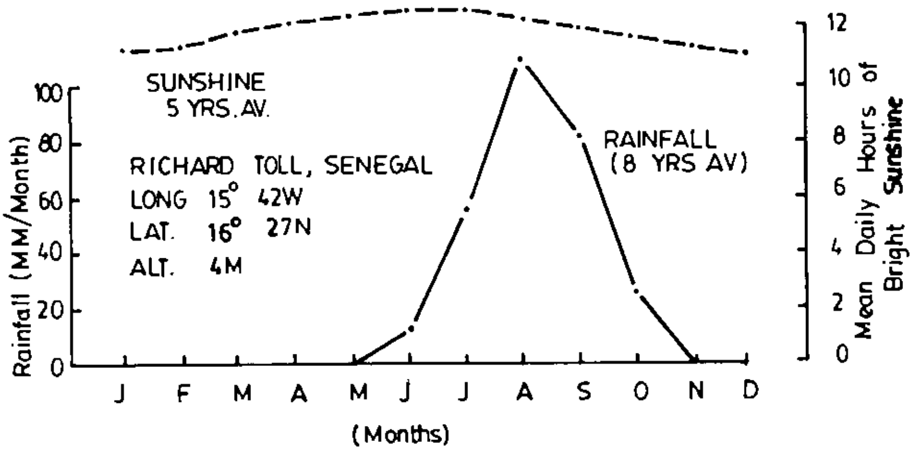

Fig.2. Comparison of climatic data for Richard Toll, Senegal

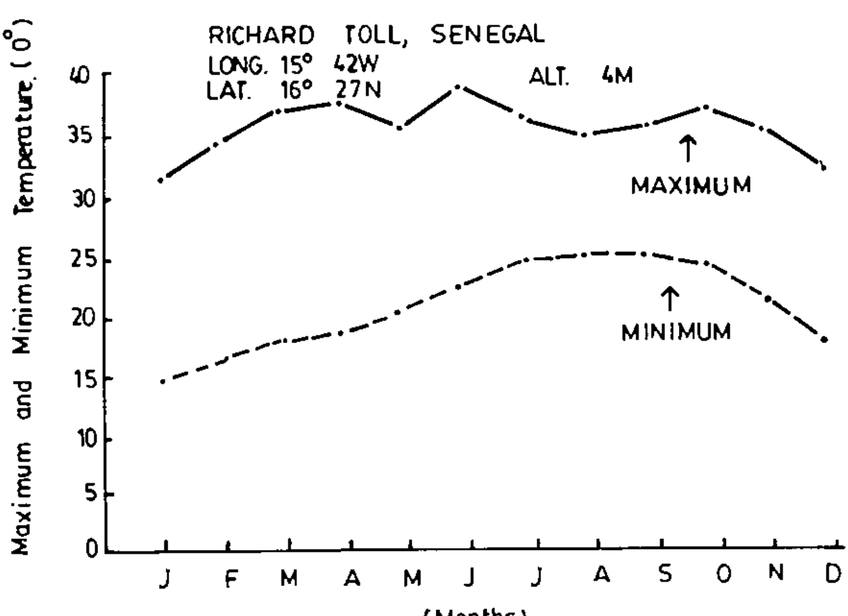

Fig.3. Temperature data for Richard Toll, Senegal

The peak of flood water level (1200 to 1600 mm) is reached in October followed by a sharp drop in flood water level under deep water and floating rice cultivation. The uncertainties in rainfall and flood waters as related to planting time, damage due to heavy floods, and loss of grain during harvest, result in low yield of the deep water/floating rice.

2.2 Temperature and sunshine hours

Richard Toll (lat. 16°27′ N) is situated about 2° N of Mopti (Lat. 14°35′ N approx.), and the former is nearer to the Sahara Desert than the latter. Sunshine hours and temperature data at Richard Toll are presented in Figures 2 and 3.

2.3 Soil type

Richard Toll/Fanaye: The station is located in the Senegal River delta or valley. There are two soil types as follows:
a) *Vertisols:* These cover an area of 2184 km^2 or about 25% of the total area of the Senegal River delta. They are considered under the American soil classification (7th approximation) as *Pallenstolic torrets,* fine clayed and are known in the FAO terminology as *Chromic vertisols.* They are known locally as 'Hollaldés'.
b) *Less developed hydromorphic soils:* These occupy 23% of the total area or 2071 km^2 and are mostly found in the middle valley, which is seldom flooded. They are known as *Ustiic thorriorthents* in the American soil terminology and in the FAO terminology as *Eutric fluvisols.* They are known locally as 'Fondé ouaka'.
Mopti: The soil type is silty clay. A large quantity of silt is deposited at the Mopti area due to flooding of the Niger River.

2.4 Results and discussion

Several fertilizer trials were conducted at Richard Toll/Fanaye (Senegal) and Mopti (Mali) under irrigated and deep water conditions, respectively. Important findings of trials are presented here separately for Richard Toll/Fanaye.

2.5 Richard Toll/Fanaye (Senegal)

2.5.1 Effect of split doses of nitrogen on grain yield in vertisol and hydromorphic soils during the wet and hot dry seasons

The objective of tbese trials was to determine the most suitable split applications and the best time for the application of nitrogenous fertilizer on the two main soil types where rice is grown during the wet season. The results of the three seasons are presented in Appendix 1.
The results show that the split doses of nitrogen caused significant yield increase on vertisol and hydromorphic soils especially in the hot dry season. The best grain

yields on vertisol in hot dry season were noted as a result of split doses of nitrogen at the following time of application:

a) 50% 1 day before transplanting (DBT)+ 50% 20 days after transplanting (DAT) (8.22 t/ha);
b) 50% 20 DAT+50% at panicle initiation (8.19 t/ha);
c) 50% 1 DBT+25% DAT+25% at panicle initiation (8.16 t/ha).

However, during the wet season on vertisol, there was no significant difference in grain yield among the various split doses and times of nitrogen application (Appendix 1).

On the other hand, on hydromorphic soils, grain yields were higher than those on vertisols during the hot dry season (Appendix 1). The best grain yields on hydromorphic soil during the hot dry season were noted in the following treatments:

i)50% 1 DBT+25% 20 DAT+25% at panicle initiation (9.4 t/ha);
ii)50% 1 DBT+50% 20 DAT (9.20 t/ha);
iii)50% 20 DAT+50% at panicle initiation (9.10 t/ha).

2.5.1.1 Conclusion

For higher grain yield on both vertisol and hydromorphic soils during the hot dry season, split doses of nitrogen are needed as indicated above.

2.5.2 Yield response of rice cultivars to levels of nitrogen on vertisol and hydromorphic soils during the wet and hot dry seasons

The objective of this study was to determine the optimum levels of applied nitrogen for the two soil types, and rice cultivars during the two growing seasons.

2.5.3 Wet season

The results of the wet season are presented in Appendices 2 and 3. On vertisol, the main effects of variety and nitrogen application on grain yield were significant, but there was no significant interaction between variety and nitrogen levels. This indicates that the five rice cultivars tested have comparable nitrogen requirements. From earlier experiments, it was calculated from the regression equation that the optimum nitrogen requirement for KH 998 was 140 kg N/ha.

On hydromorphic soils on the other hand, the main effects of variety and nitrogen and their interaction on grain yield were significant. This indicates that the yield response to nitrogen varied from one variety to another and the optimum doses were larger because of the higher relative permeability in the hydromorphic soils than those in vertisols. The optimum doses of nitrogen for four varieties used in this trial are given below:

Rice varieties	*Optimum N doses (kg N/ha)*
Jaya	150
I Kong Pao	170
KH 998	150
IET 1996	160

Rice cultivar KN-1h-350 suffered from water shortage during the reproductive phase which resulted in low grain yield in this variety.
Appendix 3 shows the regression equation of nitrogen response curves on vertisols and hydromorphic soils during the wet season.

2.5.4 Dry season

The grain yield data are presented in Appendix 4. Regardless of soil types, the effects of variety, nitrogen and their interaction on grain yields were highly significant.
On vertisol and hydromorphic soils, the high grain yields were noted in Jaya, IET 1996 and KH 998 while KN-1h-350 gave the lowest yield in both soil types. KN-1h-350 lodged at high levels of nitrogen.
The optimum nitrogen dose for each variety and soil type is given in Appendix 5. The calculation for the five varieties is based on regression equations given below and the unofficial price of 1 kg of urea at 131 francs and official price of 1 kg of paddy at 51.5 francs.

2.5.4.1 Regression equations of five varieties on vertisol (1981 dry season)

Jaya: $Y = 2478 + 56.6\ x - 0.14\ x^2$ ($r = 0.862^{**}$)
I Kong Pao: $Y = 2591 + 64.25x - 0.179x^2$ ($r = 0.926^{**}$)
KH 998: $Y = 2475 + 46.81x - 0.105x^2$ ($r = 0.900^{**}$)
KH-1h-350: $Y = 2300 + 28.95x - 0.065x^2$ ($r = 0.913^{**}$)
IET 1996: $Y = 3859 + 30.0\ x - 0.060x^2$ ($r = 0.809^{**}$)
Where Y = grain yield, x = nitrogen dose

2.5.4.2 Regression equation of five varieties on hydromorphic soils (1981 dry season)

Jaya: $Y = 2991 + 46.0\ x - 0.090x^2$ ($r = 0.972^{**}$)
I Kong Pao: $Y = 2940 + 34.25x - 0.062x^2$ ($r = 0.977^{**}$)
KH 998: $Y = 2644 + 42.78x - 0.066x^2$ ($r = 0.923^{**}$)
KN-1h-350: $Y = 2044 + 39.39x - 0.075x^2$ ($r = 0.958^{**}$)
IET 1996: $Y = 3020 + 53.39x - 0.150x^2$ ($r = 0.946^{**}$)

2.5.5 Economics of nitrogen use

Some economic aspects on the use of nitrogen as fertilizer on vertisol and hydromorphic soils for the recommended rice cultivars Jaya and I Kong Pao (IKP) during the dry season are presented in Appendices 6 and 7, respectively.
The analysis showed that the use of urea (as N) is very profitable regardless of the current price of 131 francs/kg or the subsidized price of 25 francs/kg.
Substantial profits from nitrogen application could be achieved particularly with variety Jaya (Appendix 6) during the dry season provided that the other factors of production such as irrigation water, crop protection measures and planting date are at an optimal level.

3. Irrigation, water management and economic use of nitrogen

In the Sahelian zone and more particularly in the Senegal River Valley, the uneven rainfall distribution in time and space makes it totally impossible to grow rainfed rice. The pedo-climatic environment in the Senegal River Valley, however, is very favourable for rice cultivation under irrigated conditions.
The volume and cost of irrigation water used, the arrival of salty water in February (period during which the Senegal River subsides), the low water reserves during the rainy season, the ever increasing prices of fertilizer and the failure to recognize their interactions are the factors that make it difficult to attain the objectives of high rice yields as well as net income in irrigated rice cultivation with complete water control in the Sahelian zone.
It, therefore, becomes necessary to search for irrigation techniques and water management which together with a rational use of nitrogenous fertilizer at critical growth stages of the rice plant that would likely increase the efficiency of nitrogen application.
This study was undertaken to determine a more effective use of irrigation water and nitrogenous fertilizer on the two main soil types (vertisol and hydromorphic) of the rice fields in the Senegal River Valley.

3.1 Effect of time of nitrogen application and water regime on grain yield during the cold dry season

The objective of the experiment was to determine the effectiveness of nitrogen fertilizer under various irrigation systems and also to find out the effect of drainage time after nitrogen application on grain yield.
The yield data of this experiment are presented in Appendix 8. The results showed that the effect of time of nitrogen application on grain yield is not significant regardless of the flooding duration. On the other hand, the flooding period showed a slight positive effect on grain yield. For example, a drainage period of 6–8 days resulted in a yield increase (all the plots were drained three days before nitrogen application which would bring the drainage period to 4, 6, 8 and 10 days respectively in 1, 3, 5 and 7 days after N application).
The low yields obtained in the trial are due to the high grain sterility rates. This indicates that CHINA 1939 is susceptible to cold at flowering stage.

3.2 Effect of irrigation methods and nitrogen and compost on the evolution of nitrogen in two soil types

In this study, rice variety Kuan Shu Shung was used. The experimental design was split-plot replicated four times as follows:
a) The method of irrigation and water regime consists of:
W1 = Continuous flooding with water depth maintained at 5 cm throughout the vegetative stage.

W2 = Soil water content maintained at field capacity.

W3 = Field capacity during the vegetative phase (from recovery after transplanting to panicle initiation) followed by flooding to water depth of 5 cm during the reproductive phase.

W4 = Flooding to a water depth of 5 cm during the vegetative stage followed by field capacity during the reproductive stage.

Five 2 levels of N and compost were applied respectively as follows:

i) levels of nitrogen: 0, 60, 120, 180 and 240 kg N/ha.

ii) compost 0 and 15 t/ha.

Nitrogen (urea) was applied in split doses: 50% a day before transplanting, 25% at tillering and panicle initiation stages. Compost was applied at the last stage of soil preparation. Phosphorus (triple super phosphate) and potassium (KCl) were applied as basal dressing at the rate of 60 kg P_2O_5/ha and 60 kg K_2/ha respectively.

3.3 Results

3.3.1 Continuous flooding: W1 (Figures 4 and 5)

The two soil types (vertisol and hydromorphic) studied have a low mineralization rate with NH_4^+-N as the dominant form. Under the anaerobic conditions, nitrogen mineralization stops at the ammonium stage (NH_4^+-N) due to lack of essential oxygen during nitrification. Maximum concentration in the soil was reached 15 days after transplanting and the higher the levels of applied nitrogen, the higher the concentration, especially on vertisol (Figure 4) than on hydromorphic soil (Figure 5). There was a gradual decline in concentration up till maturity. On the other hand, the addition of compost resulted in a decrease in NH_4^+-N content from the first few days after transplanting up to maturity.

3.3.2 Field capacity: W2 (Figures 6 and 7)

Nitrates constitute the dominant form and maximum concentration was reached 45 days after transplanting in applied N treatments, on the other hand, ploughing-in of compost improved the nitrate content.

3.3.3 Field capacity during the vegetative stage followed by flooding during the reproductive stage: W3

The nitrogen mineralization trend is shown in Figures 8 and 9 for vertisol and hydromorphic soil, respectively. The results indicate that as soon as flooding was carried out, nitrates disappear gradually in favour of nitrogen NH_4^+-N. Denitrification and leaching are the main causes for this.

3.3.4 Flooding during the vegetative stage followed by field capacity during the reproductive stage: W4

The two soils reacted differently (Figures 10 and 11). Drainage at the end of the

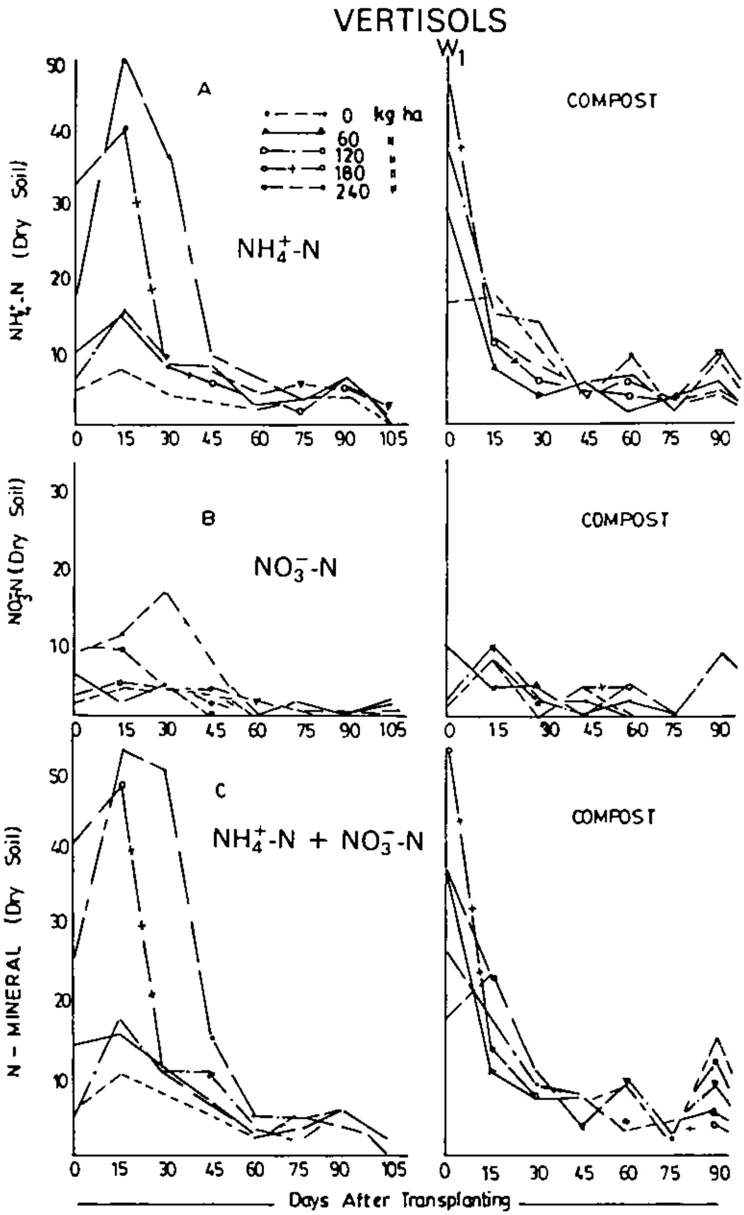

Fig.4. Effects of continuous flooding levels of nitrogen and compost on evolution of mineral nitrogen in vertisols

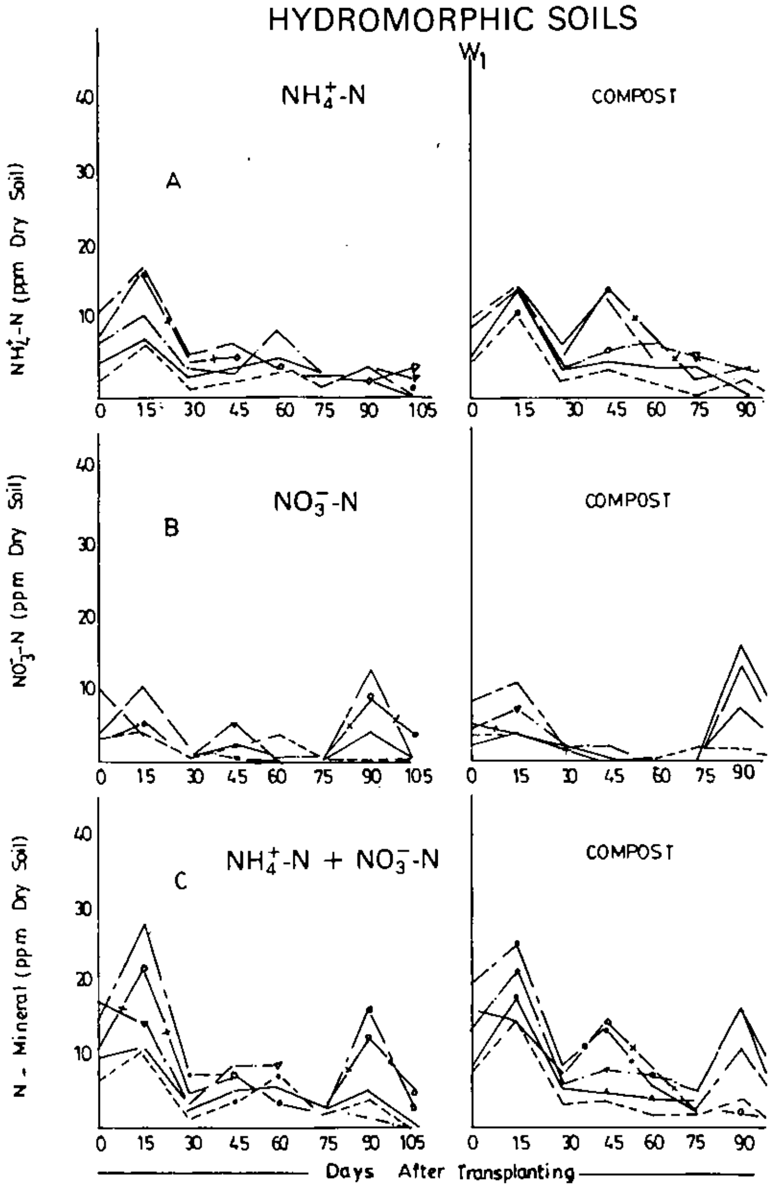

Fig.5. Effects of continuous flooding, levels of nitrogen and compost on evolution of mineral nitrogen in hydromorphic soils

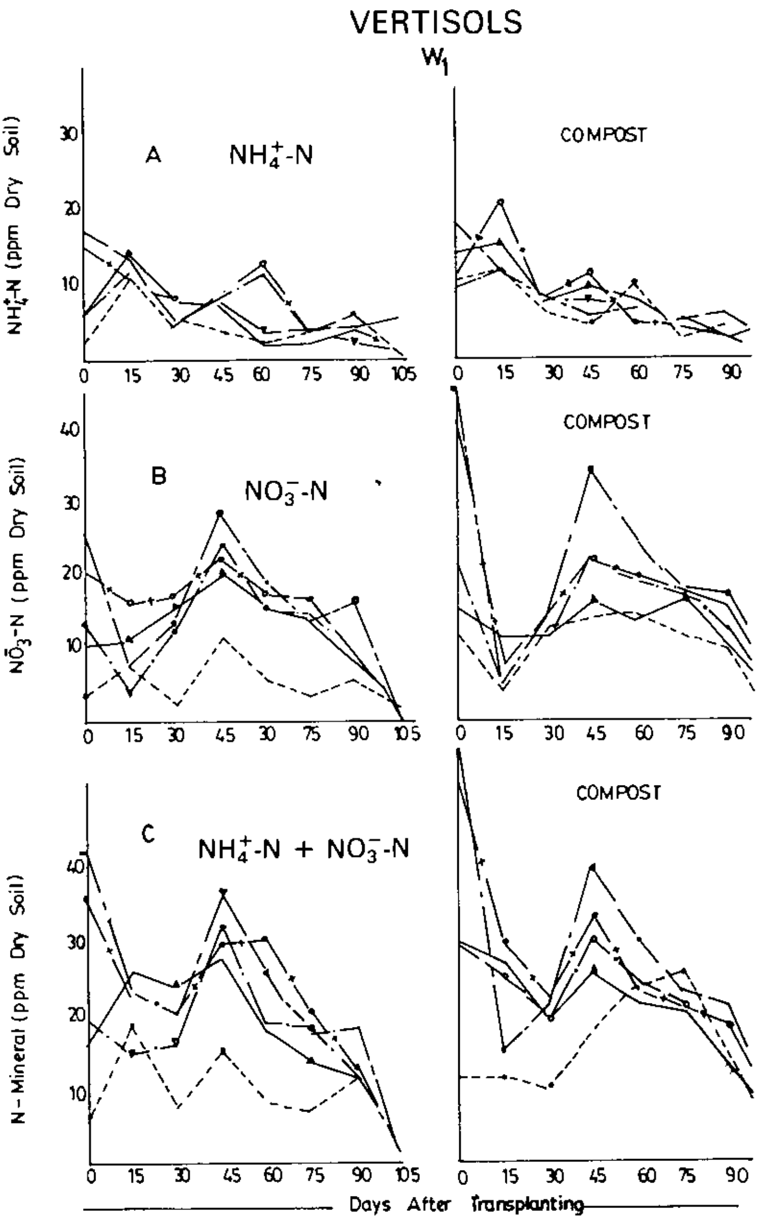

Fig.6. Evolution of mineral nitrogen at field capacity under the influence of levels of applied nitrogen and compost in vertisols

HYDROMORPHIC SOILS

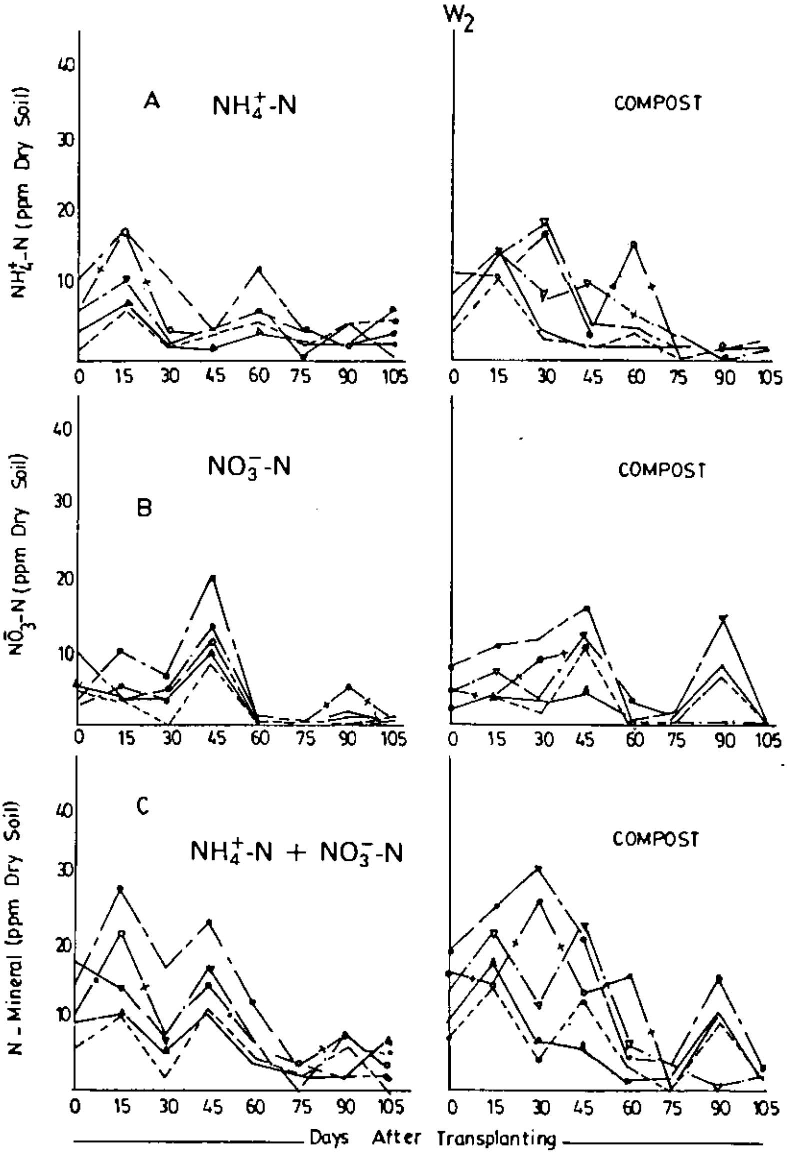

Fig. 7. Evolution of mineral nitrogen at field capacity under the influence of levels of applied nitrogen and compost in hydromorphic soils

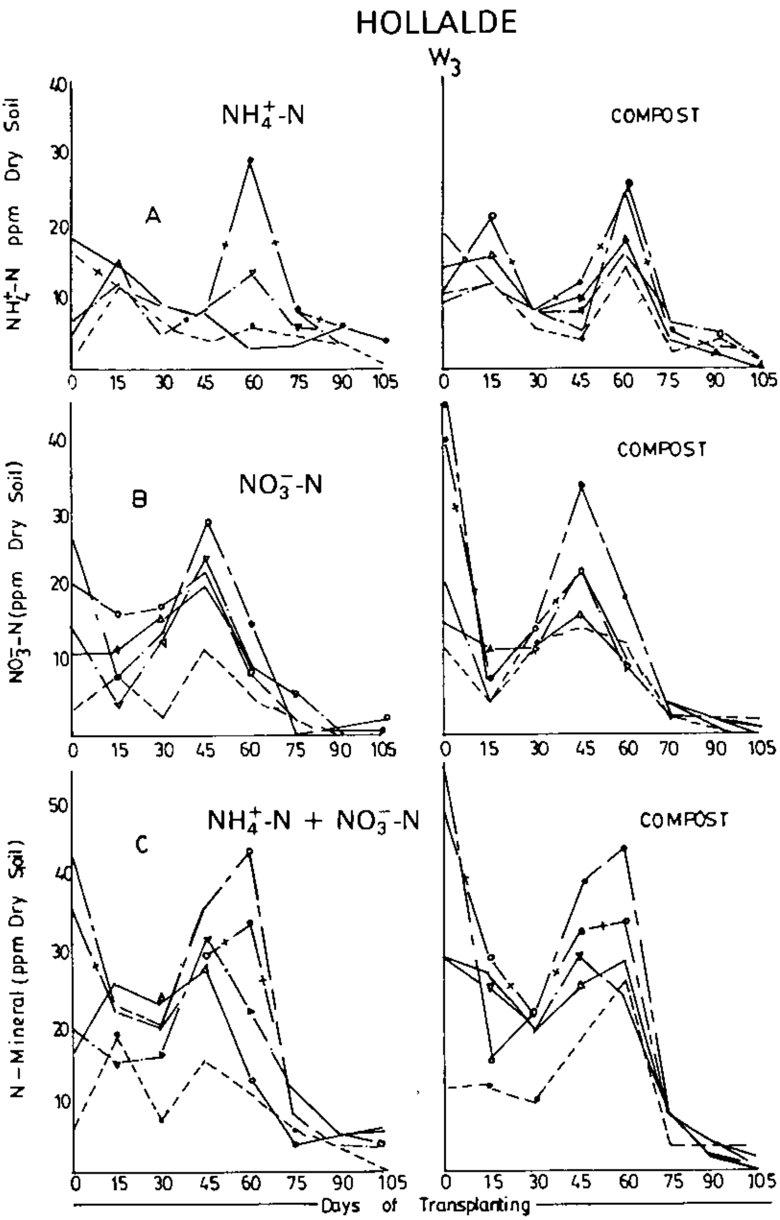

Fig.8. Evolution of mineral nitrogen at field capacity at vegetative stage followed by flooding at reproductive stage and under the influence of levels of applied nitrogen and compost in vertisols

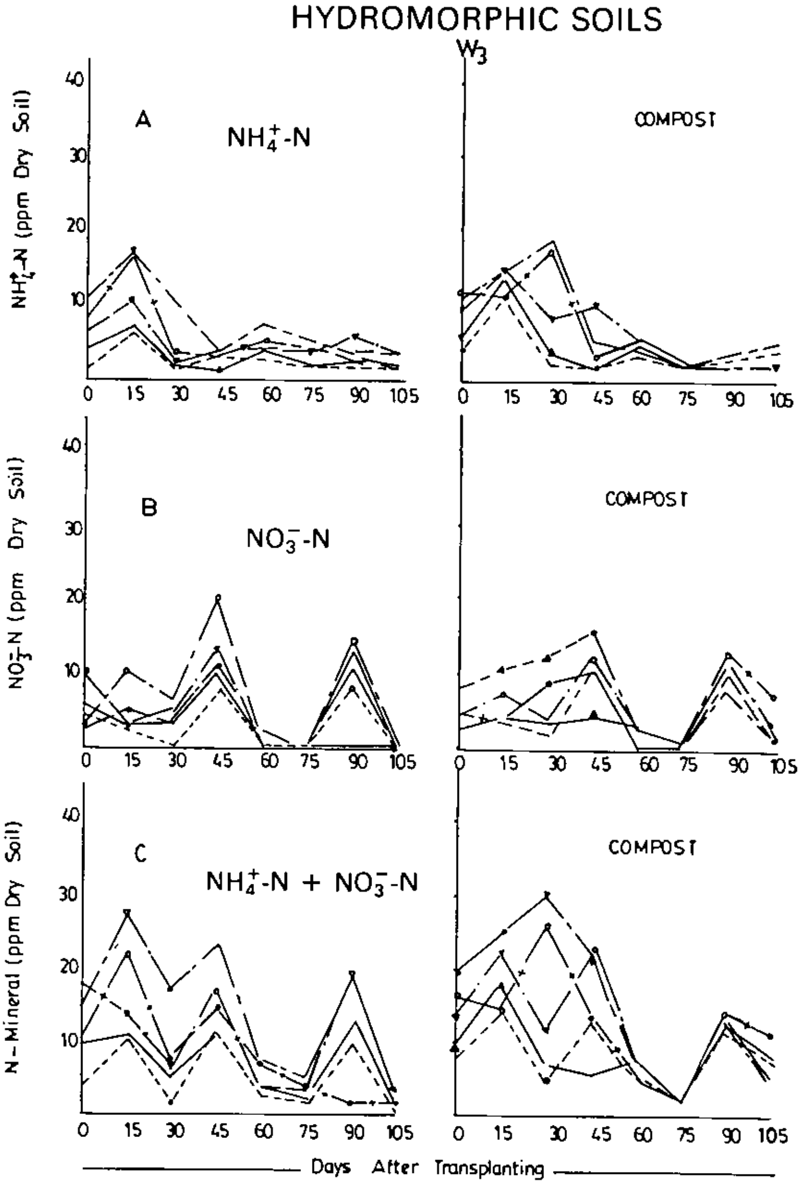

Fig.9. Evolution of mineral nitrogen at field capacity at vegetative stage followed by flooding at reproductive stage under the influence of levels of applied nitrogen and compost in hydromorphic soils

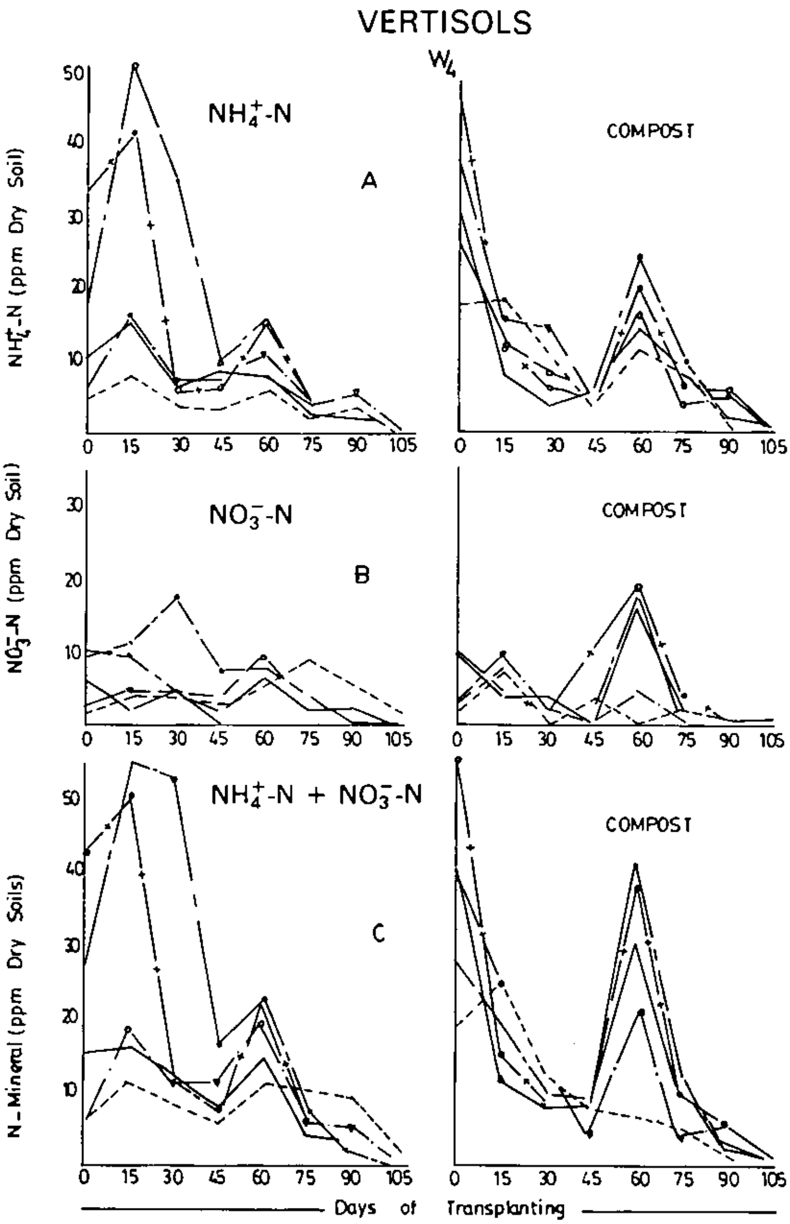

Fig. 10. Evolution of mineral nitrogen under flooding during vegetative stage followed by field capacity at reproductive stage and under the influence of levels of applied nitrogen and compost in vertisols

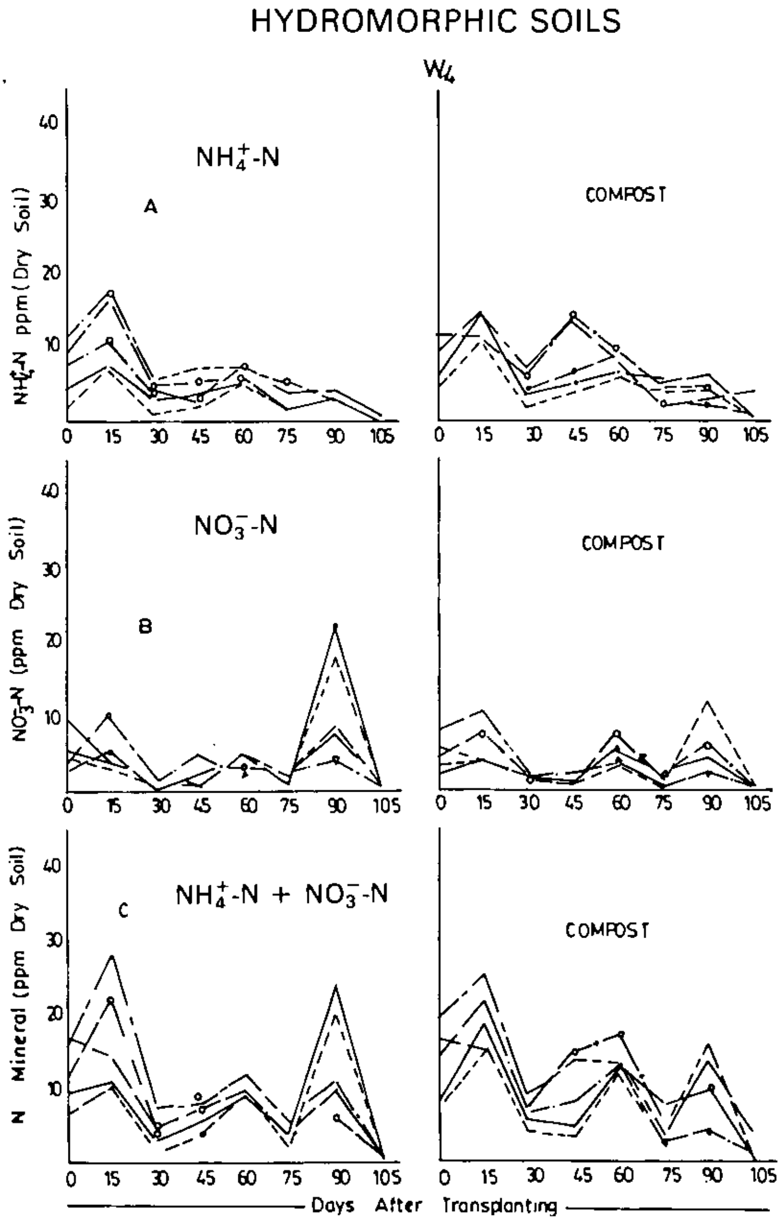

Fig. 11. Evolution of mineral nitrogen under flooding during vegetative stage followed by the field capacity at reproductive stages and under the influence of levels of applied nitrogen and compost in hydromorphic soils

vegetative cycle favoured an increase in nitrogen concentration in the soil, especially with the application of compost on vertisol (Figure 10).
On the other hand, on hydromorphic soil (Figure 11), this irrigation practice resulted in a decline in the NH_4^+-N content and a subsequent increase in nitrates and it is more marked with the application of compost.

3.4 Conclusion

From the above studies, it may be concluded that:

i) The two soil types (vertisol and hydromorphic), with low organic matter content, showed a slow rate of nitrogen mineralization with NH_4^+-N as the dominant form.
ii) Maximum concentration of NH_4^+-N is reached 15 days after transplanting and the higher the applied nitrogen rates, the higher the concentration especially in vertisol.
iii) This nitrogen fertilizer effect is much more apparent under intermittent irrigation conditions.
iv) On hydromorphic soil, it was observed that late flooding during the reproductive stage of the rice plant is conducive to greater mineralization and nitrogen availability, whereas on vertisol flooding during the vegetative stage is the best stimulant for mineralization.
v) The addition of compost in the soil resulted in a decrease in NH_4^+-N concentration in the soil at the beginning of the growth of the rice plant. However, a gradual increase in NH_4^+-N concentration is observed at the middle and end of the growing season especially during the continuous flooding on vertisol.

3.5 Effect of water regime, nitrogen and compost applications on water requirement and grain yield

3.5.1 Water requirement on two soil types

Regardless of the irrigation system, water consumption follows a sigmoidial curve with the advance of plant growth and development. Differences were noted at various times with peaks occurring between the panicle initiation and flowering stages (33–45% of total consumption on vertisol and 24–56% on hydromorphic soil according to the water regime).
The total water requirements recorded for vertisol and hydromorphic soil during the warm dry season are shown in Appendix 9.

3.5.2 Influence of nitrogen

Soil enrichment by applied nitrogen has a significant effect on water consumption (Appendix 10). The soil fertility level has an effect on evapo-transpiration by increasing the leaf area of the rice plant. The leaf area increased with the increase in nitrogen levels, especially under flooding conditions. When the same quantity is used, water is consumed faster in the fertilized plots than in unfertilized plots.

3.5.3 Influence of compost

Ploughing-in of compost in vertisol resulted in a slight increase in the water requirement by 16, 12, 17 and 4% respectively in the W1, W2, W3 and W4 treatments (Appendix 11). On the other hand, on hydromorphic soil, the effect of compost was less evident in W1 (continuous flooding), and a slight increase of 7–13% was observed in W2 (field capacity), W3 (field capacity + flooding) and W4 (flooding + field capacity).

3.6 Effect of water regime, levels of nitrogen and compost on grain yield in the warm dry season

3.6.1 Grain

3.6.1.1 Effect of water regime

The yield response to water regime (irrigation) varied with soil types (Appendix 12). For example, in vertisol, the highest grain yield (4.6 t/ha) was noted in continuous flooding (W1); this was significantly greater than in the other three water regimes (W2, W3 and W4). In comparison to continuous flooding (W1), substantial decrease in yield was noted in field capacity (W2: 67%) field capacity + flooding (W3: 37%) and flooding + field capacity (W4: 33%).
In hydromorphic soil, there was no significant difference in grain yield between continuous flooding (W1) and field capacity + flooding (W3) which gave 4.1 t/ha and 4.7 t/ha respectively. However, these two treatments gave significantly greater yield than field capacity: W2 (0.8 t/ha) and flooding + field capacity: W4 (2.0 t/ha). Thus in hydromorphic soils, as far as grain yield and water regimes are concerned, field capacity until vegetative stage followed by flooding during the reproductive stage (W3) is as good as continuous flooding, while in vertisol, continuous flooding (W1) is the best water regime.

3.6.1.2 Effect of applied nitrogen

In the two soil types, the effects of levels of nitrogen and interaction between nitrogen and water regime on grain yield were significant (Appendices 3 and 14).
In vertisol, the yield response to nitrogen was more marked in W1 followed by W4, W3 and W2. However, the highest grain yield, regardless of levels of nitrogen, was noted in continuous flooding (Appendix 14).
On the other hand, in hydromorphic soils, W1 and W3 treatments gave greater grain yields than W2 and W4 treatments (Appendix 14) at all levels of nitrogen application.

3.7 Effect of water regime, levels of nitrogen and compost application on the nitrogen efficiency index in vertisols and hydromorphic soils

The efficiency index (%) is defined as the relationship between the excess of grain yield produced per unit (kg) of nitrogen applied.
The results, presented in Appendix 15 show that when nitrogen level is increased sufficiently, the index drops in the two soil types regardless of water regime.
The highest index value of 39% was noted in vertisols with 120 kg N/ha at W1 water regime, while on hydromorphic soils, it was 38% with 120 kg N/ha and 36% with 60 kg N/ha at W3 and W1 water regime respectively.
At the same nitrogen level, the efficiency coefficient on vertisols is highest in continuous flooding (W1) while in hydromorphic soils, both W1 and W3 regimes gave high efficiency coefficient.

3.8 Effectiveness of irrigation water

The effectiveness of irrigation water is defined as the relationship between the grain yield expressed in kg/ha/mm and the water requirement of the plot, and this represents the quantity of grains produced per mm of water supplied to the plot.
The results are presented in Appendix 16.

3.9 Effect of the water regime

The result showed that on vertisol, continuous flooding (W1) gave the highest value of effectiveness of irrigation water while field capacity (W2) gave the lowest value in all levels of nitrogen application.
On the other hand, on the hydromorphic soil, the highest value was noted in field capacity + flooding (W3) followed by continuous flooding (W1), flooding + field capacity (W4) and the lowest in field capacity (W2).

3.10 Effect of levels of fertility

In general, it was noted that reasonable fertilization favours greater effectiveness of irrigation water. Nitrogen application favoured a better plant growth and development and increased the quantity of dry matter formed for every mm of water supplied (Appendix 16).

3.11 Effect of water regime, levels of nitrogen and compost on nitrogen uptake in rice grain and straw during the warm dry season

3.11.1 Water regime

The quantities of nitrogen uptake (kg/ha) in the two soil types are greatly influenced by the water regime (Appendix 17).
On vertisol, the highest nitrogen uptake of 48.0 kg/ha by rice grain occurred under continuous flooding (W1). While on hydromorphic soils, it occurred in field capacity + flooding treatment (49.93 kg/ha). Under the same water regimes mentioned above, the straw contained less nitrogen than the rice grains.

3.11.2 Levels of nitrogen

In the two soil types, total nitrogen uptake in rice grain and straw increased with the increase in nitrogen levels. In rice grain, the highest uptake of 43.68 kg N/ha was noted for vertisols at 180 kg N/ha while for hydromorphic soils, it was 65.39 kg/ha at 240 kg N/ha (Appendix 18).

3.12 Economic aspects of irrigation for the warm dry season rice cultivation

3.12.1 Vertisols

It could be inferred from the results presented above that on vertisols, continuous flooding (W1) generates a higher income and the higher the nitrogen dosage, the more income is generated. The more severe the water stress conditions, the greater the reduction in net income. The water requirement of the vertisol is also very high. Also, the nitrogen losses when the soil is flooded after field capacity conditions are high. Thus alternated field capacity and flooding is not economically advantageous to the farmers of the Senegal River Valley, especially in the face of current factors of production price unless irrigation and nitrogenous fertilizers are subsidized and the price of paddy increased (Appendix 19).

3.12.2 Hydromorphic soil

On the other hand, on hydromorphic soil under present conditions, continuous flooding (W1) is not needed for higher income. A substantial increase in income could be realized with the alternate field capacity during the vegetative stage with flooding during the reproductive stage (W3) (Appendix 20).
In spite of hydraulic structures constructed and considering the highly permeable nature of this soil type, the continuous maintenance of water on this soil resulted in high water loss through percolation thereby increasing irrigation costs. The application of high doses of nitrogen accounts for the maximum profit caused by alternate field capacity with flooding (W3).
It has also been noted that profit increased by 38% in areas under continuous flooding as a result of compost application.

A laboratory study on phosphorus mobility, using the isotopic dilution technique was conducted. The results show that:
- phosphorus concentration in solution form did not increase significantly;
- the fixing ability of these two soil types is very high which probably explains the non-significant effect of the various levels of phosphorus on grain yields.

By applying 500 ppm of soluble phosphorus, tricalcium phosphate and aluminium phosphate which is equivalent to 3750 kg P_2O_5/ha (to determine the optimum dosage before a reaction to the soil is observed), it was noted that:
- Mobility is important for the soluble forms on the two soil types. Mobility is even more important in hydromorphic soils with less wet clay content (montmorillionite).
- The same can be said to the less soluble natural tricalcium forms though to a lesser degree than the soluble forms.

It seems that pH plays an important role. In hydromorphic soils, with pH below 6.1, there is enough phosphorus in solution form (6.02 ppm of P/g of soil). By contrast, in vertisols with pH above 6.1, the fixing ability remains high and only 2.4 ppm/g of soil is noted.

4. Deep water floating rice special research project, Mopti, Mali

The yield response to fertilizer application at Mopti over the past three years (1979 to 1981) has been unpredictable and at the best, non-significant.

Appendix 1. Effect of split application of nitrogen on grain yield of I Kong Pao in two soil types at Richard Toll/Fanaye (Senegal)

	Vertisols				Hydromorphic soils	
	1979 Wet season		1979 Hot, dry season		1980 Hot, dry season	
	Paddy yield kg/ha	Number of fertile tillers/ plant	Paddy yield kg/ha	Number of fertile tillers/ plant	Paddy yield kg/ha	Number of fertile tillers/ plant
1. 100% 1 DBT	7963a	14.41c	6677c	15.42c	10 106bc	16.37a
2. 100% 10 DAT	7792a	14.10c	7293bc	18.32b	11 008ab	17.22a
3. 100% 20 DAT	8133a	14.60c	7081bc	17.27bc	8 760cd	16.35a
4. 100% 5–7 DAT	7711a	23.00a	6884bc	22.15a	9 505d	18.02a
5. 50% 1 DBT + 50% 20 DAT	8623a	14.37c	8220a	15.90bc	10 747ab	17.67a
6. 50% 1 DBT + 50% PI	7590a	18.42b	7448b	18.57b	11 091ab	18.52a
7. 50% 20 DAT + 50% PI	7983a	19.68b	8190a	17.97bc	11 046ab	18.30a
8. 50% 1 DBT + 25% 20 DAT + 25% PI	8510a	17.50b	8161a	18.20bc	11 557a	18.47a
Calculated F	ns	14.56	6.99	5.51	8.70	ns
S.E. of a mean	319.11	0.85	203.80	0.87	320.39	0.78
CV	7.94	9.94	4.43	9.68	6.11	8.83

DBT = Days before transplanting
DAT = Days after transplanting
PI = Panicle initiation

Appendix 2. Effects of nitrogen fertilizer on grain yields (kg/ha) of 5 varieties on vertisols (Hollaldé) and hydromorphic soils (Fondé) during the wet season

Rate of N (kg/ha)	Vertisols					Hydromorphic soils				
	Jaya	IKP	KH-998	KN-lh-350	IET 1996	Jaya	IKP	KH-998	KN-lh-350	IET 1996
0	3700	3500	2600	2000	4100	3400	2200	1800	1300	3200
60	6500	6200	4800	4800	6000	4400	4300	3100	1400	4300
90	8100	6100	4900	4900	7400	6500	4800	3500	1800	7000
120	8500	7700	4900	4900	6800	7600	5200	4400	1900	7100
150	7800	7200	5700	5700	8080	8000	5800	5000	1800	8600
180	8900	7400	6000	6000	8900	8600	6600	6000	4200	8600
240	8900	7900	5400	5400	8700	7600	7000	5600	2600	7000

		Vertisols	Hydromorphic soils
Test F:	Nitrogen	14.25*	27.46**
	Variety	25.62*	151.84**
	Nitrogen × Variety	1.1067 n.s.	3.3**
LSD (1%)	Nitrogen	1823.47	1256.0548
	Variety	803.79	568.9791
	Nitrogen × Variety	—	1837.2516
CV %		9.38	13.24

Appendix 3. Regression equation of nitrogen response curves on Vertisols (Holladé) and hydromorphic soils (Fondé) during the wet season

Varieties	Vertisols			Hydromophic Soils		
	Regression equation	Calculated F	R^2 Coefficient of determination	Regression equation	Calculated F	R^2 Coefficient of determination
Jaya	$Y=3903+52x-.13x^2$	23.49**	0.692	$Y=2905+5176x-.03x^2$	21.74**	0.675
I Kong Pao	$Y=3643+42x-.11x^2$	24.37**	0.700	$Y=2319+32x-.053x^2$	32.30**	0.758
KH 998	$Y=2709+29x-.25x^2$	25.11**	0.707	$Y=1584+30x-.05x^2$	35.56**	0.776
KN-lh-350	$Y=2233+40x-.011x^2$	16.37**	0.606	$Y=1038+10x-.008x^2$	6.24**	0.344
IET 1996	$Y=4095+38x-.076x^2$	13.06**	0.547	$Y=2640+60x-.017x^2$	30.69**	0.748

Appendix 4. Effects of nitrogen fertilizer on grain yields (kg/ha) of five varieties on Vertisols (Holladé) and hydromorphic soils (Fondé) during the dry season.

Nitrogen dose	Vertisols					Hydromorphic soils				
(kg/ha)	Jaya	IKP	KH-998	KN-lh-350	IET 1996	Jaya	IKP	KH-998	KN-lh-350	IET 1996
0	3100	2900	2500	2200	3600	2700	2200	2300	2000	2700
60	4200	5100	5300	4100	5200	5900	6700	6000	4500	6100
90	6000	5200	5400	4600	6100	6600	7200	5900	4800	7100
120	7900	5900	6400	4300	6800	7200	7000	6400	5200	7200
150	7600	6900	6500	4900	7300	7500	7700	6700	6200	7200
180	9200	7200	8700	5900	7600	8100	8700	8900	7200	7400
240	7400	7500	7300	5400	7300	9100	7800	9100	7000	7500
F test:										
Nitrogen				126.14**		341.35**				
Variety				29.79**		24.97**				
Nitrogen × Variety				2.92**		2.66**				

Appendix 5. Optimum nitrogen dose for varieties, Jaya, IKP, KN-lh-350, KH-998 and IET 1996 sown in the dry season on Vertisols (Holladé) and hydromorphic soils (Fondé).

Varieties	Optimum nitrogen dose (kg/ha)	
	Vertisols	Hydromorphic soils
Jaya	180	224
IKP	164	232
KH-998	197	281
KN-lh-350	180	225
IET 1996	160	203

Appendix 6. Optimum nitrogen level, expected yields and profits realized with variety Jaya during the dry season on Vertisols (Hollaldé) and hydromorphic soils (Fondé)

Price of paddy/kg CFA francs	Price of nitrogen/kg CFA francs	Optimum nitrogen level (kg/ha)		Expected yields (kg/ha)		Profits realized CFA francs	
		Vertisols	Hyd. soils	Vertisols	Hyd. soils	Vertisols	Hyd. soils
51.5	54.35*	198	250	8197	8666	411 384	432 711
	284.78**	182	224	8144	8783	367 586	388 559

* Subsidized; ** Current price; Hyd. = Hydromorphic

Appendix 7. Optimum nitrogen level, expected yields and profits realized with variety IKong Pao in the warm dry season on Vertisols (Hollaldé) and hydromorphic soils (Fondé)

Price of paddy/kg CFA francs	Price of nitrogen/kg CFA francs	Optimum nitrogen level (kg/ha)		Expected yields (kg/ha)		Profits realized CFA francs	
		Vertisols	Hyd. soils	Vertisols	Hyd. soils	Vertisols	Hyd. soils
51.5	54.35*	176	268	8354	7666	420 665	389 233
	284.78**	164	231	8314	7543	381 467	322 680

* Subsidized; ** Current price

Appendix 8. Combined effects of period of nitrogen application and duration of drainage on grain yield of the variety China 1939 during cold dry season.

Split nitrogen and period of application	Flooding period after nitrogen application (day)	Grain yield at 14% moisture content kg/ha
100% (basal application)	Continuous flooding	1944
	1 day after application	2000
	3 days after application	2875
	5 days after application	2875
	7 days after application	2110
50% (basal application) + 50% tillering	Continuous flooding	2100
	1 day after application	2000
	3 days after application	2500
	5 days after application	2400
	7 days after application	2100
Basal application and tillering Panicle emergence 50% + 25% + 25%	Continuous flooding	2000
	1 day after application	1800
	3 days after application	2200
	5 days after application	2200
	7 days after application	1700

Appendix 9. Effect of water regime on water requirement of vertisols and hydromorphic soils during the warm dry season

Water regime	Water requirement (mm)	
	Vertisols	Hydromorphic soils
W1 Continuous flooding	1333a	1566a
W2 Field capacity	599b	759d
W3 FC + flooding	1132a	980e
W4 Flooding + FC	1117a	1185b

Appendix 10. Effect of nitrogen fertilizer on water requirements during the warm dry season (Fanaye, Senegal 1981)

N Doses	W1		W2		W3		W4		Average	
Kg/ha	Verti-sol	Hyd.* soil	Verti-sol	Hyd. soil	Verti-sol	Hyd. soil	Verti-sol	Hyd. soil	Verti-sol	Hyd. soil
0	1017	1383	622	621	1027	912	942	1043	902	990
60	1114	1366	612	618	1091	914	921	1033	934	983
20	1237	1618	650	775	1064	884	1063	1140	1003	1097
180	1360	1620	707	704	1164	926	1163	1238	1097	1122
240	1442	1740	650	849	1207	1003	1205	1343	1126	1234

W1 = Continuous flooding; W2 = Field capacity; W3 = Field capacity + flooding; W4 = Flooding + field capacity. * Hyd. soil = Hydromorphic soil.

Appendix 11. Effect of organic matter on water requirements for two soil types during the warm dry season (Fanaye, Senegal 1981)

Fertility level	Water requirement							
	W1		W2		W3		W4	
	Verti-sol	Hyd. soil	Verti-sol	Hyd. soil	Verti-sol	Hyd. soil	Verti-sol	Hyd. soil
Without compost	1234	1576	707	713	1152	966	1045	1158
With compost	1434	1592	590	801	1103	1036	1171	1259

Appendix 12. Effect of water regime on grain yield of irrigated rice in the warm dry season

Water regime	Grain yield (kg/ha)	
	Vertisol	Hydromorphic soil
	Grain	Grain
Continuous flooding (W1)	4600a	4100a
Field capacity (W2)	1400c	800c
FC + flooding (W3)	2900b	4700a
Flooding + FC (W4)	3100b	2000b
Test F	22.5025**	91.0359**
Standard error	396.98	271.9381

Appendix 13. Effect of increasing nitrogen doses on rice grain yield during the warm dry season

Nitrogen doses kg N/ha	Yield (kg/ha)	
	Vertisol	Hydromorphic soil
	Grain	Grain
0	700d	700d
60	1600c	1900d
120	3300b	3100c
180	4400a	4100b
240	4900a	4700a
Calculated F. value	97.9942**	125.42**

** The figures followed by the same letter are not significantly different at the 1% level according to the Duncan Test.

Appendix 14. Effect of water regime and increasing nitrogen doses on the grain yield during the warm dry season

Nitrogen doses kg N/ha	Grain yield (kg/ha)			
	Vertisols			
	Continuous flooding (W1)	Field capacity (FC) (W2)	FC + flooding (W3)	Flooding + FC (W4)
0	900	500	600	800
60	2600	800	1900	1200
120	5800	1000	3200	3300
180	6400	1900	4300	5000
240	7400	2600	4400	5000
Mean	4620	1360	2880	3060
	Hydromorphic soil			
0	800	200	1400	400
60	2900	400	2800	1400
120	3800	900	5500	2300
180	6800	1000	6200	2300
240	6300	1200	7600	3600
Mean	4120	740	4700	2000
Mean statistic		Vertisol 6.1128**	Hydromorphic soil 14.79**	
LSD at 1% to compare the averages of 2 water regimes		1337.04	1079.49	

Appendix 15. Effect of nitrogen, water regime and compost on the efficiency index of nitrogen fertilizer in the hot dry season

Nitrogen dosage (kg/ha)	Efficiency index (%)							
	W1		W2		W3		W4	
	Verti-sol	Hyd. soil	Verti-sol	Hyd. soil	Verti-sol	Hyd. soil	Verti-sol	Hyd. soil
0	–	–	–	–	–	–	–	–
60	32	36	–	6	17	28	9	10
120	39	28	6	7	26	38	19	25
180	33	32	5	4	22	28	36	10
240	30	22	9	3	16	26	17	16
0 + compost	–	–	–	–	–	–	–	–
60 + compost	34	43	12	–	29	40	12	25
120 + compost	46	27	3	4	18	37	22	10
180 + compost	31	38	11	5	20	31	22	12
240 + compost	27	26	8	3	17	27	18	12

Appendix 16. Effect of fertilization and water regimes on the effectiveness of irrigation water on rice during the hot dry season

Level of fertility (kg/ha)	Effectiveness of irrigation water kg/ha/mm							
	W1		W2		W3		W4	
	Verti-sol	Hyd. soil	Verti-sol	Hyd. soil	Verti-sol	Hyd. soil	Verti-sol	Hyd. soil
0	0.60	0.36	0.70	0.36	0.54	1.07	1.02	0.34
60	1.80	1.94	0.67	0.97	1.45	2.87	1.55	0.94
120	4.30	2.35	1.76	1.42	3.50	6.25	2.96	2.67
180	4.85	3.89	1.85	1.35	3.82	6.42	4.50	1.72
240	5.37	3.38	4.04	1.56	3.54	7.70	4.00	3.03
0 + compost	0.86	0.79	2.20	0.35	0.65	1.66	0.67	0.29
60 + compost	1.93	2.34	2.43	0.25	2.42	2.98	0.88	1.56
120 + compost	4.33	2.33	1.51	0.93	2.55	5.86	2.88	1.48
180 + compost	4.17	4.47	3.89	1.34	3.45	5.99	4.05	2.04
240 + compost	4.50	3.61	4.42	1.22	4.02	6.73	3.95	2.29

Appendix 17. Influence of water regime on the quantity of nitrogen up take by the rice plant during the hot dry season

Water regime	Nitrogen uptake (kg/ha)			
	Vertisols		Hydromorphic soils	
	Grain	Straw	Grain	Straw
Continuous flooding (W1)	48.00a	45.15a	47.27a	22.48b
Field capacity (W2)	12.75c	19.98b	10.73c	28.87a
FC + flooding (W3)	32.86b	19.27b	49.93a	21.94b
Flooding + FC (W4)	33.13b	45.69a	26.64b	10.03c
Test F	*	**	**	*

According to the Duncan Multiple Test, there is no significant difference between figures followed by the same letter: * at 5% and ** at 1%.

Appendix 18. Effect of nitrogen dose on nitrogen uptake by rice plant during the dry season

Nitrogen dosage	Nitrogen uptake (kg/ha)			
	Vertisols		Hydromorphic soils	
	Grain	Straw	Grain	Straw
0	4.83d	9.74c	5.96d	7.02d
60	15.20c	16.09d	16.30c	12.49c
120	30.96b	20.61c	39.98b	22.66b
180	43.68a	35.15b	42.73b	26.06b
240	53.36a	45.09a	65.39a	35.95a
Test F	*	*	*	*

According to the Duncan Multiple Test, there is no significant difference between the figures followed by the same letters at 5%.

Appendix 19. Gross income, cost of production factors and net income on the basis of different water patterns and nitrogen doses on hydromorphic soil in warm dry season (F.CFA/ha)

N doses (kg/ha	Continuous submersion			Field capacity			Field capacity and submersion			Submersion and field capacity		
	Gross income	Cost of production	Net income	Gross income	Cost of production	Net income	Gross income	Cost of production	Net income	Gross income	Cost of production	Net income
N_0	31 875	115 996	– 84 121	22 287	107 500	– 85 212	28 050	118 084	–90 034	44 013	115 529	–71 516
N_{60}	113 475	142 543	– 29 068.8	21 012	124 220	–103 208	80 962	135 244	–48 288	72 675	135 500	–62 825
N_{120}	273 360	164 119.6	109 240	58 650	142 695	– 84 045	189 975	151 236	38 739	160 650	157 770	–29 120
N_{180}	336 600	185 696.4	150 903.6	68 850	161 862	– 93 012	226 950	169 856	57 093	265 200	178 250	86 950
N_{240}	395 250	205 776.2	*189 473.8*	133 875	176 868	– 42 993	218 025	189 752	28 273	246 075	197 126	58 949
N_0+C	56 712	131 918	– 75 206	28 662	10 338	– 74 676	31 813	122 646	–63 353	38 250	125 421	–87 171
N_{60}+C	135 150	152 070.6	– 16 920	59 925	119 549	– 59 624	117 300	137 981	–20 680	51 000	143 347	–92 347
N_{120}+C	316 200	171 200.8	145 000	42 738	139 264	– 65 770	138 975	152 914	–13 939	177 837	163 099	14 738
N_{180}+C	316 200	190 295	125 905	119 850	158 102	– 38 252	207 825	175 804	32 021	248 625	180 039	68 586
N_{240}+C	362 100	210 813	*151 287*	135 150	175 043	– 39 893	230 775	194 059	36 716	265 200	201 250	63 950

C = Compost.

Appendix 20. Gross income, cost of production factors and net income on the basis of different water patterns and doses of nitrogen on vertisols in dry warm season (F.CFA/ha)

N doses (kg/ha	Continuous submersion			Field capacity			Field capacity and submersion			Submersion and field capacity		
	Gross income	Cost of production	Net income	Gross income	Cost of production	Net income	Gross income	Cost of production	Net income	Gross income	Cost of production	Net income
N_0	25 500	135 312	−109 812	11 475	107 496	− 96 021	49 725	118 086	− 68 360	17 850	152 865	−105 015
N_{60}	135 150	151 742	− 16 592	30 600	124 453	− 93 853	133 875	133 875	− 1 368	49 725	139 587	− 89 862
N_{120}	193 800	167 077	26 723	56 100	137 270	− 91 170	281 775	151 240	130 535	155 550	160 580	− 5 030
N_{180}	321 800	195 186	*126 114*	48 450	161 756	−113 306	303 450	169 856	133 600	108 375	181 243	− 72 768
N_{240}	299 625	216 653	82 972	67 575	184 143	−116 568	393 975	189 743	*204 200*	207 825	202 163	5 662
N_0+C	58 650	138 415	− 79 765	12 750	111 096	− 98 346	87 975	122 646	− 34 670	17 850	128 560	−110 710
$N_{60}+C$	158 100	150 136	7 964	10 200	131 183	−120 982	150 450	137 983	12 467	94 758	145 245	− 50 487
$N_{120}+C$	188 700	179 487	9 213	38 250	148 370	−110 100	277 950	152 920	125 030	79 050	157 222	− 78 172
$N_{180}+C$	369 750	195 259	*174 491*	57 375	166 789	−109 400	332 775	175 806	156 970	130 050	181 608	− 51 558
$N_{240}+C$	342 975	221 143	121 832	52 275	183 839	−131 600	385 050	194 043	*191 007*	160 650	203 403	− 42 753

C = Compost.

Water and Fertilizer Management for Wheat in Pakistan

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Summary

The paper reviews the role of fertilizer in contributing to increased wheat production and summarizes fertilizer responses under different moisture regimes. Following are the highlights:

- Wheat production in Pakistan has increased by 67% from 6.9 million tonnes in 1971/72 to 11.5 million tonnes in 1980/81, and yield has improved by 38% from 1190 kg/ha to 1643 kg/ha during this period. The fertilizer use to wheat is estimated to have increased by 131% from 32 kg/ha to 74 kg/ha during the 10-year period. This indicates an over-riding role of fertilizer in improving wheat yield in Pakistan.
- The data from the fertilizer trials in farmers' fields show 850, 625–700, and 200 to 300 kg/ha responses to initial application of 60 kg/ha each of N, P_2O_5 and K_2O respectively in irrigated wheat, and 459, 215 and 138 kg/ha responses to 30 kg/ha each of these nutrients in rainfed wheat.
- The results from long-term fertilizer experiments indicated response only to nitrogen in the initial years but later declined while the NP and NPK responses increased over a 6-year period.
- The studies on consumptive use of water for wheat clearly indicate that fertilizer increases water use efficiency, and that reduction in yield due to moisture stress can be more than compensated by fertilizer application.

1. Introduction

Wheat is the staple food in Pakistan and during 1980/81 constituted, according to *GOP [10]* statistics, 71% of all foodgrains. Although the introduction of semi-dwarf varieties of wheat during the late sixties ushered in an era of Green Revolution yet the process of development takes its time: a number of factors, besides the variety, determine the yield production. However, fertilizer use and irrigation management are the key components of improved wheat technology. Needless to say that extension of the production technology to the farm level ultimately determines the diffu-

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sion of the package of improved practices amongst the farmers and its adoption by them. That 19 progressive farmers obtained in a wheat yield contest during 1976/77 an average of 5949 kg/ha (the highest yield being 6914 kg/ha) against the national irrigated average of 1691 kg/ha during that year, points to the big yield gap *[11, 14]*. In rainfed areas 11 farmers under FFS programme *[7]* obtained an average yield of 3250 kg/ha in 1980 against the national average of 877 kg/ha. Studies by *Kasana et al. [12]* and *NFC [15]* indicate that 56 to 80% of the yield gap in irrigated wheat and 30 to 53% in rainfed wheat can be attributed to fertilizer. Thus the pivotal role of fertilizer use for increasing wheat yield can hardly be over-emphasized. The paper reviews the effects of fertilizer use on wheat under varying moisture regimes with a view to understanding the substantial growth of wheat production in Pakistan which is typical for countries with arid to semi-arid conditions.

2. Agro-ecological conditions

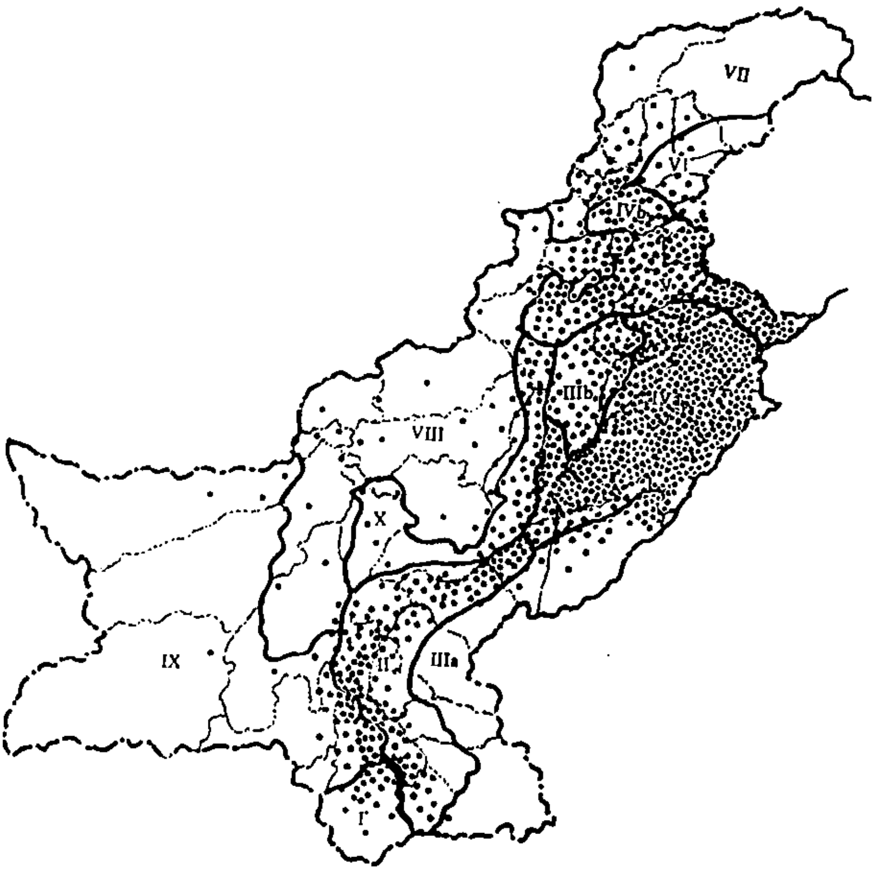
The crop yield is a function of crop, soil, climate and management *(Fitts [8])*. Since the climate and the nature of soil have an overriding influence on the crop production levels, a brief description of the agro-ecology of Pakistan will be helpful in understanding the wheat production performance and problems.

2.1 Agro-ecological zones and wheat production

Pakistan Agricultural Research Council (PARC) [19] has delineated ten agro-ecological regions of Pakistan based on physiography, geology, climate, agricultural land use and water availability, as shown in Figure 1. The wheat acreage has been indicated in the map by dots, each dot representing 5000 ha. It will be seen that wheat acreage is concentrated in northern and southern irrigated plains followed by rainfed lands and sandy desert. Brief description of the agro-ecological zones is given in Annexe 1.

2.2 Climate

Pakistan, situated between latitude 24° and 37° north and longitude 62° east and stretching over 1600 kilometers north to south and 885 kilometers east to west with a total area of 796 095 square kilometers, has a sub-tropical and semi-arid climate. The annual rainfall ranges from 125 mm in the extreme southern plains to 500 to 875 mm in submountainous and northern plains. About 70% of the total rain falls as heavy downpour in summer during July and September, and 30% in winter. The summers except in the mountainous areas, are very hot with a maximum temperature of more than 40 °C, and the winters are mild with a maximum temperature around 20 °C and the minimum a few degrees above the freezing point *[9]*.



I Indus Delta
IV Northern irrigated plain (a & b)
VII Northern dry mountains
X Staiman Piedmont
II Southern irrigated plain
V Barani lands
VIII Western dry mountains
III Sandy desert (a & b)
VI Wet mountains
IX Dry western plateau

Fig.1. Agro-ecological zones and wheat production in Pakistan. Scale – 1:7 500 000

2.3 Soil resources and conditions

Of the total land area of 79.6 million hectares only about 25% is cultivated (20.15 million ha). The irrigated area constitutes 71% (14.32 million ha) and Barani (rainfed) 29%. The average farm size is 5.3 hectares *(GOP [11])*.
The *Canal Commanded Area (CCA)* actually under cultivation occupies about 11 million ha in the Indus plain. The soil problems and the land capability classes of the cultivated area in the *CCA* are, according to *Mian* and *Ashraf [13]*, as shown in Figure 2. The bulk (92%) of the area is good or very good agricultural land (I and II land capability classes), well suited to common crops. In the case of Barani (rainfed) areas nearly one half has moderate potential where agricultural production can be considerably increased through proper management, and the other half has low potential. The normal soils in general are alkaline with pH between 7.8 and 8.1, and calcareous (around 8% free $CaCO_3$ content) in nature. They are low in nitrogen (organic matter around 0.75%), low to medium in phosphorus *(Olsen* P between 4 and 7 ppm), and have 100 to 225 ppm K content (ammonium acetate extractable) depending on soil texture.

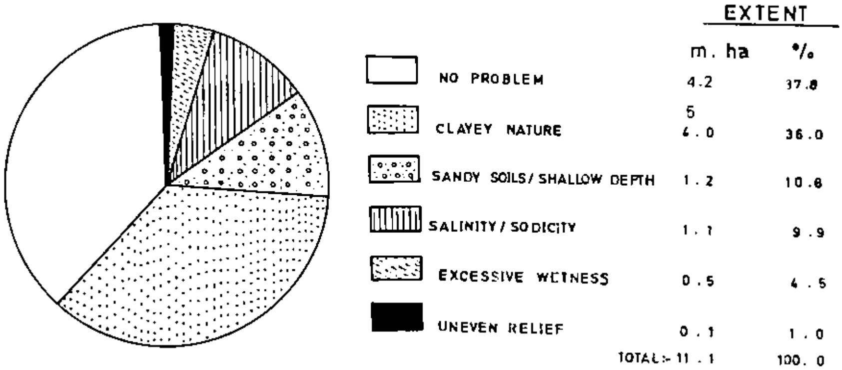


Fig.2. Soil problems in cultivated part of *Canal Commanded Area (CCA)*

3. Development of fertilizer usage in wheat

3.1 Fertilizer use development and wheat production

The rapid and phenomenal growth of fertilizer usage in Pakistan is one of the success stories in the field of agriculture. The data in Table 1 show the overall consumption figures *[11, 17]*. The fertilizer use in 1980/81 was 55 kg/cropped ha against 31 kg/ha in India *(Tandon [28])*. A number of factors contributed to the increase in fertilizer demand. They include increase in crop area, expansion of the

Table 1. Trends in fertilizer use in Pakistan

Year	N	P_2O_5	K_2O	Total	Fertilizer use
	(thousand tonne)				(kg/cropped ha)
1952–53	1.0	–	–	1.0	–
1959–60	19.3	0.1	–	19.4	1.3
1963–64	68.0	0.7	–	68.7	4.6
1966–67	110.8	3.9	0.1	116.8	7.1
1970–71	251.5	30.5	1.2	283.2	17.0
1975–76	445.3	102.5	2.8	550.6	30.8
1980–81	842.9	226.9	9.6	1079.4	54.7
1982–83*	922.0	255.0	23.0	1200.0	60.9

* Estimate

irrigated areas, adoption of the high-yielding varieties, fertilizer subsidy as well as the extension of improved technology to the farm-level providing the means to farmers for increasing incomes through higher yield production.

Of the total consumption of 1.079 million nutrient tonnes in 1980/81, 78% was N, 21% P_2O_5 and less than 1% K_2O. Overall, the NPK ratio was 3.7:1:0.04. The extent of usage is mainly on four major crops *i.e.* wheat, rice, cotton and sugarcane which comprise nearly 87% of the total consumption. The percentage distribution of usage by crops, based on the *Fifth Five-Year Plan* estimates, is shown in Figure 3.

The fertilizer consumption nearly doubled during the five-year period from 1975/76 to 1979/80 (*i.e.* from 0.55 million to 1.08 million nutrient tonnes). The proportion of the annual consumption during the Rabi (winter) season averaged 57% during this period. Wheat is the main crop fertilized during the Rabi season (Table 2).

Data on wheat production and fertilizer use for the 10-year period, from 1971/72 to 1980/81, presented in Table 2 indicate that area under wheat increased from 5.8

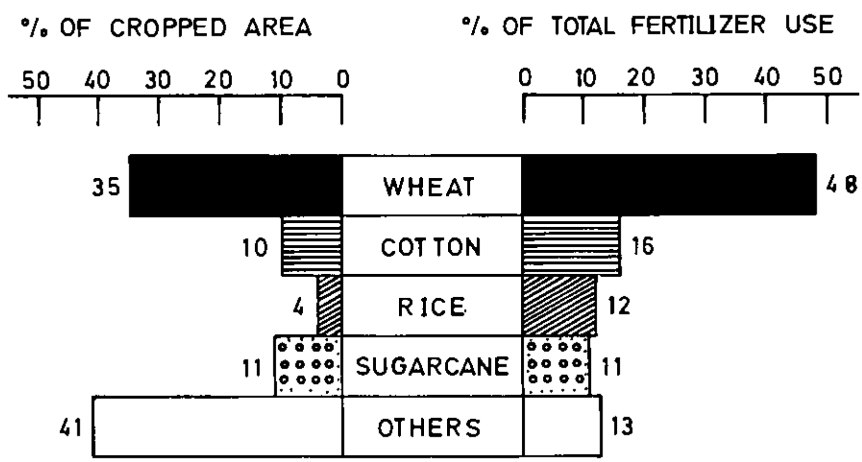


Fig.3. Fertilizer use by crops

Table 2. Wheat production and fertilizer consumption in Pakistan

Year	Area			Prod.	Yield (kg/ha)				Fertilizer consumption	
	Total m. ha	Irrig. %	HYVs %	m. ton	Average	Irrig.	Rainfed	HYVs	Annual 1000 t	Fertilizer use on wheat (kg/ha)*
1971–72	5.8	75	35	6.9	1190	1439	452	1605	382	32
1972–73	6.0	75	57	7.4	1245	1485	526	1651	437	35
1973–74	6.1	74	57	7.6	1245	1494	544	1651	403	32
1974–75	5.8	77	64	7.7	1319	1549	572	1642	426	35
1975–76	6.1	75	66	8.7	1420	1669	646	1734	551	43
1976–77	6.4	75	72	9.1	1431	1691	639	1719	631	47
1977–78	6.4	77	74	8.4	1316	1510	675	1517	712	54
1978–79	6.7	78	76	10.0	1488	1678	824	1675	880	63
1979–80	6.9	79	81	10.9	1568	1754	877	1715	1044	72
1980–81	7.0	78	90	11.5	1643	1847	908	1798	1080	74

* Fertilizer use to wheat estimated at 48% of the total fertilizer consumption in the country.

Table 3. Percentage of wheat farmers using fertilizer (Average for 1979–80 and 1980–81)

	Percentage of fertilizer users applying	
	N	P_2O_5
Irrigated wheat	84	65
Rainfed wheat	71	32
All wheat area	79	53

million ha in 1971/72 to 7.0 million ha in 1980/81. Of this the increase in area for irrigated wheat was from 75 to 78%, and under high-yielding varieties (HYVs) from 35 to 90%. During the decade the total wheat production increased from 6.9 to 11.5 million tonnes. The national average yield increased 38% from 1190 to 1643 kg/ha. During the same period the average yield under irrigated area increased by 28% to a level of 1847 kg/ha while under rainfed conditions the average yield which was lower than the irrigated, has doubled, from 452 to 908 kg/ha. The trend in the rainfed areas implies the potential of barani areas to absorb improved technology.

More fertilizers are applied to wheat than to any other crop. It is difficult to quantify, yet, according to *Saleem* and *Bertilsson [25]*, it accounts for nearly 48% of the N and 54% of the phosphorus consumption in the country. Assuming that wheat gets an average share, in total fertilizer offtake, of 48% the national average use of fertilizer per hectare in wheat has increased from 32 kg/ha in 1971/72 to 74 kg/ha in 1980/81; with the corresponding yield of 1190 to 1643 kg/ha. The NPK usage of 74 kg/ha on wheat in 1980/81 is about 50 to 60% of the recommended level. However there are large variations among different areas. In the actual farm conditions, still a number of farmers, especially in rainfed areas, apply nitrogen alone, as seen from results of *NFC* survey studies *[16]* shown in Table 3.

The NPK ratio, assuming that 48% N, 54% phosphorus and 50% potassium of the total consumption goes to wheat, works out as 3.1:1.0:0.1. This ratio indicates the degree of balance between the usage of these essential elements. While the trend is towards a more favourable balance between N and P, there is however, a need to improve the use of K. Based on the recommended usage of 75–120 kg N + 50–100 kg P_2O_5 + 30–60 kg K_2O/ha for irrigated wheat in the Punjab the desired ratio should be between 1.2 to 1.5:1.0:0.6 among N, P_2O_5 and K_2O.

3.2 Fertilizer contribution to wheat production

The complex nature of factors involved in crop growth make it difficult to say precisely how much of the production can be ascribed to fertilizers. However, it is generally agreed that fertilizer contribution to yield increase is of the order of 50%, and that 1 kg of fertilizer nutrient can be expected to produce 10 kg of additional cereals, at least for initial fertilizer application *(Dudal [5]); Peter [21])*. The results of more than 2000 fertilizer experiments on farmers' fields in Pakistan show a response ratio of 10.7–11.3 for wheat *(Saleem* and *Bertilsson [25].)* Using the average Pakistan wheat production for 1978/79–1980/81 as 10 760 million tonnes and assuming that 48% of the total annual nutrients are consumed by wheat, 44.7% of the total wheat production during the 3-year period, can be attributed to fertilizer use on the basis of nutrient grain ratio of 10. Assuming nutrient grain ratios of 9.0, 8.0 and 7.5 would mean 40.2, 35.7 and 33.5% contributions due to the fertilizer use respectively. A previous study by *Saleem* and *Bertilsson [25]* where wheat production due to increases in area and fertilizer use were delineated, an average response of 7.5 explained the wheat yield development over an 8-year period from 1971/72 to 1978/79, and indicated 31% of the total wheat production in 1978/79 due to fertilizer use. A lower wheat response ratio compared with that obtained from experimental results may be due to less efficiency of fertilizer use in farmers' conditions than at the experimental sites. In such estimates it is difficult, however, to ascertain the national figure which would represent wheat yield without fertilizer use. The 'control' yields in fertilizer experiments on farmers' fields are considered high because they lack representation of marginal and problem soils.

A look at 10-year data from 1971/72 to 1980/81 in Table 2 would indicate that increase in wheat yield per hectare over the years is associated with per hectare increase in fertilizer use. A positive correlation was found by *Saleem* and *Bertilsson [25]* between wheat yields and fertilizer use in different districts of the Punjab province of Pakistan (Figure 4). Such a correlation may be questioned because of other factors which affect the development of wheat yield. Nevertheless, it underlines the pivotal role of fertilizers in increasing wheat yield. A similar relationship between

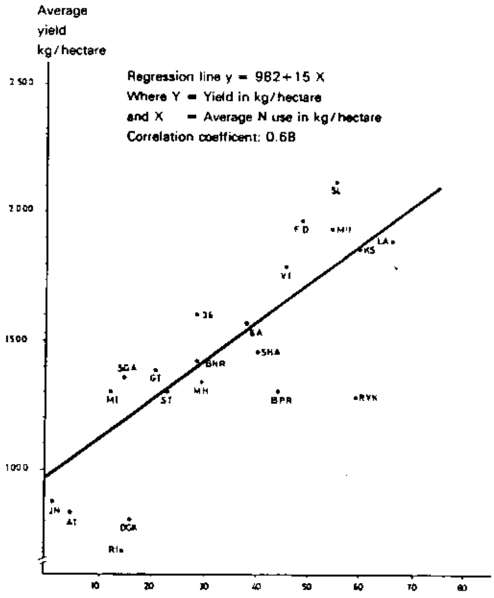


Fig. 4. Relationship between districtwise average wheat yield and average N use in Punjab for 1978–79 (Lahore and Kasur Districts taken together).

national average fertilizer usage and average crop yield has been developed by Couston as reported by *Peter [21]* by plotting the calculated crop value indices against rates of NPK for 41 countries.

4. Water management for wheat production

4.1 Available water

The Indus river basin irrigation system of Pakistan, one of the largest in the world, delivered in 1980/81 through about 63 000 km of canals, 9.7 million hectare meter (MHM) water at the watercourse to command an area of 10.4 million ha. In addition about 3.9 million ha are irrigated by over 170 000 tubewells and other sources contributing 4.0 MHM water. Due to conveyance losses and low field application efficiency only 6.2 MHM water is, however, available for consumption by crops

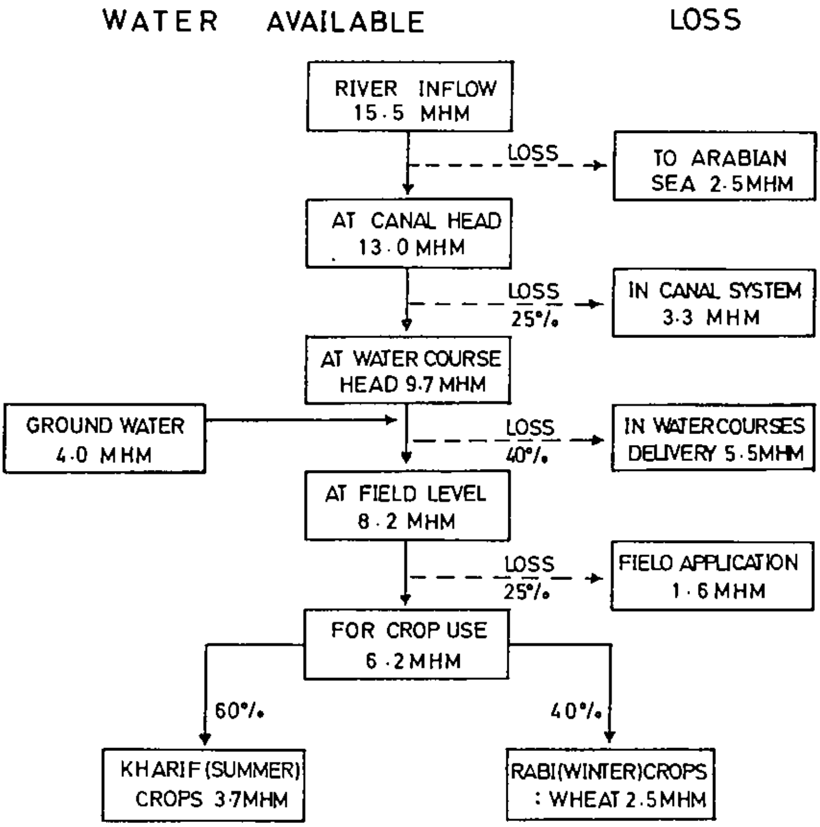


Fig. 5. Irrigation water available for Rabi (wheat) (adapted from irrigation scheduling in Pakistan, *Ahmed, Shahid [1]*)

(Figure 5). Of this 2.5 MHM water is estimated for Rabi crops. Wheat is the main crop in the Rabi season and its water requirement in the Indus Basin irrigation system has been reported by *Ahmed [1]* as 1.9 MHM.
The contribution of rain to irrigated crops in the Indus basin is estimated at about 1.7 MHM. Thus the total water available for crop production comes to 7.9 MHM, whereas the water requirements based on consumptive use of water, is 8.5 MHM *(Ahmed [1])*. The shortage can be made up by improving the efficiency of water delivery and field application.

4.2 Rainfed areas

The rainfed (Barani) areas can be broadly classified in three zones *(PARC [18])*, namely
- *Areas where average annual rainfall is sufficient (380 mm and above)* to grow wheat with proper water management and conservation techniques.
- *Areas with average annual rainfall between 200 and 380 mm* where only summer crop can be grown.
- *Areas with average rainfall less than 200 mm* where land-use is limited to grazing of the small amount of forage produced.

Substantial improvement in crop yields is possible in rainfed areas receiving about 250 mm rainfall if proper management techniques are adopted *[18]*.

4.3 Critical stages for irrigation

The water requirement for a satisfactory wheat crop, as summarized by *Arnon [2]*, in Table 4, is 350–400 mm. The spread of the water over the critical stages of wheat development is also considered important by *Arnon [2]* because the moisture stress
- *before tillering* suppresses tillers;
- *shortly before earing* reduces the rate of elongation of the internodes;
- *prior to anthesis* affects the number of grains per ear;
- *at anthesis and shortly after* reduces grain size; and
- *prolonged stress during grain formation* produces shrivelled grains.

Table 4. Water requirements of wheat

Period	Stage of development	Amount of water (mm)	Source of water
October–November	Before sowing	100–150	Irrigation
December–January	Emergence to tillering	50–100	Rainfall
February–March	Tillering to earing	100–150	Rainfall and irrigation
April	Grain formation	50	Rainfall or irrigation

Wheat in Pakistan is sown during mid-October to mid-December, depending on the variety and the area, and harvested in April (end of March in the south and early May in the north). *Qureshi et al [22]* report two critical stages for water requirements of wheat: the first at tillering and the second at flowering, between anthesis and grain formation. Moisture stress approximately 21–35 days after planting results in reduced tillers because it is at this time when the number of headed tillers is determined and the crown root development begins. With adequate root system developed by proper fertilization the probablity of severe stress occuring at the second stage is reduced.
Wheat crop gets a total of 4–5 irrigations besides a preplant irrigation, applied through inundation or level basin system in 0.4 ha units, further divided into 4–8 equal parts with dikes. The first irrigation is recommended within two to three weeks after emergence. However, in rice areas where the sub-soil is moist and the moisture retention power of the soil is high, the first irrigation can be delayed by almost over a month after emergence. The remaining irrigations, depending on the frequency of rainfall, are distributed between the two critical stages mentioned above. However, one irrigation is important towards the end of March if the season becomes warm and dry.
In a situation of limited availability of water the efficiency of fertilizer can only be optimized if water stress at the critical stages is avoided. When only one irrigation is possible that should be at two to three weeks after germination. *Vijayalakshmi et al [30]* has also reported crown root development as the most critical stage for moisture stress for wheat in India.

5. Wheat response to fertilizer application

Voluminous data generated from the fertilizer trials on wheat in farmers' fields during the last two decades, both under irrigated and rainfed conditions, are available *(Bhatti et al. [30]; Kasana et al. [12])*. These trials included tall local varieties of wheat up to the late sixties when semi-dwarf Mexican varieties were introduced. So far more than 20 000 trials have been conducted on wheat alone. The trials besides testing the graded applications of different nutrients, include sources and time of application of nutrients, studies on varietal response, etc. The data on wheat (semi-dwarf varieties) response to N, P and K are summarized below.

5.1 Irrigated wheat

The results from a large numher of fertilizer trials in farmers' fields in the Punjab presented in Table 5A indicate that wheat yield can be increased by 150%, from 1554 kg/ha to 3886 kg/ha, with balanced NPK fertilizer application. Recent data from another experimental plan from 354 trials during 1978/79 to 1981/82 *[12]* show 179% increase, from 1438 kg/ha to 4010 kg/ha, with 168:168:91 N, P_2O_5 and K_2O kg/ha. Figure 6 shows the response curve based on these four years data.
As regards response to individual nutrients, average results of 259 nitrogen response trials, during 1972/73 to 1974/75, of 132 and 129 phosphorus and potash response

Table 5. Response of wheat to fertilizer application

Treatments $N:P_2O_5:K_2O$ kg/ha	No. of observations	Yield kg/ha	Increase in yield over control kg/ha	%	kg wheat/ kg nutrient	kg wheat/ kg of N, P_2O_5 and K_2O	Water use efficiency* (WUE)
*A. Irrigated wheat***							
0: 0: 0	1225	1554	–	–	–	–	3.5
90: 0: 0	742	2667	1113	71	12.4	12.4(N)	5.9
90:60: 0	1052	3292	1738	112	11.6	10.4(P_2O_5)	7.3
90:90: 0	232	3457	1903	122	10.6	–	7.7
120:60: 0	748	3585	2031	131	11.3	–	8.0
120:60:60	748	3886	2332	150	9.7	5.0(K_2O)	8.6
*B. Rainfed wheat****							
0: 0: 0		1065	–	–	–	–	3.0
30: 0: 0		1524	459	43	15.3	15.3(N)	4.4
30:30: 0		1739	674	63	11.2	7.1(P_2O_5)	5.0
60:30: 0		1980	915	86	10.2	–	5.7
60:60: 0		2191	1126	106	9.4	–	6.3
60:60:30		2329	1264	119	8.4	4.6(K_2O)	6.7

* Assuming E_{ta} as 450 and 350 mm for irrigated and rainfed wheat respectively
** Yield results average of 11 years; 1971–72 to 1981–82
*** Yield results average of 184 trials during 1970–71 to 1976–77

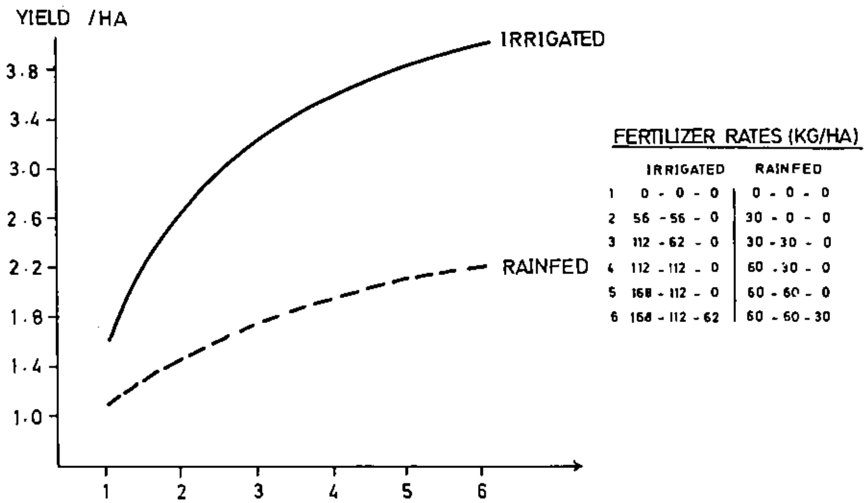


Fig.6. Response curves for irrigated and rainfed wheat in Pakistan

trials respectively during 1975/76 to 1977/78, are presented in Figure 7. The responses to 60 kg/ha each of N, P_2O_5 and K_2O work out as about 850, 625–700, and 200–300 kg/ha respectively for the initial application and about 650, 350 and 150 kg/ha for the subsequent application. The response to nitrogen and phosphorus is widespread and discernable while that to potash is in less magnitude. There are observations that response to potash can be expected in certain areas and situations such as light textured soils and wheat following rice crop.

The trend and the magnitude of response in other Provinces of Pakistan is more or less similar to the Punjab: in Sind an average response obtained by *Choudhry** during 1974/75 to 1981/82 is 870, 511 and 257 kg/ha for 134 kg/ha N and 67 kg/ha each of P_2O_5 and K_2O respectively, with control yield as 1291 kg/ha. In North West Frontier Province *Rehman*** got from 17 trials during 1977/78 and 1979/80 an average response of 1201, 664 and 373 kg/ha due to 100, 63 and 34 kg/ha of N, P_2O_5 and K_2O respectively.

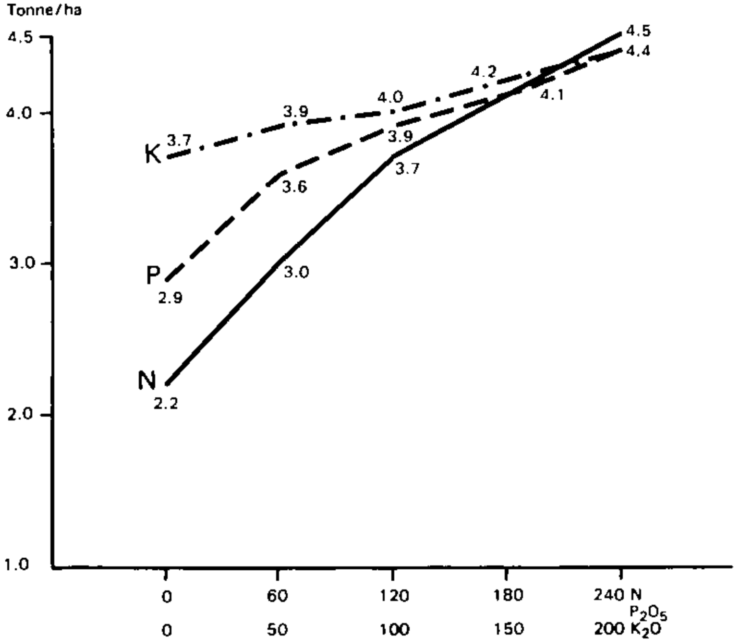


Fig. 7. Wheat response to individual nutrients (N response in the presence of 120 P_2O_5 + 60 K_2O [kg/ha], P in the presence of 175 N + 75 K_2O [kg/ha] and K in the presence of 175 N + 200 P_2O_5 [kg/ha], applied as basal dose)

* Personal communication from Dr. *Taj Mohammad Choudhry*, Agricultural Research Institute, Tandojam/Pakistan

** Unpublished data by Mr. *Habib-ur-Rehman*, Agricultural Research Institute, Tarnab/Pakistan

Tandon [28], based on 6869 fertilizer trials on irrigated wheat in farmers' fields in India over ten years, has reported a response of 1033, 696 and 233 kg/ha for 120 kg/ha N, and 60 kg/ha each of P_2O_5 and K_2O respectively, with 1919 kg/ha as control yield. For northern alluvial conditions in India, a response of 1505, 710 and 147 kg/ha for 120 kg/ha N and 60 kg/ha each of P_2O_5 and K_2O respectively has been reported by *Rao and De [24].*

5.2 Rainfed wheat

The results presented in Table 5B indicate an increase in the yield of rainfed wheat by 119%, from 1065 to 2329 kg/ha, with 60:60:30 (N, P_2O_5, K_2O kg/ha) application. The shape of the response curve is shown in Figure 6. The response to individual nutrients works out as 459, 215 and 138 kg/ha for 30 kg/ha each of N, P_2O_5 and K_2O respectively. The trend for N and K response is similar to irrigated wheat except for P which indicates a relatively less response.

The rainfed wheat in India is similar in yield performance and response to fertilizer application; the control yield based on 954 trials in farmers' fields was 910 kg/ha and response to 50 kg/ha N, and 25 kg/ha each of P_2O_5 and K_2O was 480, 310 and 80 kg/ha respectively *(ENSP [6]).*

5.3 Response pattern from long-term fertilizer trial

The pattern of wheat response to fertilizer treatment in long-term trials is outside the scope of this paper. However, a passing reference must be made to the results of a long-term experiment at the *Agricultural Research Institute,* Tandojam, Sind*, in order to show that the yield without fertilizer and with N alone declines over the years whereas the response to NP and NPK treatments increases as shown in Figure 8. The data from the same experiment on response to K (Figure 9) indicates progressively increasing response over the years, from 57 kg/ha in 1975/76 to 505 kg/ha in 1980/81. It underlines the need to monitor the nutrient balance over long periods of cropping and to apply NPK for obtaining increased wheat yield.

5.4 Response ratios

The crop response to fertilizer application is also expressed, generally for the purpose of estimating the contribution of fertilizer to food production, as grain-nutrient ratio or response ratio defined as the units of food grain produced by one unit of plant nutrients. The response ratio is, however, variable and depends upon the level of fertilizer application, soil type and other agro-climatic conditions. The response ratios for lower levels of fertilizer application are higher and for higher levels lower. However, the response ratios at levels close to fertilizer recommendations, both in irrigated and rainfed wheat, are about the same (9.7 in irrigated wheat and 10.2 in rainfed wheat).

* Personal communication from Dr. *Taj Mohammad Choudhry,* Agric. Res. Institute, Tandojam, Sind/Pakistan

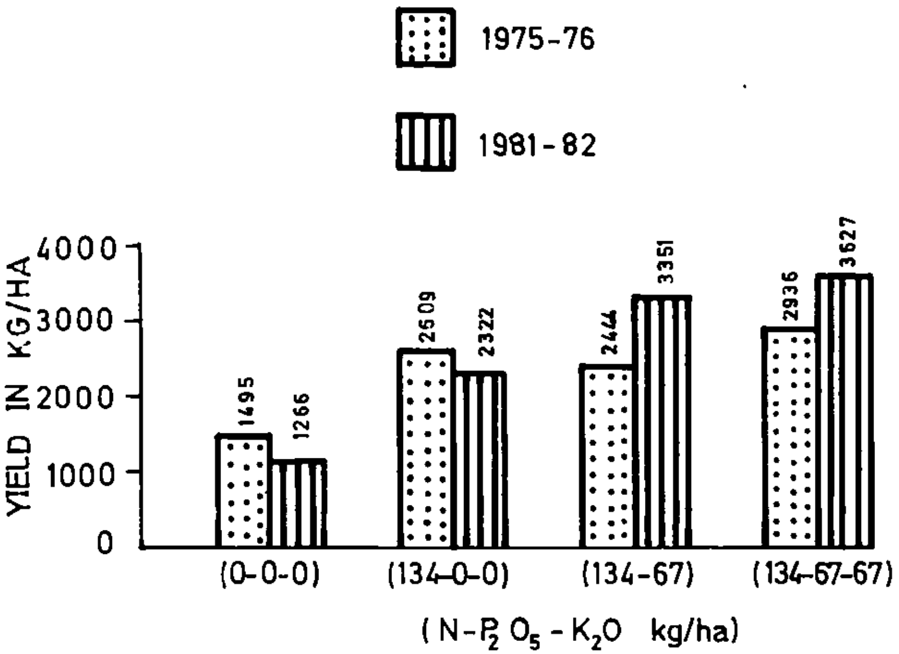


Fig.8. Wheat response to fertilizers in a long-term fertility experiment at A.R.I. Tandojam (1975–1981)

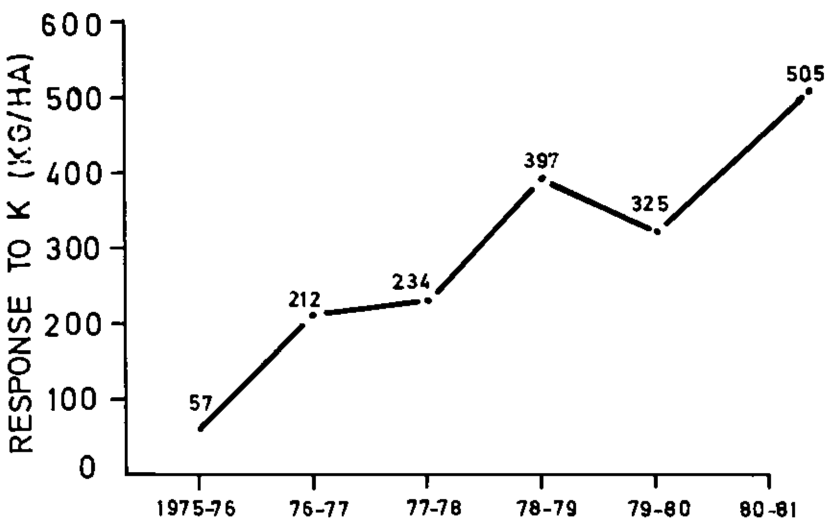


Fig.9. Wheat response to potash in a long-term experiment (kg/ha)

The average response ratios for the individual nutrients, based on three sets of data (Table 5, Figures 6 and 7) are in the range of 10.0 to 13.3 for 90 to 120 kg/ha N, 9.0 to 10.4 for 60 kg/ha P_2O_5 and 4.0 to 5.0 for 50 to 60 kg/ha K_2O in case of irrigated wheat, and 15.3, 7.1 and 4.6 for 30 kg/ha of each N, P_2O_5 and K_2O respectively in rainfed wheat. The average response ratios in India are 8.6, 11.6 and 3.9 for 120 kg/ha N and 60 kg/ha each of P_2O_5 and K_2O respectively for irrigated wheat *(Tandon [28])*, and 9.6, 12.4 and 3.2 for 50 kg/ha N and 25 kg/ha each of P_2O_5 and K_2O respectively for rainfed wheat *(ENSP [6])*.

5.5 Profitability of fertilizer use

There are two important yardsticks of profitability: *value-cost ratio (VCR)* as the ratio between the value of the additional wheat yield and the cost of fertilizer; and *net return* as the value of the additional wheat yield minus the cost of fertilizer. The VCR net profit for different fertilizer treatments, both for irrigated and rainfed conditions, are given in Table 6. The data indicate the highest VCR and net profit for $N:P_2O_5:K_2O$ treatment at 120:60:60 kg/ha rates in irrigated wheat. However, in rainfed wheat the highest VCRs are for 30 kg/ha N and 30–30 kg/ha ($N:P_2O_5$) treatments whereas the highest net profit is for 60:60:30 kg/ha ($N:P_2O_5:K_2O$) treatment. Thus considering both the VCR and the net profit 60:60:30 is the most profitable treatment in rainfed wheat as well.

Table 6. Economics of fertilizer use

Treatments $N:P_2O_5:K_2O$	Response (kg/ha)	VCR*	Net profit (Rs/ha)
Irrigated wheat			
90: 0: 0	1110	3.8	1300
60:60: 0	1300	4.0	1494
90:60: 0	1740	4.2	2124
90:90: 0	1900	4.0	2281
120:60: 0	2030	4.0	2434
120:60:60	2330	4.2	2830
Rainfed wheat			
30: 0: 0	460	4.8	582
60: 0: 0	520	2.7	524
30:30: 0	670	4.2	819
60:30: 0	920	2.9	1065
60:60: 0	1130	3.6	1302
90:60: 0	1202	2.9	1263
60:60:30	1260	3.7	1468

* The prices used are as of February 1983:
- N at Rs. 5.13/kg
- P_2O_5 at Rs. 3.30/kg
- K_2O at Rs. 1.40/kg
- Wheat at Rs. 1.60/kg
- 1$ = 12.75 Rupees (Rs.)

Table 7. Relationship between wheat and fertilizer prices in Pakistan

Year	Wheat needed to buy one kg of*		
	N	P_2O_5	K_2O
1965–66	2.73	2.08	1.90
1970–71	2.70	2.28	1.74
1975–76	2.99	2.46	1.29
1980–81	2.79	1.92	0.82
1982–83	3.21	2.06	0.88

* Price per unit of fertilizer nutrient divided by value per unit of wheat.

The wheat and fertilizer prices in Pakistan have undergone periodic revision in the past. However, it is the relative price, the commodity-input price relationship, and not the individual prices, which provides incentive to the growers. This relationship has fluctuated in Pakistan only within very narrow limits as reviewed by *Saleem* and *Gertsch [26]),* and summarized in Table 7. The price for potash has been maintained more favourable in view of the small quantity being used at present.

5.6 Fertilizer application

Fertilizer recommendations are formulated according to the specific agro-climatic conditions, fertility level of the soil and the amount of water available through irrigation and rainfall. The generalized recommendation for irrigated wheat is 120–150 N + 60 to 90 P_2O_5 + 30 to 60 K_2O (kg/ha) and for rainfed wheat 45 to 90 N + 30 to 60 P_2O_5 + 0 to 60 K_2O (kg/ha). In irrigated wheat it is primarily the fertility level of the soil and the previous cropping history which modifies the fertilizer rate, while in rainfed wheat it is the amount of rain which determines the rate. Potash is generally recommended to sandy soils, to soils continously irrigated by tubewell water, and to wheat sown after rice or sugarcane crops. Nitrogen is generally applied as urea (ammonium sulphate and calcium ammonium nitrate also available in smaller quantities), phosphorus as Nitrophos, single superphosphate and diammonium phosphate, and potassium as potassium sulphate.

In irrigated wheat, all PK and half of the N is applied broadcast and incorporated in the soil by ploughing and planking, at planting time. The remaining half N is top dressed with first or second irrigation. In rainfed wheat, however, all NPK are applied/ drilled at sowing time. Incorporation of N fertilizers is essential to minimize volatilization losses. Experience shows that the efficiency of P fertilizers can be enhanced when they are applied in combination with farmyard manure.

6. Effect of water on fertilizer response

Farmers generally list water as the most important constraint to fertilizer use. The data presented in the previous sections, however, reveal that fertilizer effects in both irrigated and rainfed conditions follow almost a similar pattern. Yield potential in

Table 8. Effect of irrigation and fertilizer treatments on the yield of wheat in Pakistan (Average of data for 1975/76 to 1979/80 except for Bhalwal which is average for 1975/76 to 1978/79)

Location	Water used		Yield (kg/ha)			Water use efficiency			Saving in water (mm)	Average loss in yield (kg/ha)
	E_{ta} (mm)	Stress Level	F_1	F_2	F_2–F_1	F_1	F_2	F_2–F_1		
Faisalabad	353	M_1	2207	3137	930	6.3	8.9	2.6	–	–
	316	M_2	2114	2899	785	6.7	9.2	2.5	37	166
	293	M_3	1837	2823	986	6.3	9.6	3.3	60	342
		Av.	2053	2953	*900*	6.4	9.2	*2.8*		
Bhalwal	401	M_1	4462	5381	919	11.1	13.4	2.3	–	–
	370	M_2	4289	5017	728	11.6	13.6	2.0	31	269
	336	M_3	4066	4594	528	12.1	13.7	1.6	65	592
		Av.	4272	4997	*725*	11.6	13.6	*2.0*		
Bhakkar	475	M_1	3496	4437	941	7.4	9.3	1.9	–	–
	397	M_2	3086	4149	1063	7.8	10.5	2.7	78	349
	360	M_3	2805	3497	692	7.8	9.7	1.9	115	816
		Av.	3129	4028	*899*	7.6	9.8	*2.2*		
Mian Channu	520	M_1	3151	3629	478	6.1	7.0	0.9	–	–
	441	M_2	2837	3268	431	6.4	7.4	1.0	79	338
	434	M_3	2718	2961	243	6.3	6.8	0.5	86	551
		Av.	2902	3287	*384*	6.3	7.1	0.8	–	–
Tandojam	562	M_1	3386	4021	635	6.0	7.2	1.2	–	–
	467	M_2	2967	3705	738	6.4	7.9	1.5	95	368
	377	M_3	2802	3287	485	7.4	8.7	1.3	185	656
		Av.	3052	3671	*619*	6.6	7.9	1.3		
Average	462	M_1	3185	4028	843	6.9	8.7	1.8	–	–
	398	M_2	2937	3687	750	7.4	9.3	1.9	64	295
	360	M_3	2721	3335	614	7.6	9.3	1.7	112	579
		Av.	2948	3683	*735*	7.3	9.1	1.8		

The package of wheat technology should further be improved and made location-specific through research especially in respect of:
- building soil fertility through an integrated plant nutrition system;
- fertilizer application to crops in cropping sequence in order to make efficient use of fertilizer and available moisture;
- refining fertilizer practices for saline-alkali soils;
- developing water schedules with a view to providing irrigation water during the critical growth stages of wheat especially when water availability is limited and thereby improving efficiency of both water and fertilizer *(Rajput* and *Singh [23]);*
- increasing the amount of water stored in the soil and reducing losses (moisture conservation practices) and making tbe maximum use of the stored water and the subsequent precipitation by appropriate crop management practices *(Bolton [4]);* and
- evolving suitable moisture indices by integrating data on climate, soils and crops *(Singh [27]).*

8. Acknowledgements

The author is grateful to Dr. *G. Kemmler* who provided many useful reference materials and valuable suggestions for improving the final manuscript of the paper. Thanks are also due to Mr. *Shahid Ahmed,* Pakistan Agricultural Research Council, for his help in providing references on irrigational aspects of the paper. Cooperation of *Malik Dost Mohammad,* Director Soil Fertility and Soil Testing Institute, Lahore, Dr. *Taj Mohammad Choudhry,* Agricultural Chemist, Agricultural Research Institute, Tandojam and Mr. *Habib-ur-Rehman,* Agricultural Chemist, Agricultural Research Institute, Tarnab for making available the crop response data is gratefully acknowledged.

Dr. *K. Zschernitz,* Regional FAO Leader Bangkok, Mr. *J.G. Davide,* FAO Agronomist, NFDC and Mr. *R.M.U. Suleman,* Project Director NFDC provided the necessary encouragement and inspiration to complete the paper.

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Annex I. Main features of agro-ecological zones of Pakistan

Zone	Physiography and climate	Soils and land use
I. Indus Delta	Represents the Indus Delta. Climate arid tropical marine; mean daily max. summer temp. between 34–40 °C and winter temp. between 19–20 °C; mean monthly summer rainfall 75 mm and winter less than 5 mm; relative humidity 67–68% in the morning and 30–35% in the afternoon.	Two types of soils: clayey and silty; clay soils found in shallow basins and silty soils are nearly level flat areas; strongly saline-alkali soils are barren and parts of clayey soils are under cultivation with rice, sugarcane, pulses, banana as main crops.
II. Southern irrigated plain	Represents lower Indus Plain formed by the meandering of Indus river. Climate arid subtropical continental with hot summer and mild winter; mean daily max. and min. temp. 40–45 °C and 8.5 °C in the northern areas, and 38–43 °C and 8–12 °C in the southern areas resp., mean monthly summer rainfall 18 mm in the north and 45–55 mm in the south; winter is practically dry.	Soil is silty and sandy loam associated with the active flood plain, upper areas of the flood plain calcareous loamy and clayey. Crops grown: cotton, wheat, mustard, sugarcane, berseem on the left bank of the Indus and rice, wheat, gram and berseem on the right bank; sorghum is the main crop in southern Dadu.
III. Sandy desert	a. Sandy desert with xerophytic vegetation; central part occupied by salt lakes; southern part rainfall 300 mm.	Sandy soils and moving sand dunes, undulating sand ridges 20–25 m high and 1–3 m long; western part has strips of clayey soils; land use: grazing.
	b. Area covered with various forms of sand ridges and dunes and sand sheets with profuse short trees and vegetation; northern part rainfall 300–350 mm.	Sandy and loamy fine sandy soil stable ridges; moderately to strongly calcareous, locally saline-sodic; land use: grazing
IV. Northern irrigated plain	a. Areas between Sutlej and Jhelum rivers; different flood plains and bar uplands. Climate semi-arid to arid (east to southwest) subtropical continental; mean daily max. (summer) and min. (winter) temp. 39.5 °C and 6.2 °C resp. in the east and 41–42 °C and 6 °C resp. in the southwest; mean annual rainfall 300–500 mm in the east and 200–300 mm in the southwest.	Soils sandy loam – clay loam; *southern and central part* calcareous silt loams and about 15% saline-sodic; *northern part* loam and clay loam, mostly non-calcareous, saline sodic in local areas. Canal irrigated agriculture; crops: wheat, rice, sugarcane, oilseeds and millets in the north and wheat, cotton, sugarcane, maize as well as citrus and mangoes in the central and southern part.

Zone	Physiography and climate	Soils and land use
	b. Alluvial valleys of Peshawar and Mardan plains. Climate semi-arid subtropical continental; mean daily max. (summer) and min. (winter) temp. 43 to 44 °C and 5.0 °C resp., mean monthly rainfall range 20–32 mm both in winter and summer	*Central valley* silty clays and clay loams, moderately calcareous with minor salinity sodicity; *sloping sides of the valley* non-calcareous to moderately calcareous loams. Main crops sugarcane, maize, tobacco, wheat, berseem, sugar beet; considerable areas under fruit orchards (pears and plums).
V. *Barani (rainfed) lands*	Covers the Salt Range, Potwar Plateau (generally open and undulating) and the Himalayan Piedmont plains. *Narrow belt along the foot of the mountains* nearly humid, mean daily max. (summer) temp. 38.5 °C and min. (winter) temp. 3–6 °C; mean monthly rainfall 200 mm in summer and 36–50 mm in winter (Jan.–Feb.). *Southwestern part* semi-arid and hot; mean daily max. (summer) temp. 38 °C and min. (winter) temp. 4–7 °C; rainfall mean monthly 85 mm in summer and 30–45 mm in winter.	*Eastern part* dominantly non-calcareous to moderately calcareous silt loams; *west southern part* mainly calcareous loams. Rainfed agriculture is the main land use and wheat and millets the main crops. Part of the eastern area irrigated and wheat, rice maize, millets, oilseeds, pulses grown.
VI. *Wet mountains*	Covers high mountains (intervened by wide and narrow valley plains) and plateaus. *Eastern part* humid with mild summers and cold winters; mean daily max. (summer) temp. 35 °C and min. (winter) temp 0–4 °C; mountain tops snow clad in winter and spring; mean monthly rainfall 236 mm in summer and 116 mm in winter. *Western part* sub-humid Mediterranean, with dry summer, rainfall confined to winter and spring.	Soils silt loam to silty clays, non-calcareous to slightly calcareous (pH 2.5–8.1); organic matter 1% in cultivated fields and 2–4% in forest areas. Only 25% of the area under rainfed agriculture, the rest under forest; main crops maize and wheat (rice grown in small areas irrigated from springs and streams); fruits (mainly apples) in areas at more than 1500 m altitude; olives grown in low hills; on 1500–5000 m altitude coniferous forests and scrub vegetation and above 5000 m permanent snow.

Zone	Physiography and climate	Soils and land use
VII. *Northern dry mountains*	Includes Gilgit, Baltistan, Chitral and Dir; valleys irrigated by glacier-fed streams. Climate undifferentiated; tops of high mountains covered with snow greater part of the year; mild summers and cold winters; mean monthly rainfall 25–75 mm in winter and 10–20 mm in summer.	Soils in valleys deep and clayey and on mountain slopes shallow; non-calcareous acid (pH 5.5–6.5) above 2100 m altitude and calcareous at lower altitudes. Most of the area is used for grazing; a part under scrub forest. Wheat and maize grown rainfed in valleys and lower mountain slopes, and rice irrigated in local areas; fruits grown in flank of streams.
VIII. *Western dry mountains*	Composed of barren hills (1000 to 3000 m) with steep slopes. Climate undifferentiated; greater part semi-arid highlands with mild summers and cold winters. *Southern area* mean daily max. (summer) temp. 30–39 °C and min. (winter) −3 °C to 7.7 °C; mean monthly rainfall 30–35 mm. *Extreme north western area* sub-humid, mean daily max. (summer) temp. 32 °C and min. (winter) temp. 2 °C; mean monthly rainfall 95 mm in summer and 63–95 mm in winter.	Soils in the valleys are loamy, deep and strongly calcareous; mountains have shallow soil. Major land use is grazing; part of the loamy soils grown to wheat with flood water; very small portion is irrigated and fruits (apples, peaches, plums, apricots, grapes), wheat and maize grown.
IX. *Dry western plateau*	Mountainous areas with inter-mountain basins and plateaus, hills generally steep and rugged with narrow valleys in between. Climate arid (desert) tropical; mean daily max. (summer) and min. (winter) temp. 40.5 °C and 3–6 °C resp. in the north and 33 to 34 °C and 11.5–15 °C resp. along the coast; mean monthly rainfall 36–37 mm in summer in the south east and other parts 2.4 mm. Coastal helt receives sea breeze.	Soils in plains silt loams, deep and strongly calcareous, and on hill slopes shallow. The lower regions have xerophytic vegetation and grasses and higher altitudes have juniper forests and wild olives. Land use mainly grazing; melons and sorghum quite extensive; fruits, vegetables and wheat grown where spring or 'Kareze' water is available.

	Zone	Physiography and climate	Soils and land use
X.	*Sulaiman Piedmont*	Comprises Piedmont plains of the Sulaiman Range and alluvial fans built by streams. Climate arid and hot, subtropical continental; mean daily max. (summer) temp. 40–43 °C and min. (winter) temp. 5.8–7.6 °C; mean monthly rainfall 13 mm in winter and 21–38 mm in summer	Soils loams in gently sloping areas but clayey further away; strongly calcareous, with narrow strips of salinity sodicity at the junction of piedmont plain and river flood plain. Torrent-watered cultivation is the main land use, and wheat, millets and some gram and rice main crops.

Co-ordinator's Report on the 4th Session

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Irrigated Farming Systems

It has been my privilege to coordinate a session of which it can be said without hesitation that the different contributors have been really up to the task of bringing forward the intricate problems associated with irrigated farming systems in semi-arid and arid zones and of discussing possible solutions and advisable practices to cope with these problems. I apologize to them, in particular, and to all the participants in this colloquium for not doing justice to their excellent papers in the short summary I will give in the next few minutes.

An overview of the subject was given in the main paper of the session, presented by Professor *Fereres.* Specific aspects were addressed by Drs. *Lekchiri, Aragüés, Enyi* and *Tahir Saleem.*

It is well known that irrigation significantly increases crop yields in areas of insufficient rainfall, where water is the limiting factor for crop production, but one should not view irrigation in these areas as a way to remove a constraint but as a factor to be optimized. In fact, when the system is considered as a whole and most of the constraints for crop production are removed with adequate management practices, crop yields of the irrigated arid and semi-arid zones are the highest anywhere for a given crop and approach the theoretical potential limits for crop production. However, there are many problems to be overcome and pitfalls to be avoided in order to maintain these high yields, both on a short-term and on a long-term basis. It was comforting to hear Prof. *Fereres* express the view that the basic home-work has been essentially done, that the science and technology to be applied is already available and that these problems can be solved if we carry out the necessary adaptive work to connect, in a pragmatic way, theory with practice.

The short-term problems are complex because of the intricate interplay of the different factors that affect production, which make optimization a hard task. Dr. *Fereres* highlighted the most important factors and interactions:

– Soil water levels play a very important role with respect to nutrient movement and uptake in many ways, some of which are now well understood. Thus, improvement of the soil water status by irrigation increases the nutrient demand as the shoot growth rate is accelerated upon relief of soil water stress; the enhanced transpiration under irrigated conditions increases convective transport to the roots and therefore a greater contribution of nutrients by mass flow; irrigation also increases diffusion of nutrients in the soil by increasing the cross-sectional area for nutrient movement.

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Although more or less elaborate models have passed the test of agreement with independent sets of data in the case of nitrogen transformations in the field, the overall dynamics of nutrient transport and transformation have not so far been domesticated into useful models at the field level able to predict patterns of nutrient uptake, because of the large spatial variations in soil water and nutrient parameters.
Irrigation affects root growth. Rooting depths in irrigated and nonirrigated crops are usually similar, provided that the soil profile is fully charged, but the distribution of root-length density in the soil profile is markedly affected. Water uptake patterns are consequently altered, which in turn affect nutrient patterns and should affect our fertilizer placement strategy.

– Irrigation methods markedly affect nutrient movement, nutrient distribution and nutrient uptake. Dr. *Fereres* has reviewed a considerable body of data that show how the irrigation method is probably the most versatile tool in our hands to solve a great variety of nutrition problems. I will not try to summarize his summary, but will make a brief comment on a pertinent example presented by Dr. *Lekchiri*. He brought us up-to-date on his progress in a long-term experiment designed to investigate the effect of irrigation method in the supply of the high phosphorus and potassium requirements of citrus trees. He has shown ways to improve the migration of P and K, both under micro- and macroirrigation conditions, to the levels where the absorbing roots are concentrated and he has been able to ascertain increased nutrient levels in the leaves. It remains to be seen what the effects of the proposed practices will be on actual yields and on the PK status of the soil.
A second general aspect of irrigated farming systems in semi-arid and arid zones is represented by the long-term effects. Irrigation can be bread for today, hunger for tomorrow. We are now becoming painfully aware of the tremendous environmental impact of the introduction of irrigation in extensive areas. Poor irrigation management as practiced by many farmers can produce irreversible damâge to soil productivity in a very short time. Salinity, soil erosion and ground water pollution are among the main long-term effects of irrigation. Salinity is probably the most difficult to deal with under the conditions of limited water supply prevailing in the semi-arid and arid zones. In connection with this problem, Dr. *Aragüés* presented interesting cases at the river basin and at the irrigation district levels (in the Ebro river), of how extreme the salinity situation and the deterioration of return flows can become as the irrigated areas are increased.
For irrigation agriculture to be permanent, the salinity problem must be controlled. Although technology already exists for a very precise irrigation water management, it will not be easy to implement such technology on a grand scale in developing countries and it will probably be necessary to develop new technologies and adapt the existing ones so that the specific circumstances of these countries are taken into account.

– *In situ* technology development is essential because technology transfer has been shown to be a slow process and, at least in some cases, has even lead in the wrong direction. Two excellent papers, one by Dr. *Enyi*, on the response of rice varieties to applied fertilizer in semi-arid zones of Senegal and Mali, and one by Dr. *Tahir Saleem* on wheat fertilization in Pakistan exemplify this idea.

Finally, I would like to bring to your attention and open up for discussion two questions, which have been only marginally treated in this colloquium: i) The first one concerns the connections (or lack of them) between theoretical studies (models), trials in experimental stations, trials in farmer's fields, and actual agricultural practice by 'contest' farmers and by average ones. ii) The second question impinges on the possible contributions of traditional plant breeding and the recently developed genetic engineering techniques to the solution of specific problems of aridoculture. Are our expectations exaggerated?

Chairman of the Colloquium

Prof. Dr. *H. Laudelout*, Soil Science Dept., University of Louvain, Louvain-la-Neuve/Belgium; member of the Scientific Board of the International Potash Institute

Conclusions

Conclusions of the Colloquium and Recommendations (to Science and Agriculture)

H. Laudelout, Soil Science Dept., University of Louvain-la-Neuve/Belgium; member of the Scientific Board of the International Potash Institute*

The discussions were as closely related to the underlying theme of the Colloquium – Nutrient balances and the need for fertilizers in arid and semi-arid regions – as were the papers presented. Thus it is fairly straightforward to discern the present direction of research and status of practice.

There was no lack of examples of the limitations of field experiments the results of which cannot be generalized; this can be a relatively inefficient and costly procedure. The limitations are the more obvious when there is little or no fertilizer response and when this behaviour confirms the results of numerous earlier experiments. The reasons may be quite clear when we are concerned with short-term experiments on the effects of potash fertilizer or with phosphate trials on some of the North African soils. There is really not much point in giving a high priority to this kind of investigation, testing practical fertilizer recommendations, if there is no apparent profit.

Relatively little time was devoted to one important topic – the effect of fertilizer placement – with only one paper devoted to the subject and little reference by way of discussion.

Most of the papers dealt with the fundamental matters of eco-physiology and soil science in relation to the use of fertilizers and this was as expected. Field experimentation, an essential step in transferring research findings to practice – if it is successful – may not yield the desired results and if this is the case we have to make a fresh start based on ideas which can only be provided by an improved understanding of the principles of plant nutrition.

There seemed to be general agreement that water stress in the plant is accompanied by chemical stress through the reduction in convective flux of nutrients to the sites of root absorption. Several examples of the effect of irrigation in improving fertilizer efficiency were mentioned, the effect being explained by improvement in nutrient flux.

Among other things it should be noted that from the point of view of net expenditure of energy there is little difference to the plant between water stress and chemical stress. There is little difference in energy consumption by the plant in taking up water between free water and soil water even when soil moisture content is near per-

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manent wilting point, hut water diffusivity diminishes very rapidly as moisture content falls and thus the renewal of water supply at the root-soil interface is hindered and in consequence mass-flow of nutrient is reduced.

Even when soil moisture content, in an arid area, is maintained (by irrigation) at a satisfactory level, we have not restored the position as regards mineral nutrition to that which applies in the humid temperate climate. This was made clear in several papers. If we accept the approximation that 1 m^3 water is required to produce 1 kg dry matter, the production of 10 kg/m^2 fresh plant material will involve the addition to the soil of 1 kg salt if the water contains 1 g/l salt. This salt has to he eliminated and account taken of the reactions which result from its passage through the profile. In other words, salt is an inevitable by-product of irrigation in arid areas and as irrigation spreads we must be concerned with the importance of return flow downstream of the point of water intake. On a national scale, the proportion of the land surface which can be irrigated is always limited not only by the quantity and quality of available water but also by the problem of desalination.

It is therefore necessary to devise techniques for fertilizer use under such conditions. It has to be recognized that, so far, results in this field have been rather disappointing from the point of view of profitability. One must admit that it is comparatively easy to increase the diffusive flux of an ion towards the root by increasing its concentration in the soil water. If for one reason or another it is low, salinity will increase and in consequence ion exchange, precipitation and complexing reactions hetween the added ions and those present in the soil will alter the ionic environment of the root. Though this is a complex problem, techniques are now available for calculating the effects on the ionic environment of the root of changes in soil moisture content and the effects of placement of fertilizers.

The practical conclusion to be drawn from this line of thought will be largely influenced by the volume of soil explored by the root-system and the rate of root colonization. Here it is likely that we are concerned with genetic factors which are not easily observed but which are, nevertheless, of great importance in plant-breeding.

If, as is often the case in arid areas, the use of fertilizers is not profitable or only marginally so, it is necessary to devise means of enabling the plant to make maximum use of the resources which the soil has to offer without falling into the trap of 'soil mining', of which we have seen plenty of examples. There do appear to be possibilities for improving the utilization of nitrogen whose behaviour in arid soils is doubtless different from that in temperate regions. Examples were cited of organic nitrogen contents of the order of 100 ppm of which up to 25% (Morocco) and 50% (Senegal) is mineralizable in a matter of weeks. Alongside this mineralizable organic nitrogen there is only a small fraction of very resistant material which probably has no agricultural significance. The restoration or building up of the organic matter stock of an arid soil should probably by regarded as a short term investment which can be preserved by partial sterilization to be placed at the plant's disposal in greater or lesser amount over a relatively short period.

At the end of this Colloquium it is possible to think that a combination of field and laboratory work in applying and adapting what is already known of physico-chemical and biological mechanisms to the conditions obtaining in arid regions will lead, without too great a delay, to the evolution of cultural techniques which will improve agricultural production.