Proceedings of the 23rd Colloquium
of the International Potash Institute
held at Prague / Czechoslovakia 1992

POTASSIUM IN ECOSYSTEMS

Biogeochemical Fluxes of Cations in Agro- and Forest-Systems

International Potash Institute
Basel, Switzerland

Potassium in Ecosystems
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23rd Colloquium of the International Potash Institute

Prague, Czechoslovakia
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Potassium in Ecosystems

Biogeochemical Fluxes of Cations in Agro- and Forest- Systems

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Opening Session

Welcome Address

Mr. *E. Wyss,* President of the International Potash Institute, Basel, Switzerland

Ladies and Gentlemen,

I warmly welcome you all in Prague to the 23rd IPI-Colloquium.

In particular, I have the pleasure to be here in the company of Prof. Jiri Petr, Rector of the University of Agriculture Prague (it is a little bit strange to me to bid welcome to him in his premises) and to bid welcome to :

- Mr VANEK Vaclav, Prof. Dipl. Ing. Dr., Dean of Agronomical Faculty, University of Agriculture, Prague-Suchdol;
- Mr. LEDVINKA Martin, Dipl. Ing., Head of Unico-Agric, University of Agriculture, Prague-Suchdol;
- Mr. KUBAT Jaromir, Dipl. Ing. Dr., Director of Research Institute for Crop Production, Prague-Ruzyne;
- Mr. BAIER Jan, Doc. Dipl. Ing. DrSc., Head of Plant Nutrition Diagnostics, Research Institute for Crop Production, Prague-Ruzyne; and coworkers;
- Mr. LABOUNEK Stanislav, Dipl. Ing., Chairman of the Board of Directors, Agrobanka Praha Ltd, Prague;
- Mr ECKERT Martin, Dipl. Ing., Chairman of the Cooperative Farm Velké Prilepy; and coworkers.

Then I would like to thank all those, whose efforts have made it possible for all of us to meet today. The organization and coordination of an event such as this, which brings together people from various walks of life, scientists from Universities, Governments, Industry and even simple bankers like me is a tremendous task.

It gives me great satisfaction to report that we have received 160 registrations for this Colloquium. This is a reflection of the widespread interest which many people are showing in the topic which will be discussing during our meeting.

To start, let me give you just a few - for us foreigners - interesting figures about the Czechoslovakian Federal Republic:

- the rate of unemployed people was 3.8% in 1991 !
Compare this to Western Europe !

- The state budget is roughly balanced. Few states in Western Europe can make this claim, if any !

Czechoslovakia is reckoned to be among the most developed industrial nations of Europe. There is no doubt, that this country will fight hard to keep or even improve its rank among the industrialized nations and we are sure, it will succeed.
But nevertheless, the Agricultural sector is also very important.

The total surface area of the Czechoslovakian Federal Republic is 12.7 million hectares. Farming land represents roughly 50%. This is equal to 0.4 hectare per inhabitant versus 0.25 hectare in the European Community.
From this comparison, you can gather the importance that the Agricultural industry has in this country.

Some of you have attended earlier IPl-manisfestations and are familiar with our International Potash Institute. For all the others, let me say a few words about IPI.

This institute was founded in 1952 by the French and German producers of Potash : that Colloquium is an excellent opportunity to celebrate the 40th anniversary of the foundation of IPI. Its headquarters then were in Berne, Switzerland, and moved to Basel only a few months ago.

Today, all the producers in Europe and the Near East are Members of the Institute and united by a common aim : to encourage agricultural research with regard to Potassium and to promote the application of Potash in the world. IPI is not concerned with sales, but- in the frame of balanced fertilization- with the aim of improving food production as well as maintaining soil fertility.

The most important task of research is to assure reliable advice based on sound scientific results.

How do we approach this task ? We collect and evaluate the results of research and then try to disseminate them in the best interest of everybody involved.

Scientific Colloquia serve this purpose best. Today, we open the 23rd !
The list of the Colloquia IPI has organized in different parts of the world is long. Each one deals with a specific item of Potassium-research, which is of

relevance to Science and Agriculture as today's topic "Potassium in Ecosystems".

Here, the latest findings are presented by internationally recognized Scientists who are generally recommended by the members of IPI's Scientific Board, in which 12 countries are represented. After being discussed, all papers presented will be printed in the proceedings, which will contain, so to say "the latest state of art" about that important topic, which is presently a major concern for scientists, agronomists, environmentalists, farmers and also for the Potash producers themselves.

In addition, there are also other Scientific Meetings all over the world organized by our Regional Coordinators. International Congresses and Colloquia organized by IPI have been attended by more than 7000 Scientists, mainly from Europe.

The economic difficulties the countries of Eastern Europe are facing have forced Governments to temporarily reduce budgets allocated to research purposes. And this, at the very moment, where many new private farmers must obtain knowledge in various aspects of farming and, of course, in the correct use of fertilizers.

Support here can't come an "Ivory Tower" in Basel without being in touch with the practical problems in the different countries. We therefore have Regional Coordinators in various parts of the world. A Regional IPI-Coordinator for Eastern Europe was nominated in order to combine knowledge and experience and to transfer those into production techniques.

We all know that this is a process which will be long. In life, big events only happen rarely; but then they have to be followed by a lot of small steps. We are here to help in the making of these small steps; if we can accomplish this, our goal has been achieved.

For its 40 years of life, IPI has either published or contributed to more than 700.000 copies of publications in the form of books, booklets or leaflets aimed at informing a wide range of people involved in fertilization. The best known of these publications is certainly the POTASH REVIEW, dispatched to more than 5.000 adressees worldwide, and which is aimed at informing scientists about the latest research-works carried out in the world and devoted to K. But many other publications have been issued, for instance the well known IPI's Bulletins and IPI's Research Topics dealing with precise subjects such as K recommendations for major crops or the behaviour of K under various soil and climatic conditions.

Since these documents are published in English, the Regional Coordinators of IPI, in cooperation with local scientists, translate some of them in several languages, updated with regional data. For your information, such a work is presently implemented by the Regional Coordinator of Eastern Europe, Dr. Ernst Andres.

And now, why are we in Prague today ? To this, we have two very clear answers. It is not only because the "Golden Town" is one of the most beautiful and famous cities of Europe.

But first, in Prague of 1992, this scientific gathering is of special importance since so much has changed in Central and Eastern Europe. Science and farming must find new directions in the frame of a market oriented economy. And secondly:

The reduction on the use of Potassium in Central Europe gives cause for concern : in 1987/88, the consumption of K_2O was 2'632'000 t, while in 1991, only 1'675'000 t were used, and in 1992 even less.

To a certain extent, common concerns are presently raised in Western and in Central Europe :

- Fundamental environmental changes are occurring which together with greater consumer interest in health require our full attention.
- A balance between productivity and adequate profitability has to be achieved by cutting costs rather than by increasing production.

Going through our program, you will see that we adress those two subjects in such a way as to deliver objective arguments aimed at clarifying the debate.

When Dr. Klaus, then Minister of Finance, was in Switzerland, he said : "I don't pay hard currencies for soft advice !"

We can assure you, our speakers will not give soft, but very valuable advice and not against hard currency, but almost for free.

(I don't think you expected Prof. Petr and me to follow the program. It alloted us one hour to speak about general matters. We thought, it was much wiser to shorten our speeches and to give some more time to the much more qualified people to adress you).

I am sure that the many highly qualified speakers who will share their knowledge and experience with you in the coming days, will not only bring you the most recent developments in the newer uses of Potassium, but also broaden your knowledge of existing applications.

I hope you have an enjoyable time and that the Meeting proves rewarding not only in scientific and technical matters, but also that

enhancing personal relationships and private meetings will lead to a better understanding and better contacts on a European and International level, which will last long after this Conference is over.
I herewith open the 23rd IPI-Colloquium.

Thank you !

Czech Agricultural Education - Present Situation, Changes and Trends

Prof. *J. Petr,* Rector of the University of Agriculture, Prague-Suchdol,
Czechoslovakia

Introduction

Czech agricultural higher education has been going through a process of transformation since the return of freedom and democracy in November 1989; this process identifies the problems that had accumulated during the long years of communist dictatorship and suggests solutions to them. Education, however, is closely linked with the development problems of the whole of society and its economy. In general nowadays, priority is given to the transformation of the planned command economy into a free market system, the establishment of a rational functioning market mechanism. At the same time, restitution of property rights is taking place with private property that was confiscated many years ago. All these changes, and many others (e.g. the development of international contacts) are manifest in the changing behaviour of business entities and individuals. The newly defined economic policy of Czechoslovakia gives priority to rapid transition of our economy towards an efficient and smooth economic development. The achievement of these tasks, however, requires a revival of all market functions and also the changes in the structure of national economy in addition to fundamental changes in economic tools. Structural changes have a considerable impact in agriculture, a sector which formerly received heavy support from the state budget. The restrictive financial policy introduced after 1990 resulted in a radical reduction of subsidies in agriculture. Subsidized prices of food that had lost this support resulted in a substantial change in the consumer demand for food products and to a quite different order of priorities. Simultaneously, the process of transformation started to change farming cooperatives and state farms into businesses and companies in private ownership.

A consequence of the changes briefly outlined above has been a shift in the interests of students and demands for graduates from agricultural schools of higher learning (namely from technical and technological courses). This demands changes in the whole system of agricultural higher education, embracing curricula, organization, personel policy and equipment.

Czech agricultural higher education started in 1789 and so has a tradition of more than 200 years. The teaching of agricultural sciences in the 19th century was included in the study programme of the Czech Technical College; from 1906 it was an independant course in agriculture and developed further in 1918 (when the Czechoslovak Republic was founded) into a College of Agricultural and Forestry Engineering. In 1920 another College of Agriculture was founded in Brno (Moravia).

In 1952, agricultural studies were separated from the system of technical colleges and independent universities of agriculture were established in Prague, Brno and Bratislava; these schools of higher learning had their own specialised departments.

Agricultural sciences are currently taught at the following schools : the University of Agriculture in Prague with four faculties: agronomy, economics, forestry and engineering; the University of Agriculture at Brno with four departments: agronomy, horticulture, economics and forestry; the College of Agriculture of the South Bohemian University at Ceske Budejovice.

Development after the Communist take-over in 1948

Forty years of the communist regime in Czechoslovakia (1948-89) had a negative effect on the whole system of agricultural higher education in the Czech lands. The chief defects of agricultural education at that time were :

1. University authorities were completely subordinated to the bodies of the Communist Party and this led to uninformed and subjective interference in the decisions on university matters.

2. Compulsory administrative unification of the curricula and of staff structure; narrow specialization and a single (uniform) system of organization of all schools of higher agricultural education.

3. Suppression of creative non-conformist approach to any problem both in education and in research.

4. Priority of the so-called Marx-Leninist approach in all sciences (not only in social sciences).

5. Limitation or elimination of certain fields of science and subjects in the curricula at the University of Agriculture (especially in the first 5-10 years after 1948 and then again after 1968: e.g. genetics, other philosophies

except marxism, economic theories, psychology, sociology, cybernetics, marketing, etc.).

6. Application of secondary-school methods of teaching (low incentives and independence of students).

7. Reduction of the role of the universities as centers of scientific research by artificially separating research from education and by creating research institutes outside the school.

8. Limiting the flow of scientific information from advanced Western countries, with little or no opportunity to travel to these countries.

9. Application of non-objective criteria in the selection of students and teachers (class approach).

These negative features with interference by state and party authorities were not characteristic of agricultural universities alone but were common in all schools of higher learning.

Changes since 1989

The return of democratic principles following November 1989 has affected the whole situation at agricultural schools of higher learning in Prague and Brno. Freedom of speech, fundamental to a democratic system, has opened a forum for wide discussion of current problems and the possible trends in future development. The students were a dynamic element in the deep social changes in society and education at this stage; they put forward the problems that they thought should be tackled at agricultural universities and initiated discussions in this direction. The main attention was focused on the curriculum and liberalization of staff structure, on the possibility of choice and combination of subjects, on teaching methods, on personal problems, on student participation in university management, on problems of equipment and finance, etc. Some of the problems were resolved immediately, others required some time for their solution.

Fundamental changes have taken place in the following points:

1. A new Universities Act has been approved by Parliament and this has increased autonomy of universities and faculties.

2. New autonomous academic bodies were established, with a high level of independence in decision-making (Academic Senates of the University and of faculties).

3. After many years, academic officials were once again elected by the academic community in free elections.

4. Lectures in Marx-Leninist philosophy as a compulsory theoretical foundation for all sciences and subjects (namely for philosophy, sociology and general economy) were discontinued and substituted by corresponding disciplines and the up-to-date knowledge and world standards.

5. Subjects included in the curricula and time devoted to them and whole course programmes have been changed. This applies particularly to those that were closely linked with the command economy (agricultural economics, organization and management, information systems, book keeping, etc.)

6. New subjects corresponding with the needs and requirements of market economy (economic theories, management, marketing, finance and business problems) have been gradually introduced and more attention is now paid to some other subjects (law, foreign languages).

7. Personal contacts with agricultural universities, with educational and research institutions in advanced countries have increased considerably and there is a greater possibility of incorporating our school into EC sponsored international programmes.

8. Competition between individual types of schools of higher learning has increased.

9. Positions for professors and associate professors have been filled by open competition in order to replace those whose knowledge and teaching was not consistent with changing conditions.

10. There are improved possibilities for obtaining funds from domestic sources and international grants and funds are also available from the University's own economic activities.

11. A new concept of the development of the University of Agriculture has been worked out and approved by the academic bodies.

12. Some faculties apply the credit system of grading and evaluation.

13. The Faculty of Forestry was re-established and it is now focused especially on ecology and landscape engineering.

14. Narrowly specialized courses were discontinued and the students are now offered more choice within the courses with regard to their future carreers.

Approach to problem solution

Following the end of the communist regime, staff of the University of Agriculture in Prague have concentrated on the innovation of systems and curriculum contents which will match European or, rather, world standards.

Some changes were suggested by our own experience and considerations, others were based on know-how from abroad.

The University of Agriculture considered it important to profit from experience of the well known schools of higher learning abroad. In 1991, in cooperation with the Agricultural University in Wageningen, we started a complex evaluation of the University of Agriculture in Prague using the methodology applied in the evaluation of Dutch universities. The first stage in this evaluation is now complete and the whole will be completed in 1993. The WAU Evaluation Commission, headed by Rector Magnificus Prof. dr. H. van der Plas, has much appreciated the reports and material submitted by the University of Agriculture in Prague and the effort made and results achieved in establishing contacts with foreigh universities and the projects of international and supranational institutions (such as the EC Programmes, U.S. Government sponsored programs, etc.).

The preliminary evaluation comments favourably upon the positive changes at the university, namely changes in the curricula, the use of foreign literature and the very high standard of diploma works, theses and dissertations, etc. Among the positive results is also the method of evaluation of lecturers and research workers based on the approved system of point scale and also the system of placements for practical experience for students as well as the new study programmes.

The evaluators also had some criticisms, such as the unclear long-term strategy in agricultural education, or duplication and insufficient coordination in the teaching programmes. They also mentioned the excessive work load on the teaching staff caused by oral examinations which could be substituted by written examinations. A continuing low proficiency in foreign languages is a problem since it is essential for the development of international cooperation.

This external evaluation of the University of Agriculture in Prague is considered to be an important tool for improvement in the standard of higher agricultural education. Contacts with partners abroad and comparing methods and results in education and research will open the way to achieving European standards. A number of cooperation agreements have been signed during the past three years with European and American Universities and some teachers, scientists and students could use scholarships and grants offered by the partner universities. Several activities are financed through the EC programmes (e.g. Tempus).

Important cooperation was started in 1990-91 with Iowa State University who had won grants from US Aid in Washington to finance a series of seminars and courses at agricultural universities in Prague, Brno and Nitra aimed at sharing knowledge and experience in the fields of economics, management and marketing.

The University of Agriculture in Prague has agreements of cooperation with more than 50 agricultural universities all over the world and also active contacts with important international organizations (UNESCO, FAO, OECD, etc.).

In 1992 the University of Agriculture in Prague organized a 6-week summer study course for students from Ohio State University as part of their study program. These courses were successful and they should continue in 1993 even for other American universities (Iowa). These activities demonstrate the efforts of our agricultural universities to become integrated in wider cooperation with European and American universities.

OECS expert groups and experts from other organizations (e.g. Citizens Democracy Corps, World Bank, etc.) contributed in 1991-92 with reports and analyses that provided agricultural universities with methodological approaches to the solution of some of the recent problems of these schools.

As mentioned above, schools of agricultural higher education were informed about the conclusions and recommendations of the OECD Commission of Experts for Education, as submitted at the beginning of 1992. These recommendations were accepted as important suggestions leading towards the improvement of the system of higher education and its contentual, organizational, personal and economic position.

Chairman of the Session 1

Prof. Dr. K. Mengel, Institute of Plant Nutrition, Justus Liebig University, Giessen, Germany; member of the Scientific Board of the International Potash Institute

Session 1

K in the Pedosphere

K-Fluxes in Soils in Relation to Parent Material and Pedogenesis in Tropical, Temperate and Arid Climates

Robert, M., Station de Science du Sol, Institut National de la Recherche Agronomique, 78026 Versailles, France

Summary

The topic concerns K dynamics in the pedosphere and a general view is given of the different K pools or compartments and of the main fluxes between these compartments. Among the compartments, the K in the mineral compartment has been most investigated: it constitutes the main reserve and the main buffer in the pedosphere. Two main fluxes are present independently of the use of fertilizers. The first vertical through leaching, the other horizontal towards the root. Various pedological situations are considered. In tropical soils the vertical flux (plus erosion loss) can be dominant; supply of K to the root depends on the presence of 2:1 clay minerals or organic matter. In temperate regions, fluxes between the different K sites which can be distinguished in the mineral compartment are the main factors which determine plant nutrition. In arid and semi-arid soils, K fixation can be very high but the chief limiting factor is water mass flow. Because our knowledge is incomplete, there are difficulties in predicting the K flux coming from the mineral pool and the way in which soils differing on the bases of soil or land classification will behave.

1. Introduction

Parent material, climatic conditions and living organisms are considered as the main factors of soil formation but they are also essential parameters to determine physical and chemical functioning of soil. This is specially true for K dynamics in soils. In such dynamics, primary and secondary minerals depend on both parent rock and pedogenesis and represent the main K supplies; climatic conditions (general and local) and natural vegetation or type of crop are responsible for the main fluxes. The different compartments of the general K cycle are first defined, then the modalities of the cycle will be described in more precise pedological conditions.

2. General aspects of K dynamics in the pedosphere

K Mineral reserve

K is a major element of the lithosphere with an average level of 1.58 %, but there is a large variation of composition inside the main rocks (Table 1). In crystalline endogenous rocks, K decreases from acid to ultrabasic rocks; in sedimentary rocks, clays and shales very often have quite a high K content and the K reserves are fairly large in loessial deposits which cover nearly a third of Europe.

Table 1. Abundance of potassium at the earth's surface (in Wedepohl, 1969)

Rocks	% K	Minerals	% K	Waters	K (ppm)
Sands-Sanstone	1.23	K feldspars			
Clays	2.33	Sanidine		Sea	39.2
Shales	2.04	Orthoclase	14		
Limestones	0.26	Microcline		Lakes	233
Soils	1.40	Adularia			
		Feldspathoids			
Calc-alkaline granites	4.53	Nepheline		Rivers	6.5
Alkaline granites	4.26	Kalsilite	24		
Granodiorites	2.55	Leucite	17		
Diorites	1.76	Micas*			
Gabbro	0.76	Biotite	7.5	Soil waters	9
		Muscovites	8.3		
		Sericite			
		Micaceous phyllites			
		Illites	8.3		
		Glauconites	7.5		

* Values used by Alexiades and Jackson (1966) for converting from % K to % mica. In fact, for micaceous phyllites, the values found are much lower.

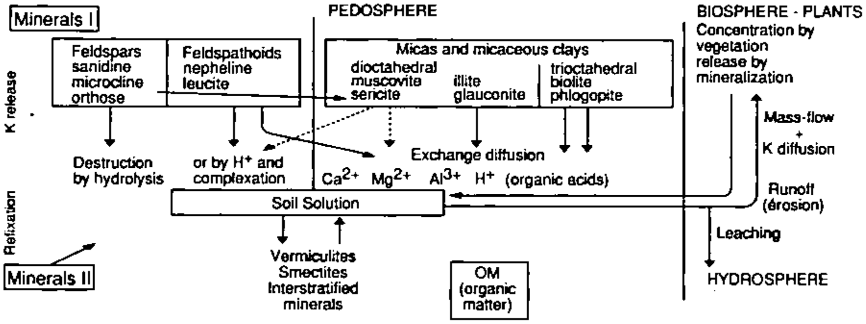


Fig. 1. General cycle of potassium in the pedosphere (Robert and Trocmé, 1979)

The large variation observed is related to the content of a few silicate minerals which represent the main K bearing compartment in soils (Table 1 and Figure 1). J. Wilson (This Colloquium) has presented a general approach to estimate K release rate by primary minerals. This approach is based upon a surface-controlled reaction and can apply to all the K-bearing silicates, if the intensity of the weathering is sufficient: destruction by hydrolysis in tropical climates (Pedro, 1973) or by H^+ and complexation in acid soils. Among these silicates, it is usual to differentiate tecto-(feldspars) and phyllosilicates (micas-illites) on the basis of K locations. In spite of their tecto-silicate structure, feldspathoids where K is located inside channels, behave more like phyllosilicates. (Robert and Veneau, 1974). In the first case (feldspars), complete breakdown of the structure is necessary to release K; in the second case, exchange and K diffusion are possible. Such diffusion reactions become important in temperate regions and when plants absorb the potassium in the solution and induce a disequilibrium in the reaction.

To consider first the supply formed by primary minerals, some new points can be underlined to complete J. Wilson's presentation. The studies of Berner and Holdren (1979) have shown that feldspar dissolution through pit formation occurs either in podzols or in oxisols. More recently, using high resolution transmission microscopy (HRTEM) Eggleton and Buseck (1980), Tazaki and Fyfe (1987) have evidenced primitive clay precursors forming inside feldspars. These clays cannot be detected by XRD, and the layers formed can represent a place where K released from feldspars can transit and be stored. Concerning mica behaviour during soil genesis, we should stress the importance of exfoliation and microdivision. These phenomena are important in crystalline or sedimentary silty rocks and they lead to an increase in both external surface area and available potassium. Such 10 A° minerals can be identified fairly well in the clay fraction and they should be distinguished from sedimentary illites (Robert *et al.*, 1991).

Concerning K-release and fixation by secondary clay minerals, new ideas have been put forward. For example, the Nadeau (1984) theory which focused on the existence of fundamental particles and on the importance of interparticular spacings, can be of major importance in soils, (Robert *et al.* 1991). Robert and Tessier, (1992) insist on the small dimensions of the soil particles both in the number of layers per particle and lateral extension. So the sites available for K are perhaps more diverse than the classical interlattice, edge, and planar. During K release or fixation (for example during wetting and drying cycles) particles can be associated or dissociated along the a-b plane. (Andreoli, 1989). In such a dynamic process, planar and interlattice sites would be interchangeable with some reorganisation of the ditrigonal cavities. Similarly redox phenomena in ferric smectite (nontronite) produce the same textural (increase or decrease of the number of layers) and structural (change in stacking order bidimensional $\rightleftharpoons$ tridimensional) modifications (Stucki and Tesssier, 1991).

Infrared spectroscopy in the past enabled a refined characterisation of the different K sites in 2:1 phyllosilicates. It has also made it possible to clearly differentiate trioctahedral from dioctahedral environments (Vedder, 1964). This distinction fits with the Bassett (1960) hypothesis which explains the highest K release from trioctahedral mica. More recently, it was possible to use far infrared spectra of micas in order to make the same distinction (Laperche and Prost, 1991). In illite smectite series, the distinction of three bands at 105, 95 and 85 cm^{-1} could correspond to different K locations (Harsh *et al.*, 1992).

X Ray diffraction studies (Sakharov *et al.*, 1990) which provide better knowledge of the structure, also made it possible to distinguish between the hexagonal cavity (micas or illite of 1 M or 2 M polytype) and the ditrigonal cavity which exists in the 1 Md illite or glauconite, or in K smectite subjected to wetting and drying cycles.

If we synthesise all these new results obtained by HRTEM, X-ray diffraction and far infrared spectroscopy, we can identify several K sites on either primary or secondary 2:1 clay minerals, which have to be compared to the 6 types of cation exchange sites identified by the enthalpies of Ca-K exchange (Goulding, 1983). The important point is that it appears as a continuum of different K sites which can all occur within the same soil, with the possibility of transition from site to site. Weathering, but also events occurring during normal soil functioning such as changes in hydric behaviour or redox conditions, can induce both textural and structural modifications with direct repercussions on K fixation or release from or to these sites.

To establish relationships between such data and soil functioning or even agricultural practices would be important but difficult because plant root development is also affected. So irrigation or no tillage may favour K diffusion by increasing the soil moisture but the decrease in root development and increasing reduction phenomenon can also affect K availability.

K organic pool

In this paper the focus is on the "mineral K pool" because it represents the main and more complex source of K. The organic K pool consists either of fresh organic matter (plant or microorganism residues) cells or of humic and fulvic substances where K is adsorbed on the carboxylic or phenolic groups. As K does not form an organic complex and the selectivity of organic matter (OM) is higher for others cations, K release will be easy either by exchange reaction, leaching or OM mineralisation. Nevertheless, in some cases (tropical soils, podzolic soils) this OM pool represents a relatively large storage.

K in solution, K leaching, and K in the plant

We distinguish two types of fluxes. The first relates to the weathering rate of primary minerals where dissolution (Wilson, 1992) or diffusion can be the predominant mechanisms. More generally, a control of the K concentration is set up by secondary clay minerals or organic matter. The second flux is vertical and has several components (Figure 2): K inputs by fertilization or manuring will be considered by other participants. K inputs in rain occur usually as soil dust; they are often less than 5 kg ha^{-1} $year^{-1}$ K and have little effect on the total K balance (Johnston and Goulding, 1990; Pieri, 1983).

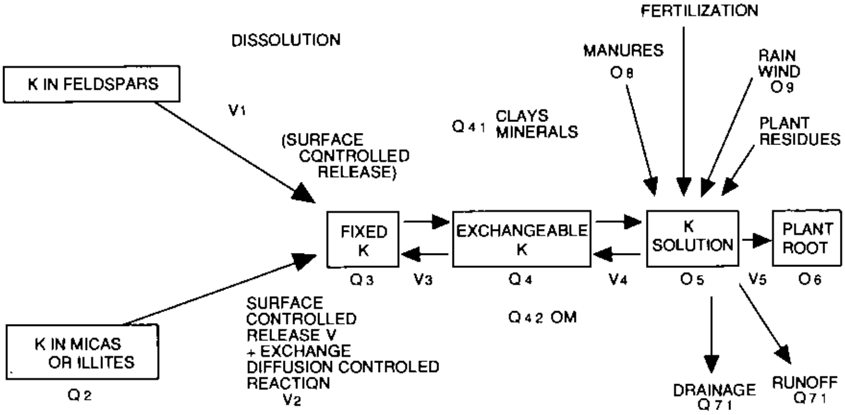


Fig. 2. Schematic K cycle showing pools and fluxes

In the absence of fertilization and plant growth, a vertical leaching flux can occur which depends directly on the K level in solution and on the volume of water drained (Lefevre, 1988). K output can also occur by erosion.

In the presence of plants, a horizontal water mass flow is drawn towards the root. Concerning K, the uptake by the root induces a concentration gradient of diffusion which is the main mechanism explaining the high flux from the mineral (or organic) K storage to the plant within the rhizosphere (Grimme, 1985).

K is the cation most absorbed by plants and needs can vary from 10 to 50 kg ha^{-1} year^{-1} for extensive cereals to 400 for alfalfa and more than 1000 kg ha^{-1} year^{-1} for banana. During the growing period the flux can be 10 kg ha^{-1} day^{-1} K.

Some measurements of potassium influx by roots have been made by Mengel and Kirkby (1987) and mean values for maize are from 50 to 0.2 µmol/m root length/day (or 2 to 0.01 nmol mm^{-1}h^{-1}). More than 50 % of the total K uptake occurred during a very short period (within a few weeks).

This driving force explains the fact that if exchangeable K is the main source of K, it is constantly sustained by K coming from the other sites previously mentioned. Even mica sites can be concerned (Steffens, 1986; Hinsinger, 1990) and in certain cases, H$^+$, organic acids or polysaccharides can be involved (Robert and Berthelin, 1984). However we notice that equilibration between solution and exchangeable K is rapid and not limiting; the K release from the other sites of phyllosilicates is a rather slow process which cannot meet the intense K requirement of the plant (Grimme, 1985). Experiments carried out with isotopic tracers demonstrate both the existence of fluxes between the different pools or the different sites, and the time dependence of the different types of K release (Fardeau *et al.*, 1992) (This Colloquium).

A schematic K cycle is presented in Figure 2. In order to speak of flux, we need both the amount of the pools (Q) and the K release or fixation in relation with time (i.e. speed = V). The mineral compartment is the most complex and it includes several interconnected pools. Several analytical determinations provide information on the composition of the K mineral compartment: sodium tetraphenylborate extraction gives a better idea about the available reserve, and the determination of the buffer capacity by Q/I isotherm (Quemener, 1986) provides information on the dynamic reaction of the different mineral pools. However considering the great diversity of soil conditions quantitative data are difficult to provide; therefore only qualitative data as Q and V will be given for the different types of soils.

3. Examples of more specific K dynamics in soils

Recently, Sharpley (1990) has studied the reaction of fertilizer potassium in 102 soils of different clay mineralogy and taxonomy. A linear increase in water soluble, exchangeable, and non exchangeable K content of each soil was obtained after a 25 week incubation with K (0 to 250 mg kg^{-1} K). Slopes of these relationships represent water solubility (S), exchangeability (E) and fixation (F) indexes (Figure 3). These indexes and the K buffer capacity were closely related both to clay content and to the dominant clay minerals. Such data point out the importance of clay mineralogy in K dynamics.

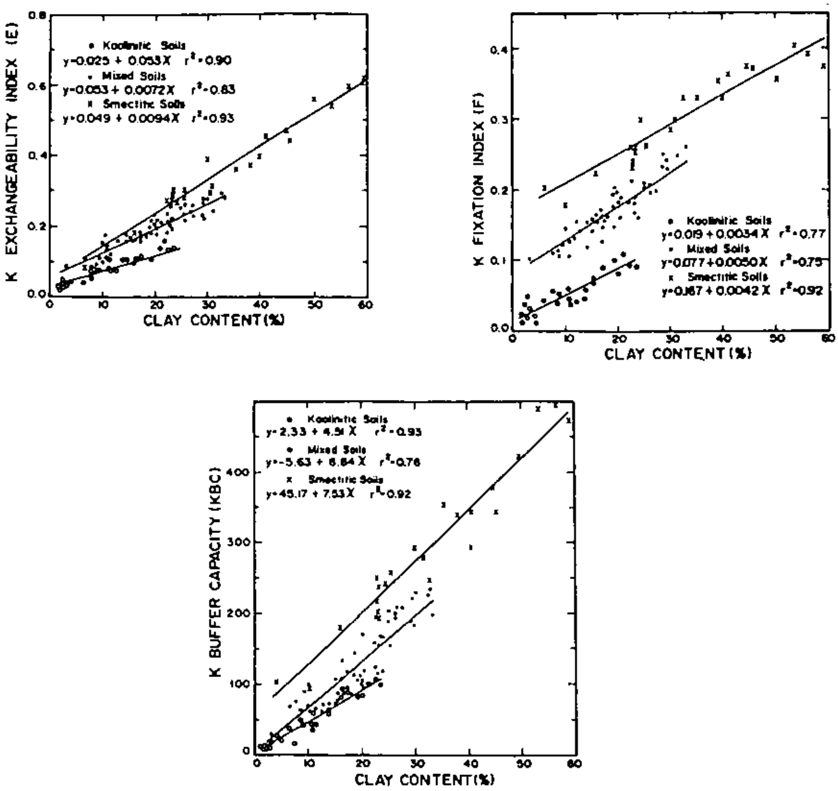


Fig. 3. Relationships between K exchangeability index (E), K fixation index (F) and K buffer capacity and clay content for the kaolinitic, mixed, and smectitic soils (Sharpley, 1990)

Soils in the humid tropics

The main soils of the humid tropics are (Lal, 1985; Sanchez 1987): oxisols (35%) ultisols (28%) or alfisols (4%) for older soils which are dominant, and, inceptisols, entisols ("sols peu évolués" or "sols bruns" in Figure 4) for younger soils which represent less than 30%.

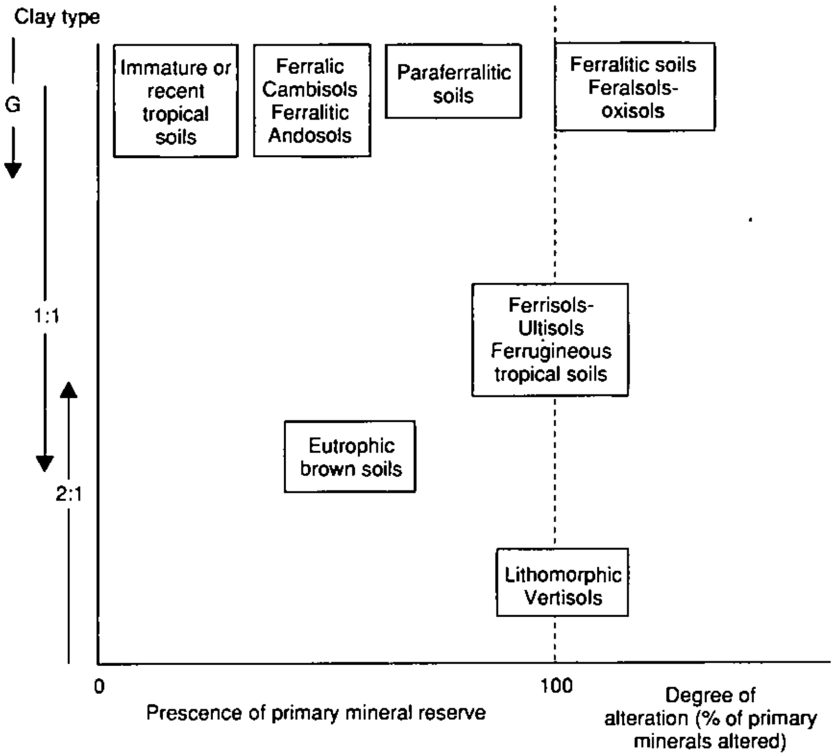


Fig. 4. Tropical soils classified in relation with the type of secondary minerals (1:1 or 2:1) and the size of the mineral pool (weathering stage) (Pedro, 1973)

Both the content in weatherable minerals which represents the nutrient stock, and the type of secondary minerals, depend on the type of rock and the weathering stage (Figure 4 from Pedro, 1973). Therefore, there are young soils with good K reserves. Oxisols and vertisols are more characteristic of the tropics: weathering rate of all the minerals by a dissolution process will be high, which implies a higher K concentration in solution subjected to rapid and major changes. The secondary minerals are generally low activity clays and the potential buffer capacity (K fixation by clay minerals) will be low (Figure 5).

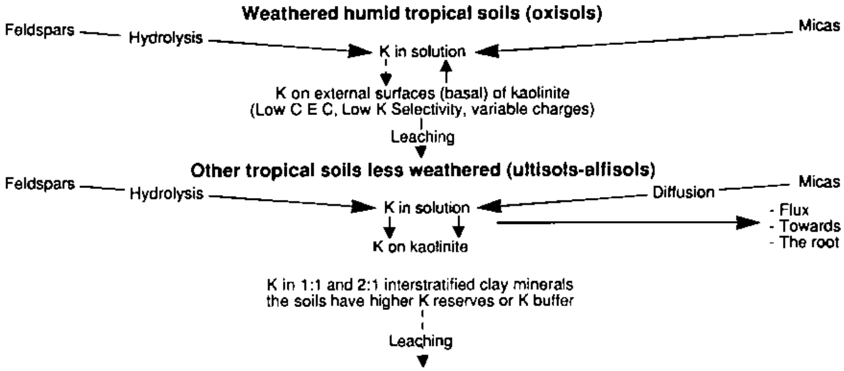


Fig. 5. K dynamics in tropical soils

This property is clearly illustrated in Figure 6 (Grimme, 1985). There is a good correlation between adsorption isotherms and the type of soils, but the correlation is even better if the mineralogy and the clay content of the different soils are considered. Thus, vertical K flux could be higher in all the soils of the tropics, especially on cleared lands or after fertilizer applications, where in some cases 30 to 50% of the K can be leached (50 kg or more). K loss can also be considerable through erosion of finer particles (10 to 47,5 kg ha^{-1} in Senegal) (Pieri and Oliver, 1986). But this general rule has to be modified: in forest ecosystems more than 90 % of the K may be contained in the vegetation (Klinge, 1976) and it may constitute a closed system (leaching < 5 kg ha^{-1} year^{-1}).

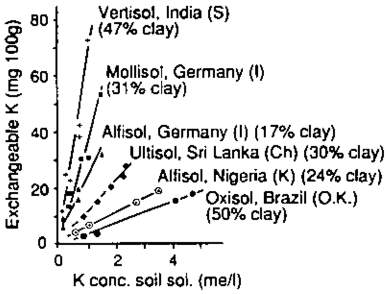


Fig. 6. Adsorption isotherm from various locations in different climatic zone (humid tropics, semiarid tropics, temperate) and with different clay mineralogy and clay content (S = smectite, I = illite, CH = chlorite, K = kaolinite, O = Al, Fe-oxides) (Grimme, 1985)

Two constituents are of major importance in regulating K fluxes: OM and 2:1 clay contents (Figures 4 and 5).

Many recent works have emphasised the importance of very small quantities of 2:1 clay minerals (generally smectites) which make it possible to transform a vertical flux to a horizontal flux towards the root (Delvaux, 1988); Arkcoll *et al.* (1985) demonstrated in oxisols of Amazonia that sites for both adsorption and available reserves (2000 to 5000 kg ha^{-1} K) exist in the top soil.

A good example is presented by Fardeau *et al.* (1992) and Poss (1991), in Togo where the climate is tropical but relatively dry (1100m). The K concentration in soil solution (0,023 mmol l^{-1}) and K-leaching (11 kg ha^{-1}) $year^{-1}$ are relatively low. The balance will depend mainly on the K output by the crop. With a maize crop, if only the grain is exported, output flux is only 30 kg ha^{-1} $year^{-1}$ for two crops (total output with residues = 110 kg). Such a balance is possible because a buffer power exists with the presence of interstratified illite smectite in small quantities.

The role of OM is also very important. For example in the state of Sao Paulo (Brazil) with ultisols and latosols, OM can participate in the total exchange capacity to the extent of 56 to 91% (Van Raij, 1969).

Productivity of oxisols and ultisols can be among the highest in the world when the chemical soil constraints are eliminated (Sanchez and Salinas, 1981). The first of these constraints is acidity with aluminium toxicity; then a K fertilization strategy must be defined which takes into account all the points mentioned above. A light K fertilizer dressing can be very effective in increasing yield.

Soils in temperate regions

If a North-South transect of Europe is considered, for example in the former USSR (Prokoshev and Sokolova, 1990), there is a relatively higher weathering rate in the northern part of Europe in relation to the development of podzolisation and acidification processes. In these conditions, as well as in sandy soils, reserve K will be low. In the same kind of North-South soil sequence established in Canada on the same parent material (medium textured glacial till deposits), St Arnaud *et al.* (1988) using an isoquartz balance (pedogenic index), have expressed the change which occurred in the K mineral pool during soil development. From forested luvisols (similar to podzols) to grassland chernozemic soils, the total K_2O loss varies from 12 % to 2 %. The K feldspars are weathered (by a dissolution process) to a greater extent than the micas. The cation exchange capacity values of the luvisols are low in the surface horizon (loss of OM and clay by leaching); in the chernozem the higher value is related to both the clay and OM contents.

If podzolic soils are first considered, some nuance can be introduced concerning the K cycle under forest vegetation: in the Vosges where the annual balance is well known (Mohamed *et al.*, 1992), input is low (2 - 5 kg ha^{-1}), output by leaching ranges from 6 to 10 kg and the whole cycle concerns 30 kg ha^{-1} K in a closed internal cycle between trees and soil. Such quantities have to be referred to the value of the mineral pools which are respectively 380 kg for exchangeable K and 200 to 300 tons for total K. The sandy podzols of the Landes (France) where high yields of maize are produced represent a specific example. These soils have a very low amount of clay, and OM represents the main source of exchangeable K. The annual rate of fertilization (50 kg ha^{-1} K) is far less than crop requirement because stover is returned to the soil; K output by leaching (20 to 30 kg) is quite important (Lubet et Juste, 1985; Juste *et al*, 1982).

Speaking again of young soils with high K reserves, wheat is still grown in the Great Plains Region of the US without any K fertilizer input for about a century. In the corn belt, only a little K fertilizer is needed even with maize, if the stover is returned to the soil. The balance is as follows: 14 kg K applied, 20 kg removed with the grain, 15 kg lost due to leaching; the remaining 21 kg is held in exchangeable and non exchangeable forms. Such a balance is due to the great fertility of the soils which are rich in 2:1 clay minerals (illite + smectite). Recent experiments by Robertson *et al.* (1992) with barley in South Alberta (Canada) have shown that K fertilization can give the maximum yield either with high initial K application (250 kg ha^{-1} K) or, even better, by annual application of 25 kg ha^{-1}. These are good examples of low input fertilization but it should also be noted that low temperatures are a major constraint for yield.

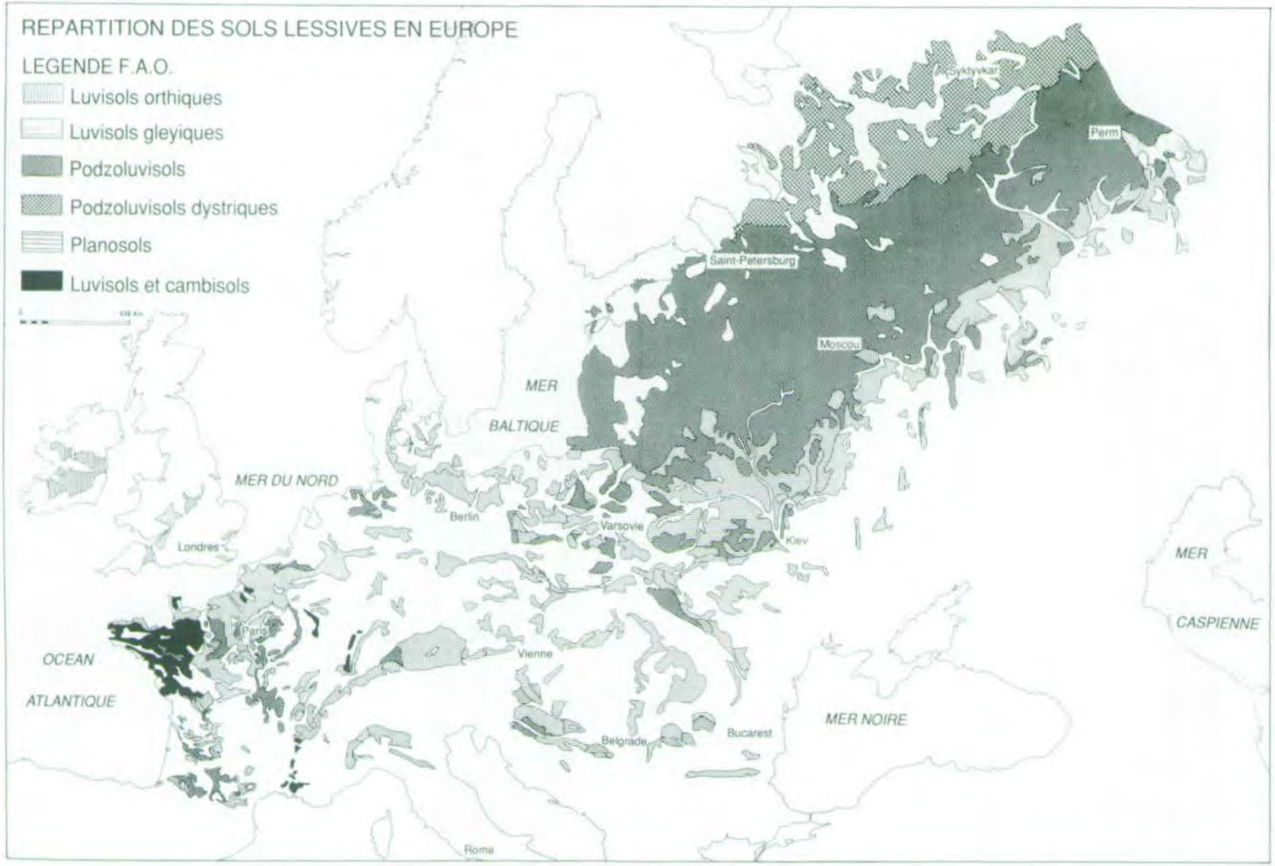
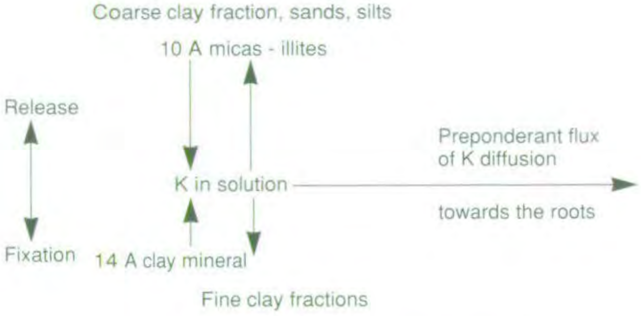


Fig. 7. Distribution of luvisols in Europe (Jamagne and Begon, 1984) podzoluvisols in black

The situation is somewhat similar in the temperate regions of Europe where the most representative situation is that of the "sols bruns lessivés" or of the luvisols developed on silty aeolian material (Figure 7) (Jamagne and Begon, 1984). On such parent material all the soils are characterised by large primary reserves and a relatively high amount of 2:1 clay minerals which contribute to K flux regulation (Sharpley, 1990).

In such soils, recent studies (Robert *et al.*, 1988) have made it possible to differentiate the coarse clay fraction made up of micas or illites, from the fine clay made up of swelling (I/S) interstratified minerals with very thin particles. Thus we can imagine an equilibrium of release and fixation between these two clay fractions (Figure 8), the smectite having a beidellitic composition and a relatively high power of fixation. This reaction certainly regulates the behaviour of certain soils which are considered to be favourable either to K fixation or high K release.



Feldspars are more resistant so 2:1 phyllosilicates are the main source of K
The equilibrium between 10 A and 14 A layers can exist within the particles.

Fig. 8. K dynamics in soils of temperate regions soils with stable 2:1 phyllosilicates

In long term experiments on luvisols in Europe, the vertical K flux is 10 to 15 kg ha^{-1} K, mainly in winter, higher values occurring on more sandy soils (Lefevre, 1988); output by runoff is also increasing. In such situations horizontal fluxes towards the roots are dominant and the K reserve in the clay fraction (2 to 3% K_2O) is very large. The limiting rate will be the release of non-exchangeable K, especially during the very short growing period and for K demanding crops. Until now K fertilization has been relatively high in order to obtain maximum yield and applications greatly exceed removal (Hebert, 1984). But this position is certainly being revised and for this better prediction tools are needed.

Soils in arid and semi-arid regions

The effect of K, on water use efficiency is well known through its influence on turgor pressure and stomatal regulation and it has therefore a specific importance in arid regions where water is the main limitation for crops.

In these areas the main soils are mollisols, inceptisols and vertisols, where the content in primary minerals is high and secondary minerals often consist of smectite. Bouabid *et al.* (1991) in a study of 44 soils of Morocco have demonstrated for vermiculitic and smectitic soil clays the predominance of tetrahedral charges and a correlative high K-fixation potential.

In the Hodna region (Algeria) soils are mainly petrocalcic, gypsum or saline-rich soils (Daoud and Moktar, 1985). These soils are rich in total K (0.53 to 3% K) but have quite a high K proportion which is rather unavailable (not extracted by Na tetraphenyl borate). Accordingly K in solution and K fluxes depend on release by primary minerals, which is relatively low, and fixation by secondary minerals, which is relatively high (Figure 9).

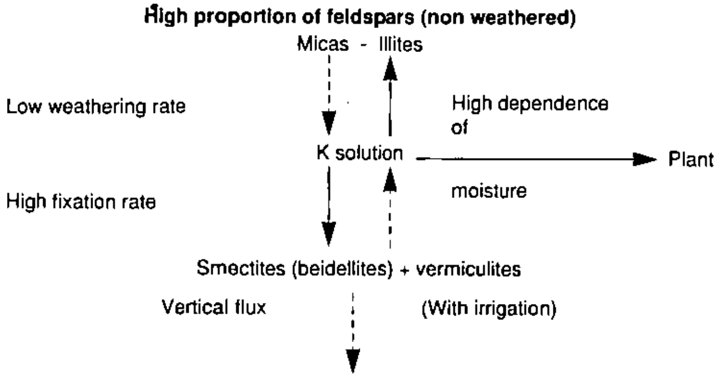


Fig. 9. K dynamics in semi-arid and arid soils (mollisols vertisols)

Due to the lack of water, the flux towards the root is low and even with low yield the crop shows a considerable response to K-fertilizer (Sekhon, 1983). The loss through surface runoff and erosion (10-50 kg K) can be regionally important in relation with the intensity of rain (Roose, 1981). In such soils, irrigation leads to several effects: increase in K availability but also in K leaching and K requirement for plants.

4. Conclusion

The future in soil science will be characterised by research on sustainable eco-systems, and for that we need more and more precise balances in relation to the type of soils and agrosystems.

Knowledge of the different fluxes has progressed. We have distinguished the horizontal flux of K to the root and the vertical flux by leaching which can be important in humid climates (and sandy soils). To this flux we have to add the loss of fine earth by runoff which is important in both tropical and arid regions. Such a loss can also be important in temperate regions.

We also have a better knowledge of the needs of the different crops and of the fluxes towards the roots even on a detailed scale (daily rate). In all agrosystems, especially in tropical and arid regions, the importance of crop residues must be emphasised because their return to the soil significantly decreases the K output. K in organic manures is also an important input flux which has to be considered (Spiess and Besson, 1992) (This Colloquium).

It appears that the part of the K-balance about which relatively less is known is the participation of the mineral reserve. We have seen that this compartment is very complex with the occurrence of several K sites of different availability. We need to know the various reactions and fluxes within this compartment in order to better adapt analytical procedures and methods of prediction. This mineral compartment shows the greater variations in relation to different soil types. Some attempts have been made in temperate regions to classify and map the potassium reserves in soils and their availability (Goulding and Loveland, 1986). Such data can permit the establishment of a better relationship between the need of the crop and the nutrient supplying power of the soil. It is even more important to make similar studies in arid and tropical regions. In this last case, we have seen that a small amount of 2:1 phyllosilicates has a considerable importance not only for the level of K-reserves but also for the buffer power which determines the fluxes.

Therefore, improved mineralogical determinations should be included in the new fertility capability classifications (Sanchez *et al.*, 1982) because, in the case of K, they can be a base for low input technology though this only allows submaximal crop yields.

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K-Bearing Minerals and their K-Release Rates in Different Climates

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Summary

The major K-bearing minerals in soils include framework silicates (K-feldspars and leucite) and layer silicates (biotite, muscovite, phlogopite, illitic minerals and glauconite). There is little comprehensive information available on K-release rates of these individual minerals under field conditions and until recently it has not been possible to extrapolate from laboratory-determined weathering rates. However, recent work from Scandinavia in the environmental field marks a significant advance in that calculated mineral weathering rates have been correlated with field rates determined by a variety of methods to within ±8%. The experimental rates for K-bearing minerals are assessed in the light of what is perceived to be the relative order of susceptibility to weathering from soil mineralogical studies. In addition, as these rates increase with temperature and with wetted surface area the likely effects of climate can also be assessed.

Introduction

The kinetic reactions of K in soils have been conceptualized as occurring between different phases representing different K pools described as mineral, non-exchangeable, exchangeable or soluble. But the nature of these pools can be problematical (Scott and Smith, 1987). Thus, mineral K may be described as including the native K in minerals such as muscovite and K feldspar, but has also been considered to include K which has been fixed following its addition to the soil (Sharpley, 1989). However, Scott and Smith (1987) demonstrate clearly that native K in unweathered biotite and fixed K in degraded biotite show marked differences in their rate of exchange to sodium and hence cannot be regarded as equivalent forms. Again, according to Sparks (1987) fixed K can be equated with non-exchangeable K which is described as being held between the tetrahedral layers of 2:1 layer silicates and not bonded into crystal structures of minerals as is mineral K. But Memon *et al* (1988) attribute to finely divided feldspars the potential to release non-exchangeable (fixed) K as well as 2:1 clay minerals.

In view of these problems of definition, it would seem logical in discussing the release rates from K-bearing minerals to deal with all K which occurs as structural cations in minerals that have been inherited into the soil from the original parent material. In this paper the emphasis will be firstly upon surface reactions, where K is released at a rate similar to that of other structural cations, so that the release of interlayer K from layer silicates can be brought more clearly into context.

K-Bearing Minerals

K-bearing minerals in soils generally belong either to the framework or layer silicates, although in each of these groups there are a number of mineral varieties which may respond to weathering in different ways. The framework silicates include K-feldspar and the feldspathoid mineral leucite. Orthoclase feldspar and microcline are the most common forms of K feldspar and both occur extensively in soils derived from acid igneous and metamorphic rocks, particularly granites and granitic gneisses, either directly or indirectly. Sanidine is a K-feldspar associated with soils derived from volcanic parent material, as does the feldspathoid leucite. An important structural feature of feldspars so far as weathering is concerned is their ability to enter into an intimate lamellar intergrowth with other feldspars of a different chemical composition, sometimes on an exceedingly fine scale. The most common such intergrowth is perthite, where Na-rich lamellae are associated with the K-feldspar host, but so-called anti-perthites are also possible where K-rich lamellae occur in a dominant Na-rich host.

There are many different varieties of layer silicate minerals which contain structural K. Muscovite, phlogopite and biotite representing aluminous, magnesian and ferromagnesian compositions respectively may be thought of as the primary layer silicates insofar as they occur as primary components of igneous rocks. Muscovite and biotite are often common constituents of soils derived from granite, granitic gneiss or schist parent materials. Biotite may also occur in soils derived from intermediate and more basic igneous rocks, whereas phlogopite is most often associated with ultrabasic parent materials. Fine-grained secondary layer-silicates include sericite, an aluminous mica generally formed by late-stage alteration of K-feldspar, and phengite which is also an aluminous mica but with a somewhat higher magnesium and iron content and which is often found in fine-grained metamorphic rocks. Glauconite has a higher content of iron and magnesium and is formed as an early diagenetic mineral in marine sediments. Illite is a fine-grained hydrous mica-like mineral and again is most often formed during diagenesis, but following sediment burial. The many different types of interstratified illite-smectites generally represent intermediate phases during the diagenetic conversion of smectite to illite (Eberl, 1984; Wilson and Nadeau, 1985). All these fine-grained layer silicates may be directly inherited into the soil from their original parent materials and should be regarded as K-bearing minerals.

Relative Rates of K-Release from K-bearing Minerals

This can be judged in a general way from the distribution of the minerals in weathering profiles and from observations of grain surfaces and associated weathering products. With regard to the common K-feldspars, generally microcline is more stable in weathering profiles than orthoclase feldspar (Huang, 1989). This is consistent with the overall order of stability of rock forming minerals to weathering (Goldich, 1938) whereby those minerals which crystallize at higher temperatures in the discontinuous reaction series are generally less stable than the minerals formed at lower temperatures. Microcline is usually formed at lower temperatures than orthoclase. Structural considerations may also be important. Thus, orthoclase has a more disordered structure than microcline in terms of the distribution of Al and Si ions, and usually contains more Na-rich perthitic intergrowths. The interface between the K- and Na-rich components of a perthite is characterized by a slight structural mismatch (Smith, 1974) and is therefore a zone of higher surface energy. Selective attack of perthitic intergrowths in K-feldspar has been documented by controlled etching experiments (Wilson and McHardy, 1980). Little is known of the relative stability of sanidine, although SEM observations on grains separated from some Italian Andosols show that the mineral is virtually unaffected by weathering. In contrast, leucite occurring in the same soils is deeply corroded and clearly much more vulnerable to weathering (Violante and Wilson, 1983).

Weathering and release of K from layer silicate minerals has been ably summarized by Fanning *et al* (1989). It has long been recognized that biotite (and phlogopite) weather much more rapidly than muscovite.. Biotite vermiculitizes and loses structural K even in cold climates. Thus, in some youthful (<3000 years) skeletal soils developed from quartz mica schist on the recently deglaciated Signy Island in Maritime Antarctica it was found that in the 75-150 µm fraction biotite had weathered to hydrobiotite thereby losing 50% of its structural K (Wilson and Nadeau, 1985). In acidic soils biotite may lose its structural integrity and weather out towards the surface (Farmer *et al.*, 1985). In contrast, muscovite weathers exceedingly slowly. An indirect recognition of this is that the oxic horizon, the diagnostic horizon of the highly weathered Oxisols in the U.S. System of Soil Taxonomy, has been redefined by the Soil Survey Staff (1987) to permit it to include up to 10% weatherable minerals in the sand fraction, including muscovite by inference (Fanning *et al.*, 1989).

The relative rate of K release from the fine grained dioctahedral micas depends upon their exact nature. Comminuted muscovitic mica might well be expected to be resistant to weathering, but the evidence suggests that illitic micas behave differently. For example, in the Alfisols (Udalfs) in central USA, illites evidently lose their K during pedogenesis and transform to a variety of mixed layer and intergrade minerals (Jackson *et al.*, 1952; Fanning and Jackson, 1965). These illites have in large part been inherited into the soil from Cretaceous sediments and were ultimately formed by the diagenetic conversion from smectite. Similarly, the fine grained metamorphic micas may weather to smectitic (Churchman, 1980) or vermiculitic products (Bain *et al.*, 1990(a)) in Spodosols. Glauconite (and celadonite) are generally considered to be somewhat more suceptible to weathering than illite because of their higher iron and magnesium contents. Release of K may lead to the formation of Fe-rich smectite (Robert, 1973).

The relative rates of K release from such studies are assessed in Table 1. Biotite and possibly leucite are considered to be the minerals which release K most rapidly in soils. K-feldspars and muscovite mica release K most slowly and the other minerals discussed fall into an intermediate category.

Table 1. Assessment of the relative rates of K-release from K-bearing minerals in soils from pedogenetic studies.

Release Rate	Mineral
Fast	Biotite > Leucite
Intermediate	Glauconite/Celadonite > Illite
Slow	Orthoclase > Microcline $\geq$ Muscovite

Laboratory Release Rates of K-bearing Minerals

There are two mechanistic approaches to the weathering of K-bearing minerals. The first views weathering as a surface-controlled reaction where the detachment of species at the mineral-solution interface is the rate-limiting step (Aargaard and Helgesen, 1982), an approach which applies to both framework and layer silicates. The second approach applies only to the layer silicates and views weathering as a transformation process where the silicate layers remain intact and K is depleted from the interlayer space. Such a model cannot be applied to the framework silicates because it is impossible to remove K ions and at the same time maintain the integrity of the structure.

In this paper attention will be focused initially on surface-controlled release rates. This is because release rates of mineral K by a transformation reaction are difficult to separate from the release of non-exchangeable or fixed K which, while being derived from the same (or similar) structural sites, are not so tightly bound. Further, under the acidic conditions which typify many soils, K is released from some layer silicates at a similar rate to other structural cations, suggesting that structural decomposition is the relevant mechanism (Feigenbaum *et al.*, 1981). If this is so, then it might be expected that the K-release rates would more or less follow the relative order shown in Table I.

The kinetics of surface controlled reactions have been accounted for by the transition state theory (Aargaard and Helgesen, 1982; Helgesen *et al.*, 1984; Lasaga, 1981), which describes the transition from the mineral to the solution. In brief, the reactants combine to form an activated complex from a surface complex with which it is in equilibrium. The surface complex is assumed to form a solid solution with the mineral and the activated complex is in equilibrium with the reactants. The overall rate of the reaction is controlled by the decomposition of the activated complex and is proportional to its concentration and, in turn, to the products of the reactants.

The most recent comprehensive review and development of this approach as applied to mineral dissolution rates is that of Sverdrup (1990), who was also able to reconcile the results obtained with field weathering rates. The weathering rate of a mineral was treated as being the sum of the rates of several individual reactions involving H^+, H_2O, CO_2, OH^- and strongly complexing organic acids. Each reaction may be coupled to aluminium and base cations in the external solution, although there is insufficient information available on the influence of these ions on the rates of all the individual reactions. The general rate equation derived from transition state theory, which is applicable to acid conditions is:

$$r = k_{H^+} . \frac{[H^+]^n}{[Al^{3+}]^y . [BC]^x} + k_{H_2O} . \frac{[H_2O]^v}{[Al^{3+}]^u . [BC]^w} + k_{CO_2} . P_{CO_2} + k_{org} . [org]^{0.5}$$

where k_{H^+} = rate coefficient in the H^+ reaction
k_{H_2O} = rate coefficient of the H_2O reaction
k_{CO_2} = rate coefficient of the CO_2 reaction
k_{org} = rate coefficient of the organic acid reaction
r = reaction rate (kmol $m^{-2}s^{-1}$)
P_{CO_2} = partial pressure of CO_2 in soil solution
n,y,x,v,u,w = reaction orders of the species shown

The reaction rate in the soil is also taken to be dependent upon the exposed surface area of the mineral and the degree to which it is wetted. For any soil horizon, the total weathering rate (Rw) is obtained by a summation of the rates for all the minerals present according to:

$$Rw = \sum_{j=1}^{\text{minerals}} rj . Aw . xj . \frac{\theta}{\theta m} . z$$

where Aw = Exposed surface area of the mineral fraction (m^2 ha^{-1})
xj = Surface area fraction of the mineral j in the soil
θ = Soil moisture content (kg m^{-3})
θm = Soil porosity (kg m^{-3})
Z = Soil layer thickness

Ways of determining surface area and soil moisture saturation are described in Sverdrup (1990) and Sverdrup and Warfvinge (1991). The rate coefficients for the minerals studied were determined by experimental data obtained by reacting the minerals with solutions of various pH and composition until steady state dissolution was reached. A plot of the negative log of the rate versus pH yields the rate coefficient as intercept and the reaction order as slope. Using this approach, the rate coefficients and reaction orders (n) for the release of K^+ (and Mg^{2+}) from K-bearing minerals are summarized in Table 2.

Table 2. Release rate coefficients of K^+ (and Mg^{2+}) for K-bearing minerals expressed as the -log of the flux in keq $m^{-2}s^{-1}$ at 25°C (after Sverdrup, 1990).

Mineral	pK_{H^+}	n	pK_{H_2O}	pK_{CO_2}	pK_{org}	n_{org}
K-feldspar I	12.7	0.5	15.5	-	-	-
K-feldspar II	12.5	0.5	15.3	14.6	13.9	0.4
Leucite	9.0	0.7	12.2	-	-	-
Phlogopite	12.0	0.5	>15.3	>14.7	10.3	0.5
Biotite	12.3	0.6	>15.3	>14.7	10.5	0.5
Muscovite	12.7	0.6	>16.2	>14.7	-	-
Glauconite	7.8	0.7	-	-	-	-
Illite	-	-	-	-	7.9	0.5

As the weathering rate of minerals is evidently related to temperature, the above rates can be adjusted to take this into account by using an Arrhenius equation in the form:

$$ln(\frac{rsoil}{rlab}) = A(\frac{1}{Tlab} - \frac{1}{Tsoil})$$

where A = Arrhenius pre-exponential factor (which is related to the activation energy of the reaction)

T = Absolute temperature

The rate coefficients obtained for 8°C, a temperature appropriate to soils of cool temperate climates are shown in Table 3. Comparison with Table 2 shows that most of the minerals examined release their K 4 to 8 times faster at 25°C compared with 8°C.

Table 3. Release rate coefficients of K^+ (and Mg^{2+}) for K-bearing minerals expressed as the -log of the flux in $keqm^{-2}s^{-1}$ at 5^oC (after Sverdrup, 1990).

Mineral	pK_{H^+}	n	pK_{H_2O}	pK_{CO_2}	pK_{org}	n_{org}
K-feldspar I	13.4	0.5	16.2	-	-	-
K-feldspar II	13.2	0.5	16.0	15.8	14.2	0.4
Leucite	10.4	0.7	13.0	-	-	-
Phlogopite	12.6	0.5	>16.1	>15.0	10.6	0.5
Biotite	13.1	0.6	>16.1	>15.0	10.8	0.5
Muscovite	13.5	0.6	17.0	14.6-15.1	-	-
Glauconite	8.7	0.7	-	-	-	-
Illite	-	-	-	-	8.6	0.5

Release Rates for K of K-Bearing Minerals in Soils

Field weathering rates can be determined in both the long- and short-term. Long-term weathering rates can be calculated from soil profiles by comparing the chemical/mineralogical composition of each horizon with that of the C horizon which is taken to represent the unweathered parent material. The method requires that the soil is developed upon uniform parent material, that the age of soil is known and that a suitable inert element/mineral can be used as a reference. Short-term weathering rates may be calculated from input/output budgets of catchments. More recently, a method based on the difference between the Sr isotope ratio of the deposition and that of the parent material has been used to determine the weathering rate of soil minerals (Jacks, 1990). There are problems with each of these methods, particularly when applied to individual minerals. Thus, long term weathering rates most often are expressed in overall chemical terms because of the difficulty in quantifying soil mineralogy. The catchment budget method cannot readily be applied to individual minerals and encounters difficulties with K in particular which is usually held and cycled within the biomass. Therefore, K release rates tend to be greatly underestimated when inferences are made on the basis of catchment water analysis. Again, the Sr isotope method is best suited for determining the weathering rates of minerals rich in Ca, an element for which Sr is a suitable surrogate.

Nevertheless, Sverdrup and Warfvinge (1991) have succeeded in reconciling field weathering rates from various sites in Europe and North

America with weathering rates calculated from the PROFILE model (Sverdrup *et al.*, 1990). This model uses experimentally-derived mineral reaction rates with adjustments for wetted surface area and temperature as described above. It was found that correlation between calculated weathering rates and field determined weathering rates was excellent, within ±8%. Table 4 shows weathering rates for feldspar and mica minerals, mostly determined from chemical analysis of historical soil profiles where the preponderance of K was associated with a single mineral species.

Table 4. K-release rates from feldspar and mica minerals expressed as -log of K flux (keq $m^{-2}s^{-1}$).

Location	Mineral	Rate	Reference
Gårdsjon (Sweden)	Microcline	12.5-11.6	Olsson *et al.* (1955)
Mharcaidh (Scotland)	K-feldspar	12.8-11.7	Bain *et al.* (1990b)
Kelty (Scotland)	Fine Muscovite	13.2-12.2	Bain *et al.* (1990b)
Chon (Scotland)	Fine Muscovite	13.8-11.2	Bain *et al.* (1990b)
Solling (Germany)	K-feldspar	12.5-11.9	Fölster (1985)
Solling (Germany)	Mica	12.8-12.2	Fölster (1985)
Coweeta (USA)	Biotite	12.2	Velbel (1986)

The rates compare reasonably well with those determined by Sverdrup for reactions with the H^+ ion at 8°C. Most of the sites are in Northern Europe and have a mean annual temperature approaching this value. For a climate with a mean annual temperature of 25°C these rates would be increased by between 3 to 15 times (Sverdrup and Warfvinge, 1991).

Discussion and Conclusions

The question arises as to whether these K release rates, which are exceedingly low, truly represent K-release rates from soil minerals. One point of difficulty is in reconciling the relative order of weathering as assessed from soil mineralogical studies (Table 1) with the order that may be determined from the experimental approach (for the H ion reaction, for example, which is likely to be most important) as seen in Tables 2 and 3. There is agreement that microcline, orthoclase feldspar and muscovite would be the slowest weathering minerals. However, the experimental rate coefficients would seem to indicate, although the data are fragmentary, that illite and glauconite would release K at a faster rate than biotite or phlogopite, which would generally be contrary to the interpretations arising from mineralogical studies of soil profiles. It should be noted though that if organic acid weathering is dominant, as it may be in podzolic soils, then the weathering rate of the trioctahedral micas increases by two orders of magnitude. However, the major point is that natural weathering of layer silicates is likely to encompass the combined effects of both surface-controlled and transformation processes. In many soils it would seem that the transformation mechanism plays a dominant role in K release, at least for the trioctahedral micas, as the frequently observed natural conversion of biotite to vermiculite demonstrates. The transformation reaction is quite different to the surface-controlled reactions discussed above. Here, the rate of release of structural K is a diffusion-controlled process which is characterized by a linear relationship between the K released and the square root of time (Rausell-Colon *et al.* (1964). The driving force of the diffusion is the difference in concentration between newly released K and the external solution K (Martin and Sparks, 1985). The external solution may therefore reach a critical K concentration at which point the release of structural K effectively stops. The critical concentration varies according to the particular mica mineral and is much lower for dioctahedral micas than for trioctahedral micas (Table 5).

Table 5. Critical solution K concentrations for layer silicates at 25°C with 1M NaCl as replacement solution (after Scott and Smith, 1966; Newman, 1969)

Mineral	Conditions	Critical K level (mgl^{-1})
Phlogopite	10-20 µm (1M NaCl)	23
Biotite	10-20 µm (1M NaCl)	11
Muscovite	10-20 µm (1M NaCl + 0.01M EDTA)	0.1
Illite	≤2 µm (1M NaCl +0.01M EDTA)	1
Glauconite	<50 µm (1M NaCl with pH 4.5-5.50)	0.6

The rather high critical solution K levels for biotite and phlogopite, which would be well in excess of what is found in most soil solutions, probably accounts for the marked susceptibility to weathering of these minerals and underlines the predominant role of transformation versus surface-controlled reactions. For the dioctahedral micas, the opposite could be the case although further work would be required to substantiate this point.

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Effect of Potassium Fertilization on K-Cycling in Different Agrosystems

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Summary

K cycles in agricultural systems are described by classifying soil K into five pools (Figure 1) : [1] K in plants, [2] available soil K, [3] unavailable soil K, [4] K in fertilizers and [5] K in harvests. It has been proved, using the isotopic exchange kinetic method applied to K^+ ions between the soil and its solution, that potassium accessible to plants is not confined to one homogeneous pool. Accessible K is a pluricompartimental system in which K ions move to the solution instantaneously or in times between 0 and the infinite. Thus the usual partitioning between available and non available soil K appears unjustified. It is shown that concentration of K ions in the soil solution can be used, in place of activity ratio, as intensity factor to characterize soil K availability. Examples of K cycles with maize under various conditions of production are discussed : soil, climate, K fertilization and sociological conditions, all influence K cycles. The main lack of knowledge encountered in predicting K cycles in differing ecosystems remains the difficulty to determine potential rates of K transfer from soils or soil-fertilizer systems to the soil solution and from the soil solution to the plant roots. These matters call for further research.

Introduction

This colloquium is devoted to "K in ecosystems". An ecosystem has been defined as "a functional system which includes one community of living organisms and their environment" (Soukatchev, 1954). So, the frontiers of an ecosystem are defined by the chosen community of living organisms. Therefore, this paper mainly deals with potassium that can be taken up by living organisms or potassium whose states or displacements can be modified by the organisms living either in a "natural" plot or in a field : this kind of potassium is generally called available potassium. Therefore, this paper will be mainly devoted to "Life and Death" of the available potassium of soils and fertilizers.

Global K biogeochemical cycle in ecosystems

The biogeochemical K cycle, like any nutrient biochemical cycle in an ecosystem, can be represented by pools linked with arrows showing K fluxes between pools. It is usual to consider five K pools : K in plants [1], available soil K [2], unavailable soil K [3], K in fertilizers [4] and K in harvests [5].

In "natural" ecosystems, like forests or permanent grasslands, plant nutrients return to soil at or near the place where they were previously taken up by plants. The main K input is the K carried by rains and the main exit is leaching. The K cycle remains close to the place where K is taken up by plants. The quantities entering or leaving the ecosystem each year remain low in comparison to the quantities present or cycling each year in the living organisms. This cycle is not really open under temperate climates, but may be more open under tropical climates due to low CEC clay minerals and heavier rains. A "natural" ecosystem can be considered, in a first approach, as a closed system in which solar energy, captured by photosynthesis, is the sole source of energy supplied to the "motor" of the nutrient cycles in ecosystems.

In agrosystems part of the potassium taken up from soil is exported out of fields in crop produce and is transported to towns (Frissel, 1978; Mengel and Kirkby, 1980). Usually this potassium does not return to the soil. In some countries, additional potassium, extracted from mines, is applied on soils and crops as K fertilizer. Therefore, in agrosystems, K cycle must be considered as open and this paper could be also entitled : "Potassium from soils and mines to rivers or soils via crops and Man". The K quantities cycling each year in crops are about the same as K inputs. In agrosystems two or three kinds of energy must be supplied together to feed the motor that works nutrient cycles : solar energy, animal or human energy and fossil energy.

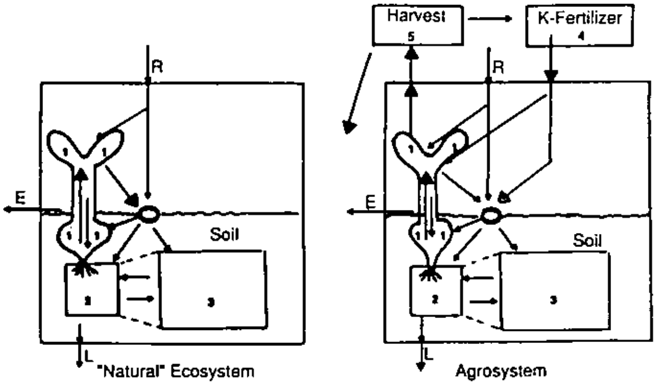

Fig. 1. Simplified K biogeochemical cycles in "natural" ecosystems and agrosystems. Pool [1] : K in plants; Pool [2] : available soil K; Pool [3] : unavailable soil K; Pool [4] : K in fertilizers; Pool [5] : K in harvests; R : rains; E : erosion; L : leaching.

K pools in ecosystems.

Pool [1] : K in plants. Its size depends firstly on the dry matter yields. It can be included between some kg ha^{-1} K and 300 kg ha^{-1} K for a sugar beet field and can reach more than 1000 kg ha^{-1} K for a forest (Frissel, 1978).

Pool [2] : available soil K assessment. It has long been thought that soil potassium was not homogeneously available for plants. Available soil potassium must be defined as soil K that can be taken up in a given time by plants. As potassium enters into roots as K^+ ions, available soil K is the fraction of the total soil K that can move as K^+, in a given time, from the soil to the soil solution. This kind of soil K is estimated using various chemical, physical or physico-chemical procedures.

Available soil K as a monocompartimental system : use of chemical extractions. The first use of chemical extraction to determine the probably available soil K was described about 150 years ago (Daubeny, 1845). Now, extraction is usually performed using 1 M ammonium acetate, but other salts as calcium lactate and inorganic or organic acids can also be used. The so extracted K is said to be available and the rest non available. According to these methods, total soil potassium can be represented by a bicompartimental model where available K appears as a compartment in which the availability of each K ion seems to be independent of time.

Available soil K as a pluricompartimental system : use of chemical or physical determinations. Some workers have thought that all the available K could not be uniformly accessible to plants. They have proposed dividing extractable K in three (Sharpley, 1990) or four compartments (Sharpley, 1989). These compartments can be determined using sequential extractions either with chemical reagents such as TBPNa (Quemener, 1978) or by physical procedures like electro-ultrafiltration (Nemeth, 1985). But physical compartmental analysis can also be achieved without extraction using spectrometric methods like far infra red (Prost and Laperche, 1990) or solid-state NMR (Lambert *et al.*, 1992). In these procedures, K availability is supposed to depend on the chemical or physical bindings between K and soil particles but to remain independent of time.

Available soil K as a pluricompartimental system : use of isotopic exchange kinetic procedures. Isoionic exchange of ions, carried out with isotopes, is one of the best methods to perform compartmental analysis (Sheppard, 1962). This is possible with $^{42}K^+$ or $^{43}K^+$; $^{43}K^+$ is the most appropriate for this use because it can be produced carrier-free and its half-life is twice as long as that of ^{42}K. An isotopic exchange occurs between $^{43}K^+$ ions applied in a soil-solution system and K^+ ions located on the solid phase of the soil. This isotopic exchange is time dependent (Tendille *et al.*, 1956; Sumner and Bolt, 1962; Fardeau *et al.*, 1977; Fardeau *et al.*, 1979; Diatta et Fardeau, 1979). The mathematical function characterizing the isotopic exchange kinetic of K^+ ions in all soil-solution systems is :

$$(r_t/R)/q_K = [(r_1/R)/q_K]\, t^{-n} \quad [1],$$

where R is the quantity of radioactivity applied to the soil-solution mixture at time t=0, r_t the radioactivity remaining in solution after t minutes of isotopic exchange, r_1 that remaining after 1 minute, n an empirical parameter generally lower than 0.2 and q_K the K quantity observed in the solution during the isotopic exchange. The quantity of K, isotopically exchangeable at a given time t, is calculated using the following equation :

$$E_{Kiet} = (R/r_t)\, q_K \;\; \text{-->} \;\; E_{Kiet} = E_{Kie1}\, t^n \quad [2].$$

The conclusion about isotopically exchangeable soil potassium was similar to that about isotopically exchangeable soil phosphate (Fardeau *et* *al.*, 1991; Fardeau and Frossard, 1992) : isotopically exchangeable K is a ***pluricompartimental mamellary system*** (Sheppard, 1962).

Relation between K^+ isotopically exchangeable during the first minute and exchangeable K^+ determined with NH4-Ac. The quantity, $E_{Kie1} = q_K(R/r_1)$, of K isotopically exchangeable during the first minute of isotopic exchange is slightly higher (about 10 %) than the quantity of exchangeable K extracted from soil with 1M NH_4-Ac (Tendille *et al.*, 1956; Fardeau *et al.*, 1979; Poss *et al.*, 1991). Therefore K extraction with 1 M NH_4-Ac can be considered a good method to determine the most labile K.

Relation between isotopically exchangeable and available soil K. By carrying out simultaneously pot experiments using $^{40}K^+$ and isotopic exchange kinetics using $^{43}K^+$, it has been shown that plant roots take up potassium only from isotopically exchangeable potassium (Fardeau *et al.*, 1979). It was concluded that ***the available soil potassium is the isotopically exchangeable soil potassium*** : available soil K is then a pluricompartimental mamellary system that can be described using the same parameters as those used to describe isotopically exchangeable K, *i.e.* : c_K, r_1/R and n. A central compartment contains a quantity of K^+ ions of the same order of magnitude as the quantity $E_{Kie1} = q_K(R/r_1)$; the ions it contains can move from soil to the solution in less time than 30 seconds; therefore they can be considered directly accessible to plant roots. The other mobile ions observed with isotopic exchange have been classified into four compartments based on the time required to move towards the soil solution. The first compartment contains ions which can be released to the solution between 1 minute and 1 day; this period is about the same as the active uptake period for a given zone of a root hair (Barber, 1968; Barber, 1984). The second compartment contains ions which can move to the solution between 1 day and 3 months, this period corresponding to the activity of a rooting system. The third compartment contains ions which can be released into the solution between 3 months and one year. The fourth compartment contains ions able to leave the solid phase of the soil in more than one year. The quantities contained in each compartment were determined using equation [2]. So, when using the isotopic analytical procedure, available K appears time depending, as it actually is.

Availability of soil potassium. As for phosphate, availability of potassium depends, at least, on three factors : intensity factor, (I), quantity factor, (Q) and capacity factor, (C=Q/I) (Beckett, 1964a). The last factor characterize the ability of soils to maintain constant intensity when either roots take up potassium or K fertilizers are applied on soils. The I, Q and C values depend on the experimental parameters used (Mengel and Busch, 1980; Sharpley, 1990). Different analytical methods were proposed to quantify these factors. It has been also suggested from results obtained with cation exchange studies that the activity ratio, $AR_K = a_K/(a_{Ca}+a_{Mg})^{1/2}$, of the soil solution could provide a satisfactory measurement of the intensity factor (Beckett, 1964b) and that the Q/I curves should give general information about soil K availability (Parra and Torrent, 1983; Jimenez and Parra, 1991). Change, $dF_K = RT \ln[c_K/(c_{Ca}/c_{Mg})^{1/2}]$, in the free energy of the exchange reaction has been also suggested to characterize K availability (Feigenbaum and Hagin, 1967; Goulding, 1983). Data observed on 3 soils for c_K, the K ion concentration in the soil solution, and calculated for AR_K and dF_K are given in Table 1.

Table 1. Variations of c_K (micromole l^{-1}), AR_K ((mole $l^{-1})^{1/2}$) and dF_K (cal mol^{-1}) with the soil-solution ratio

Soil/solution	Grignon			Causse			Combourg		
ratio	c_K	AR_K	dF_K	c_K	AR_K	dF_K	c_K	AR_K	dF_K
1/500	5	0.010	-3680	25	0.09	-2475	8	0.034	-3089
1/100	8	0.012	-3475	87	0.17	-1780	31	0.046	-1989
1/30	15	0.017	-3100	200	0.24	-1340	48	0.16	-1995
1/10	25	0.021	-2730	350	0.30	-1055	90	0.24	-1605
1/3	33	0.020	-2590	600	0.34	-771	160	0.32	-1200
1/1	55	0.024	-2310	600	0.33	-754	350	0.46	-680
1/0.25 (Extrap)	99	0.030	-2100	600	0.34	-760	500	0.52	-250

Two main conclusions can be drawn from these results and several other unpublished data :

- In a given soil : (i) AR_K and c_K are highly correlated (r^2=0.98); (ii) c_K and dF_K also highly correlated (r^2=0.99). Therefore c_K, that is the simplest value to determine, can be chosen as intensity factor in place of AR_K or dF_K.

- c_K, like all cation concentrations, increases if soil/solution ratio increases. In soils, under growing crops, the mean water content is about 0.25 cm^3 cm^{-3}. For a better understanding of the processes involved in the root zone, the expected values of c_K, AR_K and dF_K values at this water content have been extrapolated from the last data. These results show that the values of AR_K determined in a standard condition can be very far from the values expected in the rhizosphere.

As K uptake by crop is a time dependent process, K availability must also be defined by the ability of K to move, in function of time, from soil to the soil solution and further to crop. This can be achieved using two data deduced from isotopic exchange determinations, namely the mean sojourn time, $T_m = [(r_1/R)^{(1/n)}]/n$, of K^+ in the solution and the mean flux, $F_m = 10\ c_K\ (1/T_m)$, of K^+ between the soil and its solution (Fardeau *et al.*, 1991).

Available soil potassium : Conceptual compartmental model. The proposed model contains a visual representation of the intensity, quantity and capacity factors useful to characterize available soil potassium properties. Each compartment is schematized by a rectangle whose area is proportional to the K quantity it contains. The width of the central compartment, E_{Kiel}, is proportional to the c_K value, *i.e.* to the intensity factor I; so, as the pool surface is proportional to the E_{Kiel} quantity, *i.e.* to the quantity factor Q, the length of this rectangle is proportional to the capacity factor C = Q/I. Without information about intensity factor of the other compartments, their widths are represented with an equal value. Figure 2 is one application of this conceptual model to two soil samples taken in two K treatments (K_0 and K_2) of a field experiment of Southern Togo (Poss, 1991).

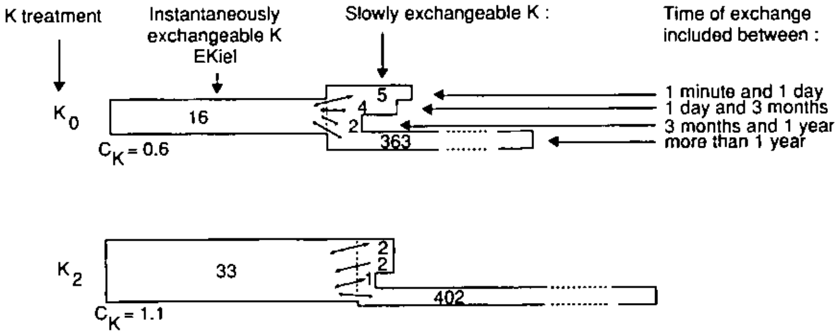

Fig. 2. Mamellary model for available soil potassium. c_K values are given in mg l^{-1} K and quantities in each compartment in mg kg^{-1} K

Results show that, in this soil, K fertilization higher than K output (i) increased significantly the compartment E_{Kie1}; (ii) did not modify significantly the amounts of K in compartments leaving solid phase between 1 minute and one year but increased significantly the compartment of very low mobility, information that can be interpreted, for agronomic purpose, as a fixation (Poss et *al.*, 1991); (iii) did not modify significantly the capacity factor, i.e. the buffer power of the soil for K ions. This last observation is general.

Pool [3] : unavailable soil K. This pool contains the total soil K minus the pool of available K. But as shown by the isotopic exchange kinetic analysis, available K depends on the chosen period. Therefore it can be said that there are no frontiers between "available" and "unavailable" soil potassium.

Pool [4] : K in fertilizers. This pool appears in agrosystems. Its size which greatly depends on economic conditions is included between 0 kg ha^{-1} K and 400 kg ha^{-1} K just after application on field.

Pool [5] : K in harvests. In many crops this K pool can be much smaller than pool [1] : K in crops. This is clear for orchards where the major part of K remains in wood. But this is also true for many other crops. For example, with maize, K in straw can be three times higher than K in grain (Poss, 1991) and this factor greatly depends on the ability of soil to feed the crops. The transfers between pools [1] and [5] has to be known with accuracy to establish K balances in a cropping system.

K fluxes between K pools

The prediction of the potential fluxes between each pool is the main difficulty encountered in describing K biogeochemical cycle in an ecosystem (Gachon, 1988). K cycling studies, like any nutrient cycling study, could benefit from experiments with isotopic tracers. ^{42}K and ^{43}K have sometimes been used; but their half-lives, 12.4 hours and 22 hours respectively, are too short for agronomic trials. There are three other natural isotopes, ^{39}K, ^{40}K and ^{41}K; but their isotopic ratio analyses are difficult and expensive. So, ^{86}Rb, or ^{134}Cs and ^{137}Cs have sometimes been used as substitutes for K isotopes (Haunold, 1989). These isotopic tracers should not be used as substitutes for K : they compete with K either for exchange sites in soils or during their uptake by roots (Oien *et al.*, 1959; Fried and Heald, 1960; Claasen and Jungk, 1982).

K outputs of the soil layer in the rooting zone. Uptake by roots, leaching and soil erosion contribute to decrease the total K content of the upper soil layers. K uptake by plants is generally the main exit for K.

K uptake by plants. The roots are the main entry for potassium into plants. If no K fertilizer is applied, 100 % of the potassium taken up by roots come from the available soil potassium. When K fertilizer is applied, potassium can be taken up by roots from two nutritive sources: the available soil potassium and K in fertilizer. The quantity of K derived from each K source is determined using two experimental designs. In the indirect but general design, the quantity of K taken up by a crop with K fertilizer minus the quantity of K taken up by a crop without K fertilizer is compared with the K quantity applied as fertilizer. The major assumption of this comparison is that the quantity of potassium derived from the soil does not depend on the quantity of K applied as fertilizer. In the direct method, ^{40}K-labelled fertilizers are required. Due to analytical difficulties and cost of the ^{40}K, only three papers report data on the true value of the percentage utilization of K from fertilizers. The values obtained were between 10 and 30 % (Slutskaya *et al.*, 1980; Medvedva *et al.*, 1983) and between 6 % and 12 % (Fardeau *et al.*, 1984). Due to the fact that the quantities of K applied were slightly higher (about 1.5 times) than the quantities of K taken up by crops, the K derived from fertilizer (Kdff) in crop was between 10 % and 45 % . So 94 % to about 70 % of the K applied a given year remain in soil after the first crop. These react with soil components and are distributed between the various compartments of soil K. *As a consequence, available soil potassium is, with or without K fertilizers, the main source of potassium for plants.*

A mean value for c_K is about 2 mg l^{-1} K. When growing crops evaporate 1 l water containing about 2 mg K, the dry matter yield increases of about 3 g containing about 30 mg K. So mass-flow can only explain 100(2/30) = 7 % of the total K uptake : 93 % of the K taken up during a cropping season must be desorbed from the solid phase of the soil (Nye and Tinker, 1977). But desorption can arise if, and only if there is a water film between soil particles and root hair.

In all circumstances, quantity and availability of soil K decrease each time that K is taken up by crops. In pot experiments (Hinsinger, 1990; Daklia, 1991; Badraoui *et al.*, 1992) or under very intensive cropping conditions (Blanchet et Bosc, 1962; Beckett and Nafady, 1969) or under continuous cropping without K fertilization (Bosc, 1988; Poss, 1991), K quantities taken up during a given period can be higher than heteroionic or isoionic exchangeable K quantities measured at the beginning of cropping . Similar results were often explained by the assumption that roots of some crops can take up non exchangeable K (Bosc, 1988). In fact, they showed that slowly exchangeable K^+, identified by isotopic exchange method, turns into fast exchangeable K during the cropping period and, so, can participate in the K nutrition of crops (Poss, 1991). This process, sometimes associated with clay transformations (Hinsinger, 1990), has been also observed with soil microorganism activity (Berthelin, 1983).

K leaching. K leaching occurs in soils whenever there is drainage. The quantities leached depend on numerous factors like dry matter yield and its K content, amounts of K applied or water drained; they ranged between a few kg ha^{-1} $year^{-1}$ K and more than 50 kg ha^{-1} $year^{-1}$ K (Warren and Johnston, 1962; Quemener, 1978; Lefèvre, 1988). Under special crops receiving very high dressings (600 kg ha^{-1} $year^{-1}$ K), leaching can reach up to 450 kg ha^{-1} $year^{-1}$ K (Pieri and Oliver, 1986).

K inputs in agrosystems. Rains, fertilizers and crop residues are the main entries of K in agrosystems. K in rain falls on soils mainly as particles. K fertilizers are generally applied as water soluble salts and K in crop residues is mainly in the ionic form but is included in plant cells.

K applied as fertilizer enters pools [1], [2] and [3] and is sometimes leached. The distribution between these four pools depends on K quantity applied, quantity and mobility of available soil K, crop needs and the type of clay in each soils. Entry in compartment [3] has been called "fixation" (Way, 1850; Volk, 1938; Attoe, 1946). The part of K applied which is "fixed" in a given soil depends on the method used to determine fixation (Van der Marel, 1959). The processes involved in fixation remain in discussion (Gaultier et Mamy, 1988; Poss, 1991).

K contained in crop residues returned to soils becomes available when crop residues are broken down by microorganisms. The efficiency of this K appears of the same order as that of K in fertilizers. Two assumptions can explain this observation : (i) K in crop residues is, for a time which depends on pedoclimatical conditions, protected from reactions with clay particles; (ii) the K content in dry matter of crop residues is about 0.5 % to 1 % whereas K concentration in the soil solution is about 2 mg l^{-1} K. In fact K in crop residues appears more like K fertilizer than the available soil K.

Nevertheless whenever available K is applied, the soil acts as a sink.

Comparison of K cycles under various management conditions

This comparison can concern different crops in a given pedoclimatical condition or a given plant cropped in different pedoclimatical and sociological conditions. The second condition was preferred to the first. Maize, a plant cropped under very different pedoclimatical conditions (FAO, 1989; Corazzina *et al.*, 1991), was retained as model.

The first example concerns K cycling observed under continuous cropping of maize with or without K fertilizer, in a developing country : Togo. A K balance (Table 2) was established for 11 years in a Ferralsol called "Terres de Barre" (Poss, 1991; Poss *et al.*, 1991). From 1976 to 1980, crop residues were removed from the field; after 1980 they were returned to soil. At the end of this experiment, in 1986, exchangeable K contents were 36 and 200 mg kg^{-1} K respectively for K_0 and K_2 treatments in the upper layer (0-10 cm) of soil. Inputs with rain and outputs by leaching are low compared to outputs in harvests. The fate of straw is the most important factor in the K balance in these cropping conditions.

Table 2. K balance in a long term trial in Togo. Maize with and without K fertilization (mean K applied K_2 : 120 kg ha^{-1} yr^{-1} K)

Period		1976-1980 (Straw removed)		1976-1986 (Straw returned from 1981)	
Treatment		K_0	K_2	K_0	K_2
Mean yield (t ha^{-1} yr^{-1})		2.9	5.5	2.1	4.6
Inputs (kg ha^{-1} yr^{-1} K)	Rain	1	1	1	1
	Fertilizer	0	39	0	86
Outputs (kg ha^{-1} yr^{-1} K)	Grain	13	22	9	20
	Straw	51	85	23	38
	Leaching	2.5	4.2	2.6	4.5
Balance (kg ha^{-1} yr^{-1} K)		-65	-72	-34	+23

The second set of data (Table 3) concerns maize cropped in a developed country. Results were obtained in a long-term trial (1967-1980) carried out in France by INRA (Bosc, 1988). Yields were about twice those in the Togo experiment.

Table 3. Yield and K balance in a long-term trial (1967-1980) in France (La Grande Ferrade) (mean per year for K_1=30 kg ha^{-1} K and for K_2=60 kg ha^{-1} K; straw returned)

Treatment		K_0	K_1	K_2
Mean yield	(t ha^{-1} year^{-1})	5.9	8.1	8.3
Fertilizer	(kg ha^{-1} year^{-1} K)	0	31	60
Output	(kg ha^{-1} year^{-1} K)	20	31	32
Balance	(kg ha^{-1} year^{-1} K)	-20	0	28
Exch K	(mg kg^{-1} K)	18	38	42

The most interesting fact is that average annual K fluxes from soil to crop for treatments K_0 and K_2 were respectively 32 and 58 kg ha^{-1} year^{-1} K in Togo but were respectively 54 and 88 kg ha^{-1} year^{-1} K in France, even with a lower quantity of exchangeable soil K and a lower K fertilization in France. But in 1950 maize yield in France was between 2 t ha^{-1} and 4 t ha^{-1} with K inputs of about 40 kg ha^{-1} K (Malterre, 1953). So it appears that : (i) in a developed country like France, maize yield was thirty years ago the same as now obtained in a developing country like Togo, even with a K fertilization significantly higher than K output; (ii) K flux from soil to plants can be increased significantly not only by K fertilizer applications but also by suitable management methods.

In USA, average maize yield has increased with time (Pimentel *et al.*, 1973). Over the same period, K fertilizer use has also increased but most of the increase has been due to a large increase in consumption of fossil energy for maize production. Therefore, when native soil K is limiting, simply removing the K constraint may not be sufficient to secure production : it is also necessary to use much energy, fossil or not.

Why and how modify K fluxes from pool [2] (available soil K) and/or [4] (fertilizer) to pool [1] (crops)

Why modify K fluxes? Agricultural policy varies with time in a given country. At a given period, agricultural production must increase in some countries to feed the increasing population but must decrease in some other countries. Therefore farmers must be able to control K fluxes from soil to crops and harvests (Villemin, 1991).

How modify K fluxes ? When K uptake ([2]+[4]->[1]) is the first limiting factor, control of K uptake by crop change crop yields. Results often quoted, obtained some time ago mainly from one long-term English field experiment (Cooke, 1967; Cooke, 1984; Johnston, 1990), showed that high crop yields were only obtainable on soils high in available K which, in this case, was the result of applying over a long period more K than was removed in crops. This led the opinion that residual K was more important than the amount of K applied to crops. Many other experiments were made on this topic (Barbier et Trocmé, 1964; Trocmé et Barbier, 1961; Trocmé et Boniface, 1972; Amberger and Gutser, 1976) but led to no definite conclusion. More recent findings show that, in present day conditions, fresh K fertilizer is more efficient than residual K (Bosc, 1988). Under western European conditions, then, it appears easier to modify quickly K fluxes by using K fertilizer frequently rather than by aiming to create a large reserve of available soil K. A similar policy remains to establish for the low activity clay soils of tropical regions.

The following data (figures 3 and 4) show that the quantities of available soil K and rates of K fertilization are not always the main factors determining crop yields and K uptakes. In Southern Togo (Fig. 3) maize is cropped twice a year. Figure 3 shows seasonal changes in maize yield: climatic effects observed in these conditions were higher than interannual effects even with a non limiting K fertilization. Figure 4 shows that in the INRA long-term trial (La Grande Ferrade) interannual variations of maize yield were of the same magnitude as variations observed between two treatments, with (K_2) and without (K_0) fertilization. This conclusion stands also for field conditions where no yield response was obtained over a long period. It seems that variations in climatic factors (principally availability of water), should be taken into account when considering K fertilizer needs.

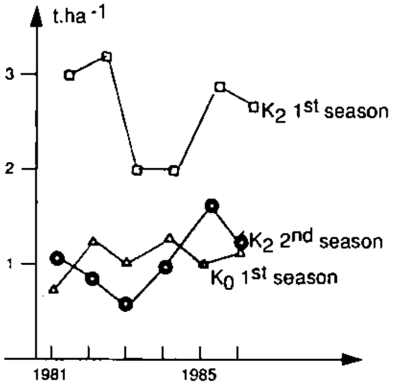

Fig. 3. Effects of climatic conditions on maize yield under two K fertilization regimes

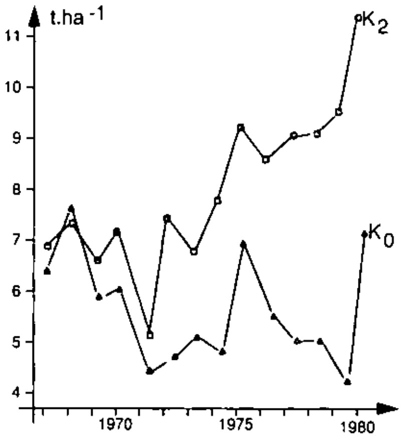

Fig. 4. Effects of long term K fertilization on maize yield (Exch. K in K_0:27 mg kg^{-1} K in K_2:42 mg kg^{-1} K)

In fact K uptakes by crops depend on many biotic and abiotic factors in the agrosystems : yield of a given crop and its K content (Nelson, 1968), length of the uptake period, available soil K and its availability (Jen-Hshuan Chen and Barber, 1990), amount of K fertilizer, root extent (Tanner, 1967), rate of root growth (Bosc et Maertens, 1981; Curl and Truelove, 1986), water content of soil (Blanchet *et al.*, 1962) and soil structure, pests and diseases.

Conclusions and needs for the future

Sustainability of the Human life on our earth (Lubchenco *et al.*, 1991) depends on sustainable agriculture. So far as potassium does not pollute soils, crops or waters, its use as a fertilizer can be discussed only on purely economic grounds depending, for a part, on technical knowledges about the K biogeochemical cycles. If K is not return to soil, K soil fertility declines; sustainability depends upon its return (Van der Pol, 1990; Poss, 1991). In comparison with "natural" ecosystems the most important change to the K cycle observed in agrosystems is due to the fate of crops residues which is greater than the effect of K fertilization. It was thought formerly that increase in the K flux from soil to crop could be achieved only by increasing available soil K and it was recommended to apply more K than was actually needed by the crops. Recent experiments in developed country have shown that under modern management : (i) residual effects are lower than expected and that immediate effects of fresh K fertilizer were greater than predicted; (ii) K flux can be increased without increasing available soil K. Consequently, and because leaching of K is generally low compared with crop uptake, average K applications can be of the same magnitude than K outputs.

Research needs on the K biogeochemical cycle depend on agricultural policy of each country. Formerly, the universal goal was to increase crop production. This is still the aim in many developing countries : K fluxes from soils to crops must increase quickly to increase crop production. Elsewhere, as in Western Europe, overall K fluxes should be decreased quickly; but it is still open to discussion whether it would be decreased in every field or whether there should be a steep decrease in some with a continuous increase in others. It appears that in all countries it is more important to predict K flux than to determine quantity of available soil K. All routine soil analyses give information on quantity but no information on potential flux. We need to perfect analytical methods for measuring potential flux of K ions from soil to soil solution and to classify the mechanisms that control, in all major types of agricultural systems, the transfer of K from soil solution to crops.

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Fertilizer Recommendations as Determined by Chemical and Physical Parameters of Soil and by K Requirement of Crops

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Summary

Crop yields and soil fertility in Czechoslovakia have greatly improved over the past 30 years due to intensive fertilizer usage. Research has concentrated on crop requirements, nutrient balance, soil properties and plant analysis, resulting in an improvement in fertilizer efficiency. Nutrient uptake is a prime criterion for K fertilization but this varies with environmental and genetic factors as confirmed by long-term experiments since 1957. Interactions with other cations are important and can lead to imbalance in nutrient uptake with undesirable effects on crop performance. It is difficult to determine the optimum soil K level and joint use of other methods to describe the behaviour of soil potassium is discussed. The present methods for deriving K fertilizer recommendations are described.

1. Introduction

Scientific fertilizer usage is based on the knowledge that crops require specific amounts of available nutrients in order to express their full yield potential. Thus crop production depends largely on fertilization and it is impossible to produce high yields of good quality without using fertilizers.
A prime purpose of fertilization is to replace nutrients removed from the soil in harvested crops.

In our country, as in others with progressive farming, crop yields are high (Table 1) and it is not now a question as to whether or not to use fertilizer but, rather, as to what methods of application are economically and environmentally sound.
Average nutrient uptake by crops in the Czech Republic are as follows (Vostal, 1992):

N 121 kg ha^{-1}, P_2O_5 47 kg ha^{-1}, K_2O 113 kg ha^{-1} and MgO 21 kg ha^{-1}.

Average fertilizer usage (1986 - 1990) was:

N 95, P_2O_5 65, K_2O 63 and MgO 7 kg ha^{-1}.

Rather more phosphate than crop uptake was used but considerably less potash and magnesium.

Table 1. Crop yields in CSFR (mean 1986-1990)

Crop	t ha^{-1}
Wheat grain	5.1
Barley grain	4.6
Rape seed	3.6
Sugar beet roots	34.9
Arable hay	7.4

Table 2. Range of potassium uptake in heavy and medium soils (Bohuslavice, 1985 - 1987; Pácalt, 1988)

Soil	kg t^{-1} grain	
	winter wheat	winter barley
Heavy	20.6-27.7	47.2-49.4
Medium	18.6-20.8	41.8

Fertilizer policy should:

1. Make good any deficiency in soil nutrient supply so that crop development is not restricted;
2. Replace nutrients removed by crops;
3. Improve soil fertility in the longer term.

It would seem from the above and other considerations that our fertilizer policy has largely satisfied the above objectives. It is evident from Figure 1 that N uptake has almost doubled between 1961/65 and 1986/90. Soil contents of P_2O_5 and K_2O have increased with a positive balance for P_2O_5 and a neutral position for K_2O.

Table 3. % of total nutrient uptake originating from soil sources

Soil	N	P	K
Grey-brown	76	80	60
Brown	74	66	55

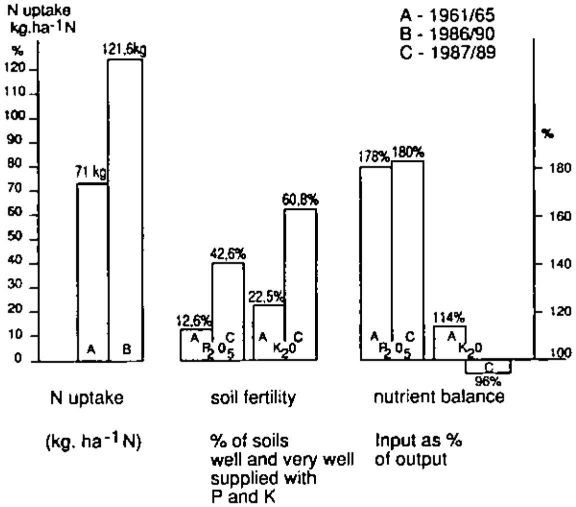

Fig.1. Changes in Czech agriculture as exemplified by N uptake, P-K status of soils and nutrient balance.

2. Definition of optimum K fertilizer rates

Yield is not determined just by the amount of nutrient applied as fertilizer, supply from soil reserves also contributes. According to Table 3 nutrients of soil origin make a larger contribution than fertilizer to crop requirements. It is thus essential to be informed about the available nutrient reserve in the soil.

The uptake of one nutrient is much influenced by the supply of others (Baier, 1974). Plant analysis shows that many factors (soil chemistry, biology and weather) affect nutrient uptake and these must be taken into consideration, if possible expressing them in quantitative terms. If not we have a "black box" situation and cannot explain the variability in yield formation. Plant analysis early in crop development is a useful method for diagnosing nutrition problems which can be corrected by spray application of nutrients.

Czechoslovakian experience in refining fertilizer applications has been positive, especially with respect to nitrogen, with higher yields, increased fertilizer efficiency, savings in fertilizer costs, decreased nutrient loss and avoidance of environmental damage (Baier *et al.*, 1988).

2.1. Crop demands for potassium

Potassium uptakes are normally stated in terms of long-term average crop and by-product yields, or, more conveniently in terms of uptake per unit yield of produce. These vary over time, with variety and management but mainly, of course, with yield level.

Cereals have a relatively low K requirement. Modern wheat varieties require 18% less K than the old and modern malting barleys some 40% less. This is mainly due to the lower straw to grain ratio of the modern and higher yielding varieties. This leads to the somewhat strange conclusion that crop demand expressed per unit grain yield is lower at higher yield levels; the following data refer to winter barley.

t ha^{-1} grain	kg t^{-1} K_2O	straw/grain
< 4	19.7	1.30
4.1 - 5	18.3	0.93
5.1 - 6	17.2	0.66
> 6	15.4	0.70

Experiments at Bohuslavice nad Metují showed that K consumption by winter wheat, spring and winter barley (and also by sugar beet) was reduced as the proportion of grain (or roots) to total biomass increased (Figure 2).

Trials on soils of differing texture at Bohuslavice showed higher K uptakes on heavy soils by both winter wheat and winter barley (Table 2).

2.2. Influence of growing conditions

In making fertilizer recommendations it is impossible to take into account annual (mainly weather) variation. As shown in Figure 3, potassium uptake was sometimes inadequate for high yield and/or the amount of K leached from straw varied. Correlation between K uptake and yield can be expected only when potassium is the limiting nutrient in accordance with the law of the minimum.

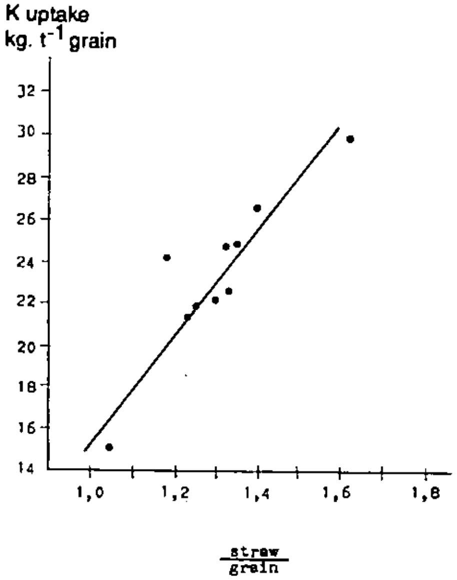

Fig. 2. Effect of straw/grain ratio on K uptake per unit grain yield (Bohuslavice 1985-'87).
Rotation : winter wheat, winter barley, spring barley.

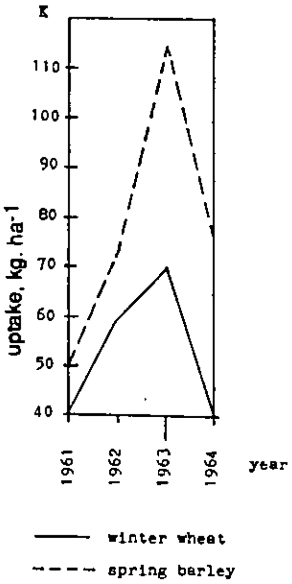

Fig. 3. Influence of annual weather on potassium uptake by winter wheat and winter-barley at harvest.

Contrary to crops in which assimilates are partitioned in storage tissue, experiments with red clover (Baier and Baierova, 1974) show that dry matter yield of the green biomass was related to K uptake (Figure 4). K content in leaf dry matter was from 2.8 to 3.0% but seasonal yield was remarkable.

2.3. Influence of the treatment of plant residues

The fate of plant residues at harvest has an overriding effect on removal of potassium from the soil. If residues (straw of grain crops, tops of beet) are left in the field and only grain or roots removed K removal is greatly reduced - a reduction of 64% in our sugar beet experiments on 4 sites for 4 years.

In the case of cereals even the total uptake at harvest is not a good indicator of potassium requirement because the content at maximum vegetative development of the crop exceeds that at maturity.

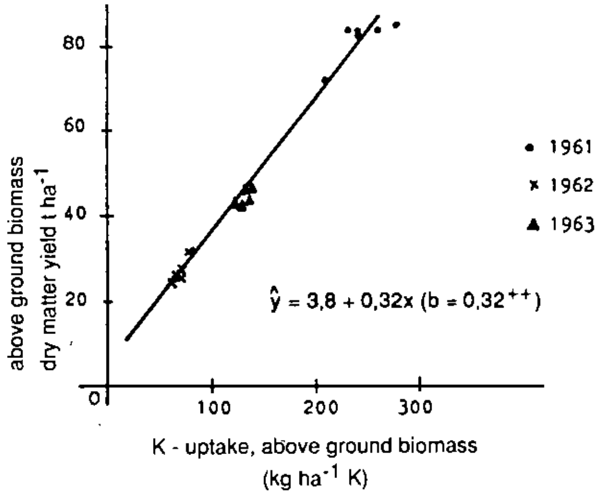

Fig. 4. Dependence of dry matter yield of red clover on K uptake at Hadacka (Baier and Baierova, 1974).

2.4. Importance of balanced nutrition

We have also to take into account the possibility of antagonistic effects if potassium supply is excessive. The contribution to K supply from farm manures is variable and often unknown. It is difficult to correct deficiencies during the growth of the crop and to take into account changes in K bondings in the soil.

All these difficulties make for problems in forecasting K requirement and suggest that it is useful to rely on calculation of the potassium balance.

3. Modification of K fertilizer recommendations by research

It seems that in Czechoslovakia in the past oversimplified and too rigid opinions have resulted in some soils being over-generously fertilized with potassium and that the consequent high K levels in soils have led to the occurrence of magnesium deficiency. Using average values for potassium uptake can be misleading since uptake varies between years and according to soil conditions. Therefore there is a need for careful monitoring under different conditions and this should include monitoring of other nutrients to check on inter-nutrient balances.

No doubt average values will still be widely used in the future but our research shows that as compared with guidelines used in the eighties, there is now a decreased potassium fertilizer requirement (5-20%) for cereals and grain maize and the same applies to other crops: potatoes (13%), red clover (18%), oilseed rape (30%) and silage maize (4%). On the other hand sugar and fodder beet and sunflower require more K fertilizer than thought previously.

3.1. The influence of potassium in soils

Since fertilizer and soil potassium both contribute to the supply of K to the crop it is necessary to know, in order to forecast fertilizer need, how much potassium the soil can supply. We (Baier and Bystrá, 1975), like other workers, have investigated the effect of the level of available K in the soil on crop yield and the level which, in the absence of K fertilizer, will support maximum crop yield. As shown in Figure 5, the response curve is parabolic, yield increasing up to a maximum and declining slightly if this level is exceeded. The probable explanation is that at very high levels of K, other nutrients become limiting (interaction with Ca^{++} and Mg^{++} and sometimes H^{+}). Other ecological and physiological factors may also be concerned (Baier, 1979).

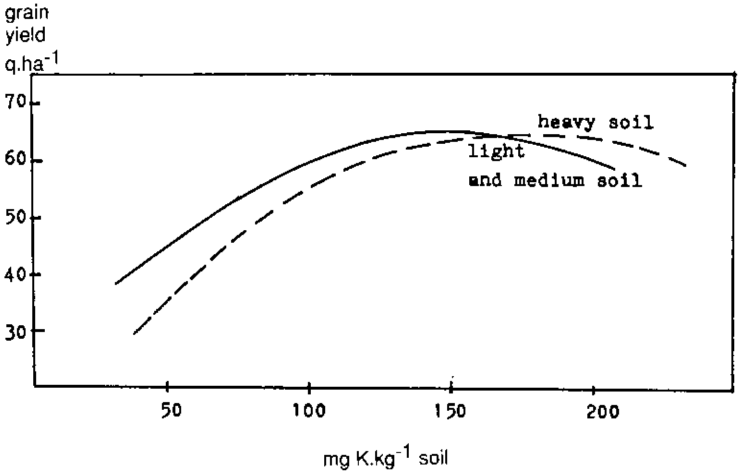

Fig. 5. Grain yield of winter wheat as related to soil available K content.

Three years study of potassium uptake showed that K uptake by wheat from soil not receiving K fertilizer varied from 48.0 to 75.6 kg ha^{-1} K_2O on chernozem and from 32.4 to 86.4 kg ha^{-1} K_2O on brown soils due to variation in weather conditions from year to year.

Potatoes did not respond to K fertilizer on slightly acid and neutral soils but responded well on acid soils.

In view of these and other problems, the concept of "optimum level of available soil K" is somewhat theoretical in practice, we have to confine ourselves to the use of soil analysis to determine how much fertilizer potassium is required to make up for the lack of sufficient soil K for the production of optimum yields. In interpreting the results of soil analysis, other soil characteristics must be taken into account. Among these soil texture is most important; it is widely recognised that, for a given yield, available potassium must be higher on heavy soils than on light. We developed the system illustrated in Table 4 which shows how rates of K fertilizer required for increasing target yields differ between soils of differing texture. This table allows for the higher K fixation which is to be expected in heavy soils.

The older methods of predicting K fertilizer requirement which aimed to enrich low K soils to the optimum level of available K (Baier *et al.*, 1963) were successful in reducing the proportion of low K arable soils in the Czech Republic from 37.6% in 1961-1965 to 9.2% in 1987 - 1989; comparable data for the Slovak Republic were 46.2 and 3.5% respectively.

3.2. Improving the precision of K fertilizer recommendations

There is no doubt that predictive methods need to be improved. In the small agricultural regions of Bohemia, Moravia and Slovakia, soils of different physical and physico-chemical properties but with the same content of available K respond to potassium fertilizer in very different ways.

Vopěnka and Smetánková (1986) showed that, in high K fixing soils, exchangeable K is not the main source of K supply to plants. The low level of exchangeable K in these soils is little changed by either applying potassium or as a result of plant uptake. According to our long-term experiments, however, applying K fertilizer does increase soil K content (Table 5).

Table 4. Available soil K levels required for different yield levels.

Yield level (cereal units ha^{-1})	Available soil K (mg kg^{-1})			Average recommended rate of K fertilizer (kg ha^{-1} K_2O)		
	Light soils	Medium soils	Heavy soils	Light soils	Medium soils	Heavy soils
4.0	87	116	145	48	48	65
4.5	110	146	182	70	80	106
5.0	139	185	231	77	87	116
5.5	173	231	288	82	93	124

Table 5. Effect of long-term (20 years) K application on exchangeable K content (ppm) of soils of differing K fixation capacity.

		Mean annual K dressing (kg ha^{-1} K_2O)	
Soil	Initial value (ppm)	0	83
Caslav (strongly fixing)	108	75	96
Lukavec (weakly fixing)	218	94	235

Vopěnka (1989) considers that using particle size distribution alone to modulate K availability is not sufficient and that two categories of soil potassium should be measured : exchangeable plus water soluble and mobile potassium reserve. Hudcová (1991), based on study of quantity-intensity relationships, agrees. If the K reserve is high (> 1200 mg kg^{-1} K) the rate of K fertilizer should be decreased by one step.

Without doubt there are methods capable of characterising the K regime in different soils more precisely but, because they are tedious and expensive, they are little used in practice. An approach similar to that of Andres (1991) using a network of monitoring field experiments is an attractive possibility for improving on the present system for determining fertilizer requirements.

At the present time the "Complex Methodology of Plant Nutrition" (Neuberg *et al.*, 1990) is recommended nationwide for determining basic annual application of potassium for a crop rotation. This is based on soil K category including reserves and soil type and allows for K applied in organic manures. It recommends suspending K fertilization for three years if exchangeable K exceeds 290, 350 and 460 mg kg^{-1} on light, medium and heavy soils respectively.

Under this system, potassium fertilizer is applied to cover total requirement for a two or three year period and rates are adjusted for climatic region, soil texture and soil K level. Application at such infrequent intervals is not recommended for light sandy soils, soils with pH below 5.0 or soils with very low K reserves which should receive K fertilizer every year.

For soils with medium K content it is recommended that K fixation capacity should be measured by the Reichenbach-Schroeder method. Some agricultural laboratories use the CEC method for specifying balanced application of potassium, magnesium and calcium (Matula, 1984).

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Potassium in Animal Manure and Plant Residues : Efficiency and Losses

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Summary

Animal manure and plant residues are organic fertilizers which cover a great part of the nutrient requirements of the crops. This is demonstrated by the potassium cycle of the Swiss agriculture. As the cycle is not closed, the nutrients exported (animal products, vegetable produce, losses) have to be replaced by mineral fertilizers and imported feedstuffs. In animal husbandry, potassium exports via milk and meat are minimal due to the relatively low utilization of minerals in animal nutrition.

For an optimal use of fertilizers their quantity, nutrient content and efficiency have to be known. The amount of farmyard manure applied is difficult to determine. The nutrient content of different manures and plant residues varies much. In the long term, potassium in animal manure is as effective as mineral potassium. Certainly, the short-time efficiency is often lower in comparison with mineral fertilizer, but the residual effect is better. The plant availability of potassium in straw and other plant residues in some trials was lower than that of fertilizer K. Losses of K by leaching are only of importance on sandy and organic soils.

1. Introduction

Animal manures and plant residues are organic fertilizers, which are produced on the farm and do not have to be purchased. For their optimal use, farmers have to know their quantity, nutrient content and efficiency. Less knowledge on these parameters exists for animal manures and plant residues than for mineral fertilizers, where the quantity applied is easy to calculate, the content is indicated on the bag and the efficiency is more predictable.

2. Potassium cycle and losses

The importance of animal manures and plant residues for plant nutrition can be demonstrated by the example of the potassium cycle for the Swiss agriculture (Figure 1). The most important nutrient path leads from plant production via forage to animal husbandry and from there via manure back to plant production. Nutrients enter the cycle via imported feedstuffs and mineral fertilizers. They replace the amount of nutrients exported from the system in animal products (milk, meat etc.), plant produce (wheat, potatoes etc.), leaching, surface run-off and other losses. In Switzerland, only a small amount of potassium is imported in feedstuffs. An equivalent amount of K leaves the farms in the form of agricultural products. Three subcycles are of importance : animal products as milk and whey are used for feeding calves and fattening pigs; large amounts of nutrients are contained in harvest losses (e.g. losses during hay or silage making, grazing losses), in feeding losses and in plant residues (straw, beet tops etc.). The nutrients in these subcycles do not leave agriculture. The potassium losses by leaching and surface run-off and the accumulation in the soil are not given in detail in figure 1 due to lack of precise data. They correspond to the parameter "balance".

The amount of potassium exported in animal products is quite low in comparison with the amount of K in the manure. In Switzerland, dairy cattle are fed mainly with roughage and the consumption of concentrate is low. About 75% of the milk is produced with basic forage (Menzi and Gantner, 1987). Mineral substances are very inefficiently used by the animal, especially potassium which is always in excess. Only a small amount of the potassium ingested is contained in milk and meat, while the greatest part is excreted in dung and urine. For dairy cows, the percentage in milk is only between 5 and 15% while the remaining 85-95% are excreted (Flückiger *et al.*, 1989). The potassium cycle for cattle production, therefore, is nearly closed (Figure 2). An excess of 10 kg K per ha is exported in the milk in comparison with the concentrate importation. This amount has to be replaced with fertilizer.

In Switzerland, the exportation of potassium from agriculture with marketed produce is low (Figure 1) because the surface used for the cultivation of vegetable produce amounts to less than 20% of the agricultural area. Furthermore, yield and K content of most crops are low in comparison with grassland (Table 1).

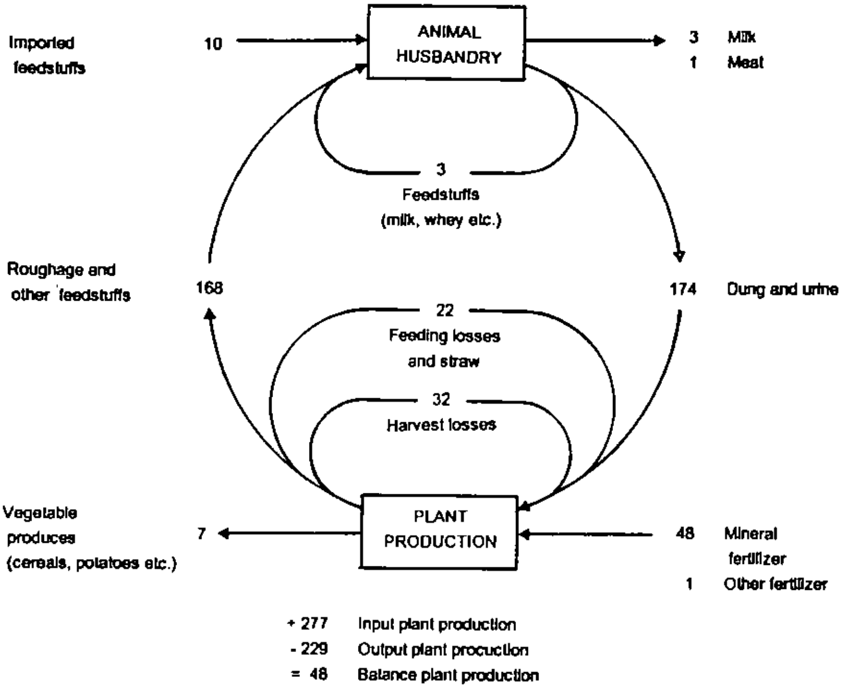

Fig. 1. Potassium cycle of the Swiss agriculture 1985 (in kg ha^{-1} K; according to Spiess, 1989)

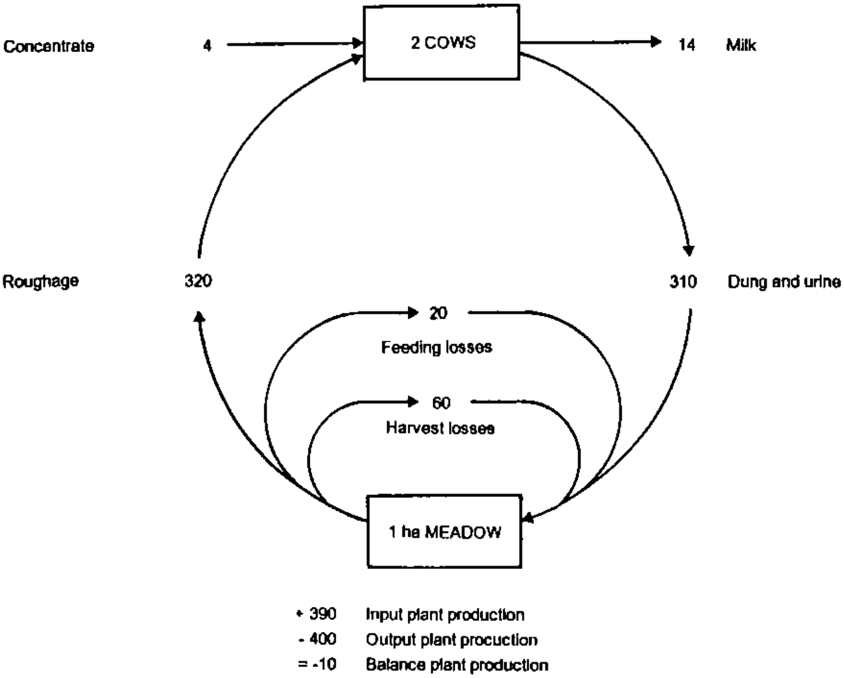

Fig. 2. Potassium cycle of cattle keeping under optimal conditions in Switzerland (in kg ha^{-1} K) 1).

1) In Switzerland, the roughage for two dairy cows can be produced on one hectare of grassland with a yield of 125 dt DM ha^{-1} (110 dt DM ha^{-1} excluding harvest losses).
Basis for the calculation of the annual production of nutrients by dairy cows (according to Flückiger, 1987) :
- milk yield : 5000 kg per cow and year
- daily feed ration per cow : summer : 15 kg DM grass; winter : 6.5 kg DM hay + 6 kg DM grass sillage + 1 kg concentrate
- botanical composition of grassland : 50-70% grasses, 10-40% legumes and 0-30% herbs; K content of the grass: 3.3% in DM

Table 1. Yield, content and K offtake of various harvested products (FW = fresh weight, DM = dry matter, K = potassium; mean values calculated according to Düngungsrichtlinien, 1987).

Crop	FW yield dt ha^{-1}	DM content %	DM yield dt ha^{-1}	K content % DM	K offtake kg ha^{-1}
Wheat	60	85	51	0.5	25
Oilseed rape	35	90	32	1.0	32
Sugar beets	600	22	132	1.1	149
Potatoes	450	22	99	2.2	218
Grass-clover mixture			110	3.3	363

3. Potassium in animal manure

3.1. Amount and content

The amount of nutrients excreted per animal unit depends on performance, feed ration and mineral content of the feed. Among dairy cows, the amount of nutrients excreted increases by 10% for an increase in performance of 1000 kg per year (basis : 5000 kg milk per year; Menzi and Flückiger, 1991). The herbage K content has a greater influence than the feed ration (Flückiger, 1987). The herbage K content is mainly dependent upon the botanical composition and the level of fertilization. Over the last 50 years, the mean content in herbage has increased due to the higher level of fertilization and the earlier time of cutting (Hasler *et al.*, 1966). Therefore, the amount of nutrients in urine and dung has also increased. Among pigs, the composition of the feed ration influences K excretion more than the level of performance because feedstuffs like cereals, potatoes or whey differ considerably in their K content. Table 2 shows the mean annual amount of nutrients excreted by different species.

Table 2. Amount of nutrients produced per year and animal unit (Menzi and Flückiger, 1991)

Type of animal	N	P	K
		kg per year	
Dairy cow	105	15	150
Sow (incl. piglets to 15 kg)	39	10	14
Fattening pig	15	3.2	5
100 laying hens	71	20	21
100 broilers	7	8	11

In contrast to the calculation of the quantity of slurry applied the amount of farmyard manure is difficult to assess because the volume and above all the specific density is difficult to estimate. The specific density varies depending upon the type of farmyard manure, the amount of litter and the degree of decay. In practice, the amount of nutrients applied as farmyard manure is often greatly underestimated (Spiess and Besson, 1992).

The nutrient content of manure varies not only between different farms but also on a given farm within the year. Table 3 shows the variation in the content of liquid cattle manure and slurries. As potassium is mainly excreted in urine, liquid cattle manure (short of dung), which is produced together with farmyard manure, is rich in potassium and has a low P:K ratio. In contrast, pig slurry is rich in phosphorus and poor in potassium because of the high percentage of cereals in the feed ration. Therefore, the P:K ratio is high. Best balanced for the fertilization of most crops are cattle slurry and farmyard manure. Differences in dry matter content of liquid manure are mainly due to dilution with water.

Table 3. Dry matter and nutrient content (mean and range) of some types of manure (Huber *et al.*, 1989; Spiess and Besson, 1992)

Type of manure	DM	N	NH_4-N	P	K
	g kg^{-1} manure				
Cattle slurry					
mean	44	2.0	1.0	0.4	2.7
lowest value	19	1.3	0.6	0.2	1.7
highest value	71	3.2	1.6	0.7	4.4
Cattle liquid manure (short of dung)					
mean	33	2.3	1.2	0.3	3.6
lowest value	7	1.1	0.2	0.1	1.7
highest value	84	3.7	2.1	0.6	5.3
Farmyard manure					
mean	196	5.4	1.2	1.6	4.7
lowest value	160	4.2	0.2	1.0	2.9
highest value	240	7.1	2.6	2.4	8.3
Pig slurry					
mean	29	3.1	2.1	0.9	1.7
lowest value	10	1.3	0.9	0.2	0.7
highest value	50	5.3	3.7	2.1	3.8

3.2. Storage losses

Whereas no potassium can escape from watertight slurry pits and animal houses, up to a third of the potassium is leached during storage of farmyard manure (Köhnlein and Vetter, 1953; Gisiger, 1962; Besson, 1991). Since the drainage water of farmyard manure normally flows into the slurry pit, the nutrients contained in it are not lost but the already high K content of liquid manure (short of dung) is further increased and the P:K-ratio of farmyard manure increases due to loss of potassium. When farmyard manure is composted on the field, some nutrients (K, N, Mg etc.) may be leached out or accumulated in great amounts in the soil (Berner, 1990).

3.3. Efficiency

The efficiency of nutrients in manure is difficult to assess as liquid manure and farmyard manure are "multinutrient fertilizers". Therefore, an increase in yield is not only due to potassium but a response to many nutrients. Nitrogen certainly has the greatest influence on the yield. But even when the ammonium nitrogen is volatilized by intensive aeration before a trial, manure still contains organic nitrogen, phosphorus and other plant nutrients.

Potassium in slurry is inorganically bound and 83-90% of it is soluble in water (Amberger *et al.*, 1984). For this reason, the efficiency is in general the same as for mineral fertilizer (Voss, 1981). Buchner and Sturm (1980) write that the phosphorus and potassium efficiency both of manure and mineral fertilizer are considered equal.

In a pot trial with Lolium perenne (Amberger *et al.*, 1984), fertilization with cattle, pig or poultry slurry gave yields as good as mineral fertilizers. In the first four cuts, plants took up less potassium from slurry, but in subsequent cuts the residual effect of slurry was better than that of potassium chloride. In pot and field trials short-term K efficiency of manure is often low, but long-term trials suggest potassium of manure and mineral fertilizer to be equal (Smith and van Dijk, 1987).

Potassium leaching is generally low (< 10 kg K per ha and year). On sandy or organic soils with a low adsorption capacity, however, more K may be leached out, mainly when great amounts of slurry are spread in autumn or winter (Mengel, 1982; Steffens and Vetter, 1985; Smith and van Dijk, 1987).

3.4. Pasture

Most of the potassium ingested by cows during grazing is excreted on the pasture again (Williams *et al.*, 1989). However, the urine and dung patches are not evenly distributed. At the entrance, near the watering tank and at resting-places, the cattle stay for a longer time and therefore excrete more dung and urine (Lombaert, 1985). In these places DM yield and consequently the nutrient requirements are especially low. Furthermore, the nutrient ratio in the excrements is unbalanced. While the P content of dung is high, urine contains much potassium (Murphy, 1986). The amount of nutrients excreted in a urine patch corresponds to about 500 kg ha^{-1} N and 1000 kg ha^{-1} K (Saunders, 1984). Dung and urine patches overlap to some extent. Due to the uneven distribution the nutrient efficiency is lower on pastures than on cut meadows. Lombaert (1985) found in her trials with urine a K utilization coefficient of about 50% after three to four years. The residual potassium was leached out or accumulated in the soil. In the first year, one third of the potassium was taken up by the plants. Jourdan (1987), however, found a good residual effect. In the second half of a nine-year trial, yield increased on the grazed plots and decreased on the cut plots.

4. Potassium in plant residues

4.1. Amount and content

Plant residues of various crops differ much in potassium content and uptake (Table 4). Straw of cereals and rape is rich in potassium and contains about three quarters of the potassium in the whole plant (grains and straw). Straw of oats and maize has the highest uptake. The amount of K in potato leaves is low; only about 20% of the potassium taken up is in the leaves. On the other hand, the uptake by the tubers is very high (more than 200 kg ha^{-1} K). Although beet tops have a low K content, they take up about 200 kg ha^{-1} K due to the high leaf yield.

Table 4. Yield, K content and K uptake of some plant residues (according to Düngungsrichtlinien, 1987); total plant uptake = uptake by harvested products and plant residues

Produce	Yield dt ha-1	K content g kg-1	K uptake kg ha-1	K uptake in % of the total plant uptake
Wheat straw	75	10.4	78	76
Barley straw	65	14.5	94	78
Oats straw	70	18.7	131	84
Maize straw	95	15.4	146	79
Rape straw	65	13.3	86	73
Potato leaves	125	5.0	62	22
Beet tops	500	4.1	207	58

4.2. Efficiency

The efficiency of nutrients in plant residues is difficult to determine in field experiments because plant residues like animal manure contain many nutrients and the efficiency of different nutrients cannot be assessed separately.

Potassium is easily leached out of dead plant material. In a field trial with sugar beet and cereals, Orlovius (1986) found that the potassium of incorporated beet tops is less efficient than mineral potassium. But the differences in yield decreased in the course of time. This suggests a good residual effect of the beet tops. K fertilization had a greater influence on the yield of sugar beet than of cereals. Burgdorf and Beringer (1984) concluded from their trials that the K efficiency of straw and beet tops is equal to that of mineral fertilizer. On luvisol and on podzol, the utilization coefficient was the same for plant residues and for mineral fertilizer but on black earth mineral potassium was more efficient.

Burgdorf and Beringer (1984) and Gutser (1986) point to the different time of fertilizer application. While straw and beet tops are incorporated in summer or autumn, mineral fertilizer is only applied before sowing the following crop. Gutser suggests that potassium of plant residues is partially fixed in winter or leached out on sandy or shallow organic soils.

5. Conclusions

The short-time efficiency of potassium in animal manure and plant residues often is not as good as for mineral fertilizer. In the long-term, however, the utilization coefficient is the same as for mineral fertilizer, if the organic fertilizers are applied within the growing season and in amounts not exceeding the crop requirements. For optimal fertilization, the amount of nutrients applied has to be known. For that, farmers should record the application rate of manure as precisely as possible and determine the nutrient content by means of standard values or analysis.

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Coordinator's Report on Session 1

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The basic sources of K$^+$ are K$^-$ bearing minerals, mainly framework silicates and layer silicates. In these minerals K is a structural element and may be released by weathering. As M.J. Wilson showed in his presentation the forces with which these minerals bind K$^+$ differ and hence also the release rates for K$^+$. Generally the release rates from mica are higher than those from feldspars. Potassium release rates can be described by equations which may form the basis for modelling K$^+$ release and may allow a prediction as to how much K$^+$ is provided to plants in a given period. Such models require a precise knowledge of the type and concentration of K$^-$ bearing minerals in the soil. In this context it should be kept in mind that not only soil minerals but also plant roots are directly involved in the release K$^+$ of minerals.

Potassium release from K minerals is considered under agronomic and ecological aspects. The former is of importance for crop nutrition, the latter means a gradual dissolution of soil minerals and hence also of soil fertility. This process of mineral degradation can be delayed or even blocked by K fertilizer application.

M. Robert in his leading paper gave a broad view on K$^+$ reactions in soils, K$^+$ fluxes and equilibrium conditions integrating in his concept the plant root as a strong sink for K$^+$. He emphasized the importance of intensity, quantity, and buffer power for K$^+$ as main basic parameters for soil K$^+$ availability and he showed an example of how the K$^+$ buffer power differs for various soil types. The buffer power denoted on the ordinate of the graph not only represents the so called exchangeable K$^+$ but also non-exchangeable K$^+$ since both fractions are involved in buffering the K$^+$ concentration of the soil solution. There is no clear cut difference between the exchangeable and non-exchangeable soil K$^+$ as was emphasized by J.C. Fardeau *et al.* in their presentation. Following the concept of K$^+$ concentration in the soil solution (intensity) and the K$^+$ buffer power (plot of the exchangeable + non-exchangeable K$^+$ on the K$^+$ concentration in the soil solution) one comes up with the conclusion that the level of available K$^+$ for an optimum K$^+$ nutrition should be the higher the larger the K$^+$ buffer power of a soil. This was exactly shown by the posters of Richter and Kerschberger, Villemin and Schneider, and Van Diest.

For the farmer the theoretical considerations of K^+ availability are of less interest than the available soil K^+ level at which he obtains the optimum yield. This may depend on various factors as was stressed by J. Baier in his paper based on his long-term field experiments. For further improving the prediction of K fertilizer rates based on whatsoever soil test, calibriation field experiments are required for the individual soil types, sites and crops, similar to the trials described by Margarita Nikolova in her poster where it can be seen that the response to K fertilizer depended on soil types and also much on crop species. An analogous finding was presented by the poster of Orlovius and Andres. It is assumed that rooting and growth rate of crop species have an impact on the optimum level of available soil K^+, the former decreasing, the latter enhancing it. Therefore K fertilizer application should target on the crop species of a rotation which gives the highest response to K fertilizer. This species needs the highest level of available soil K^+. To maintain an optimum level of available soil K^+ not only mineral fertilizer should be considered but also the potassium which is present in plant residues, slurries and farmyard manure, a problem which was treated in the presentation of Spiess.

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Session 2

K in the Hydrosphere

Size of Minimal Catchment Area for Drinking Water as Influenced by Climate and Population Size

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Summary

Hydrological concepts for the assessment and evaluation of various parameters of a catchment area are described. Out of the numerous methods for the determination of precipitation and runoff the unit hydrograph is discussed. Reference is made to the importance of the water balance for the supply with drinking and process water, which can be positive or negative, depending on the climatic regime. It is explained that the water supply for many urban regions can no longer be obtained from their immediate vicinity. Some regions are at the hydrological and ecological limits of their water supply possibilities, so that continued urban growth will have to come to an end.

Importance of pure drinking water

In a discussion on the foundations of the Roman Empire it was pointed out that the Romans not only put much emphasis on their excellent road system but equally so on the purity of their drinking water. The reduction of diseases in their settlements was regarded as a major element of Roman success. In a most impressive way long aqueducts transported drinking water to Roman settlements, even when they were located along rivers with a good water supply. A case in point is the towns along the middle Rhein valley that were supplied with drinking water from the Eifel Mts.

This example from history shows the importance of a good water supply for a population. It makes clear that the mere presence of water is not enough, but that it has to have certain properties in order to be used as drinking or process water. Water quality largely depends on the nature of the watersheds and on their hydrological characteristics. The latter are open to scientific analysis, whereas problems of water supply are greatly dependent on economic, sociological and technical factors. Studies in the field of water economics is a rapidly growing discipline.

Basic hydrological concepts

Following the definition by de Haar (1974) hydrology comprises the study of water above, on and below the earth's surface, with respect to its distribution in space and time, its circulation, its physical, chemical and biological properties and effects. It also includes the interplay between natural preconditions and anthropogenic influence. For the purpose of this paper marine waters are to be excluded.

The aims of research expressed in this very general form can be described more precisely by a systems approach. According to Herrmann (1977) a hydrological system is the interrelated existence of geocomponents of a certain part of the earth's surface that affect water behaviour. Figure 1 presents two such systems. The first is the spatially smallest system of water, soil and plant. The second describes the hydrologic cycle within a catchment. The size of the latter depends on the selected scale of analysis within the hierarchical pattern of fluvial systems.

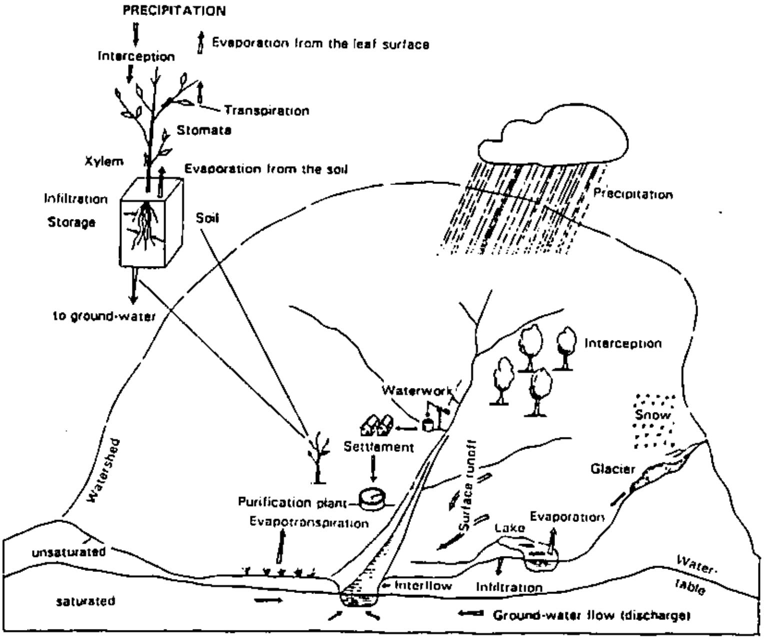

Fig. 1. The hydrologic cycle in the systems catchment area and water-soil-plant (after R. Herrmann, 1977).

For the present discussion the hydrologic cycle of a given catchment is the more important one as it is the prime supplier of drinking and process water. A catchment is separated from others by its watershed. Where the subsurface and the superficial watersheds coincide, the catchment is identical with the precipitation area. Where the subterranean catchment area is larger, water from an adjacent precipitation area will be transferred to it. Part of the precipitation will leave the catchment as runoff; another part will infiltrate; and part of that will be stored as a ground-water reserve for different lengths of time. Runoff has a superficial and a subsurface component; averaged over a longer period of time runoff is the difference between precipitation and evaporation. For shorter periods several factors affect the relationship between precipitation and runoff. These are bedrock, weathering debris, soil, vegetation, and land use, as well as landforms.

It is one of the major tasks of hydrology to determine the characteristics of a catchment with respect to the factors just mentioned, and to analyse their interrelationship. Another set of factors influencing a catchment's water balance comprises the spatial and temporal variation of precipitation. In order to understand how the water in a catchment will react an understanding of the precipitation characteristics listed below is called for :

1. the pattern of dry periods between precipitation events;
2. the identification of the onset of a new, individual precipitation event;
3. the duration pattern of precipitation events;
4. the temporal pattern of amounts of precipitation of a certain duration;
5. the spatial pattern of precipitation (Herrmann, 1977).

Models based on random processes are necessary to determine these properties as precipitation events are place and time dependent. Knowledge of all the catchment characteristics mentioned is necessary for determining and understanding superficial runoff and ground-water renewal.

This is not the time to discuss the methods employed today for calculating runoff curves etc.; they are mathematical and physical models suitable for both qualitative and quantitative description. All models rest on empirical foundations that limit their application. Except for some very general statements each catchment has to be calculated individually.

The unit hydrograph method

There is only one method, which should be mentioned here. It is the unit hydrograph method, a procedure to derive the hydrograph of runoff due to any amounts of effective or excess rainfall. This method was first presented by Sherman (1932).

The unit hydrograph is the hydrograph of surface runoff on a given basin due to an effective rain falling for a unit of time, after the definition given by Sherman (1949). Groundwater runoff has to be excluded. The unit of time may be one day or less. The term "effective rain" means rain producing surface runoff. The unit hydrograph method takes cognizance of the following facts, among others, that from a given basin the observed hydrograph of runoff due to a given period of rainfall reflects all the combined physical characteristics of the drainage basin, including infiltration, surface detention and storage. It has further been found that, within close approximate limits, the ordinates of a unit hydrograph are proportional to the total volume of surface runoff from such unit time rains, irrespective of the amount of such unit rainfalls. The time duration of the hydrograph of surface runoff, due to an effective rain in a unit of time, is practically a constant. The distribution of runoff, represented by the ratios of volume of runoff during a particular unit of time to the total runoff, is a constant for all unit hydrographs of runoff derived from the same basin. This holds true for all storms on the basin, without regard to their intensity (Sherman, 1949).

Herrmann (1977) criticizes the unit hydrograph method because the unit hydrograph can be derived for one basin only. He points out that it is a black-box model, a model which transforms an input (effective rain) into an output (runoff), every time in the same way without taking into account physical laws. Figure 2 shows the compilation of a unit hydrograph after Herrmann (1977). The example of the unit hydrograph method is given here to explain the variety and difficulties of methods which can be used for describing the hydrologic situation in a catchment area.

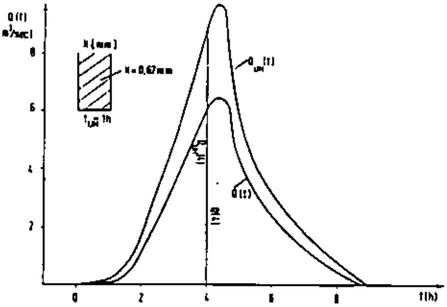

Fig. 2. Compilation of an Unit Hydrograph (UH).

1. $N = \int^{9} Q(t)dt = 67.10^3 m^3$

2. for $F_E^0 = 100 km^2 is N = 0.67 mm$

3. Dividing every ordinate by 0.67 results in the UH ($Q_{UH}(t)$) for 1 mm surface runoff.

The ordinates of UH can be calculated as follows :

$$Q_{UH}(t) = \frac{Q(t)}{N}$$

$Q_{UH}(t)$ = Ordinate of the UH
Q(t) = Ordinate of the runoff graph
N = Effective rain producing Q(t)

provided that :

$t_{UH} = t$
t_{UH} = duration of rain that produces the UH
t = duration of rain that produces the graph Q
(after Herrmann, 1977)

The water balance

This glimpse of the behaviour of water within a catchment must be supplemented by a brief look at the water balance. It is defined here as the average state of input and output within a system. The quantitative determination of the hydrologic cycle for a longer period of time is described by the water balance equation which, in its simplest form, reads P = E + R (precipitation being equal to evaporation and runoff). Of course, the terms of this equation can be further subdivided for more precision, but then it becomes more and more difficult to determine the figures for each term. For the supply of drinking water the figure for storage change is very important, i.e. for the increase or decrease of water stored. Precipitation, runoff and evaporation, all governed by climate, together with the rock properties, determine the storage characteristics. Ice and snow are major elements of storage, especially affecting areas linked with glaciated high mountains.

Within the humid regions the water balance is always positive. The part of it that is used for human consumption is relatively small and, in general, is available in sufficient quantity in the humid regions. Regional problems of water supply may occur, however, in highly populated areas, as at present in the Frankfurt area. The principal problem there is not to get water at all, but to produce enough good quality drinking water. Regions with an arid climate, where evaporation exceeds precipitation, have the double problem of both insufficient water supply in general and of good drinking water at that. They either have to rely on water transferred from humid areas, as e.g. in southern California, or they have to exploit groundwater reserves accumulated during pluvial periods of the recent geological past. Wherever groundwater recharge is less than groundwater extraction a catastrophe is pre-programmed. Libya is a good (or really, bad) example. Population concentration along the Mediterranean coast has caused over-exploitation of the wells where marine brackish water is about to replace fresh water. To alleviate the problem groundwater from the desert is being pumped to the coast at enormous costs. It is fossil water, however, coming from an area where the present rate of recharge is practically nil. The water import to the coast, therefore, can only postpone the catastrophe for a few decades at best.

The water situation of the big stream oases along the Nile, Euphrates and Indus river is rapidly worsening. More intensive use of water along the upper reaches reduces the amount of water available downstream in regions with enormous population growthly thus increasing water demand. The widening gap between declining water supply and growing population is about to create a very explosive situation.

Climatic regimes and the water balance

The water balance of a wet region is mentioned above. The influence of a climatic regime on the water balance can be expressed by the water surpluses and deficiencies. The main types of climatic regimes and the water balance will be given in a short survey after Strahler (1954).

We observe a vast water surplus in the wet equatorial climate. It rains the whole year and the potential evapotranspiration shows only a small annual variation; no water deficiency occurs.

In a tropical desert regime the potential evapotranspiration greatly exceeds rainfall, a large water deficiency prevails.

The potential evapotranspiration graph of the tropical wet-dry climate in lower latitudes follows a cycle with high values in the dry season of lower-sun and lower values during the rains of the high-sun period. The water surplus of the rainy season can exceed the deficiency of the dry period; it depends on the duration of each period.

In the Mediterranean (dry summer, subtropical) a large summer deficiency results from the fact that the summer rate of potential evapotranspiration coincides with the summer precipitation minimum.

Continentality of climatic regime is expressed by a summer maximum of precipitation coinciding with a summer maximum of potential evapotranspiration. Normally there is no water deficiency in this climatic regime.

Each type of climate has its own characteristic annual water balance which should be well known for planning the water supply and the water use for all purposes.

Water supply of large urban areas

In planning the water supply for urban areas the parameters referred to in the chapter on hydrology have to be taken into consideration. They are the basis for the master plans for water management that also have to consider the economic and population structure of the area. The basis of all planning, however, is the water balance, the relationship between water supply and water needs. The use of process water has equally to be included in the calculation, especially in view of the rising thermal pollution of rivers by power plants. The principal problem certainly is to ensure that water quality remains sufficiently high. Water quality depends on the natural characteristics of the extraction area modified by anthropogenic pollution.

The non-watery contents of groundwater that originate from the rocks of the respective catchment area almost completely occur in solution. Table 1 lists the average composition of rocks. Concentration of minerals in the groundwater depends on the geochemical mobility of the elements in a given chemical environment. Solubility further depends on their ion potentials (Matthess, 1973). Categories have been established for both parameters. With respect to ion potential, K (potassium), for instance, belongs to the category of elements that stay in true solution up to high pH values. With respect to geochemical mobility, however, potassium belongs to category III, indicating that it is not especially mobile.

The chemical behaviour of surface water partly depends on the characteristics of the groundwater that seeps into the surface water. As water from superficial runoff is likely to carry less dissolved material than groundwater, water derived from a mixture of both will be less mineralized. Most rivers, unfortunately, carry a high load of waste water masking the original chemical composition. Detailed knowledge of riverwater composition is mandatory where it is going to be used in infiltration wells for artificial groundwater recharge.

In most highly urbanized areas of the world water supply can no longer be secured from the immediate vicinity. It has to be piped in sometimes over long distances from areas with a large water supply that has not yet been negatively affected by man. In the Federal Republic of Germany, for instance, the coastal city of Bremen and other northern German cities get their water from the reservoirs of the Harz Mts. Stuttgart, in southwestern Germany, gets its water from Lake Constance, and the Ruhr Industrial Region is supplied from the reservoirs of the Sauerland. By pooling water from different sources waters of different natural chemistry can be mixed for improving water quality. Problems may occur where the land surrounding large reservoirs is used more and more for recreation, increasing the dangers of pollution and reduction of water quality. These will become particularly apparent in drought years up to the point of causing shortages of good quality water.

Table 1. Mineral components of groundwater - Average composition of rocks (after Horn and Adams, 1966 and Hem*, 1970) and sea water (after Turekian, 1969) in mg kg^{-1}.

	Magmatite	Resistate (Sandstones)	Hydrolysate (Clays)	Precipitate (Limestones)	Evaporite	Sea water
Si	285000	359000	260000	33900	386	2.9
Al	79500	32100	80100	8970	29	0.001
Fe	42200	18600	38800	8190	265	0.0034
Ca	36200	22400	22500	272000	11100	411
Na	28100	3870	4850	393	310000	10800
K	25700	13200	24900	2390	4280	392
Mg	17600	8100	16400	45300	3070	1290
P	1100	539	733	281		0.088
Mn	937	392	575	842	4.4	0.0004
F	715	220	560	112	24	1.3
Ba	595	193	250	30.1	173	0.021
S	410	945	1850	4550	26800	904
Sr	368	28.2	290	617	234	8.1
C	320*	13800*	15300*	113500*		28.5
Cl	305	15	170	305	525000	19400
Cr	198	120	423	7.08	10.6	0.0002
Rb	166	197	243	46.0		0.12
V	149	20.3	101	12.6	0.3	0.0019
Cu	97.4	15.4	44.7	4.44	2	0.0009
Ni	93.8	2.57	29.4	12.8	1.4	0.0066
Zn	80	16.3	130	15.6	0.6	0.005
N	46*		600*			16.17
Li	32.2	15	46.2	5.16	30.0	0.17
Co	23	0.328	8.06	0.123	1.6	0.00039
Ga	18.5	5.87	22.8	2.69		0.00003
Pb	15.6	13.5	80	16.5	0.9	0.00003
Th	11.4	3.94	13.1	2.01	0.2	0.000000
B	7.5	90	194	16	1.2	4.45
Cs	4.3	2.15	6.2	0.771		0.0003
Be	3.65	0.258	2.13	0.175		0.000000
U	2.75	1.01	4.49	2.2	0.2	0.0033
Sn	2.49	0.115	4.12	0.166		0.00081
Br	2.37	1.0	4.3	6.6	33	67.3
As	1.75	1.0	9.0	1.75		0.0026
W	1.42	1.56	1.92	0.561		<0.000001
Ge	1.39	0.881	1.32	0.363		0.00006
Mo	1.25	0.50	4.25	0.75	1.5	0.01
I	0.45	3.75	4.4	1.59	1	0.064
Hg	0.32	0.057	0.272	0.0456		0.00015
Cd	0.19	0.019	0.183	0.0476		0.00011
Ag	0.15	0.122	0.271	0.189		0.00028
Se	0.05	0.525	0.60	0.315	0.2	0.00009
Au	0.00	0.004	0.003	0.0017		0.000011

(after Matthess, 1973)

7. Conclusions

The increasing urbanization of the earth goes hand in hand with the modification of the drainage systems by surface sealing, decrease of vegetated area and changes of land use for agricultural and gardening use. There is an apparent trend towards accelerated runoff and decreasing storage. Another trend is that urban water supplies are becoming more difficult and costly. Natural storage is clearly declining where water is derived from glaciers, due to the climatically induced retreat of mountain glaciers.

In the drought-prone regions of the subtropics and the drier margins of the tropics the destruction of natural vegetation by agriculture and animal production has a negative effect on surface runoff and groundwater recharge. This progressively leads to the reduction of available water to the extent that the natural oscillations of precipitation and ground-water recharge can no longer be buffered.

The increasing scarcity of water for urban areas will consequently lead to a reduction in urban growth. Away from the cities it is the unchecked population growth in many parts of the world that creates increasingly severe problems of water supply.

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Potassium in Natural Groundwater Systems

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1. Introduction

The basic information about the chemistry of potassium in water is deficient. Many of the existing chemical analyses of water do not include potassium determinations. Some of the old wet-chemical methods for potassium required considerable analytical skill; consequently, the accuracy of some of the earlier published values for potassium concentrations obtained using these methods appears to be questionable.

Research aimed at attaining a better understanding of the chemical behavior of potassium in natural aqueous systems is still needed (Hem, 1985). In this article, the abundance of potassium in the lithosphere and in the various components of the hydrological cycle are reviewed, and the controls on its concentrations are discussed.

2. Abundance of potassium in rocks

The lithosphere contains 2.6% potassium, the seventh most abundant element. Primary potassium-containing minerals are the K-feldspars (16%) and the K-micas (5.2%). Secondary minerals include illite and transitional-clay minerals (Schroeder, 1978).

2.1. Potassium in igneous and metamorphic rocks

Igneous rocks generally contain 0 to 5% of K_2O and 0 to 7% of Na_2O. A few volcanic rocks from continental areas are extremely rich in potassium up to 12.66% (Wyomingite, from Leucite Hills, Wyoming) (Brownlow, 1979). Table 1 presents the chemical composition of some common igneous rocks.

Table 1. Chemical compositions of some common igneous rocks (from Brownlow, 1979) © 1979, reprinted by permission of Prentice Hall, Englewood Cliffs, New Jersey.

	1 Oceanic alkali olivine basalt	2 Oceanic tholeiite basalt	3 Continental tholeiite basalt	4 Island arc dunite	5 Island arc andesite	6 Island arc rhyolite	7 Continental rift leucite nephelinite	8 Gabbro of continental layered mafic pluton	9 Continental anorthosite	10 Continental batholith quartz monozonite
SiO_2	50.48	49.20	52.05	39.53	58.60	74.22	39.77	48.08	53.40	65.49
TiO_2	2.25	2.03	1.70	0.01	0.89	0.28	3.82	1.17	0.77	0.65
Al_2O_3	18.31	16.09	12.43	0.93	15.38	13.27	12.53	17.22	23.96	14.49
Fe_2O_3	3.21	2.72	5.18	0.65	2.22	0.88	6.02	1.32	0.91	2.11
FeO	6.03	7.77	10.08	7.62	6.71	0.92	8.62	8.44	3.02	2.90
MnO	0.21	0.18	0.24	0.12	0.18	0.05	0.27	0.16	-	0.10
MgO	4.21	6.44	3.95	48.83	3.22	0.28	4.45	8.62	1.88	2.45
CaO	7.21	10.46	7.33	Trace	7.02	1.59	11.88	11.38	9.85	4.29
Na_2O	4.80	3.01	2.76	Trace	3.84	4.24	4.86	2.37	4.17	2.80
K_2O	1.93	0.14	2.07	-	1.46	3.18	5.35	0.25	0.80	3.66
P_2O_5	0.74	0.23	0.28	-	0.25	0.05	1.35	0.10	0.18	0.21
Other	-	-	-	1.41	-	-	-	-	0.43	0.15
Total	100.22	99.92	100.33	100.15	100.14	99.99	99.84	100.17	100.06	99.91
K/Rb	267	950	498	215	807	251	352	550	>1 000	232

Primary potassium-containing minerals are feldspars and K-micas. Feldspars are potassium aluminosilicates, their general formula being $KALSi_3O_8$. The following polymorphs have the same formula but vary in detailed structure and origin (Schroeder, 1978): orthoclase, in plutonic rocks; sanidine, mainly in volcanic rocks; microcline, a low-temperature modification, magmatite-pegmatite; and adularia, similar to orthoclase, mainly in lodes and fissures. The following variants also contain sodium (Schroeder, 1978): anorthoclase $(K, Na)AlSi_3O_8$, leucite $KAlSi_2O_6$, with lower Si and higher potassium content, nepheline $(NaK)AlSiO_4$, containing more Na than K, and plagioclase (Ca,Na-feldspar), which may also contain small amounts of potassium.

K-micas are like feldspar, potassium aluminosilicates, but their composition is more complex (Schroeder, 1978). Along with the Si terahedra, they contain Al octahedra with varying substitutions of the central ions. According to chemical composition, color, and origin, the following micas can be distinguished (Schroeder, 1978): Muscovite $KAl_2(AlSi_3)O_{10}(OH)_2$, bright colored plates derived from magmatites and pegmatites; sericite like muscovite but finer grained, mainly from metamorphic origin; biotite $K(Mg,Fe)_3(AlSi_3)O_{10}(OH)_2$ dark plates, from magmatites, pegmatites, and metamorphites; lepidolite and zinnwaldite with additional lithium in the octahedra.

Igneous and metamorphic rocks can be classified according to the overall alkali/aluminum ratio. According to this classification, Shand (1951) proposed the following four groups :

1. Peraluminous, for which molecular $Al_2O_3 > Na_2O+K_2O+CaO$ (e.g., muscovite $KAl_3Si_3O_{10}(OH)_2$ and andalusite Al_2SiO_5);
2. Metaluminous, for which molecular $Al_2O_3 > Na_2O+K_2O$ but $<Na_2O+K_2O+CaO$ (e.g., biotite $K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$ and hornblende $NaCa_2(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$);
3. Subaluminous, for which molecular $Al_2O_3 \approx Na_2O + K_2O$ (e.g., olivine $(Mg,Fe)_2SiO_4$ and hypersthene $(Mg,Fe)SiO_3$); and
4. Peralkaline, for which molecular $Al_2O_3 < Na_2O + K_2O$ (e.g., aegirine $NaFeSi_2O_6$ and riebeckite $Na_2Fe_3Fe_2Si_8O_{22}(OH)_2$).

2.2. Potassium in sedimentary rocks

Common potassium-containing minerals in sedimentary rocks include orthoclase, microcline, plagioclase, muscovite, biotite, and illite (Table 2) (Brownlow, 1979). In the United States observed variations in potassium concentration range from 0.08 to 0.66% in sandstone, from 0.03 to 0.07% in shale, and from 0.004 to 0.006% in carbonate rocks (range of means) (Brownlow, 1979). Carbonate rocks have high values of CaO and low values of K_2O and Na_2O. The presence of K_2O is a result of silicate impurities. Shale and sandstone are low in Na_2O and CaO and high in K_2O because of detrital feldspar, authigenic feldspar, detrital muscovite, illite, authigenic glauconite, or potassium adsorbed by clay minerals (Brownlow, 1979).

Complete evaporation of seawater results in the precipitation of a variety of minerals of which polyhalite ($K_2Ca_2Mg(SO_4)_4 \bullet 2H_2O$), kainite ($KMg(SO_4)Cl \bullet 3H_2O$), and carnallite ($KMgCl_3 \bullet 6H_2O$) contain potassium.

These salts are the last minerals to precipitate from an extremely concentrated brine (5% of the original water volume).

3. Weathering of potassium-containing minerals

Busenberg and Clemency (1976) studied the dissolution kinetics of feldspars over long periods of time and at 25° and 1 atmosphere CO_2 partial pressure. They found that cations (K, Na, Ca) and silicic acid are released into solution in four different stages. A short (~1 min) initial stage involves the exchange of surface cations for hydrogen ions from solution. This is followed by a process in which large amounts of cations, including potassium, at exterior sites are rapidly liberated into the solution. This stage may last ~1.5 h for K-feldspars. As a result of the second stage, feldspar grains begin to be armored with a coating of material, which may be similar in composition to kaolinite or illite. Further potassium will be released only from internal sites after breaking of the stable Al-O and Si-O bonds, involving the destruction of the Si-rich protective shell. Thus, the third stage occurs at a different rate from that of the second stage and is

Table 2. Compositions of the major minerals of common sedimentary rocks (Brownlow, 1979). © 1979, reprinted by permission of Prentice Hall, Englewood Cliffs, New Jersey.

Mineral	Composition
Quartz	SiO_2
Orthoclase	$KAlSi_3O_8$
Microcline	$KAlSi_3O_8$
Plagioclase	$NaAlSi_3O_8$-$CaAl_2Si_2O_8$
Muscovite	$KAl_3Si_3O_{10}(OH)_2$
Biotite	$K(Mg, Fe)_3AlSi_3O_{10}(OH)_2$
Kaolinite	$Al_4Si_4O_{10}(OH)_8$
Montmorillonite	$(Al, Mg, Fe)_4(Al, Si)_8O_{20}(OH)_4 \bullet nH_2O$
Illite	$K_{0\text{-}2}Al_4(Al, Si)_8O_{20}(OH)_4$
Chlorite	$(Mg, Fe, Al)_3(Al, Si)_4O_{10}(OH)_2 \bullet (Mg, Al)_3(OH)_6$
Calcite	$CaCO_3$
Aragonite	$CaCO_3$
Dolomite	$CaMg(CO_3)_2$

controlled by the rate at which material can diffuse through the surface coating. Hydrogen ions diffuse into the feldspar, and cations plus silicic acid diffuse outward. According to Busenberg and Clemency (1976), this third stage lasts ~19 d. After this, a steady-state equilibrium is reached in which the surface layer has a constant composition. Further diffusion then occurs at a slower rate than that of the third stage. The rate of this final stage ranges from $3.2 \times X10^{-17}$ to 2.5×10^{-15} mole/cm^2/s.

Factors enhancing the above-mentioned processes include the presence of sodium, irregularities of the crystal lattice, small particle size (larger surface area), high temperature, pH, humidity, and migration of the weathering products. The humid tropics provide the most favorable conditions for feldspar weathering, whereas in temperate climate only a little takes place.

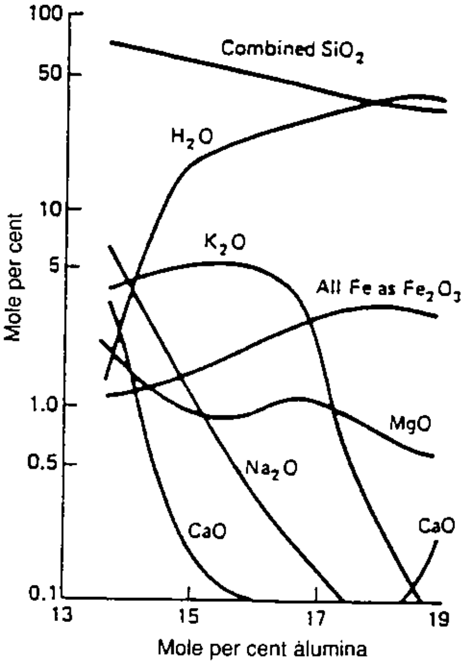
The weathering of a granite gneiss also demonstrates this sequence of phases (Brownlow, 1979). Since aluminum tends to stay at the weathering site in the form of clay minerals, the stages of weathering can be represented by the increasing percentage of Al_2O_3 in the weathering products (Figure 1). Following a short increase, as weathering progresses K_2O eventually shows a rapid decrease. Plagioclase and biotite break down rapidly. K-feldspar is more resistant. The difference in the stabilities of the two feldspars is the reason why K_2O in Figure 1 drops off after Na_20 and CaO.

Goldich (1938) pointed out that the major minerals of igneous rocks tend to have a susceptibility to weathering that is the reverse of their order of crystallization (Table 3). Elements removed most quickly from a weathering site are sodium, calcium, and magnesium. Potassium is generally less mobile, followed by silica and then iron and aluminum.

The stability relations of the clay minerals, K-feldspars, and gibbsite can be calculated using equilibrium constants of reactions. Figure 2 indicates the relationships among these minerals. When there is increasing activity of dissolved silica, kaolinite is more stable than gibbsite. Increasing activities for potassium along with increasing pH make illite and K-feldspar stable relative to kaolinite.

Table 3. Mineral stability series in weathering (from Brownlow, 1979, after Goldich, 1938). © 1979, reprinted by permission of Prentice Hall, Englewood Cliffs, New Jersey.

	Mafic minerals	Felsic minerals
Increasing susceptibility to weathering ↑	Olivine Pyroxene Amphibole Biotite	Calcic plagioclase Intermediate plagioclase Sodic plagioclase K-feldspar Muscovite Quartz



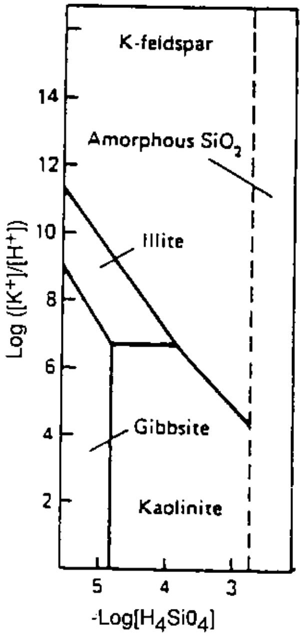


Fig. 1. Weathering of Morton granite gneiss, Minnesota. Fresh rock composition is plotted on the left, intermediate soils in the middle, and the final soil at the extreme end (Brownlow, 1979). © 1979, reprinted by permission of Prentice Hall, Englewood Cliffs, New Jersey.

Fig. 2. Activity-activity diagram showing stability relations in the system K_2O-Al_2O_3-SiO_2-H_2O (Stumm and Morgan, 1970). © 1970, reprinted by permission of John Wiley & Sons, Inc.

4. Potassium in the hydrological cycle: Concentrations and controlling mechanism

As shown in Tables 1 and 3, potassium is slightly less common than sodium in igneous rocks but more abundant in all the sedimentary rocks. In the ocean, the concentration of potassium, though substantial (390 mg L^{-1}), is far less than that of sodium (10,500) (Hem, 1985). The figures point out the very different behavior of these two alkali metals in natural systems. Sodium tends to remain in solution rather persistently once it has been liberated from silicate-mineral structure. Potassium is liberated with greater difficulty from silicate minerals and exhibits a stronger tendency to be reincorporated into solid weathering products, especially certain clay minerals. Consequently, in most natural waters, the concentration of sodium generally exceeds that of potassium (Hem, 1985).

4.1. Potassium in seawater

Reactions between low-temperature seawater and marine sediments and basalts commonly result in reduced concentrations of potassium in the overlying seawater column. Increased seawater temperature, however, results in the significant release of potassium to the ocean (Drever, 1988).

Measurements of the composition of interstitial waters in marine sediments suggest the formation of authigenic potassium minerals in marine sediments is taking place. Results published by Sayles (1979) indicate that interstitial waters in the top 1 m of sediments are systematically depleted in potassium and magnesium and enriched in calcium, sodium, and bicarbonate. Sayles (1979) concluded that potassium and magnesium are being taken up by solid phases in the sediment from the overlying water. Sayles' best estimates of the diffusional fluxes calculated from the concentration gradients in the interstitial waters are shown in Table 4.

Table 4. Diffusional fluxes across the sediment-water interface based on the composition of interstitial water in sediments* (from Drever, 1988, after Sayles, 1979).

Ion	Flux (10^{14}g yr^{-1})		Percentage of river input	
	A	B	A	B
Na^+	-0.6	-1.0	-30	-48
Mg^{2+}	0.8	1.3	60	94
Ca^{2+}	-1.9	-2.5	-40	-52
K^+	0.6	0.8	84	105
HCO_3^-	-4.6	-5.7	-24	-29

*The two sets of values result from two different ways of extrapolating the gradients in interstitial water composition to the sediment-water interface. Positive numbers indicate a flux into the sediment.

Marine basalts exposed to ordinary seawater at low temperature undergo alteration that results in the uptake of potassium from the ocean water by the basalt and loss of calcium, silica, and usually magnesium from the basalt. The observation of extensive low-temperature alteration in basalts drilled by the Deep Sea Drilling Project suggests that low-temperature alteration of basalts could be the major process by which potassium is removed from the ocean. Local areas of altered basalt have been found where the K_2O content is as high as 6% (Donnely and Francheteau, 1977). If such areas were common, they would represent an important removal site for potassium in seawater.

In addition to low-temperature alterations of basalts, high-temperature reactions are known to occur at the spreading centers of sea floors. Information about these reactions comes from (1) laboratory experiments in which basalt was heated with seawater (Bischoff and Dickson, 1975; Mottl and Holland, 1978); (2) direct sampling of submarine hot springs at the Galapagos spreading center and the East Pacific Rise (Corliss *et al.*, 1979; Edmond *et al.*, 1979; von Damm *et al.*, 1985); and (3) geothermal water on the Teykjanes Peninsula of Iceland, which originates from interaction between hot basalt and seawater (Tomasson and Kristmannsdottir, 1972). During these reactions, potassium, calcium, silica, iron, and other transition metals are commonly released from the basalt to the sea. Calculations indicate that high-temperature alteration of basalt may contribute about as much potassium to the ocean as the river input does (Drever, 1988).

4.2. Potassium in precipitation

Potassium concentrations in open precipitation in various geographical locations and climates range from 0.1 to 4 mg L^{-1}. Handa (1975) reported a concentration range of 0.1 to 2.3 mg L^{-1} in the monsoon-affected area of Calcutta and Bankipur, India. A mean value of 0.1 mg L^{-1} was reported in the humid eastern United States in Carolina and Virginia (Gamble and Fisher, 1966). At higher elevation (1950 m) and cold, humid climate in southeastern France, Durand *et al.* (1992) reported a mean potassium concentration of 0.23 mg L^{-1} (K:Na ratio of 0.36). They reported increased concentrations (0.43 mg L^{-1}) for spring storm events that were affected by suspended Saharan dust. Potassium concentrations in snow cores from the Cascade/Sierra Nevada Mountains at sites above 1,600 m in elevation varied from a maximum of 0.3 mg L^{-1} to 0.01 with a mean of 0.019 mg L^{-1} (Taylor, 1987). Feth *et al.* (1964) reported similar values (0.3 mg L^{-1}) in snow samples from Sierra Nevada. However, higher concentrations, ranging from <1 to 4 mg L^{-1} were reported by Angino *et al.* (1964) in Antarctic ice. Potassium measurements in the arid Negev desert, Israel, resulted in a greater range of concentrations of 0.2 to 2.5 mg L^{-1} (mean value was 0.8 mg L^{-1}, and K:Na ratio was 0.07) (Nativ and Mazor, 1987; Nativ *et al.*, 1983), presumably because of the large amount of dust in the atmosphere preceding some of the sampled rain events.

Analyses of throughfall (or under the canopy) indicated that forest canopies are biologically active substrates on which airshed-watershed interactions take place. Consequently, throughfall may change its concentration as a result of canopy interactions. It was observed (Puckett, 1987) that the canopy acts as a sink for nitrogen and as a source of potassium, among other ions such as calcium and magnesium. In a study in northern Virginia, Puckett (1987) demonstrated that the net flux of potassium in throughfall in a deciduous forest was an order of magnitude higher than in the open precipitation. Coniferous throughfall was about fivefold concentrated in potassium than open precipitation (Table 5). An indication of similar results was observed in the Walker Branch, in the Valley and Ridge province, in east Tennessee. Throughfall concentrations range from 0.24 to 1.82 mg L^{-1} (Wilson *et al.*, 1991), but the K:Na ratio was extremely high (1.9 to 16.7), suggesting the potential for a potassium source in the canopy. Mulholland *et al.* (1990) suggest that because dry deposition contributes as much as 50-75% of the total annual inputs of potassium (among other ions) in this watershed, there should be relatively large soluble pools available on canopy surfaces to be dissolved by the throughfall.

Table 5. Net flux as precipitation, and deciduous (DT) and coniferous (CT) throughfall during the year 1983 to the Mill Run Watershed. Units are equivalents ha^{-1}. Negative values indicate net retention by the forest canopy (from Puckett, 1987). © 1987, Lewis Publishers, Chelsea, MI. Used with permission.

Ion	Rain	DT	CT
H^+	434.2	-112.2	151.6
Ca^{2+}	57.5	201.8	292.7
Mg^{2+}	11.9	77.2	80.2
Na^+	58.9	10.8	96.0
K^+	27.5	266.6	149.6
NH_4^+	145.1	-61.2	-8.3
Cl^-	151.0	35.0	82.4
NO_3^-	191.1	36.9	210.8
SO_4^{2-}	418.3	230.1	314.4

4.3. Potassium in surface water

In a watershed, potassium can be dissolved into the stream water, following the weathering of K-bearing minerals. Alternatively, potassium can be adsorbed on mineral surfaces, and its concentration can be reduced. Baron and Bricker (1987) demonstrated that in an alpine-subalpine watershed (Loch Vale Watershed, Rocky Mountain National Park, Colorado) potassium (among other species such as calcium, magnesium, sodium, and silica) leaves the basin in greater amounts than its atmospheric input loading due to weathering of the bedrock and talus (Table 6).

Table 6. Annual budgets for major ions for 1984 and 1985 in Loch Vale Watershed. Values (kg ha^{-1}) have been normalized to the balanced chloride budget (from Baron and Bricker, 1987). © 1987, Lewis Publishers, Chelsea, MI. Used with permission.

Species	1984			1985		
	In	Out	Out/In	In	Out	Out/In
	kg ha^{-1}	kg ha^{-1}		kg ha^{-1}	kg ha^{-1}	
Ca^{2+}	2.61	7.55	2.90	2.46	8.21	3.34
Mg^{2+}	0.57	1.36	2.40	0.42	1.24	2.95
Na^+	1.07	2.76	2.59	0.79	2.69	3.41
K^+	0.31	1.25	4.02	0.40	1.03	2.58
NH_4^+	1.88	0.37	0.20	1.21	0.11	0.09
SO_4^{2-}	10.68	8.25	0.77	8.18	9.30	1.14
NO_3^-	10.23	7.14	0.70	8.25	6.49	0.79
Cl^-	1.39	1.39	1.00	1.21	1.21	1.00
SiO_2	-	11.84	-	-	9.68	-
pH	5.01	6.33	-	5.06	6.27	-

Similar observations were documented in the Walker Branch experimental watershed in east Tennessee (Mulholland *et al.*, 1990). Nativ *et al.* (1983) confirmed this pattern also under arid conditions in the Negev desert, Israel (Table 7). They related the increase in concentration of all ion species leaving the studied watersheds to weathering and to the dissolution of residual atmospheric salts that precipitated during previous events that did not result in flooding. Reported values of potassium in stream water range from 1 to 13 mg L^{-1} (and a mean of 3.39 mg L^{-1}) in all major rivers of India sampled by Handa (1975). Mulholland *et al.* (1990) reported potassium concentrations of 0.5 to 2 mg L^{-1} in stream water in Walker Branch (a 38.4 ha forested experimental watershed in the Valley and Ridge, east Tennessee). In this watershed, an increase in concentration of potassium (among other species) was observed with increasing flow rate. Nativ *et al.* (1983) measured potassium concentrations ranging from 5.7 to 12.3 mg L^{-1} (mean value was 8.14 and K:Na ratio ranged from 0.075 to 0.25) in major ephemeral streams in the Negev Desert, Israel. Sarin *et al.* (1989) reported potassium concentrations in selected world rivers (Yamuna, Ganga, Brahamputra, Indus, Mekong, Chiang, Amazon, and Zaire), which vary from 0.98 mg L^{-1} (Amazon) to 2.65 mg L^{-1} (Ganga). Their reported world average is 1.48 mg L^{-1}.

Table 7. Salt addition to drainage basins (kg km^{-2}) - a balance between rainwater and floodwater for individual events.

Date	Rain (mm)	Flood volume (10^3 m^3)	Chemical species						
			HCO_3	Cl	SO_4	Ca	Mg	Na	K
Besor drainage basin (Ashalim station) :									
8-13.12.78	18.7	264.2	450.0 (59)	-156 (-69)	-149 (-54)	-38.0 (-24)	n.d.	98 (37)	-14.5 (-57)
5-7.12.79	17.9	442.1	39.7 (13)	122.1 (60)	34.4 (31)	-7.9 (-7)	21.9 (58)	11.7 (17)	10 (43)
14.12.79	19.9	481.8	76.8 (28)	192 (71)	85.4 (60)	24.7 (28)	30.2 (66)	60.9 (59)	7.6 (35)
23.1.80	23.7	127.5	444.0 (89)	185 (92)	130 (87)	165 (89)	13.4 (80)	38 (77)	15.6 (84)
Zin drainage basin (Lower Zin station) :									
8-13.12.78	9.0	225.5	307 (90)	10.2 (31)	18.3 (30)	95.1 (80)	-7.9 (-29)	2.4 (14)	12 (32)
5-7.12.79	16.5	248.2	258 (85)	65.3 (51)	11.6 (12)	77.1 (62)	41.1 (86)	6.8 (15)	0.01 (<1)
14.12.79	13.9	1424.2	52.6 (20)	28 (17)	-283 (-74)	-89.8 (-47)	24.2 (51)	-16 (-20)	-9.1 (-62)
23.1.80	8.4	23.3	154 (96)	72.9 (98)	47.6 (90)	55.4 (94)	14.8 (98)	20.6 (95)	6.5 (97)

n.d. = not determined.

Numbers in parentheses are the percentage of residual salt in the drying basin after the flood.

Potassium in groundwater

In dilute natural groundwaters in which the sum of sodium and potassium is <10 mg L^{-1}, it is not unusual for potassium concentrations to equal or even exceed the sodium concentration. In most freshwater aquifers, however, if the sodium concentration substantially exceeds 10 mg L^{-1}, the potassium concentration commonly is half or a tenth that of sodium (Hem, 1985). Potassium does not form any salts, except at very high concentrations, and calculations such as those of Garrels and Mackenzie (1967) and Hardie and Eugster (1970) predict that potassium should, like sodium, simply build up in solution during weathering and evaporation. In practice, however, potassium is almost always found to be depleted relative to sodium (Drever, 1988). Concentrations of potassium more than a few tens of milligrams per liter are unusual except in water having a high dissolved solids concentration or in water from hot springs. In these cases, potassium concentrations may be high, but the K:Na ratios are still low (Hem, 1985).

Potassium concentrations in groundwater are commonly low partly because of the high degree of stability of potassium-bearing alumino-silicate minerals. Consequently, unaltered K-feldspar grains can be found in many sandstones. However, an even more important reason is the effect of exchange reactions on potassium removal from solution. The preference of clay and most other natural ion exchanger for potassium over sodium provides a ready explanation of why Na:K ratios in natural groundwater are much larger than 1, although potassium is only slightly less abundant than sodium in igneous rocks. Much of the evidence cited to support this mechanism is data showing progressive change in water chemistry along the direction of groundwater flow. Chapelle and Knobel (1983) were able to demonstrate in the Aquia aquifer, southern Maryland, that along the flow path, the chemical evolution of the groundwater is mirrored by the chemical modification of the exchanging medium (glauconite). As shown in Figure 3, an increase of dissolved sodium coincides with the increase of exchangeable sodium on the glauconite. Similarly, the increase of dissolved potassium at ~20 miles downgradient coincides with the increase of exchangeable potassium on the glauconite. The coincidence between increases of dissolved species and the increased availability of these species on exchange sites is consistent with the hypothesis that glauconite composition has been altered by cation exchange reactions. The order at which the cations are removed from solution (Ca, Mg, K, and Na) along the flow path agrees exactly with the order predicted by the stability of the cations on exchange sites and provides additional evidence for this interpretation.

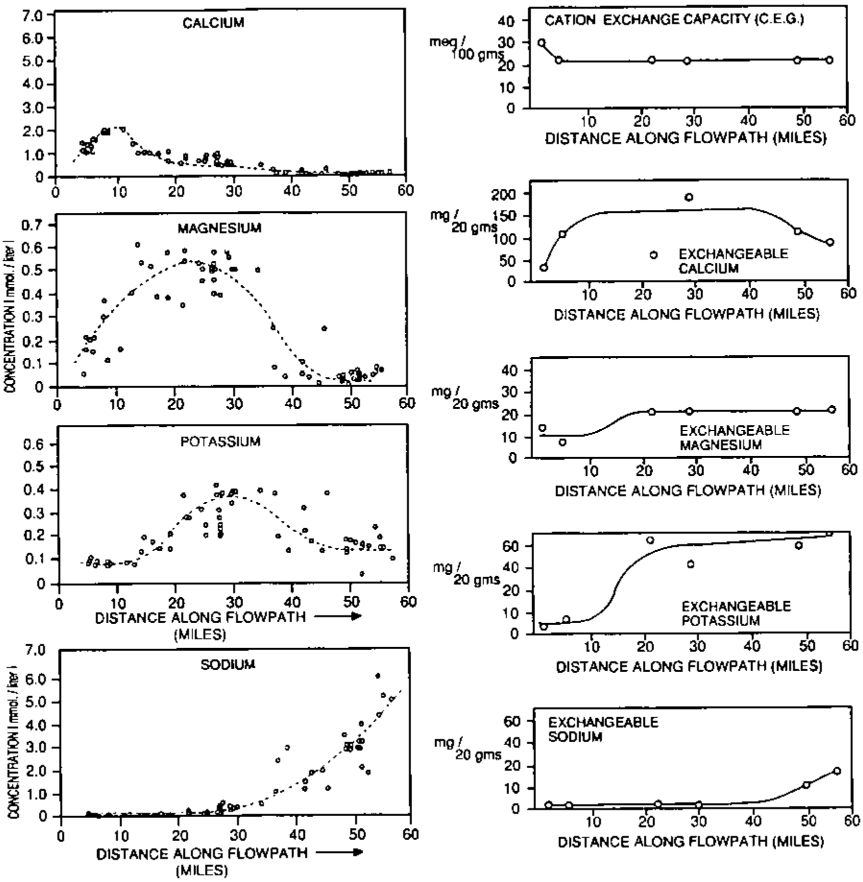


Fig. 3. Concentrations of dissolved calcium, magnesium, potassium and sodium in grounwater (left), and cation exchange capacity and concentrations of exchangeable calcium, magnesium, potassium and sodium in the aquifer glauconite (right) as a function of distance along the flow path in Aquia aquifer, Maryland (from Chapelle and Knobel, 1983).

Cation exchange is enhanced in the presence of saline water (Eugster and Jones, 1979; Drever, 1988), and the depleted ratio of K:Cl in saline water was used to identify connate water in sedimentary rocks (Bath and Edmunds, 1981). In a coastal aquifer, Oregon, the low K:Cl ratio characterized the freshwater-seawater interface and was presumably caused by the formation of authigenic K-feldspar (Magaritz and Luzier, 1985).

Some of the potassium, however, is also removed from water by the conversion of clays, for example montmorillonite into illite and chlorite. In these clays, potassium is incorporated in a special way into their structures. In illite, potassium ions are incorporated in spaces between crystal layers, where they cannot be removed by further ion-exchange reactions (Hem, 1985).

Eugster and Jones (1979) showed in their study in Lake Magadi region, the East African Rift Valley, that the removal of potassium took place only when the water was flowing underground (and not in a lake, for example) and argued that the removal process for potassium was sorption on cryptocrystalline surfaces or ion exchange.

In an injection test designed to simulate the migration of major ions in the sandy Borden aquifer, Canada, Dance and Reardon (1983) demonstrated the strong attenuation of potassium near the injection site, as opposed to sodium which appeared to be transported at nearly the same rate as chloride. Ceazan *et al.* (1989) obtained similar results in a glacial outwash aquifer in southern Cape Cod, Massachusetts, suggesting that even in the near absence of clay (<0.1%), cation exchange is an important attenuation mechanism for potassium.

5. Summary

The abundance and forms of potassium in igneous and sedimentary rocks were reviewed and the weathering processes and rates of potassium-containing minerals was discussed. Although potassium is almost equally abundant as sodium in rocks and minerals, it is preferentially lost in aqueous phases. Typical concentrations of potassium in the various components of the hydrological cycle are presented. Potassium concentrations are depleted relative to sodium in seawater, precipitation, surface water and groundwater because it is liberated with greater difficulty from minerals and exhibits a stronger tendency to be reincorporated into solid weathering products.

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Potassium Concentrations in Surface and Groundwaters and the Loss of Potassium in Relation to Land Use

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Summary

Losses of potassium (K) from the rooting zone of soils are a financial loss to the farmer and the magnitude of such losses is important if it affects the quality of water intended for human consumption. Across a wide range of rainfalls, farming systems, surface soils and underlying geological strata in the UK there is little dramatic change in the range of K concentrations in drainage from either agricultural soils or soils under other land use systems. In upland areas, with less intensive farming and often greater rainfalls, the upper value for the range of K concentrations rarely exceeded 3 mg K l^{-1}. Even in areas of intensive arable production, usually associated with lower rainfalls and smaller quantities of through drainage, water taken from rivers only occasionally had K concentrations approaching 10 mg l^{-1}. From measured losses of K in lysimeters the relationship, K leached (kg ha^{-1}) = 0.012 x drainage + 0.089 ($r^2 = 0.75$) was found. It suggests that for each 100 mm through drainage about 1 kg K ha^{-1} would be lost.

Potassium in the soil solution is at risk to loss by leaching but its rapid transfer to exchangeable and non exchangeable categories of soil K minimises this risk. Almost all sites capable of holding exchangeable and non exchangeable K would have to be saturated before there was serious risk of large amounts of K being leached from soil. To predict such losses a model (KLEACH) has been constructed to predict the retention of K by 1 cm horizons in soil and thus the risk of K eventually passing out of the soil to streams or aquifers.

Whilst there is little evidence that K in drinking water is detrimental to human health, the maximum admissible concentration of K in drinking water in the EECs Drinking Water Directive is unlikely to be exceeded in most cases. This situation is unlikely to change because most soils have a

great capacity to retain K and the amount of KCl used as fertilizer is changing little. Increasing levels of chloride in drinking water are associated with ever increasing amounts of chloride in atmospheric deposition not increasing use of potassium fertilizers.

1. Introduction

Much of the water used for human consumption is taken either from rivers and lakes (surface water) or from deeper strata (aquifers) often many metres below the surface. At least within the European Community, there are quality standards for water intended for human consumption. For potassium, the Drinking Water Directive (80/778 EEC) imposes a maximum admissible concentration (MAC) of 12 mg K l^{-1} with a guide level of 10 mg l^{-1}.

The chemical composition of water leaving surface soils depends on complex interactions which may or may not reach equilibrium as the water passes through air, soil, subsoil and if appropriate, deeper strata. Rain absorbs impurities introduced into the atmosphere by pollution. It then percolates at different rates through top soils of different texture which will have been enriched to varying degrees with soluble salts added to enhance crop growth. It then passes through subsoils with widely ranging chemical and physical properties before being discharged to streams and rivers or, where the lower strata are permeable, into aquifers. This paper discusses factors affecting the concentration of K in water mainly from agricultural soils.

2. Sites and soils

Much of the recent data given here is from five research stations in South Eastern England together with survey data collected from water supply organisations in England and Wales. The research stations together with their soil type and average annual rainfall are as follows. Rothamsted, silty clay loam, 700 mm; Woburn, sandy loam but some light-textured soils overlying Oxford clay, 600 mm; Saxmundham, calcareous sandy clay loam, 600 mm; Broom's Barn, soils developed in glacial drift range from sandy loams to clay loams, 500 mm; Brimstone Farm, clay with more than 93% clay plus silt, 680 mm.

Only at Saxmundham and Brimstone would artificial drainage be considered necessary because the subsoils are only slowly permeable. A new system of clay pipe drains at 0.8 m depth with pebble (stone) backfill to plough layer was installed at Saxmundham in October 1972 to replace an older system which did not cover all the experimental site. Water was led into the backfill and pipe drains through mole channels made in the soil at 0.6 m depth and 2.7 m spacing using a mole-plough. This consisted of a rigid vertical tine with an enlarged bullet-shaped expander, about 10 cm diameter, at the base of the tine. At Brimstone Farm large, hydrologically separated plots were established in 1978 to study the interaction of cultivation, minimum v ploughing, and mole and tile drainage v none, on rates of water loss from soil. Surface runoff, interflow, at the junction of the Ap and subsoil horizons, and drainflow on the drained plots, can all be intercepted, collected and measured. The silty clay loams at Rothamsted do not require under drainage, the water passing through clay subsoils of varying depth into the chalk strata below. However, Lawes and Gilbert installed horseshoe and sole drains, an early form of clay pipe drain on Broadbalk, in 1849 at about 0.7 m depth to aid removal of surface water. There was no pebble backfill. Sandy loams at Woburn and Broom's Barn are free draining, but on parts of both farms surface soils of this texture overlay slowly permeable subsoils and to speed the removal of surplus water from the surface, pipe drains have been installed. Those at Woburn are without backfill.

At all five research stations mainly arable crops are grown and they are generously manured especially with P and K to ensure that these nutrients do not limit growth.

3. The K cycle in agricultural soils

A simplified potassium cycle for agricultural soils recognises various categories or pools of soil K (Figure 1). Their precise definition is less important than the realisation that K can transfer in both directions between categories. Plant roots take up K^+ from the soil solution and this pool of readily available K can be maintained by adding soluble K fertilizers, K-rich organic manures or by transfer from the readily soluble pool as shown in Figure 1. The term readily soluble K is used here because this is the K extracted by various reagents used world-wide to estimate the availability of K to crops. All methods of analysis will include the water soluble fraction. When 1 M ammonium acetate or 1 M ammonium nitrate are used the K extracted is called exchangeable K because K^+ held on cation exchange sites has been replaced by NH_4^+. But many other extractants have been suggested and a number are widely used today e.g. ammonium acetate/acetic acid at pH 4.8 (Morgan's reagent), calcium lactate, ammonium acetate-lactate (AL) and calcium acetate-lactate (CAL). In general the amounts of K extracted by these reagents are strongly correlated with exchangeable K. For a brief historical review see Johnston & Goulding (1990).

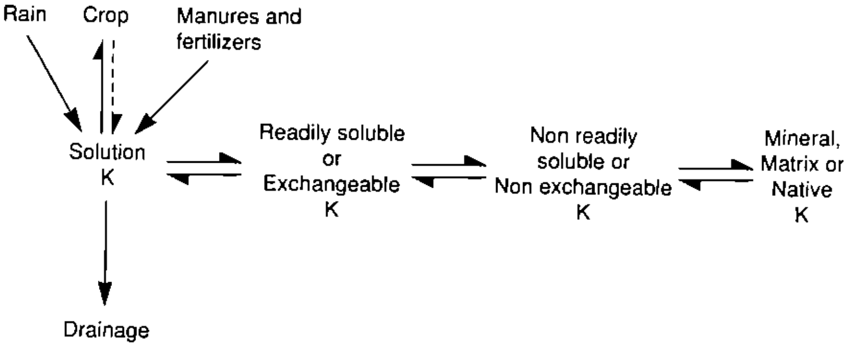

Fig. 1. Categories of soil K in a simplified potassium cycle for agricultural soils.

Figure 1 also shows that K can be lost by drainage. This is a financial loss to the farmer and the magnitude of such losses is important because of the EEC's Drinking Water Directive. However, it is important to recognise that losses in drainage will depend on how rapidly water soluble K residues from fresh applications of fertilizers or manures transfer to readily-soluble reserves, which can be measured using extractants like those listed above, and to non-soluble reserves, which cannot be measured in this way. The reversible transfer of K between the various soil pools shown in Figure 1 is discussed below. However, there is little evidence to suggest that K is released so quickly from the non-readily soluble pool in the absence of a growing crop that such a transfer could increase the risk of K leaching.

4. Transfer of K between soil pools

Examples of the transfer of K between pools were summarised by Johnston and Goulding (1990) using results from a number of long term field experiments. One, from an experiment on a silty clay loam, is given here as an example (Table 1). This experiment was started in 1854 on a soil which contained 593 mg kg^{-1} exchangeable K. Only small amounts of K were added during the next 100 years whilst clover was grown continuously and the produce removed. This depleted soil K reserves and by 1956 the soil contained only 85 mg kg^{-1} exchangeable K, equivalent to 171 kg ha^{-1} exchangeable K in the top 23 cm (Table 1), and a test of K, applied as KCl, was made between 1956 and 1966. Where K was applied clover yields were increased but the amount of K removed was less than that applied and there was a positive K balance, (balance = amount applied minus amount removed in harvested produce). However, Table 1 shows that only about 42% of this K balance remained exchangeable. The remainder had moved into the non-exchangeable pool in Figure 1 or had been leached below 23 cm. There was little change in exchangeable K on soils not given K despite a negative K balance of nearly 250 kg ha^{-1}. This quantity of K had come from non-exchangeable or non-readily soluble reserves. In subsequent periods of the experiment changes in exchangeable K were always between 30 and 40% of the K balance (Table 1). Because not all of a positive K balance will be accounted for by an increase in exchangeable K, it is impossible to calculate K losses in drainage by subtracting the increase in exchangeable K from the K balance, the two parameters which can be most readily determined.

Table 1. Effect of K balance on exchangeable K in soil, Garden Clover experiment, Rothamsted.

Period	Average K applied annually kg ha^{-1}	Total K balance in period kg ha^{-1}	Exchangeable K, kg ha^{-1}, during each period			Change in exch. K as % of K balance
			At start	At end	Difference	
1956-66	None	-246	171	194	+23	-
	136	+617	171	431	+260	+42
1967	437	+437	194	338	+144	+33
1968-78	250	+1667	375	1065	+690	+41
1979-83	125	-1494	1065	502	-563	-38

5. Early data on losses of K in drainage

In 1868, twenty five years after the start of the Broadbalk experiment at Rothamsted, Dr A. Voelcker analysed the drainage collected from the variously manured plots. At that time very little, if any, K was applied as fertilizer on farms although some K would be recycled through occasional applications of farmyard manure (FYM). The amount of K tested on Broadbalk (90 kg ha^{-1}) is similar to that applied to cereals today so that these early results have relevance to current practice.

Table 2. Concentration of K in drainage water from Broadbalk plots, Rothamsted, in 1868 and estimated annual loss of K.

Treatment	K applied kg ha^{-1}	K in drainage mg l^{-1}	K lost kg ha^{-1}
None	None	1.5	3.7
K_2SO_4	90	2.7	7.0
FYM	220	4.5	11.3

The results (Lawes *et al.*, 1882), summarised in Table 2, showed that although large amounts of K were applied annually both as potassium sulphate and in FYM there was only a small increase in the K content of the drainage from fertilized plots compared to the unmanured. Soils treated annually with FYM, 35 t ha^{-1}, received much more K and, compared with the fertilized soils, the extra K lost in drainage was in proportion to the extra K applied. The amount of K lost from the fertilized soil was very small compared with the loss of Ca (only about 3%) and the authors (ibid page 103) commented on this as follows "... the potash and magnesia being to a large extent retained by the soil, ...". The authors (ibid page 104) also commented that, "In the absence of drain pipes a part of both the phosphoric acid and potash in the drainage water would doubtless be retained by the subsoil".

These results showed that K could be lost from agricultural soils receiving large amounts of K but the quantities lost were likely to be small; they also suggested that K could be retained in subsoils. Unfortunately there is no information on the proportion of the rainfall passing to these shallow drains. Other data (see Section 8) suggest that the quantities of K lost were larger than might be expected.

6. Soil factors controlling the downward movement of K

6.1. Water soluble K

Warren and Johnston (1962) found a good relationship between water soluble K and exchangeable K where the latter ranged from 100 to 900 mg kg^{-1} in the top 23 cm of a silty clay loam at Rothamsted. Above 170 mg kg^{-1} K about 15% of the exchangeable K was water soluble, below this value the proportion was smaller. Whether similar proportions of water soluble to exchangeable K would be found on other soils is not known, nor is it known what the proportion would be in subsoils.

However, water soluble K must be at risk to loss by leaching whenever rainfall leads to water moving downwards through the soil profile. The amount of K moving downwards will depend both on the quantity of water and the speed at which it moves downwards. Water moving quickly through large pores and channels is likely to have a smaller concentration of K than water retained for long periods in small diameter pores.

Once K enriched water has moved from one soil layer to the next the availability of cation exchange sites in the lower layer, and to a lesser extent, the residence time of water in that layer, will govern how much K is removed from the soil solution to be held on cation exchange sites. Thus K can be progressively removed from the soil solution as it passes through the soil. Provided the subsoils contain sufficient cation exchange sites, drainage passing to streams and rivers or to deep aquifers may contain little or no K (see later for further discussion).

6.2. Retention of K in soil

The relationship between movement and retention of K by soil is not a simple one. Table 3 shows the gain in exchangeable K at four depths in a silty clay loam (25% clay) after more than 100 years of applying K as fertilizer or in FYM (Warren and Johnston, 1962). With all treatments there was a much smaller increase in exchangeable K at 46-54 cm than there was in the top 23 cm. However, each soil horizon had not become saturated with exchangeable K before the enrichment of deeper horizons commenced. Table 4 shows the gain in exchangeable K at four depths in a sandy loam soil when FYM and FYM composted with additional vegetable material (FYM compost) were each added at 37.5 and 75.0 t ha^{-1} annually for 20 years. All plots received a small application of K as fertilizer. Results from this experiment are quite different to those in Table 3. On the lighter textured soil (10% clay) the 23-30 and 30-46 cm horizons for each treatment contain as much extra exchangeable K as the ploughed surface soil (0-23 cm), and there is only a little less in the 46-61 cm layer. In both experiments the increase in exchangeable K was related to the amount of K added and although the increases were large, the largest values were still less than 10% of the cation exchange capacity. The difference in behaviour between the two soils, the development of a K profile with depth in the Rothamsted soil compared to almost uniform enrichment in the Woburn soil, is probably related to the rate at which water flowed downwards through the profile and the speed at which K exchanged with adsorbed cations.

Table 3. Amount of K added and exchangeable K at four depths on a silty clay loam.

	Treatment and K added, kg ha^{-1}			
	No K none	FYM 16700	PK 20500	FYM & PK 28800
Depth cm	Exch K mg kg^{-1}	extra exch K, mg kg^{-1}, over no K		
0 - 23	119	174	380	641
23 - 30	129	104	179	386
30 - 46	139	23	102	225
46 - 54	152	-2	79	152

Table 4. Amount of K added and exchangeable K at four depths on a sandy loam.

	Treatment and rate*				
	NPK	FYM 1	FYM 2	FYM compost 1	FYM compost 2
K added kg ha^{-1}					
in fertilizer	950	950	950	950	950
in organic manure	0	5450	10850	3950	7850
Depth cm	Exch K mg kg^{-1}	extra exch K, mg kg^{-1}, over NPK			
0 - 23	111	163	266	144	205
23 - 30	101	169	265	137	213
30 - 46	93	174	268	134	226
46 - 61	83	143	226	91	186

* rate 1,2: 37.5, 75 t ha^{-1} fresh organic manure each year for 20 years.

6.3. Modelling K leaching

The data given above show that exchangeable K and, presumably, non-exchangeable K is increased at increasing depths within the soil profile as K moves downwards in drainage. Also each soil horizon does not become "saturated" with readily soluble K before K enrichment of the lower horizons starts. It would be of great benefit to have a model that predicted this build up of K and also the risk of K moving so far down the profile that it is lost from the soil in drainage either to streams or to aquifers.

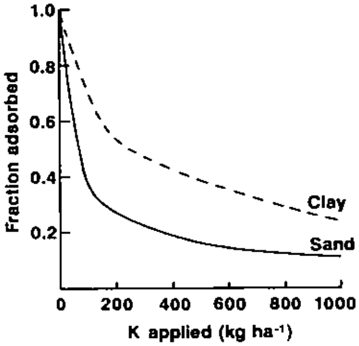

Fig. 2. The relationship between the fraction of K adsorbed by two soils and the K applied.

A model (KLEACH) has been constructed to do this. It is based on data for K adsorption (Goulding and Talibudeen, 1984) which, after modification to allow for non-equilibrium conditions during leaching, is used to generate curves like those in Figure 2. They show the fraction of an application of K that would be retained by a layer of soil 1 cm deep. As expected, the larger the amount applied, the smaller the fraction adsorbed although the amount adsorbed will be larger. The model calculates the fraction of K retained in each successive 1 cm layer as the K, less the amount retained in the previous layer, moves down through the soil. The model output is of the distribution of the applied K through the soil profile. The two examples in Table 5 show that eventually all the K is adsorbed. Depending on the depth of the soil to the field drains or to the water table the risk of K, and the amount of K, being lost can be assessed.

Table 5. Predicted K distribution from applied manures through two arable soil profiles.

	Soil type and K added, kg ha^{-1}	
Soil layer 1 cm depth	Clay loam soil 200 kg K as KCl	Sandy soil 800 kg K as slurry
	K adsorbed, kg ha^{-1}, in each 1 cm layer of soil	
1	114	96
2	64	85
3	20	75
4	2	67
5		60
6		56
7		52
8		49
9		48
10		48
11		48
12		46
13		39
14		23
15		7
16		1
17		
18		
19		
20		

At present the model has been used to predict K distribution for several soils ranging in clay content from 3 to 50%, but only one set of climatic conditions. It can be modified for other climates and agricultural systems. It can be made to take account of increasing amounts of exchangeable K in surface soil from past applications of inorganic fertilizers and organic manures. It can also be extended to allow for changes in amounts of clay down the profile.

7. K in rainfall

Table 6 shows the mean K concentration and range in rainfall collected at Rothamsted, Woburn and Saxmundham during the years 1969-73 and at Rothamsted, Woburn and Broom's Barn during 1986-91 together with the amount of K added to soil each year. The K concentrations were similar at all four sites, the average ranged from 0.22 to 0.72 mg l^{-1} and only small amounts of K, 1.4 to 4.5 kg ha^{-1}, were added to soil in rainfall. These amounts are within the range 1.1 to 9.6 kg ha^{-1} K reported by Low and Armitage (1970) for sites in England, Germany, Sweden and Australia. They recorded one very large value, 39.3 kg ha^{-1} K, for a site in South Africa but no explanation was offered.

Table 6. Mean annual concentration and content of K in rainfall at four experimental stations in South Eastern England.

Site		Annual rainfall mm	Concentration mg l^{-1} K mean	range	K added to soil kg ha^{-1}
Rothamsted	1969-73	619	0.72	0.1 - 3.8	4.5
	1986-91	682	0.22	0.2 - 0.4	1.5
Woburn	1969-73	548	0.39	< 0.1 - 1.0	2.1
	1986-91	625	0.23	0.1 - 0.5	1.4
Saxmundham	1969-73	574	0.55	< 0.1 - 2.4	3.2
Broom's Barn	1986-91	574	0.25	0.1 - 0.4	1.4

8. K in drainage water from experimental soils

8.1. The effect of soil pH on losses of K

One consistent effect, noted in published work where comparisons were made, was that the addition of $CaCO_3$ to soil, liming, caused a decrease in leaching losses of K (see Munson and Nelson, 1963 and references therein). Johnston (1988) summarised data from laboratory experiments made on soils from long-term experiments at Rothamsted which had very similar clay contents and mineralogies but different pHs, range 5 to 8, and different levels of exchangeable K, range 80 to 940 mg kg^{-1}, as a result of past treatments over many years. In the laboratory increasing amounts of K were added to the soils which were put through a 12-week cycle of alternate wet and dry periods each lasting one week. For each soil the proportion of the added K which remained exchangeable was independent of the amount of K added and about 15% of the exchangeable K was water soluble. However, a larger proportion of the added K remained exchangeable in the acid soils, pH 5 to 6, than in the neutral soils, pH 7 to 8. Therefore more of the K added to the acid soil was water soluble and at risk to leaching down the profile.

Soils of similar mineralogy are likely to have a smaller CEC when acid than when alkaline, thus acid soils can hold less exchangeable K. Also, Ca^{2+} ions occupy a larger proportion of the CEC in neutral than in acid soils and K^{+} can more readily replace Ca^{2+} than Al^{3+} or H^{+} ions. Thus again, more K will be retained as exchangeable K in alkaline soils.

8.2. K in drainage from lysimeters

For all their limitations lysimeters still offer an acceptable, often the only, practical way of measuring losses of plant nutrients from soil.

In 1919, 0.0004 ha monolith lysimeters 1 m deep were set up at Craibstone at the North of Scotland College of Agriculture (Hendrick and Welsh, 1927). The soil, light textured and granitic, contained 1.25% K much of which was in feldspars which had undergone little weathering. From 1921 the three lysimeters were either unmanured or received FYM with N and P fertilizers with and without limestone. These treatments were applied only to turnips, the first crop in the six-course rotation : turnips, oats, grass hay, grass cut, grass cut and oats grown between 1921 and 1926. The amount of K applied was 170 kg ha^{-1} in 30 t ha^{-1} FYM. Average annual rainfall was 870 mm and annual through drainage of 470 mm differed little between lysimeters. On average, the drainage from the three lysimeters contained almost identical concentrations of K, average 2.5 mg l^{-1}, range 2.2 to 2.9. Thus the amounts of K lost each year were nearly the same 9.8, 9.2 and 8.6 kg ha^{-1} from the unmanured, manured without lime and manured with lime treatments respectively. Least K was lost in the first year when the K was applied because there was least through drainage.

In 1951 monolith lysimeters, 88 cm deep, were set up at ICI's Jealotts Hill Research Station in Southern England (Low and Armitage, 1970). The top 23 cm of soil was a sandy loam with 160 mg kg^{-1} exchangeable K. Below 23 cm the subsoil was a coarse sand. The lysimeters were either without a crop (fallowed) or grew grass or clover. Before sowing the seeds in July

1951 all the lysimeters received the equivalent of 280 kg ha^{-1} K. Initially the leachate was analysed mainly for mineral nitrogen but for three years 1953-55 other cations and anions were measured. The average annual loss of K was 4.7, 1.9 and 2.0 kg ha^{-1} from the fallow, grass and clover lysimeters respectively. The volume of leachate from the fallow lysimeter was almost double that from the cropped lysimeters, thus the concentration of K in all the leachates was similar and independent of cropping. The amounts of K lost were much less than the 10 kg ha^{-1} K deposited in the 650 mm of rainfall, even on the lysimeter without a crop. Surprised by the small losses of K in the leachate and concerned that much K might have been lost in the 17 months between the application of K fertilizer and the commencement of measurements, the authors determined the K fixation capacity of the top 15 cm of soil in the laboratory. They added the equivalent of 305 kg ha^{-1} K, as K_2HPO_4, to the soil and then left it to equilibrate for either three hours or nine days before leaching the soil slowly with the equivalent of 500 mm of rain. After only three hours equilibration only about 6% of the added K was in the leachate whilst after nine days the amount was less than 1% of that added. Thus it is unlikely that there had been large losses of K from the lysimeters before measurements were started and the small losses recorded are representative of what would happen on a field scale even on light textured soils.

8.3. The relationship between drainage and losses of K

Most quantitative data on losses of K from soil are from lysimeter studies. From some of the data in the literature and some given here, it was possible to construct the relationship between drainage and K losses in Fig. 3. The data are from North America and Europe between 1920 and 1990. The lysimeters were mostly monolith lysimeters ranging in depth up to 1 m. The soils varied from sands to clays; some were cropped, some fallowed; some were given K, others not. The period of measurement varied from one to ten years but only data for whole years were used here and where possible averages of a group of years were taken.

Across this wide range of soils, climates, cropping and manuring, K leached, in kg ha^{-1}, and drainage, in mm, were related:

$$\text{K leached} = 0.012 \times \text{drainage} + 0.089 \quad (r^2 = 0.75,\ p < 0.001)$$

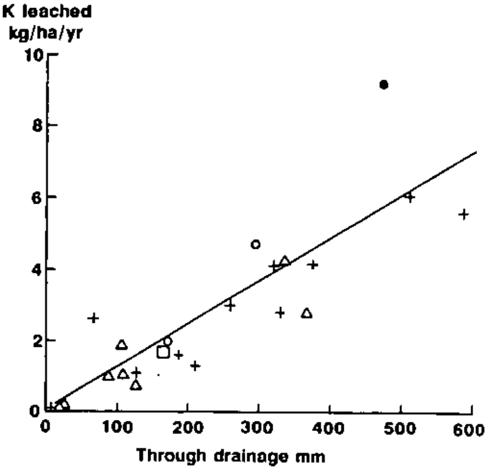

Fig. 3. The relationship between the amount of potassium leached from soil and the quantity of through drainage.

This suggests that, on average, for each 100 mm through drainage, about 1 kg ha^{-1} K would be lost. The major outlier in the relationship is the soil from Craibstone, Scotland. Here in both manured and unmanured but cropped lysimeters, the amount of K lost was the same. One factor which seemed to distinguish this site, and was occasionally seen in other data sets, was that K losses were larger than expected when the amount of drainage exceeded 50% of the rainfall.

8.4. K in drainage from field soils

Between 1968 and 1974 drainage water was sampled regularly whenever drain flow occurred at Rothamsted, Woburn, Saxmundham and Broom's Barn (Williams, 1976). At Saxmundham, K concentrations were small and varied little throughout the period (Table 7). Six drains were sampled at Woburn and the mean concentration of K from all the drains was twice that at Saxmundham. Three of the drains which flowed regularly had a mean K concentration of 2.6 mg l^{-1} whilst another which flowed only intermittently had about 14.9 mg l^{-1} K. Large concentrations of K in drainage have been recorded occasionally also at Broom's Barn. They invariably followed a period of dry weather when there had been little or no drain flow.

Table 7. Mean annual concentration of K in drainage water at four experimental stations in South Eastern England.

Site	Period	Concentration mg K l^{-1}
Saxmundham	Mar 68 - Mar 70	1.6
	Nov 70 - Mar 72	2.4
	Dec 72 - Mar 74	1.4
	Mar 74 - Mar 75	1.2
Woburn drains	Mar 68 - Mar 70	5.0
	Mar 70 - Mar 74	5.2
Woburn stream	Mar 68 - Mar 70	4.2
	Mar 70 - Mar 74	4.3
Broom's Barn	Jan 70 - Feb 74	0.28
	Jan 86 - Dec 92*	0.26
Rothamsted	Jan 70 - Feb 74	15.8

* excluding 1990-91

In the absence of flow meters and an accurate knowledge of the area drained by each drain it was not possible to calculate losses of K in kg ha^{-1} but they might have been more nearly the same than were the concentrations in drainage. The composition of water in a small stream at Woburn remained remarkably constant (Table 7). Water flow is maintained by a spring on the farm and it was thought that the water comes from deep drainage from soils on the farm. Drain flows at Broom's Barn during 1970-74 were extremely variable and intermittent; the range in K concentrations was 0.2 to 7.3 mg l^{-1}. In this first period three drains had an average K concentration of 0.3 mg l^{-1} and these three drains were sampled again during the period 1986-1991 whenever possible, although drain flow was even more intermittent than previously. Average K concentrations in this second period were almost identical to that in the first period (Table 7).

There is data for only one drain at Rothamsted in Table 7. The mean K concentration, 15.8 mg l^{-1}, is large and the reason is unknown. The concentration is certainly much in excess of that recorded for the Broadbalk plots (Table 2). The drain is shallow, 0.6 m, and it probably collects water from a small catchment of a few hectares. The maximum K concentration recorded, 40 mg l^{-1}, was matched by large Ca and NO_3-N concentrations (see Section 11).

The concentration of K in drainage at Brimstone Farm under well fertilized arable crops has only been measured throughout one drainage season, 1979/80 (Harris *et al,* 1984), largely because the concentrations of K in drainage were very small, range 0.5 to 3.5 mg l^{-1}. On drained plots, i.e. those with clay pipe drains with pebble back fill into which mole channels discharged, 1.18 kg ha^{-1} K was lost in water draining from depth. There was much less K, 0.49 kg ha^{-1}, in the smaller volumes of water removed as surface run off and interflow. On undrained plots most of the excess water moved laterally through the soil as surface runoff and interflow and these removed 0.50 and 0.87 kg ha^{-1} K respectively. Thus the total loss of K from both treatments was small and similar, 1.67 and 1.37 kg ha^{-1} from drained and undrained soils. In practice all three types of drainage would discharge to streams and rivers. However, the method or speed at which the drainage reached the stream had little effect on the amount of K lost.

9. K in boreholes on experimental farms

Boreholes into the underlying aquifers exist at Rothamsted, Broom's Barn and Woburn. It is assumed that the local hydrology causes a continuous flow of water out of and into the borehole. Certainly the water level varies appreciably throughout a 12 month period. They have been sampled as dipwells regularly each month for some years. The exception is the Rothamsted Farm borehole where the sample is taken by pumping out about 20 l of water on each sampling occasion.

The Rothamsted Farm borehole is deep (99 m); it goes into the chalk at 13 m and the depth to the water is 35 m. It is used to extract water for irrigating experimental crops. The mean K concentration and range has changed little between two periods 1968-74 and 1986-91 (Table 8). As part of a study of the movement of nitrate into aquifers, two shallower boreholes were drilled into the chalk in the late 1970s. That at Knott Wood goes into chalk at 1 m and the water is at 15 m. It is situated under deciduous woodland on sloping ground. Water from this shallow borehole had K concentrations remarkably similar to those in the much deeper Farm borehole about 500 m away.

Table 8. Concentration of K in borehole water at three experimental stations in South Eastern England.

Site	Period	Depth to water, m	Concentration mg K l^{-1}	
			mean	range
Rothamsted Farm	1968 - 74	99	0.9	0.8 - 1.6
	1986 - 91		1.2	1.0 - 1.4
Knott Wood	1986 - 91	15	1.2	1.1 - 1.2
Highfield	1986 - 91	45	2.7	2.3 - 3.9
Broom's Barn	1970 - 74	29	4.4	3.8 - 7.6
	1986 - 91		4.2	4.0 - 4.3
Woburn	1988 - 91	7	2.1	1.9 - 2.2

The borehole on Highfield reaches chalk at 15 m and the water at 45 m. It is on flat ground on the edge of a large experiment on ley arable farming systems with other arable cropping adjacent. Over a six-year period the water contained only 2.7 mg l^{-1} K. The borehole at Woburn was drilled in 1978 to sample water from a sandstone aquifer underlying intensive arable cropping for nitrate studies. The nitrate analyses suggest that the water quality responds rapidly to treatment at the surface and there was some indication that K concentrations increased briefly following large applications of KCl. This rapid response is perhaps not surprising because the depth to the water is only 7 m. However, the average K concentration over four years was only 2.1 mg l^{-1}, very similar to that at Rothamsted. The Broom's Barn borehole is sunk into chalk overlain by mainly coarse texture soils heavily fertilized with K for sugar beet in particular. The depth to the chalk is 11 m and the water is at 29 m. Of the five boreholes sampled this water had the largest K concentration, just over 4 mg l^{-1}, but the K concentration changed little over a 20 year period and was still well below the EEC guide level of 10 mg l^{-1}.

10. K in water, the regional picture in England and Wales

During the period 1968-74, Williams (1976) analysed the water supplied to the laboratories at Rothamsted and Woburn by their respective water supply companies. At Rothamsted the water was blended from three deep boreholes in the chalk and 98 samples averaged 1.3 mg l^{-1} K (range 0.9 to 4.8). At Woburn the 70 m deep borehole is in a sandstone aquifer and 67 samples averaged 3.4 mg l^{-1} K (range 2.4 to 6.4).

By 1987 the Potash Development Association in Britain was concerned about the Maximum Admissible Concentration (MAC) for K in water supplied for human consumption under the EC Drinking Water Directive. At that time water supply was the responsibility of Regional Water Authorities. Each Authority was asked to supply what information it could on the concentration of K in potable water. All were able to supply data with varying degrees of detail and in different formats, usually for years around 1986, and the information is discussed briefly here by courtesy of J.D. Hollies (personal communication).

None of the Authorities saw a problem either then or in the foreseeable future to supply water below the MAC limit. One Authority pointed out that larger than normal levels of K can indicate pollution, for example by leachate from land-fill sites, which usually leads to more detailed investigation, especially for possible organic and inorganic pollutants and microbial contamination.

There were some interesting similarities and differences within the data which relate not only to the agriculture of the region but also to estimates of the mean excess winter rainfall which can result in either surface run off or through drainage. Excess winter rainfall can be put into three bands, less than 150 mm, 150 to 250 mm, and more than 250 mm, and the Water Authorities grouped by having most of their catchments in one of the three bands.

Regions with predominantly more than 250 mm excess winter rainfall include Wales, the North West, South West and Wessex. Welsh Water get their supply from 260 sources which can be grouped as : upland surface water mainly derived from streams and reservoirs draining peaty or afforested catchments with K concentrations which ranged from 0.2 to 2.5 mg l^{-1}; lowland surface water mainly taken from the middle and lower reaches of rivers contained 2.0 to 7.5 mg l^{-1} K, and similar concentrations, 2.5 to 9.5 mg l^{-1}, were found in groundwaters derived mainly from aquifers in limestone or stony gravel at shallow depths. Like Welsh Water, North

West Water also derives its supplies from upland reservoirs, lowland rivers and boreholes. It also noted that upland reservoirs directly fed by streams had the lowest K levels. Averaged over all supplies, concentrations ranged from 0.5 to 6.0 mg l^{-1} K. In both regions water which could be draining from agricultural land into lowland rivers and shallow aquifers had a larger K concentration than that from upland areas. Welsh Water noted that K concentrations showed seasonal variation but this may relate to the volume of water flowing into the reservoirs or streams at any one time. Similarly, South West Water supplying Devon and Cornwall, which are mainly livestock areas, recorded an average of 1.5 mg l^{-1} K (range 0.4 to 5.0) over two years and 52 sources.

Northumbrian Water in the North East of England has about half the area with 150 - 250 mm excess winter rainfall and the rest over 250 mm. It covers an area with mainly low input agriculture and forestry. Data for 23 water supply sources gave a mean of 1.6 mg l^{-1} K (range 0.6 to 3.7). There was one value of 15 mg l^{-1} K out of 12 observations at one site (see Section 11). On the other hand Southern Water with more than half the area with more than 250 mm but mainly arable agriculture, reported K concentrations usually below 3 mg l^{-1} and with maximum values of 6 mg l^{-1}.

Yorkshire Water, Anglia and Thames have about two thirds of their areas with 150 - 250 mm excess winter rainfall. Yorkshire with the remaining third over 250 mm covers an area of variable geology and farming and includes some large industrial conurbations. It divides its region into zones. The Pennine area with low input stock rearing had K concentrations ranging from 0.5 to 2.0 mg l^{-1} and this range was very similar to that (1 to 2 mg l^{-1}) in the East of the region where water is taken from chalk boreholes but where the agriculture includes the intensively farmed Vales of York and Pickering. Water supplied from sandstone boreholes in the south east of the region, in an area of arable cropping, and that in the north of the region, the Northern Springs, with more mixed farming, both had K concentrations in the range 1 to 3 mg l^{-1}. By contrast, Anglian Water has the other third of its area with less than 150 mm excess winter rainfall and it covers the eastern counties of England with the largest concentration of arable agriculture. Recorded K concentrations were normally between 1 and 6 mg l^{-1}; thus the largest values in the range are greater than those in the Yorkshire region. Anglia also has one or two geologically old underground waters with up to 14 mg l^{-1} K. They consider that these levels are naturally occurring and the Authority has been granted derogations under the EEC Drinking Water Directive. It is interesting that some other spring waters derived from underground sources also have larger K concentrations than those found in surface waters. It should also be noted that Welsh Water reported that groundwaters derived from limestone aquifers had the largest concentrations of K in their region although these were still below the MAC.

Severn Trent Water in the central midlands and Wessex Water in the Bristol region together with Somerset and Dorset are both in areas of mixed arable and animal husbandry. Wessex Water, with the majority of its region with more than 250 mm excess winter rainfall, has 130 different sources of supply and K concentrations range from < 1 to 10.6 mg l^{-1}. Severn Trent, with most of its region with 150 to 250 mm, has 259 sources which supplied 1704 million litres a day with K concentrations ranging from < 1 to 5 mg l^{-1} and a further 20 sources which supplied 315 M l day^{-1} with 5 to 10 mg l^{-1} K. Thus the range of K concentrations appears to be little affected by the quantity of excess winter rainfall.

It is interesting to compare the range of K concentrations in UK drinking waters with those in bottled mineral waters. Nine bottled waters, available widely in the UK, declared the K concentration on the label. These values ranged from 0.3 to 5.7 mg l^{-1} K (mean 2.2 mg l^{-1}).

11. Large concentrations of K in drainage

Attention has been drawn to the large concentration of K in one of the Rothamsted drains, most probably due to pollution, and in one source of supply on one occasion in data from Northumbrian Water (Section 10).

Van Schreven (1970) also reported very large losses of K in drainage during 1962-66 from the Eastern Flevoland polder which emerged from the water in 1957. Rainfall averaged 854 mm each year and added about 7 kg ha^{-1} K. On average 162 kg ha^{-1} K (range 105 to 226) was lost each year in drainage from the polder; the concentration of K was not given. These losses are very much larger than others given in this paper. The large annual rainfall, the shallow depth of soil above the water table and the very recent commencement of drainage probably all contributed to the large loss of K. Smaller losses, 54 kg ha^{-1} K, were reported in 1963-64 for the North eastern polder (emerged from the water in 1942), so the age of the polder was probably important. Unfortunately the amounts of Na lost were not given, neither was the ratio of Na to K in the drainage or in nearby sea water, which might have allowed the K losses to be related to the drainage of water which previously saturated the soil. The soil was described as very heavy with the clay fraction containing about 80% illite and initially much exchangeable K. It is difficult to see why the true exchangeable K content should have fallen on drainage but as pointed out previously "exchangeable K" as measured analytically will include water soluble K held in the soil matrix. This water soluble K may have been a large proportion of the initial exchangeable K and would have been lost on drainage. It is also possible that the oxidation of organic matter decreased the CEC which would have released K, and that the disintegration of clay minerals on drying after many years of immersion in water released fixed K.

It is almost certain that these exceptionally large losses of K were not related to the use of fertilizers or manures because the amounts of N lost were very much smaller, about 15 kg ha^{-1} N each year, from both polders. This was only about 10% of the K lost from the Eastern Flevoland polder.

It would be helpful in future if authors reporting larger than anticipated K losses from soils, or water supplies or drainage with large concentrations of K, could attempt to offer an explanation. If this is not done then those responsible for framing legislation do not know whether to ignore the values as aberrant or take them into serious consideration when deciding on limiting values.

12. Conclusions

The reason for setting a maximum admissible concentration of 12 mg l^{-1} K in the EEC Drinking Water Directive is not known to the authors of this paper. If organisations supplying water for human consumption can use K concentrations as an easily measured indicator of possible contamination of sources of water supply then this is good but within a Directive the choice of any MAC should be soundly based.

At present water supply organisations in England and Wales foresee little difficulty in supplying water with less than 12 mg l^{-1} K. Across a wide range of rainfalls, farming systems, surface soils and underlying geological strata in the UK there is little dramatic change in the range of K concentrations in drainage from either agricultural soils or soils under other land use systems. In upland areas with less intensive farming and often greater rainfalls, the upper value for the range of K concentrations rarely exceeded 3 mg l^{-1} K. Even in areas of intensive arable production, usually associated with lower rainfalls and smaller quantities of through drainage, water taken from the middle or lower reaches of rivers and from boreholes only occasionally had K concentrations approaching 10 mg l^{-1}. It is unlikely that this situation will change appreciably in the foreseeable future. One possible cause for increased losses of K in drainage could be that sites capable of holding exchangeable and non-exchangeable K in both topsoils and subsoils become saturated. This seems very unlikely except on the very lightest textured soils. On such soils good farm practice applies K annually in amounts sufficient to match crop requirement.

Current awareness of increasing levels of chloride in water must not be linked to the use of KCl fertilizers which has changed little in recent years. Goulding *et al* (1986) showed that chloride deposited in rain increased through the 1970s and 1980s in some areas and has continued to increase in recent years.

The use of K fertilizers is increasing only very slowly and, with present rates of use, the national K balance is very small. Church and Skinner (1986) calculated K balances for England and Wales in 1982 for winter wheat, spring barley, oilseed rape and potatoes. For all four crops the K balance was positive based on average national yields and % K in dry matter and data from the Survey of Fertilizer Practice on the average amounts of K applied to each crop. However the balance was small; for winter wheat, 4 kg ha^{-1} K, for spring barley 21 kg ha^{-1} and for oilseed rape 12 kg ha^{-1}. It was much larger for potatoes, 69 kg ha^{-1}, but because potatoes are not grown frequently and often only on the lighter textured soils then the effect on the overall national K balance for arable rotations is likely to be small. Incorporating straw into soil,because of the ban on straw burning, will make little difference to the national K balance for cereals because much of the K in the straw was returned to the soil in the ash and this was allowed for in these calculations.

With only a very small positive K balance for agriculture in England and Wales and little change likely during the coming years, with many soils having a large capacity to retain both exchangeable and non-exchangeable K, there seems little prospect that the concentration of K in drainage from agricultural land will increase to levels which could cause problems for water supply organisations to meet the maximum admissible concentration of K, 12 mg l^{-1}, imposed by the EEC Drinking Water Directive.

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Ion Composition of Mineral Waters in Czechoslovakia with Special Reference to K Concentration

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Summary

Mineral waters in Czechoslovakia contain from 5 to 141 mg l^{-1} K^+. Their ion composition depends not only on the parent geological material but also on additional factors like contents of dissolved CO_2 and H_2SO_4, temperature and rate of evaporation.

Introduction

The following discussion refers to Table 1, giving details of waters originating from the sites shown in Figure 1.

2.64% Na and 2.40% K by weight occur in the **earth's crust**; the Na:K ratio by weight is 1.1 and the ionic ratio 1.87.

More sodium than potassium derived from the weathering of minerals has been carried away in **river waters** as a result of the differing mobilities of the ions in solution and differential adsorption by clay minerals (analyses 17a and b in the table).

Thus we find in **soils** only 0.63% Na and 1.36% K with the Na:K ratio by weight 0.46 and ionic ratio 0.79.

As a result of preferential adsorption of K^+ by sediments, **sea water** contains 10561 mg l^{-1} Na^+ and 380 mg l^{-1} K^+ or 459.2 meq l^{-1} Na^+ and 9.72 meq l^{-1} K^+, the ionic ration being 47.2 (Analysis 18).

Waters from mineral springs

In the formation of mineral waters by the action of water on rocks, there are marked interactions between the following factors :

a) CO_2 of postvolcanic origin (sites 1-9 and 11-12);

b) free H_2SO_4 derived from oxidation of pyrites (sites 15, 16);

c) elevated temperature (sites 1, 10);

d) frequently part of the water concerned in determining the final ionic composition is of relict origin which to a varying extent is altered and concentrated through evaporation (sites 1, 2, 11, 12, 13, 14 and to some extent 8 and 10). At sites 15 and 16 (bitter water containing $MgSO_4$) recent evaporation is a factor.

All these factors raise water solubility. Often only one factor may be concerned but frequently they operate in combination, as indicated in the last column of the table.

A distinct **lithogenic water chemistry** is concerned in CO_2 saturated waters of the Kaiserwald mountains, the Tepler uplands of western Bohemia (sites 3, 6, 7) and in the centre of the Ore mountains (sites 4, 5). Here low concentration mineral waters (1-2 g l^{-1} TDS) occur with K^+ contents usually 5-20 mg l^{-1} and $Na^+:K^+$ ratio around 5 to 14. The rocks of these sites are metamorphic (gneiss, mica-schist and phyllite) with a high K content (gneiss 2.75% Na and 2.29% K with the ionic ratio $Na^+:K^+$ 2.04; mica schist and phyllite 1.80% Na and 2.72% K, Na:K ionic ratio 1.12).

From the above it is clear that the effect of CO_2 in the water is to dissolve more sodium than potassium. A comparison may be made with water from the river Labe in the Bohemian massif for the year 1892 (17a in the table) before the water had been affected by human activity as applies to the later analysis in the year 1976 (17b). These representative data for river waters shows the ionic ratio $Na^+:K^+$ to be only 3.8 with contents 4.4 and 9.7 mg l^{-1} for K^+ and Na^+ respectively.

Granites of the Bohemian massif contain on the average 2.63% Na and 3.74% K ($Na^+:K^+$ = 1.20). There is no true mineral water originating from the granite. At Karlovy Vary (site 1) and on the metamorphic rocks and tertiary sediments in Frantiskovy Lazne (site 2a, b, c) relict evaporation lake waters are much involved and, because of this, the K^+ contents are higher at 37, 97 and 136 mg l^{-1} respectively but the $Na^+:K^+$ ratio at 30 to 86 is finally shifted strongly in favour of Na^+.

The waters from **chalky marlstone** (sites 8 and 9) have K^+ contents of 56 to 66 mg l^{-1} with $Na^+:K^+$ ratio 9-15.

The hot springs of Teplice v Cechach (site 10) on metamorphic rocks also with chalky marlstone contain 10 mg l^{-1} K^+ ($Na^+:K^+$ ratio=31). On the same rocks with fossil water (site 11) the CO_2 water contains 93 mg l^{-1} K^+ ($Na^+:K^+$ ratio similar at 33).

CO_2 waters from early **tertiary clays and sands** at Luhacovice (site 12a and b) with relict saline waters show a high K^+ content of 81 to 108 mg l^{-1} (Na^+:K^+ ratio about 31).

The **bitter waters** of Saratica and Zajecice (sites 15 and 16) occupy a special position as regards interaction between rocks and water. These waters were formed recently under present-day conditions by evaporation and interaction with free H_2SO_4 from oxidation of pyrites on $CaCO_3$ and $MgCO_3$ and clay-mineral complex. As a result of these processes, strongly mineralized sulphate waters occur with 83 and 102 mg l^{-1} K^+ (Na^+:K^+ ratio 16 and 59). The contents of K^+ in meq % remain low at about 0.7 as alkaline earth cations are concerned in the final stages. The highest value for meq % K is found in lithogenic CO_2 water at Kyselka (site 4).

The complex evaluation of mineral water chemistry shows that the lithogenic mineral waters are formed under natural conditions through the enhanced dissolution of rocks by water containing CO_2 and H_2SO_4 at high temperature. More potassium is dissolved from the rock with contents of 10-20 mg l^{-1} K^+ in the water. This process is connected with stronger dissolution of sodium as in normal water. In straight river waters the Na^+:K^+ ionic ratio is about 4 compared with 5-15 in lithogenic CO_2 mineral waters.

In special cases, the formation of mineral waters involves evaporation and further K^+ adsorption by sediments (aluminosilicate clay minerals) and K^+ contents can reach more than 100 mg l^{-1} (max. 141). At the same time Na^+ contents are significantly higher (ionic Na^+:K^+ ratio up to 140 or 160). Sea water contains 380 mg l^{-1} K^+, with Na^+:K^+ ratio 47.

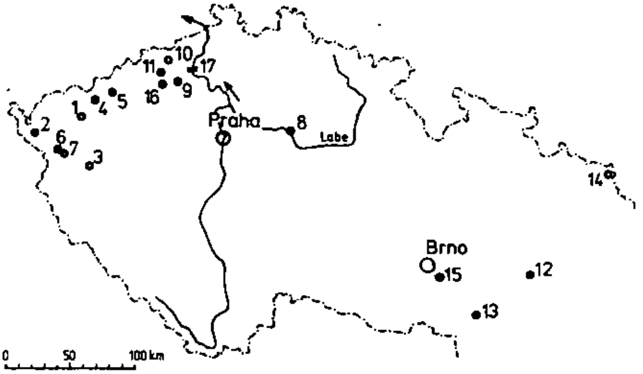

Fig. 1. Map of the mineral water springs evaluated.
Number of the locality corresponds to the numbers and names in the table.

Nr.	Locality Spring Type of water	K^+ mg l^{-1}	K^+ meq l^{-1}	Na^+ mg l^{-1}	Na^+ meq l^{-1}	TDS g l^{-1}	K^+ meq%	Ratio Na^+:K^+ meq%	Rock environment	Special local conditions
1 x)	Karlovy Vary Sprudel - spring Na- -SO_4 -HCO_3 -Cl	97	2.48	1724	75.0	6.5	2.8	30	granite	T : 72° C CO_2 participation of relict evaporation lake waters
2a x)	Frantiskovy Lazne Kostelni - spring Na- -SO_4 -HCO_3 -Cl	16	0.42	667	29.1	2.3	1.3	72	granite metamorphic rocks tertiary chalky clay and sands	CO_2 participation of relict evaporation lake waters
2b	Frantiskovy Lazne Glauber II - spring Na- -SO_4 -Cl -HCO_3	37	0.95	1888	82.1	6.3	1.0	86	"	" borehole 29 m
2c	Frantiskovy Lazne Glauber IV - spring Na- -SO_4 -Cl -HCO_3	136	3.48	6479	281.7	23.0	1.1	81	"	" borehole 92 m
3	Konstantinovy L. Prusik - spring Na - Mg - Ca - HCO_3	13	0.32	98	4.3	0.9	3.3	13	metamorphic rocks (phyllite)	CO_2

Nr.	Locality Spring Type of water	K^+ mg l^{-1}	K^+ meq l^{-1}	Na^+ mg l^{-1}	Na^+ meq l^{-1}	TDS g l^{-1}	K^+ meq %	Ratio Na^+:K^+ meq%	Rock environment	Special local conditions
4 x)	Kyselka Lazne BJ 10 - spring Na- - HCO_3	71	1.82	358	15.6	2.0	7.8	8	metamorphic rocks	CO_2
5 x)	Korunni BJ 11 - spring Ca - Na - Mg - - HCO_3	20	0.51	59	2.6	0.7	6.1	5	metamorphic rocks	CO_2
6	Lazne Kynzvart S 2 - spring Ca - Mg - - HCO_3	5	0.13	23	1.0	1.4	0.8	8	granite metamorphic rocks	CO_2
7a	Marianske Lazne Balbin - spring Mg - Na - Ca - - HCO_3	18	0.47	154	6.7	1.9	2.0	14	metamorphic rocks	CO_2
7b x)	Marianske Lazne Antonicek - spring Ca - Mg - - HCO_3	6	0.14	36	1.6	1.5	0.8	11	metamorphic rocks	CO_2

Nr.	Locality Spring Type of water	K^+ mg l^{-1}	K^+ meq l^{-1}	Na^+ mg l^{-1}	Na^+ meq l^{-1}	TDS g l^{-1}	K^+ meq %	Ratio Na^+:K^+ meq%	Rock environment	Special local conditions
8 x)	Podebrady Lazne BJ 11 - spring Na - Ca - - HCO_3 - Cl	66	1.68	567	24.6	3.4	3.7	15	cretaceous chalky claystone	CO_2
9a x)	Brvany BV 5 - spring Na - Ca - Mg - - HCO_3 - SO_4	61	1.57	333	14.5	2.5	4.7	9	cretaceous chalky claystone	CO_2
9b x)	Brvany BV 1 - spring Ca - Na - Mg - - HCO_3 - SO_4	56	1.44	206	9.0	2.1	5.0	6	cretaceous chalky claystone	CO_2
10	Teplice L. v C. TP 41 - spring Na - Ca - - HCO_3 - SO_4	10	0.25	177	7.7	0.9	2.2	31	permian quartzite cretaceous chalky claystone	T : 46° C
11 x)	Bilina BJ 6 - spring Na - - HCO_3	93	2.39	1836	79.9	7.6	2.5	33	metamorphic rocks cretaceous chalky claystone	CO_2

Nr.	Locality Spring Type of water	K^+ mg l^{-1}	K^+ meq l^{-1}	Na^+ mg l^{-1}	Na^+ meq l^{-1}	TDS g l^{-1}	K^+ meq %	Ratio Na^+:K^+ meq%	Rock environment	Special local conditions
12a x)	Luhacovice L. Vincentka - spring Na - - HCO_3 - Cl	108	2.76	1966	85.5	7.9	2.7	31	old tertiary clays and sands	CO_2 participation of relict salt waters
12b	Luhacovice L. BJ 26 - spring Na - - HCO_3 - Cl	81	2.06	1483	64.5	5.9	2.7	31	old tertiary clays and sands	CO_2 participation of relict salt waters
13	Hodonin Lazne Josefov - 1 - spring Na - - Cl (+ J^-)	59	1.51	4906	213.4	13.8	0.7	141	young tertiary clays and sands	relict salt waters - borehole 2150 m
14	Darkov Lazne NP 744 - spring Na - - Cl (+ J^-)	141	3.60	13607	591.9	41.0	0.5	164	young tertiary clays and sands	relict salt waters - borehole 700 m
15 x)	Saratica springs Mg - Na - - SO_4	102	2.60	3524	153.3	28.1	0.6	59	tertiary chalky clays with pyrite	free H_2SO_4 from pyrite + evaporation (shallow wells)

Nr.	Locality Spring Type of water	K^+ mg l^{-1}	K^+ meq l^{-1}	Na^+ mg l^{-1}	Na^+ meq l^{-1}	TDS g l^{-1}	K^+ meq%	Ratio Na^+:K^+ meq%	Rock environment	Special local conditions
16 x)	Zajecice S 8 - spring Mg - - SO_4	83	2.12	757	32.9	18.1	0.7	16	cretaceous chalky clays and claystones with pyrite	free H_2SO_4 from pyrite + evaporation (shallow wells)
17a	River "Labe" in Bohemian Massif at Lovosice - town	4.4	0.11	9.7	0.42	0.21		3.8	(in the year 1892 A.D.)	(T. Paces, 1983)
17b	River "Labe" in Bohemian Massif at Lovosice - town	7.7	0.20	34.6	1.50	0.38		7.5	(in the year 1976 A.D.) - progressive influence of human activities	(T. Paces, 1983)
18	Sea - water	380	9.72	10561	459.2	35.0		47	(diameter)	(H.J. Rösler - H. Lange, 1965)

Explanatory note : x) = Mineral waters bottled for table or currative use.

Composition of Deep-Well Water and Hydroponics

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Abstract

Most water resources in Israel contain high concentrations of dissolved salts, beyond the level suitable for hydroponics. Dedicated techniques were developed to by-pass this limitation.

Underground water constitutes two thirds of the water potential of Israel. Generally, the quality of the underground water is better than that of the surface water and deep-well water is favored over surface water in soilless culture. Chemically active media are preferred in hydroponic culture. They provide buffer capacity, moderate fluctuations in ion composition and improve the tolerance of plants to salinity.

Open systems are favored over the closed ones. Recirculation of the nutrient solution in close systems may increase salt concentration to detrimental level.

Roses and tomatoes were chosen to demonstrate the effect of water composition on hydroponics.

Introduction

Agriculture in Israel has to cope with severe shortage of land and water. The total arable land is 450,000 ha. and the estimated annual water potential is of roughly 2 billion m^3 (Goldberger, 1992). Rainfall is restricted to six months in the winter, from November to April. The annual rainfall varies from 800 mm in the north to 30 in the south. Half of the country is arid with annual precipitation less than 200 mm. Only one half of the arable land is irrigated. Despite these constraints, Israel is self-sufficient in fresh fruit and vegetable production. The export of agricultural commodities offsets the cost of imported products like grains, fodder and meat.

Population growth and the rise in the standard of living, has increased water demand by the urban population and decreased the available water amount for agriculture. The expansion of intensive greenhouse agriculture is the only way to guarantee adequate standard of living for farmers, steady supply of fresh food to the local market and profitable export of high quality agricultural products.

The advantages of the controlled environment in greenhouses can be fully exploited by the optimization of the air-water relations and the chemical composition of the nutrient solution in the root-zone. Such optimization can be achieved only in soilless culture.

Two factors impede wide-scale utilization of hydroponics in Israel: the high cost of the investment required and the low quality of the water.

Definitions

Soilless culture means the growing of plants in nutrient solution - water containing dissolved chemical elements which are essential to plant growth and development.

The soilless system may be "open" or "close".

In open systems the solution is not recovered, excess water is drained and poured out from the system.

In close systems, the solution is recovered and recirculated.

The plants grown in soilless culture have to be mechanically supported. The support can be limited to the stabilization of the shoot while the bare roots are immersed in the solution ("true hydroponics"). In another version the whole root system is anchored and develops in the solid medium.

The medium (substrate) may be natural, artificial or a mixture of both forms. The media can be inert or chemically-active.

Natural substrates are: sand, gravel, quartz, tuff (volcanic ash), coal ash, peat, sawdust and tree bark.

Artificial beds include rockwool, vermiculite, perlite and expanded plastic foam.

Rockwool, expanded plastic foam and perlite are regarded as inert materials.

Flushed sand, riverbed flint aggregates, basalt and granite gravel are slightly chemically active.

Volcanic tuff, calcareous gravel and vermiculite are further more active.

Organic materials like peat and compost are the most chemically active media in soilless culture.

The principal growing techniques of bare root plants (true hydroponics) are (Adam, 1985):

1. Deep Flowing System: plants are grown in long shallow pools and the nutrient solution is continuously aerated.

2. Nutrient Film Technique (NFT): plants are grown in a thin film of recirculating nutrient solution.
3. Aeroponics: the bare roots are continuously sprayed with oxygen-rich nutrient solution.
4. Ein Gedi System (EGS): combines the deep flowing technique with aeroponics.

The main advantages of hydroponics are as follows:
1. The chemical composition of the nutrient solution can be continuously measured and optimized.
2. Automatic regulation of water, air, nutrient supply and pH level.
3. No interference of soil properties with the uptake of the nutrients by the plants.
4. Feasibility of sterilization of the bed and the nutrient solution.
5. Avoiding water and nutrient losses by deep percolation.
6. Convenient harvest.
7. Full exploitation of the yield potential.

The main drawbacks of hydroponics are the high cost of investment needed, the complexity of operation and the limited number of crops suitable to profitable commercial hydroponics.

Water quality and hydroponics

The chemical composition of the water used may affect hydroponics in three ways:

1. Nutritional value: The economic value of the nutritional elements contained in the water, has generally little significance.
2. Interactions between the ions contained in the water and the applied fertilizers: Intervention in the uptake of nutrients and harmful elements by the plants and precipitation of insoluble salts from the solution.
3. Contribution to the salinity of the nutrient solution, either by increasing the Electrical Conductivity (EC) and the osmotic pressure or by specific detrimental elements.

The water supply system in Israel is organized as a country-wide integrated network. The majority of the water resources are located in the north of the country while more than half of the cultivated land is in the south. The backbone of the water supply system is the National Carrier, delivering water from the Sea of Galilee in the north to the Negev region in the south. On its way, the National Carrier supplies water to lands where local resources are low and collects excess water from other wells.

Underground water is the main source of water in Israel - two thirds of the total annual water potential. Underground water resources are distributed in seven regional basins. A significant fraction of the water is brackish (above 400 mg l^{-1} chloride).

Table 1. Natural water resources in Israel: annual potential in millions m^3 (Goldberger, 1992)

Basin	Total potential	Brackish water
SURFACE WATER		
Sea of Galilee	500	20
West of watershed	100	
East of watershed	90	
Total surface water	**690**	**20**
UNDERGROUND WATER		
Sea of Galilee Basin	140	
Western Galilee	150	15
Carmel	40	15
Yarkon - Taninim Basin	350	35
The Coastal Basin	340	40
The Eastern Mountains Basin	330	120
Negev and Arava	100	85
Total Underground water	**1 450**	**310**
Total water potential	**2 140**	**330**

Chemical composition of the water in the main underground aquifers

The two main underground aquifers in the Coastal Plain are the Rock Aquifer (Yarkon - Taninim) and the Coastal Aquifer. Two smaller aquifers extend to the north - the Western Galilee and the Carmel aquifers. Along the Coastal Plain, water is pumped from some 1500 wells. Well depth varies from 40 to 120 m., with some exceptions of depths up to 200 m. In the Western Galilee and the Gaza Strip exist some shallow wells, 10 - 40 m. deep.

The chemical composition of the water in the wells varies according to location, distance from the sea, depth and proximity to polluting sites like urban localities, garbage deposits and irrigated areas. The level of chloride (Cl) and nitrate (NO_3) in the underground water in the Coastal Plain Aquifers is increasing at 1-5 mg l^{-1} per year. This process is related to continuous dwindling of the aquifers due to overpumping, penetration of sea-water and deep saline layers from the bottom of the aquifers and percolation of excessive nitrogen (N) from agricultural land and urban areas (Magaritz, 1986).

The most important constituents of deep-well water in the Coastal Plain which may affect hydroponic culture, are: Bi-carbonate (HCO_3^-), chloride (Cl^-), calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^+), nitrate (NO_3^-) and sulfate (SO_4^{--}). Potassium (K) is found at low levels (1-10 mg l^{-1}) in the Coastal Plain aquifers. Phosphorous (P), ammonium (NH_4) and boron (B), exist in negligible concentrations.

Table 2. Levels of principal chemical constituents in underground water in the Coastal Plain of Israel (mg l^{-1}) (Ronen, 1978)

Sub-region	HCO_3^-	Cl^-	Ca^{++}	Mg^{++}	Na^+	NO_3^-	SO_4^{--}
Western Galilee	183-488	24-691	28-178	8-115	11-321	0-65	19-120
Carmel Coast	329-420	397-1407	108-218	42-93	193-701	0-62	67-221
Sharon	73-408	24-372	30-330	1-75	16-218	0-173	5-124
Shefela	152-457	21-1240	32-286	4-154	30-292	0-100	5-86
Negev	146-427	31-443	28-78	13-75	23-381	0-82	10-129

The Total Dissolved Salts (TDS) range is 200-2750 mg l^{-1}. Most of the wells fall within the range 500-1000 mg l^{-1}.

The EC range is 0.4-2.5 ds m^{-1}. The majority of the wells are included in the 0.6-1.25 ds/m. range.

The pH level is 7.0-8.2, with the great bulk of the wells being around the 7.5 value.

The K level is generally negligible (1-3 mg l^{-1}). In some dozens of wells its concentration amounts to 10-35 mg l^{-1}. These wells are located in urban areas, prone to water pollution and show a high level of NO_3.

More sources of deep-well water are spread in the peripheral zones. Many of them contain high concentrations of dissolved salts. In the upper Galilee, in the north, some wells have extremely low salt content (220-400 mg l^{-1}. TDS) (Tausig, 1976).

Hydroponics in Israel

Hydroponic systems irrigated by deep-well water are located mainly in the plains. The relatively high content of salts in the underground water, as well as in the surface water, called for the elaboration of suitable techniques to overcome this constraint.

The total area of protected crops in Israel in 1991, was roughly 2000 ha., located mainly in the Coastal Plain and in the Jordan Valley. About 600 ha. were grown on detached beds, the common term used for soilless culture. The main crops grown were tomatoes, cucumbers, strawberry, melons, roses, carnation, gypsophila, chrysanthemum and gerbera.

In some crops, yields on detached beds are much higher than in soil culture. In roses, record yields of more than 3 million flowers per ha. were achieved, comparing with 1-1.5 million, the common yields in soil culture. In tomatoes, 250-300 tons/ha. were harvested comparing with 100-120 in soil culture. The growing season for tomatoes in Israel is shorter than in Europe and the yield potential is not fully exploited (Avidan, 1991).

Water quality affected the development of hydroponics in Israel in two major aspects :

1. The majority of the growing systems are open. Closed systems are rare. In the process of recirculation of the nutrient solution in closed systems, salt concentration may increase to harmful degree.

2. Chemically active media are commonly preferred to the inert. Only few underground water resources correspond with the limits of ion concentration for rockwool culture, defined by Verwer and Wellham in 1980. Namely : 50-100 mg l^{-1} Cl, 30-50 mg l^{-1} Na and 40 mg l^{-1} HCO_3 (Adam, 1985). Chemically active beds moderate fluctuations in ion composition and pH level and increase plant tolerance of salinity. The addition of organic materials - peat and compost, further increases the buffer capacity and enhances the tolerance of the plants to root diseases.

The leading growing bed in hydroponics in Israel is the volcanic tuff. It is composed of porous aggregates of volcanic ash. The apparent density is 0.75-0.85 while the specific density of the compressed material is 2.8. The porosity is 65%-75% by volume. After irrigation, granular unweathered tuff holds 300-400 ml. water and 300-350 ml. air in 1 l. volume of the substrate. Most of the water, some 85%-90% is retained at low tension, under 0.5 bar. That provides optimal balance between air and water in the root-zone and a large amount of low-tension available water (Dan, 1989).

The Cation Exchange Capacity (CEC) of unweathered tuff is roughly 5 meq 10^2 g^{-1}. of substrate. In due time, the tuff gradually weathers and the CEC may amount to 25 meq 10^2 g^{-1}. The main cations absorbed by the tuff are: Ca^{++}, Mg^{++} and K^+. Phosphate is also absorbed.

Rockwool culture is used on a smaller scale, some 60 ha., mainly for the growing of roses. Preliminary work has been started with tomatoes but the results are not yet satisfactory. The low water quality commits high ratio of leaching and has environmental implications of the removal of the drainage solution.

In the usual bed layout the substrate is contained in expanded polystyrene trays, 10-20 cm. deep.

Another widespread layout is V-shaped trenches dug in the soil. The bed is isolated from the soil by polyethylene sheets. Adequate drainage is achieved by the V-shaped bottom and longitudinal slope of 1.5-3%.

Hydroponic culture in bags and small pots is common in nurseries. The media are composed of tuff or perlite mixed with organic substances.

The Vertical Column Technique is another interesting growing method used on a limited scale. The column is composed of conical plastic pots, 15-20 cm. in diameter, laid one above another. The medium is a mixture of perlite and vermiculite. This composition provides light weight, good balance between air and water and good nutrient retention. Water flow through the column is continuous and the excess solution is collected in the bottom of the column and recirculated. In the process of recirculation, the composition of the nutrients and the pH level are adjusted. The solution is tested for the presence of pathogens and can be sterilized by heating (Orlov, 1990,1991).

Nutrient Film Technique (NFT) and aeroponics are only rarely used. The Ein Gedi System (EGS) which combines Deep Flowing Technique and aeroponics, is not popular, due to the complexity of operation and its sensitivity to malfunction.

Roses and tomatoes were chosen to demonstrate the effect of deep-well water composition on hydroponics in Israel.

Growing of roses in hydroponic culture

Roses are grown in different regions in Israel. The highest yields are achieved in the south of the country, due to high sun radiation and low cloudiness in winter, the profitable season for export. Unfortunately in this region, many of the local underground water resources are brackish (above 400 mg l^{-1} Cl) and are not suitable for roses. The Cl level in the National Carrier water supplied in this region is 250-300 mg l^{-1}. Yield and flower quality decrease when the Cl level in the water exceeds 150 mg l^{-1} and the EC exceeds 1 decisiemens/meter (ds m^{-1}). Some growers use water from local underground sources with high concentration of Cl and EC levels up to 2 ds m^{-1}.

Table 3. Typical nutrient concentration in a nutrient solution for roses - mg l^{-1} (Avidan, 1991)

Nutrient	N	P	K	Ca	Mg	Fe	Mn
Concentration	120-200	35-50	150-200	100-150	50-100	0.05	0.1

The influence of individual constituents

Nitrogen

The N concentration in the water is taken into account in making up the nutrient solution. It may amount to 20% of the required level in the solution. All the N in deep-well water is in the NO_3 form. The optimal ratio N-NO_3:N-NH_4 in the nutrient solution is 5:1-10:1, depending on bed temperature, the phenological stage and the content of the other ions in the solution (Zachs, 1991).

Potassium

The low concentration of K in deep-well water is ignored in making up the nutrient solution.

Calcium

Ca application is uncommon in soil culture in Israel due to the relatively high content of this element in the soil and the irrigation water. In roses grown on sand dunes and detached beds, severe deficiencies of Ca have been identified. Experimental work has shown that when the rate of water absorption by the plant is low, the Ca uptake is deficient. Low water absorption occurs in winter, when the transpiration rate is low and in events of heat stress. In these circumstances, the Ca supply in the nutrient solution has to be increased, considering the content of Ca in the supplied water. Complementary treatments of foliar nutrition with calcium-nitrate ($Ca(NO_3)_2$) are recommended. The reaction to increased supply of Ca in the nutrient solution is more pronounced when the $N\text{-}NO_3:N\text{-}NH_4$ ratio is higher than 8:1 (Zachs, 1991).

Magnesium

The Mg content in most deep-well water in the Coastal Plain does not fulfill the roses' demand. High K and NH_4 level in the nutrient solution depresses the uptake of Mg. Mg deficiency is characterized by typical chlorosis in the older leaves. As with Ca, the addition of Mg to the nutrient solution, is not enough to correct severe deficiencies. Foliar spraying with magnesium nitrate ($Mg(NO_3)_2$) is the complementary treatment.

Bi-carbonate

The HCO_3 concentration in deep-well water is a key-factor in the regulation of the pH-level in the nutrient solution. Deep-well water in Israel contains much HCO_3, in comparison with underground water in Western Europe. This difference contributed to failures in the adoption of the European growing schemes in soilless culture in Israel in the past. Due to the high HCO_3 concentration, the pH-level of deep-well water in Israel is 7-8.2. To adjust the pH-level to 6, the optimal value for rose culture, the concentration of the HCO_3 in the nutrient solution has to be reduced to 50 mg l^{-1}. The neutralization of the HCO_3 is accomplished by acidification with H_3PO_4, H_2SO_4 and HNO_3. The ratio between the different acids is determined by water composition and plant nutrition demand (Elad, 1990).

Chloride

The high level of Cl in irrigation water induces non-uniform chlorosis and typical leaf-burns. The stems grow shorter and the flowers are smaller. A comparative survey in the Jezreel Valley, indicated a 20% decrease in yields when the water contained 300 mg l^{-1} of Cl, compared with water containing 200 mg l^{-1}. An adjusted irrigation and fertilization regime can decrease Cl damage. Watering has to be done at short intervals, the level of the N has to be kept higher and the ratio N-NO_3:N-NH_4, has to be kept above 8:1. The high NO_3 concentration depresses Cl uptake.

The use of Cl-rich water in rose culture leads to high drainage. Growing roses on detached beds, requires watering with excess water, above the crop consumption. Differential absorption of water and chemicals by the plant, as well as losses of water by evaporation, cause continuous increase in ion concentration and in the EC of the nutrient solution. The only way to prevent damage to the crop is by the drainage of the concentrated solution. Since Cl is one of the most detrimental ions, the higher the level in the supplied water, the higher will be the required drainage ratio. In roses grown on tuff beds, a Cl concentration of 150 mg l^{-1} in water, necessitates drainage ratio of 25%, while a level of 200 mg l^{-1} increases the ratio to 35%-50% (depending on other constituents in the solution) (Schwartz, 1968; Avidan, 1991).

Sodium

Na is another detrimental ion existing in deep-well water. The ratio of Na:Ci in deep-well water varies from 1:1.25 to 1:3. Increasing the supply of K and Ca in the nutrient solution, decreases Na uptake. In extreme cases of exceptionally high level of Na in the water, the water is treated by ion-exchange. KNO_3 is used to exchange Na^+ ions with K^+. The system is experimental, some technical problems were encountered but the results are quite satisfactory.

Sulfur

The S requirement of roses is low, compared with other macronutrients. In soil culture, superphosphates and ammonium sulfate ($(NH_4)_2SO_4$), applied in preplant treatments, provide enough S to fulfill the crop demand. In soilless culture, S deficiencies were observed in roses grown on rockwool and irrigated with water extremely low in S. The S content of the water is taken into consideration when applying acids for acidification.

The Electrical Conductivity (EC)

Apart from the effect of specific ions, roses are sensitive to excessive total dissolved salts (TDS). The TDS is indirectly measured and expressed by the EC. The contribution to the increase in the EC value of the nutrient solution by the added fertilizers is 0.75-1.25 ds m^{-1}. The cumulative EC of the supply water and the dissolved fertilizers, determines the required drainage ratio. EC of 2 ds m^{-1} in the nutrient solution, requires 25% drainage while a cumulative EC of 3 ds m^{-1}, may increase drainage ratio to 50%. The drainage solution is measured and analyzed for EC and ionic composition. An increase of more than 25% in the Cl level in the drainage solution, above the level in the supply water, indicates a too low drainage ratio.

A high salt level in the water enhances the occurrence of iron (Fe) deficiencies and higher applications of Fe fertilizers have to be given (Mor, 1991).

Growing of tomatoes in hydroponic culture

Tomatoes are more resistant to salinity than roses. Profitable yields were achieved in soilless culture in EC level of 6 ds m^{-1} in the water. Salinity affects yield, fruit size and fruit quality. Yield at EC of 4 ds m^{-1}, is 10%-15% lower than at an EC of 3 and the fruits are somewhat smaller.

Fruit quality of plants irrigated with brackish water is higher snd the tomatoes are tastier, more solid, contain more sugar and have longer shelf-life. The breeding of high-quality tomato varieties for export, facilitates the choice of those with bigger fruits to be grown with brackish water when the decrease in fruit size can be regarded as desirable. (Schwartz, 1968; Asaf, 1990).

Table 4. Typical nutrient concentration in a nutrient solution for tomatoes - mg l^{-1} (Asaf, 1990)

Nutrient	N	P	K	Ca	Mg	Fe	Mn
Concentration	160-250	40-60	250-400	100-150	50-80	0.05	0.1

The influence of individual constituents

Nitrogen

The N level required in the nutrient solution is higher than for roses. The favorable ratio of $N\text{-}NO_3$:$N\text{-}NH_4$ is 5:1-10:1. The NO_3 concentration in the supplied water is taken into account in the composition of the nutrient solution (Dayan, 1990).

Potassium

Tomatoes consume significantly more K than roses. An adequate K supply is particularly important during the harvest season. The low content of K in the water is not taken into consideration in the composition of the nutrient solution. In Cl-rich water, KNO_3 is the preferred fertilizer while in Cl-low water, KCl is applied without detrimental effects.

Calcium

Tomatoes are sensitive to disturbances in Ca supply. In the winter season and when heat stress occurs, Ca transfer in the plant lags behind the demand of the biochemically-active sinks. This phenomenon causes blossom end rot. In these circumstances, increase in Ca concentration in the nutrient solution is needed, as well as complementary foliar sprays.

Magnesium

An adequate Mg supply is essential when growing tomatoes on soilless culture. Since the level of Mg in the underground water varies widely, growers are encouraged to check the Mg content in the water and to adjust the Mg supply. Mg deficiency is induced by abundant fertilization with fertilizers containing K and NH_4. Mg deficiency symptoms appear on the old leaves, towards the beginning of the fruit ripening season. Mg applications have to be prophylactic. The increase in Mg supply in the nutrient solution and the complementary foliar treatments with $Mg(NO_3)_2$ have to be applied before the appearance of the deficiency symptoms on the leaves.

Sulfur

In S-low water, H_2SO_4 is applied as the major constituent of the acidifying solution. High S concentrations in the water enhances the uptake of Na by the plants while no damage to the yield was observed.

Microelements

Tomatoes are less sensitive than roses to Fe and Mn deficiencies but when using brackish water; Fe supply has to be increased. High applications of P may induce Zn deficiencies.

EC

The optimal EC of the nutrient solution is 3-4 ds m^{-1}. At lower EC values, fruits are inferior in taste and length of shelf-life. When EC values are higher than 4 ds m^{-1}, the drainage ratio has to be increased to 25% or more (Asaf, 1990).

Conclusions

The chemical composition of deep-well water in Israel directed the development of hydroponics in different path than that in countries owning high-quality water resources. Growing schemes were developed in order to enable the use in hydroponics of waters that were regarded as unsuitable to this culture. It will no doubt have implications on the pattern of the development of hydroponics in the future.

The growing demand for high-quality agricultural commodities, the deterioration in the quality of water resources and the higher awareness of environmental issues, call for the elaboration of new techniques that will enable the expansion of hydroponics beyond its contemporary limited extent.

The customary open systems threaten to pollute the underground aquifers and surface water bodies. The main contaminant is N because of its fast percolation and movement in the soil. The cations like Ca, Mg and K, are significantly less mobile. At the moment there is no proven evidence of hazard to human health from the existence of these cations in drinking water. Cl affects the quality of the water in the aquifers for irrigation and excessive Na may damage soil structure. In the future, the environmental pressure will enforce the use of only close recirculating systems with adequate arrangements for drainage removal.

Collecting of rain-water runoff from greenhouse roofs, now in preliminary examination, may enable the refreshing and recirculation of low-quality drainage water. Local desalination by reverse osmosis is economically feasible for high-value crops. This technology will enable the recirculation of water in close systems at an affordable cost.

In some circumstances the desalination of sea-water, despite the high costs of this technique, will be the only way to make soilless agriculture profitable.

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Coordinator's Report on Session 2

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The use of the ecosystem-watershed concept has been most fruitful during the last thirty years since it was initiated in the United States.

Many results have been obtained by this approach on the biogeochemical cycles of nutrients especially in forest ecosystems. This is because the streamflow mirrors the processes occurring in the ecosystem as a whole through seasonal changes of its composition. The processes will be reflected more closely if most of the water movement occurs through subsurface flow with little loss through the unsaturated zone towards ground water.

The presentation of Hagedorn on "Size of minimal catchment area for drinking water as influenced by climate and population size" is an interesting summary of the hydrological concepts necessary for the study of a watershed-ecosystem irrespective of the aims of the investigation. This paper is a very clear demonstration that the study of watersheds may yield indispensable information not only for the understanding of biogeochemical cycles in relation to the sustainability of forest ecosystems but also for the highly practical problem of finding reliable water supplies for urban regions.

The communication of Johnston and Goulding has extended the application of this type of study to agro-ecosystems in relation to the biogeochemical cycle of K in these systems with emphasis on the possible leakage of K towards ground water. They suggested a useful rule of thumb according to which for each 100 mm of drainage about 1 kg ha^{-1} K would be lost.

In spite of the unrealistically low level of K in drinking water which has been set by the EEC's Drinking Water Directive, it is unlikely that this level will ever be exceeded from losses by agroecosystems due to the great capacity of most soils to retain K and the comparatively low level of K manuring.

In countries where mineral waters are of great economic importance, monitoring their composition is an interesting subject as done by Dvořák for the mineral waters in Czechoslovakia, a country in which their use for health purposes has been known for centuries.

Sne's study dealt with the use of underground water for hydroponics in Israel despite its concentration of dissolved salts, though this is better than that of surface water. Problems bound to concentration of salts and soil contamination by used water are solved by recirculating the nutrient solution.

Most of the above aspects, from the abundance of K in igneous rocks and the weathering of K bearing minerals to K in the hydrological cycle including input of minerals by precipitation and their interception by the forest canopy, were comprehensively treated by Nativ.

Chairman of the Session 3

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Session 3

K in the Food Chain

Potassium in Human Nutrition

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Summary

The K requirement of animals amounts to 5 to 7 g/kg ration dry matter, adults should consume 2 g K daily.

The analysis of 108 and 126 foodstuffs and beverages in nine- and sixfold repetition allows the determination of their K content in the case of a local (1988) and a European offer of foodstuffs and beverages (1991). It was demonstrated that e.g. white cabbage, tomatoes and cucumbers contained highly significantly more K in 1991 than in 1988 (cucumbers 130 g/kg DM). Several other foodstuffs (e.g. meat, sausage, bread, confectionery, farinaceous products) too, were significantly K-richer in 1991 than in 1988. This is due to the fact that the cooking salt of the former GDR contained 15, that of Germany contained and contains 68 g K/kg.

Mondamin, sugar, semolina, flour, vanilla pudding, candies, mixed mushrooms, margarine, butter and several kinds of cheese proved to be particularly K-poor (< 2 g K/kg DM). White beans, most spices, coffee, cocoa, black tea, oranges, kiwi, lemons, bananas, many kinds of vegetables and milk deliver more than 15 g K/kg DM.

The K intake of women and men was only insignificantly increased (4 and 6 %, resp.) by the transition from the local offer of foodstuffs and beverages in 1988 to the European offer in 1991. This increased K consumption might result from the higher K content in the cooking salt.

On an average, the K intake of men and women amounted to > 2 g/day. Thus, the consumption is assumed to meet the requirements.

Women and men excreted 85 % of the K renally and 15 % faecally. On the average, the K balance of women was slightly negative, that of men was well-balanced with - 3 %.

The comparison of the K consumption with the duplicate method and the basket method showed that the calculated K consumption of women was by 20 % higher and that of men by 25 % higher in both test years than

the K intake registered analytically with the duplicate method. The reasons are discussed.

Neither K deficiency nor K excess were found for humans in Central Europe.

1. Introduction

The K requirement of mammals and birds amounts to 5 - 7 g/kg ration dry matter (Anke, 1988) and is regularly met via feedstuffs or grazing (Anke *et al.*, 1990). The K requirement of humans is not exactly known. In the USA (anonymous, 1980) and Germany (anonymous, 1991), a daily K consumption of 1875 to 5625 mg or < 2000 mg/day is regarded as meeting the requirements of adults.

In contrast to herbivores, a potential K excess is unusual in humans; there seems to be rather the danger of K deficiency. In India and Taiwan, a K consumption of 500 and 1029 and 1350 mg/day, resp., was registered in adults (Parr and Crawley, 1989). For these reasons, the K intake of adults in the new states of Germany was investigated with the basket and the duplicate method both in 1988 with the local production of vegetables, meat and dairy products and in 1991 with a European offer of foodstuffs and beverages. The K excretion of two test populations served as control. Thus, it was possible to calculate the K balance of adults.

Furthermore, this kind of experiments made it possible to compare the results of the basket method, which calculates the K intake, with those of the duplicate method, which measures the K intake during seven days, and to draw conclusions about the exactness of both procedures.

2. Material and methods

The analysis of the K content of foodstuffs and beverages was carried out by means of 108 foodstuffs typical of the former GDR. They were bought in Jena, Weimar, Leipzig, Berlin (twice), Potsdam, Greifswald, Stralsund and Rostock in June and July, 1988. After the reunification of Germany, 126 foodstuffs and beverages were collected in sixfold repetition in Erfurt, Dresden, Magdeburg, Schwerin, Potsdam and Berlin and analyzed. The K content of the foodstuffs was summed when there was no difference between the samples of 1988 and 1991. The foodstuffs and beverages marked with * were only analyzed in 1988, those marked with ** only in 1991.

In 1988, the investigation of the K intake of adults was carried out in four test populations from Brandenburg (Wusterhausen, Vetschau) and Thuringia (Bad Langensalza, Jena), each consisting of 7 women and men between 20 and 60 years of age. In 1991, after the reunification of Germany, the same analyses were carried out according to the same scheme in another four test populations from Bad Liebenstein and Bad Langensalza (Thuringia), Wusterhausen (Brandenburg) and Greifswald (Mecklenburg-Western Pomerania). On 7 subsequent days, 56 test persons collected all individually consumed foodstuffs and beverages every day (duplicate method). The fruit, sweets, chocolate and beverages consumed in the leisure time, during gardening and sports activities were also collected and added to the daily sample.

The individual samples of each healthy test person of the seven experimental days were analyzed. Thus, it was possible to determine both the weekly and the daily consumption. The collected samples of each day (foodstuffs and beverages) were weighed, frozen in closed plastic bags or vessels at -20°C and afterwards the K content was determined apart from the dry matter.

The comparison of the K intake of men and women with the duplicate and the basket method was carried out according to the procedure described by Müller *et al.* (1991).

It was possible to register the K excretion via urine and faeces in women and men from Bad Liebenstein and Bad Langensalza in 1991. The urine and the faeces of these 28 persons were collected daily and analyzed individually. All samples were dried to constant weight at 105°C. The foodstuffs were raw and ready for use in the kitchen. After dry ashing of the samples at 450°C, K was determined flame photometrically. The K concentrations are either related to dry matter (DM) or to fresh matter (FM).

3. Results

3.1. Potassium content of foodstuffs and beverages

The K content of all investigated foodstuffs was not subjected to such variations as their Na content since it is not essentially changed by "salting" (Anke *et al.*, 1990).

The K concentration of "cereals" is low apart from flour for dumplings and leguminous seeds (Table 1). The starch-rich cornflour and maize flour proved to be particularly K-poor. Semolina, rice, wheat flour, pearl barley, oatflakes and oat pulp contained 1.6 to 5.3 g K/kg DM, whereas flour for dumplings, lentils, peas and white beans stored 10 to 18 g K/kg DM.

Table 1. Potassium content of several cereals in mg/100 g edible percentage (FM) or in g/kg DM

Kind	DM	mg/100 g FM	g/kg DM	
	%	$\bar{x}$	$\bar{x}$	s
cornflour**	87,4	6	0,07	0,02
maize flour*	88,4	10	0,11	0,06
whole wheat flour*	88,9	16	0,18	0,04
semolina (1991)	88,8	29	0,32	0,43
semolina (1988)	86,0	134	1,56	0,19
rice	87,7	143	1,63	0,89
wheat flour	85,5	152	1,78	0,35
pancake wheat	88,6	304	3,43	0,57
pearl barley	88,2	288	3,27	0,79
oatflakes	88,5	419	4,73	1,03
oat pulp	89,2	557	6,25	3,83
flour for dumplings	88,1	947	10,74	1,79
lentils**	87,3	1071	12,27	0,31
peas, peeled	89,3	1322	14,81	1,34
white beans	88,3	1547	17,53	1,36

Apart from the flour for pancakes and dumplings, which got their high Na content by NaCl supplementation, the investigated cereals stored considerably more K than Na (Anke *et al.*, 1990). The K content of bread and confectionery (Table 2) only varied between 2 and 6 g/kg DM and thus corresponded with its Na content (Anke *et al.*, 1990). Crisp-bread and coarse-grained whole-meal bread mainly produced of rye grain ground very little stored the most K. Both kinds of bread delivered 6 g K/kg DM. K exposure of humans via bread and confectionery need not be reckoned with.

The K content of sugar, vanilla pudding, synthetic and bee honey is extremely low with <1 g/kg DM (Table 3), that of vermicellis and macaronis corresponds with the K content of wheat flour. Depending on the kind of fruit, the different sorts of jam contained considerably varying K concentrations, which, however, did not exceed 4 g/kg DM on an average. The high K content of chocolate spread for bread and chocolate pudding only results from the rich K content of cocoa (Table 5). The high

K content of ready-to-serve soups is due to their vegetable supplements (Table 7).

Table 2. Potassium content of several kinds of bread and cake in mg/100 g edible percentage (FM) or in g/kg DM

Kind	DM	mg/100 g FM	g/kg DM	
	%	$\bar{x}$	$\bar{x}$	s
thin sponge cake with crumble topping	81,0	142	1,8	0,6
sponge cake	76,6	148	1,9	0,8
cornflakes **	96,6	204	2,1	0,7
biscuits	97,0	242	2,5	0,6
rusk	94,0	266	2,8	0,5
rolls	75,8	218	2,9	0,3
toasted bread	67,5	213	3,2	1,2
white bread**	63,5	213	3,4	0,1
cake with egg topping	37,2	141	3,8	1,3
wheat and rye bread	62,4	256	4,1	0,5
coarse-grained wholemeal rye bread**	53,9	329	6,1	0,9
crispbread	93,8	582	6,2	0,8

Table 3. Potassium content of sugar, honey, puddings, several farinaceous products and ready-to-serve soups in mg/100 g edible percentage (FM) or in g/kg DM

Kind	DM	mg/100 g FM	g/kg DM	
	%	$\bar{x}$	$\bar{x}$	s
sugar	98,9	6	0,06	0,04
vanilla pudding	86,4	18	0,20	0,13
synthetic honey*	75,2	21	0,28	0,23
bee honey**	71,0	62	0,88	0,17
vermicellis	89,9	191	2,12	0,69
jam	55,5	121	2,18	1,85
macaroni	87,1	238	2,73	0,99
chocolate spread for bread**	95,7	417	4,36	1,70
chocolate pudding	87,0	594	6,83	1,84
ready-to-serve soups	89,5	810	9,05	3,11

Unlike farinaceous products, all spices are K-rich (Table 4).

Apart from cooking salt, however, their K content does not take effect on the K intake of humans since they are only consumed in tiny amounts.

Cinnamon contained the least K with 6.4 g K/kg DM whereas caraway seeds, mustard, pepper, marjoram and particularly sweet and strong paprika delivered between 14 and 30 g K/kg DM.

The K content of cooking salt differed significantly between 1988 and 1991 (Table 4). The cooking salt in 1991 was much K-richer than that of the GDR production. The iodine-poor "Sanisal" of the GDR contained about the twofold K amount of the cooking salt of the former GDR.

The K content of luxury food varies considerably depending on its sugar and milk content (Table 5). On an average, candies, chocolate cream and milk chocolate contained between 1.5 and 6 g/kg DM whereas cocoa, coffee and black tea delivered much more K with 18 to 22 g/kg DM.

Table 4. Potassium content of several spices in mg/100 g edible percentage (FM) or in g/kg DM

Kind	DM	mg/100 g FM	g/kg DM	
	%	$\bar{x}$	$\bar{x}$	s
pepper (1991)	85,8	281	3,3	5,0
cinnamon	87,7	561	6,4	1,0
mustard seeds	92,9	797	8,6	0,7
caraway	90,9	1271	14,0	1,3
mustard	25,3	354	14,0	8,4
cooking salt (1988)	100,0	1479	14,8	4,1
pepper (1988)	90,7	1787	19,7	2,6
marjoram	87,1	2198	25,2	6,6
paprika, sweet	87,6	2698	30,8	5,1
paprika, strong	88,2	2715	30,8	5,8
"Sanisal"*	100,0	3260	32,6	9,0
cooking salt (1991)	100,0	6837	68,4	6,3

Table 5. Potassium content of several luxury foods in mg/100 g edible percentage (FM) or in g/kg DM

Kind	DM	mg/100 g FM	g/kg DM	
g/kg DM	%	$\bar{x}$	$\bar{x}$	s
candies	96,4	152	1,6	0,6
chocolate cream	93,4	398	4,3	0,4
milk chocolate	95,1	573	6,0	1,0
cocoa (1991)	88,1	1009	11,5	1,3
coffee	96,2	2039	21,2	1,0
cocoa (1988)	92,4	2008	21,7	2,3
black tea	93,3	2025	21,7	2,0

The K concentrations of different fruits (Table 6) varied from 8 to 25 g/kg DM between the different sorts tested. On an average, pineapples, apples and pears contained > 10 g K/kg DM whereas oranges, kiwi, bananas and lemons accumulated between 18 and 24 g K/kg DM.

The K content of different kinds of vegetables is subjected to the greatest variation of all investigated foodstuffs (Table 7).

Mixed mushrooms stored least K. Cultivated champignons and green peas already contained between 13 and 19 g K/kg DM whereas chives, red cabbage and sauerkraut accumulated between 20 and 30 g K/kg DM. Carrots, asparagus, dill, cauliflower, parsley and dwarf beans contained between 35 and 75 g K/kg DM. In 1991, kohlrabi and cucumbers accumulated the most K with 105 and 130 g/kg DM, resp.

Table 6. Potassium content of different fruits in mg/100 g edible percentage (FM) or in g/kg DM

Kind	DM	mg/100 g FM	g/kg DM	
	%	$\bar{x}$	$\bar{x}$	s
pineapple**	13,4	100	7,4	2,1
apple purree	14,7	131	8,9	1,6
pear**	12,2	136	11,2	2,8
apple	12,1	137	11,4	2,2
orange	13,5	241	17,9	4,9
kiwi**	15,9	333	21,0	2,4
lemon	10,1	240	23,8	5,2
banana**	18,4	448	24,4	2,8

If humans consume cucumbers, kohlrabi, lettuce and white cabbage, their K intake via vegetables can be enormous.
There was a significant difference between the K content of white cabbage, lettuce, kohlrabi and cucumbers in 1988 and 1991. In 1988, the vegetables mentioned above were produced locally in the living areas of the test regions. In 1991, white cabbage, lettuce, kohlrabi and cucumbers came from Western Europe when the samples were collected and had a high K content, perhaps to keep their nitrate content below the limit value.

Table 7. Potassium content of several kinds of vegetables in mg/100 g edible percentage (FM) or in g/kg DM

Kind	DM	mg/100 g FM	g/kg DM	
	%	$\bar{x}$	$\bar{x}$	s
mixed mushrooms**	6,0	8	1,3	0,5
peas, green	21,8	248	11,4	2,6
champignons**	5,2	101	19,4	5,3
chives	10,6	275	26,0	10,9
white cabbage (1988)	9,8	262	26,7	5,1
sauerkraut	7,8	225	28,9	8,5
red cabbage	9,2	273	29,8	12,3
potatoes	18,3	552	30,2	4,5
lettuce (1988)	6,0	192	32,0	5,2
carrots, tinned	6,4	232	36,1	10,8
carrots, fresh	7,0	266	37,7	12,3
asparagus**	4,6	197	42,9	11,8
sauerkraut, tinned*	9,7	436	45,0	21,3
dill	10,0	483	48,3	12,8
parsley	17,8	933	52,6	15,2
dwarf beans, tinned	6,7	359	53,7	36,9
tomatoes	5,8	319	54,9	13,3
kohlrabi (1988)	11,4	650	57,0	16,4
white cabbage (1991)	8,0	528	66,1	25,3
cucumbers (1988)	5,2	372	71,5	9,6
cauliflower**	8,0	603	75,4	15,0
kohlrabi (1991)	9,0	943	104,8	20,1
lettuce (1991)	7,3	930	127,4	21,2
cucumbers (1991)	5,2	678	130,4	13,7

Compared to vegetables, the K content of animal foodstuffs is low. Apart from milk and yoghurt, dairy products contained between 0.2 and 6 g K/kg DM (Table 8).

As demonstrated by the K content of margarine and butter, plant and milk fat is generally K-poor.

Table 8. Potassium content of several dairy products and milk in mg/100 g edible percentage (FM) or in g/kg DM

Kind	DM	mg/100 g FM	g/kg DM	
	%	$\bar{x}$	$\bar{x}$	s
margarine	77,0	12	0,15	0,07
butter (1991)	84,8	33	0,39	0,17
butter (1988)	47,9	74	1,54	0,38
Emmental cheese**	62,6	103	1,65	0,49
Edam cheese*	55,0	121	2,20	0,50
Gouda cheese	57,4	129	2,24	0,48
Tilsit cheese**	56,8	135	2,37	1,40
Tollenser*	55,2	166	3,00	0,25
Limburg cheese*	45,9	174	3,80	1,07
Camembert	45,6	178	3,91	0,62
goat's cheese*	47,9	227	4,74	0,65
soft cheese	42,4	236	5,55	2,86
curds	18,5	115	6,19	1,02
yoghurt**	17,7	178	10,08	5,20
condensed milk	20,2	368	18,25	2,59
milk	11,5	226	19,66	11,94

On an average, the different kinds of cheese contained between 1.6 and 5 g K/kg DM. Curds proved to be slightly K-richer. Related to DM, milk stores the most K with about 20 g/kg, the highest percentage of which leaves the dairy products via whey during milk and curd production.

The K content of several kinds of baby food, which were offered in the former GDR or in Germany, is summarized in Table 9.

Table 9. Potassium content of several baby foods in mg/100 g edible content (FM) or in g/kg DM

Kind	DM	mg/100 g FM	g/kg DM	
	%	$\bar{x}$	$\bar{x}$	s
Alete **	88,2	400	4,5	3,3
Manasan **	89,4	628	7,0	0,4
Ki-Na Neu	89,5	713	8,0	1,5
Hipp **	87,6	714	8,2	1,5
Milasan	91,0	743	8,2	0,6
Babysan	87,9	1074	13,4	2,6

The comparison shows that the K content of the different kinds of baby food differs highly significantly. The difference between the K content of Manasan and Babysan amounts to almost 10 g/kg DM. The K concentration of Alete and Hipp also showed a mean difference of 5 g/kg DM, which is probably due to the different kinds and amounts of vegetables and fruits used in this food.

Table 10. Potassium content of meat, offal, sausage and hen's eggs in mg/100 g edible portion (FM) or in g/kg DM

Kind	DM	mg/100 g FM	g/kg DM	
	%	$\bar{x}$	$\bar{x}$	s
salami (1988)	70,7	262	3,7	0,5
blood sausage	51,8	204	3,9	1,6
liver sausage	54,4	249	4,6	0,6
thick Frankfurter	44,9	249	5,5	1,1
hen's eggs	25,7	155	6,0	0,8
meat loaf**	45,8	303	6,6	1,3
mortadella**	41,2	282	6,8	0,7
liver, cattle (1988)	31,3	218	7,0	1,9
salami (1991)	55,6	469	8,4	1,9
pork (1988)	28,2	235	8,5	1,8
kidneys, cattle (1988)	26,6	245	9,2	4,0
liver, cattle (1991)	28,9	318	11,0	0,8
poultry meat	31,2	357	11,4	2,6
mutton	33,1	384	11,6	1,4
beef	27,2	368	13,5	1,5
kidneys, cattle (1991)	20,7	299	14,5	1,2
pork (1991)	27,6	413	15,0	3,0

The K content of sausage, meat and hen's eggs varies between 4 and 15 g/kg DM (Table 10). The different kinds of sausage contained between 4 g/kg DM (blood sausage) and 6.8 g/kg DM (mortadella). The K content of hen's eggs was also within this range.

In 1991, liver, kidneys and pork stored higher K concentrations than in 1988. Their significantly higher K content may result from the supplementation of the K-richer cooking salt. Offals and meat accumulated between 7 and 15 g K/kg DM.

The lower K content of the different kinds of sausage results from the high fat content of these foodstuffs. Fat only accumulates minimal K amounts.

Table 11. Potassium content of several kinds of fish and tinned fish in mg/100 g edible portion (FM) or in g/kg DM

Kind	DM	mg/100 g FM	g/kg DM	
	%	$\bar{x}$	$\bar{x}$	s
Bismarck herring**	28,7	93	3,2	1,6
fried herring**	30,1	213	7,1	1,4
herring fillet	30,7	259	8,4	4,0
mackerel fillet	36,9	352	9,5	5,7
sardines**	43,3	481	11,1	2,9
salted herring*	37,6	426	11,3	3,0
herring in tomatoes**	31,0	445	14,4	1,6
trout, fresh*	28,9	424	14,7	1,0
trout, smoked*	28,9	434	15,0	2,0
rosefish fillet**	23,6	387	16,4	1,6

The K content of fish and several kinds of tinned fish is varied by their mean oil and vegetable content (Table 11). The different kinds of tinned herring, tinned mackerel and tinned sardines proved to be relatively K-poor with 4.0 to 9.4 g/kg DM, whereas tinned fish with tomatoes contained significantly more K than fish.

Compared to herring, trout and rosefish fillet stored significantly more K. The portion of bones in the fish ready for eating may also take effect on its K content.

Though, on an average, the K content of beverages per liter is lower than that of foodstuffs, humans can increase their K intake considerably by their consumption (Table 12).

Table 12. Potassium content of several beverages and drinking water (n 185) in mg/100 ml or in mg/l

Kind	mg/100 ml	mg/l	
	$\bar{x}$	$\bar{x}$	s
drinking water	1,2	12	17
coke	1,5	15	15
brandy	2,0	20	12
corn schnapps	2,2	22	31
lemonade	4,0	40	28
beer with 11-14 % original wort	50,4	504	297
Pilsner	55,5	555	267
advocaat	63,0	630	264
vermouth	66,2	662	271
champagne	70,9	709	303
white wine	81,5	815	367
red wine	90,4	904	301
juice**	126,2	1262	387

Coke, corn schnapps, brandy and lemonade do not essentially contribute to the K intake whereas beer, champagne and wine can be much more important for the K balance. This is particularly true for beer since as much as 1 g K can be consumed with two liters of beer.

3.2. The potassium intake of adults according to the duplicate method

The K intake of men and women with the local production of foodstuffs and beverages in 1988 only differed insignificantly from that in 1991 with the consumption of European foodstuffs and beverages (Table 13).

Table 13. Potassium intake of adults depending on sex and time of testing in mg/day

Year	Women		Men			
	s	$\bar{x}$	$\bar{x}$	s	p	%
1988	781	2475	3084	1024	< 0,001	125
1991	1019	2582	3273	1179	< 0,001	127
p	> 0,05		> 0,05		-	
%	104		106		-	

In 1991, the test persons consumed 4 or 6 % more K than in 1988. Men consumed 25 or 27 % more K than women. This difference is due to the 28 % higher DM intake of men. All test populations had a mean daily K intake of > 2 g in both experimental years. Thus, the K requirements of women and men seem to be met by the K offer. This statement is underlined by the K content of the consumed foodstuff and beverage DM (Table 14). On an average, it contained > 8 g K/kg and thus delivered more K than needed by the fauna. The almost completely changed offer of foodstuffs and beverages after the reunification of Germany did not take effect on the K consumption and the K content of the consumed DM.

Table 14. Potassium content of the consumed foodstuff and beverage DM depending on sex and time of testing in mg/kg DM

Year	Women		Men			
	s	$\bar{x}$	$\bar{x}$	s	p	%
1988	1876	8334	8052	2123	> 0,05	97
1991	1684	8527	8358	1889	> 0,05	98
p	> 0,05		> 0,05		-	
%	102		104		-	

Table 15. Potassium intake of adults depending on living area and sex in mg/day in 1988

Living area		Women		Men		Influence of sex
		s	$\bar{x}$	$\bar{x}$	s	
Brandenburg	Wusterhausen	933	2590	3436	1044	< 0,01
	Vetschau	729	2565	2809	1165	
Thuringia	Bad Langensalza	719	2307	2854	977	
	Jena	743	2439	3239	909	
Influence of living area		> 0,05				-

Table 16. Potassium intake of adults depending on living area and sex in mg/day in 1991

Living area		Women		Men		Influence of sex
		s	$\bar{x}$	$\bar{x}$	s	
Brandenburg	Wusterhausen	745	**2118**	**2707**	747	< 0,001
Western Pomerania	Greifswald	962	**2565**	**2235**	827	
Thuringia	Bad Liebenstein	1058	**2434**	**2943**	828	
	Bad Langensalza	966	**2731**	**3602**	1379	
Influence of living area		< 0,001				-

Sex did also not influence K consumption. All differences are accidental.

The analysis of the K consumption of the different test populations did also not show any K deficiency in 1988 (Table 15) and 1991 (Table 16). Local differences of K intake can occur.

3.3. Potassium excretion and potassium balance of women and men

The K excretion of women and men was investigated in two test populations in 1991 (Table 17). It was possible to demonstrate that both sexes excreted 85 % of K renally and 15 % faecally.

The K balance of both sexes was negative (Table 18). Women excreted 15% and men 3% more than they had taken in. There is no explanation for the negative balance of women, that of men is within the error range of the procedure.

Table 17. Potassium excretion of women and men via urine and faeces in mg/day

Excretion	Women		Men			
	s	$\bar{x}$	$\bar{x}$	s	p	%
urine	1050	**2521**	**2868**	1223	< 0,05	114
faeces	382	440	506	344	> 0,05	115
excretion via urine, %	85		85		-	
excretion via faeces, %	15		15		-	

Table 18. The K balance of women and men

Parameter	Women $\bar{x}$	Men $\bar{x}$	p	%
K intake, mg/day	**2582**	**3273**	< 0,001	127
K excretion, mg/day	**2961**	**3374**	< 0,05	114
K balance, mg/day	**- 379**	**- 101**	-	
K balance, %	**- 15**	**- 3**	-	

3.4. Comparison of the potassium intake of women and men with the duplicate and the basket method

At present, the quantitative intake of macro and trace elements is either calculated with the basket method or analytically determined with the duplicate method all over the world (Table 19).

The necessary intake data were taken from the Statistical year-book (1989) and the paper published by Thiel *et al.* (1991). Their data were obtained with a weighing-record-method within the MONICA project. The intake data obtained by Müller *et al.* (1991) represent a typical shopping basket.

The comparison of the K intake which was analytically found with the duplicate method and the K consumption calculated with the shopping basket method shows clearly that the calculated K intake is by 20 and 19 %, resp. too high for women and 26 and 23 %, resp. too high for men.

Table 19. Potassium intake of adults with the duplicate and the basket method

Procedure	Women		Men	
	1988	1991	1988	1991
duplicate method	2475	2582	3084	3273
basket method	2963	3082	3884	4010
percent1)	120	119	126	123

1) duplicate method ≙ 100 %, basket method ≙ x %

This results from several mistakes of this procedure, e.g. from the assumed DM consumption of men and women, which is 30 % too high, the losses when the dishes are prepared and the changing composition of consumed foodstuffs and beverages. In contrast to the duplicate method, the basket method allows the calculation of the percentage of the different groups of foodstuffs in the total K consumption (Fig. 1).

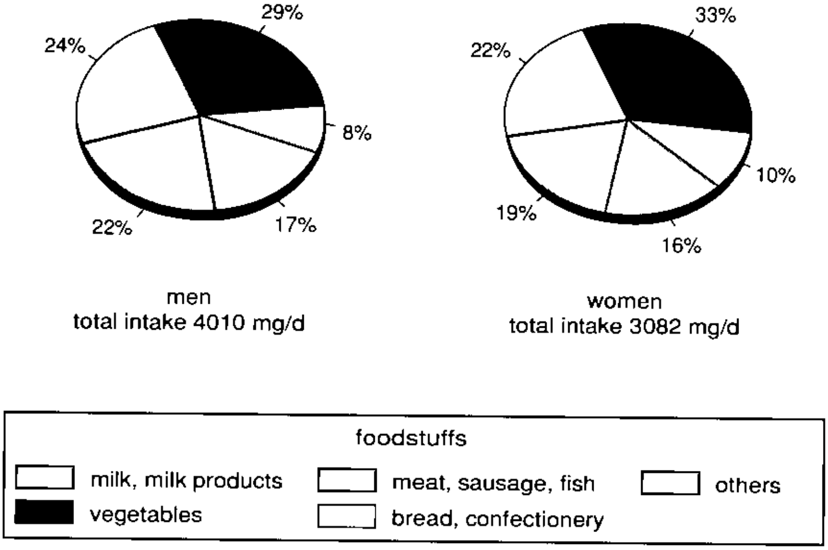

Fig. 1. K intake of men and women calculated with the basket method (1991)

4. Discussion of the results

The K content of foodstuffs and beverages and thus the K consumption of humans can be influenced by most different factors, e.g. by the fertilization of the land, the K content of drinking water and by supplements in foodstuffs. The systematic analysis of 108 foodstuffs and beverages in 1988 and that of 126 in 1991 allowed to show certain influences. Several kinds of vegetables and fruits (e.g. white cabbage, cucumbers, tomatoes) contained highly significantly more K in 1991 than in 1988.

On the other hand, several kinds of meat and sausage as well as bread and farinaceous products also proved to be significantly or insignificantly K-richer in 1991 than in 1988. The reason for these changes is the K content of cooking salt. In 1988, it contained 15 and in 1991 68 g K/kg. This change took effect on the K content of salted foodstuffs to the above-described extent and probably also led to the insignificant increase of the K consumption of women and men to 2582 and 3273 mg/day. On the average, this K intake meets the K requirement of humans and can also be compared with that of adults in other countries. In Finland, they consumed 4500 mg/day (Varo and Koivistoinen, 1980), in the Netherlands 4378 mg/day (Van Dokkum *et al.*, 1989), in Switzerland 2825 mg/day (Wyttenbach *et al.*, 1987), in Great Britain 2956 mg/day (Lewis and Buss, 1988). In the USA, a consumption of 1938 mg/day (Pennington *et al.*, 1988) and of 3120 mg/day (Kim *et al.*, 1984) was registered in women and of 2889 mg/day (Pennington *et al.*, 1988) and of 3120 mg/day (Iyengar *et al.*, 1987) in men. Thus, the K consumption found in Germany is within the international trend. Only the adults in Finland and the Netherlands had a higher K intake. In spite of the registered slightly negative balance, the K requirement might be much lower than the recommended K intake of 2 g/day.

The main K amount is renally (85 %) excreted by both sexes. It could be of considerable practical importance that the K intake calculated with the basket method is by 20 to 25 % higher than the values determined analytically with the duplicate method. The results of nutrition studies obtained with two procedures cannot be compared.

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Absorption and Secretion of Potassium in the Gastrointestinal Tract

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Summary

In animal cells potassium (K) is the major intracellular cation with an average concentration between 120 and 150 mmol·l-1. K^+ concentration in the extracellular fluid is only around 4.5 mmol·l-1 and is kept within narrow limits by regulatory mechanisms. Extracellular K^+ concentration plays an important physiological role in determining the excitability of muscles (skeletal, smooth and heart cells) and nerves, because the resting potentials in these cells are largely determined by K^+ diffusion through special K^+ channels. In epithelia in general and in the gastrointestinal tract in particular only the membranes facing the blood side of the tissue are exposed to the rather well regulated K^+ concentration of extracellular fluid. The luminal (apical) membrane, however, can be exposed to greatly varying K^+ concentrations depending on the K^+ content of the diet. In mammals K^+ homeostasis is regulated by the mineralocorticoid aldosterone primarily through urinary K^+ excretion by the kidney. However, dietary K^+ intake and subsequent K^+ transport in the gastrointestinal tract and final excretion of K^+ with feces are also involved in the regulation of K^+ balance. This review focuses on the mechanisms of K^+ transport across the gastrointestinal wall.

Structural considerations

The inner surfaces of gastrointestinal organs (stomach, small and large intestine) are lined by a single layer of specialized cells, the gastrointestinal epithelium. The epithelial cells are columnar in shape and are connected to each other by unique structures, the tight junctions. The formation of tight junctions allows the development of polarity, e.g. in the cellular membranes facing the gastrointestinal lumen (apical membrane) and the blood side (basolateral membrane) different ion transport systems can be established. This functional polarity is the hallmark of epithelia and enables them to vectorially transport substances like electrolytes and nutrients from the intestinal lumen into the body and vice versa. The cellular organization of epithelia principally allows two different routes for solute transport, the paracellular and the cellular pathway, as is schematically depicted in fig. 1.

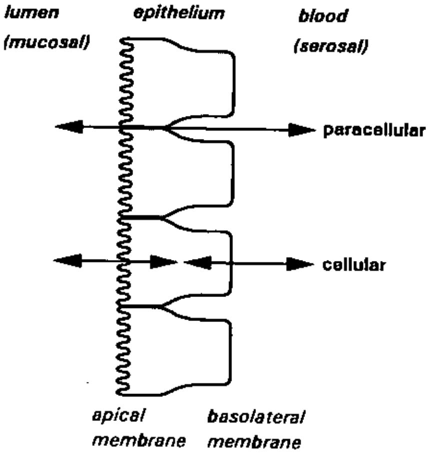

Fig. 1. Schematic illustration of the organisation of simple columnar epithelia and the pathways for transepithelial transport of solutes.

Passive and active transport

Passage through the paracellular pathway is passive and depends on the existence of electrochemical gradients for the permeating substance. The other route is cellular transport. This pathway involves two barriers in series, the apical and the basolateral membrane. Biological membranes in general and also epithelial cell membranes are constituted by a double layer of lipids into which proteins are incorporated. These membranes are easily permeable for lipid soluble uncharged molecules, however, permeation of ions like K^+ across cell membranes requires the presence of either ion channels or ion carrier systems. These transport proteins are embedded into the membrane. The magnitude of transport depends on the characteristics of these systems and the direction is related to the activity of these systems in the apical and basolateral membranes.

Passive transport is determined by the concentration gradient for the solute and the permeability characteristics of the epithelium and is described in quantitative terms by Ficks's law of diffusion:

$$J = -P \bullet \Delta c$$

J: flux
P: permeability
Δc: concentration difference

Diffusion of charged molecules like inorganic ions can establish diffusion potentials if the membranes separating two compartments have ion selective permeability characteristics. The magnitude of the diffusion potential can be calculated by Nernst's law:

$$E = \frac{R \bullet T}{z \bullet F} \cdot \frac{[c]_o}{[c]_i}$$

E: electrical potential difference
R: gas constant
T: absolute temperature
z: charge of the ion
F: Faraday's constant
c_o: concentration in outer solution
c_i: concentration in inner solution

In all segments of the gastrointestinal tract substances can move from the lumen to blood and vice versa. These unidirectional fluxes (J) are high especially in the small intestine. The net flux (J_{net}) results from the difference between the flux from lumen to blood, or in the terminology of epithelial transport physiologists from the mucosal (m) to the serosal (s) side J_{ms} and in the opposite direction J_{sm}. A positive J_{net} ($J_{ms} > J_{sm}$) is designated as absorption, a negative J_{net} ($J_{ms} < J_{sm}$) as secretion.

The unidirectional fluxes can be measured by using radioactive isotopes added to either the luminal or the blood side of the epithelium and measuring the appearance on the side which previously did not contain any isotope. The flux measurement can indicate whether an ion moves across an epithelial barrier according to its electrochemical gradients, e.g. by passive mechanisms, or whether active transport systems are involved in the translocation process. According to the Ussing-flux ratio:

$$\frac{J_{ms}}{J_{sm}} = \frac{[K^+]_m}{[K^+]_s} \cdot e^{\frac{z \cdot F \cdot \Delta\Psi}{R \cdot T}}$$

$[K^+]$: activity of K^+ in the mucosal (m) and serosal (s) solution
e : natural logarithm
$\Delta\Psi$: transepithelial potential difference

In in-vitro studies it is possible to control the conditions under which flux measurements are performed. Chemical gradients can be abolished by incubating an epithelial preparation with the same solutions on both sides. Electrical gradients which may develop by transport processes of the tissue may be compensated by external current sources clamping the transepithelial voltage to a certain value. Usually for in-vitro ion transport studies the tissue is short-circuited to eliminate any electrical gradient, e.g. $\Delta\Psi$ becomes zero. Under such conditions for a purely passive transport both unidirectional fluxes have to be equal and thus the flux ratio is 1. Any deviation of the flux ratio from unity indicates an active transport process.

In all epithelial cells of the gastrointestinal tract a Na^+, K^+-ATPase, exchanging intracellular Na^+ for extracellular K^+ with a stoichiometry of 3 Na^+/2 K^+, is located in the basolateral membrane. This system generates a low intracellular Na^+-concentration and a high K^+-concentration. Since both Na^+ and K^+ have to be moved against their respective electrochemical gradients metabolic energy in the form of ATP is needed to operate the Na^+, K^+-ATPase. K^+ channels are present in the basolateral membrane allowing the recycling of K^+ (figure 2). Diffusion potentials generated by K^+ movement provide electrical driving forces for the movement of other ions in epithelial cells. The basolateral membrane potential in epithelial cells is predominantly determined by K^+ diffusion through specific K^+-channels.

The systems described above and shown in figure 2 are present in all cell types of gastrointestinal epithelia studied so far.

In addition to these basic systems specialized transport mechanisms are present in the different cell types of the various gastrointestinal epithelia which will be discussed in the following paragraphs.

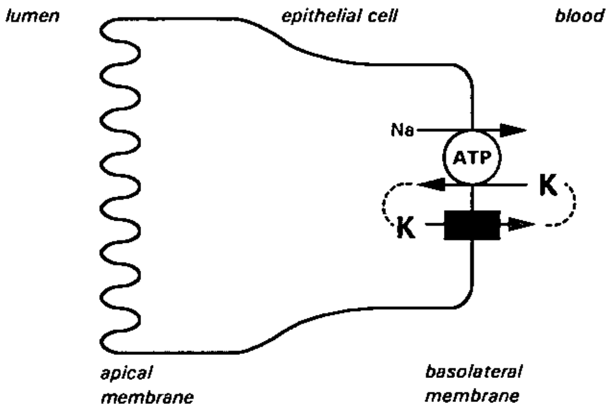

Fig. 2. Model of Na^+,K^+-ATPase and K^+ channels in the basolateral membrane

Stomach

Acid secretion in the stomach is related to the activity of a K^+, H^+-ATPase located in the apical membrane of the gastric parietal cell. Gastric acid secretion is under neurohormonal control and is stimulated by acetylcholine, the neurotransmitter of vagal nerves, by gastrin, a hormone secreted from special endocrine cells in the gastric epithelium and by histamine, which is released from mucosal mast cells under different conditions (Sachs *et al.*, 1978). Upon stimulation of acid secretion the parietal cell changes its ultrastructure remarkably. An extensive network of intracellular canalicular membranes now fuses with the apical membrane. These canalicular membranes contain a specialized transport system, the gastric K^+, H^+-ATPase. The enormous enlargement in apical membrane surface area and the activation of the K^+, H^+-ATPase causes a tremendous acid secretion.

The gastric K^+, H^+-ATPase has been extensively characterized biochemically and functionally in the past years (Sachs, 1987). It has been demonstrated that parietal cell K^+, H^+-ATPase belongs to the same family of transporting ATPases as the Na^+, K^+-ATPase (Sachs, 1987). Recently drugs were developed inhibiting specifically the parietal cell K^+, H^+-ATPase and thus blocking acid secretion very efficiently. One of these new drugs is a substitued benzimidazole, omeprazole, and is now used clinically for the treatment of gastric ulcers and reflux oesophagitis (Wallmark, 1989).

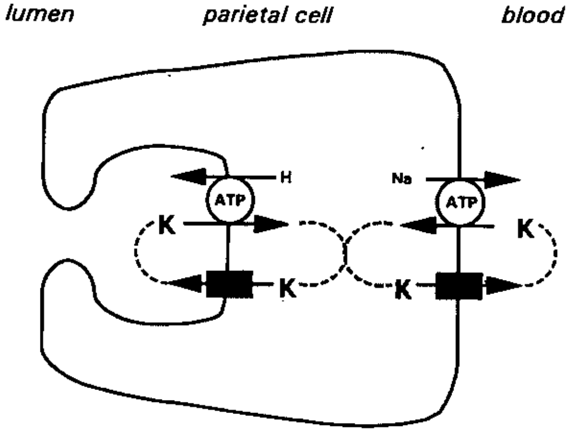

Fig. 3. Mechanisms of acid secretion in the gastric parietal cell involving K^+ transport, other ion transport systems required for acid secretion are not shown.

Small intestine

In the small intestine K^+ movement appears to be mainly passive and be restricted to the paracellular pathway (Turnberg, 1971). The luminal K^+ concentrations in small intestinal contents are only slightly higher than in the blood in accordance with the small lumen negative transepithelial potential difference. The high paracellular permeability of the small intestinal epithelium allows high unidirectional fluxes of K^+ and leads to a rapid equilibration between the lumen and the blood. Basolateral K^+ channels have been identified and characterized in small intestinal enterocytes (Sepulveda *et al.*, 1991). However, these channels are not involved in transepithelial K^+ transport but rather control the membrane potential during Na^+-coupled absorption of nutrients (Sepulveda *et al.*, 1989; Mintenig *et al.*, 1992), play a role in the intestinal response to secretagogues (Hardcastle and Hardcastle, 1986) and may participate in cell volume regulation (cf. Donowitz and Welsh, 1987; Dawson and Richards, 1990; Backman *et al.*, 1992). Recently a K^+, H^+-exchanger has been demonstrated in the brush-border membrane of rat ileum (Binder and Murer, 1986). The physiological function of this exchanger, however, is questionable since in the intact epithelium the prevailing gradients would drive K^+ out of the cell in exchange for H^+ influx.

Large intestine

As in the small intestine K$^+$ transport across the large intestinal epithelium had long been regarded as being purely passive (Frizzell *et al.*, 1976; Schultz, 1981; Fromm and Schultz, 1981). In the large intestine a higher lumen negative transepithelial potential difference than in the small intestine is established due to a lower paracellular permeability and a high rate of electrogenic Na$^+$ transport. Thus a higher driving force for passive K$^+$ secretion is established. However, also evidence for active, cellular K$^+$ secretion was presented already 25 years ago (Edmonds, 1967 a,b,c; Hawker *et al.*, 1978; Edmonds and Smith, 1979). The adaptation of K$^+$ transport in the large intestine to varying levels of dietary K$^+$ uptake plays an important role in the maintenance of K$^+$ homeostasis (Hayslett and Binder, 1982).

Cecum and proximal colon

In the cecum of guinea pigs a linear inverse relationship between the Na$^+$ and the K$^+$ concentration was detected (Figure 4). The slope of this relationship was close to 1, indicating a 1:1 exchange of Na$^+$ and K$^+$. On feeding of a low-sodium diet the Na$^+$/K$^+$-ratio in the cecum changed significantly from 1.21 ± 0.18 to 0.83 ± 0.14 (Rechkemmer *et al.*, 1987). The luminal K$^+$ concentrations are always much higher than would be expected from the correspondingly measured transepithelial potential differences and thus provide evidence for active cellular K$^+$ secretion in the guinea pig cecum (Rechkemmer, 1988).

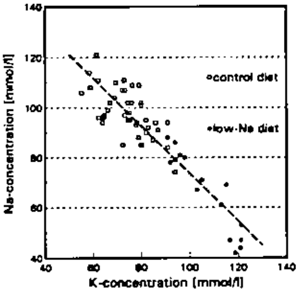

Fig. 4. Relation between Na$^+$ and K$^+$ concentration in guinea pig cecal contents (Rechkemmer *et al.*, 1987).

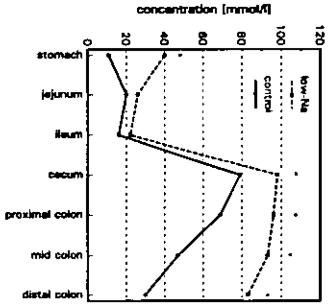

Fig. 5. Concentrations of K$^+$ in different segments of the guinea pig gastrointestinal tract. (Rechkemmer *et al.*, 1987).

* indicates significant difference

Using in-vivo and in-vitro techniques a net K^+ absorption has been observed for the rabbit proximal colon (Clauss and Hörnicke, 1984). In contrast to these findings other investigators found no evidence for active K^+ uptake but could demonstrate net K^+ secretion in the in-vitro rabbit proximal colon (Sullivan and Smith, 1986). In in-vivo perfusion studies a significant K^+ secretion was observed in the guinea pig proximal colon (Rechkemmer, 1992). K^+ secretion in-vivo was not altered when the animals were kept on a low-Na diet for 2 weeks (Rechkemmer, 1992), however, under in-vitro conditions an approximately 3-fold stimulation of K^+ secretion was observed (Rechkemmer, 1988). Thus the active cellular K^+ secretion is increased by a low-Na diet and an increased plasma aldosterone level but by unknown mechanisms is compensated in the in-vivo situation.

Distal colon

In the distal colon much progress has been made in the characterization of active transport systems for K^+ absorption and K^+ secretion (Smith and McCabe, 1984, Halm and Frizzell, 1986). Both processes and their regulation have been extensively studied in different species and will be considered separately in the following paragraphs. In chronic renal failure in men and animals net colonic K^+ secretion is increased and thus the colon at least partially compensates for the kidney (Sandle *et al.*, 1988; Siga *et al.*, 1989). The adaptation of these systems to different dietary K^+ loads participates in the regulation of K^+ homeostasis and it has been shown that the major regulatory factor is the mineralocorticoid hormone aldosterone (Hayslett and Binder, 1982).

K^+ absorption

K^+ absorption in the rat distal colon is stimulated by dietary K^+ depletion (Wolffram *et al.* 1985; Tannen *et al.*, 1986) and depressed by dietary K^+ loading (Foster *et al.*, 1986). The system responsible for K^+ absorption in the distal colon has recently been identified as a K^+,H^+-ATPase similar to the gastric enzyme in several laboratory animal species (Gustin and Goodman, 1981, 1982; Kaunitz and Sachs, 1986; Suzuki and Kaneko, 1989; Takeguchi *et al.*, 1990; Watanabe *et al.*, 1990; DelCastillo *et al.*, 1991).

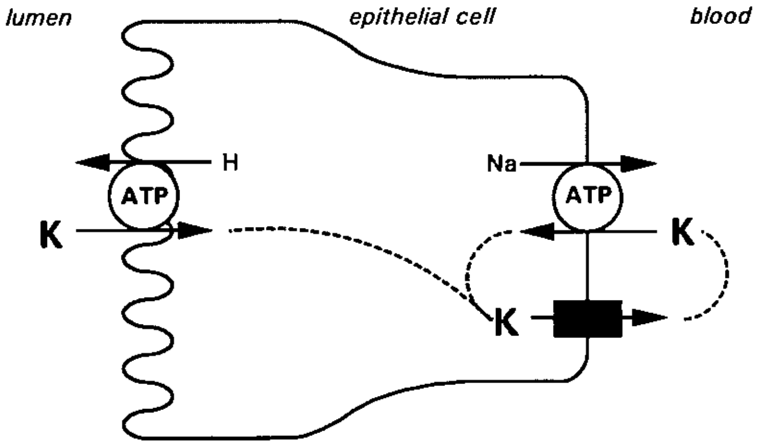

Fig. 6. Mechanisms for active K^+ absorption in the distal colon.

In the distal colon this system is responsible for K^+ absorption and luminal acidification and thus may also participate in the regulation of acid-base balance in animals (Suzuki and Kaneko, 1987). In contrast to the gastric K^+,H^+-ATPase the colonic counterpart is not only inhibited by vanadate but in some species is also sensitive to ouabain, a substance which so far was considered to be a specific inhibitor of the ubiquitous Na^+,K^+-ATPase. Ouabain-sensitivity of the colonic K^+,H^+-ATPase varies greatly among different species. In the guinea pig distal colon K^+ absorption as well as H^+ secretion are inhibited by mucosal ouabain already in micromolar concentrations with inhibitor constants between 1 and 4 µmol ouabain/l for half-maximal inhibition (Suzuki and Kaneko, 1987, 1989; Watanabe *et al.*, 1990), while in the rat much higher concentrations in the millimolar range are needed to inhibit K^+,H^+-ATPase activity (DelCastillo *et al.*, 1991). Using monoclonal antibodies it was demonstrated that the colonic K^+,H^+-ATPase is primarily confined to cells in the crypt region of the rabbit distal colon (Takeguchi *et al.*, 1990).

K^+ secretion

Active K^+ secretion in the gastrointestinal tract is particular prominent in the distal colon. The parallel operation of active K^+ absorption, however, may obscure K^+ secretion and lead to the observed very small net fluxes under short-circuit current conditions. In-vivo perfusion studies showed a net K^+ absorption under control conditions. The induction of secondary hyperaldosteronism by feeding a low-Na diet for two weeks largely augmented electrogenic Na^+ absorption and concommitantly also the transepithelial potential difference, K^+ absorption was abolished (Rechkemmer, 1992). After inhibition of electrogenic Na^+ absorption with the drug amiloride, a specific blocker of epithelial Na^+ channels, the transepithelial potential difference changed from -24 ± 6 mV to 33 ± 5 mV (with reference to blood) and a considerable K^+ absorption was measured, indicating that K^+ secretion was reduced by the large potential change.

The secretion of K^+ is an electrogenic process and involves apical membrane K^+ channels (figure 7). Apical membrane K^+ channels have been demonstrated in the rabbit distal colon by microelectrode measurements (Wills, 1985) and noise analysis (Wills *et al.*, 1982). These apical membrane K^+ channels can be blocked by Ba^{2+} or TEA (Wills *et al.*, 1982; Wills, 1985; Sandle *et al.*, 1985; Halm and Frizzell, 1986; Ishida and Suzuki, 1987; Pacha *et al.*, 1987; Siga *et al.*, 1989; Sweiry and Binder, 1989).

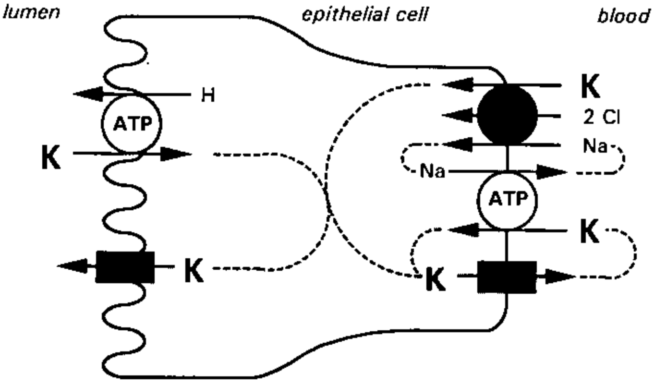

Fig. 7. Mechanisms involved in active K^+ secretion in the distal colon.

K^+ secretion is dependent on the operation of a basolateral $Na^+,K^+,2\ Cl^-$ cotransporter as has been demonstrated by using specific inhibitors of this basolateral membrane transport system, namely loop diuretics like bumetanide (Halm and Frizzell, 1986; Ishida and Suzuki, 1987; Rechkemmer, 1988). K^+ secretion is also dependent on the activity of the basolateral membrane Na^+,K^+-ATPase. Inhibition of Na^+,K^+-ATPase activity by serosal application of ouabain abolishes K^+ secretion (Halm and Frizzell, 1986; Ishida and Suzuki, 1987; Rechkemmer, 1988). The ratio between apical and basolateral membrane K^+ conductance probably determines the magnitude of K^+ secretion.

K^+ secretion in the distal colon is related to dietary K^+ uptake. Dietary K^+ loading of rats stimulates a Na^+ and Cl^--dependent K^+ secretion (Foster *et al.*, 1986; Tannen *et al.*, 1986).

K^+ secretion is regulated by the hormone aldosterone independently of its effects on Na^+ absorption in the distal colon of guinea pigs and rats (Rechkemmer and Halm, 1989; Sweiry and Binder, 1989). In the distal colon of neonatal rats not only aldosterone but also the glucocorticoids corticosterone and dexamethasone stimulate K^+ secretion (Pacha *et al.*, 1988).

Secretagogues like prostaglandins (McCabe and Smith, 1985; Halm and Frizzell, 1986), adrenergic agonists (Halm and Frizzell, 1986; Smith and McCabe, 1986; Ishida and Suzuki, 1987), histamine (McCabe and Smith, 1984), cyclic adenosine-monophosphate (cAMP) (Foster *et al.* 1983; McCabe and Smith, 1985; Halm and Frizzell, 1986; Ishida and Suzuki, 1987) or calcium-ionophore A23187 (Smith and McCabe, 1984) can induce K^+ secretion. A recent study using electron microprobe analysis in the guinea pig distal colon epithelium indicated that prostaglandin E_2 or epinephrine induced K^+ secretion is confined to cells in the lower two-thirds of colonic crypts (Halm and Rick, 1992).

Conclusions

Detailed studies of K^+ transport across epithelia of the stomach, the distal small intestine and the large intestine have now convincingly demonstrated that active cellular mechanisms are the major pathways for K^+ absorption and secretion. The regulation of these cellular pathways by hormones and neurotransmitters indicates that gastrointestinal epithelia are actively involved in overall K^+ homeostasis. During acute dietary K^+ loads or K^+ depletion passive transport in the small intestine mainly determines the uptake or loss of K^+ into or from the body, respectively. If under those conditions the capacity of the active K^+ absorptive or secretory mechanisms of the large intestine and the kidney is overloaded then a change in K^+ concentration in the plasma may occur and lead to subsequent physiological changes in excitability of muscles and nerves. During slowly occuring chronic dietary changes in K^+ uptake, particularly in K^+ loading, the active regulatory mechanisms of the large intestine and kidney adapt to these changes. In the intestine, particularly the stimulation of K^+ secretion in the distal colon during dietary K^+ loading, elevetad plasma aldosterone concentrations, induced by prolonged feeding of a Na^+ deficient diet or in renal failure significantly contributes to the maintenance of K^+ homeostasis in the body. To elucidate the physiological functions of the distal colonic K^+,H^+-ATPase and the participation of this system in the regulation of acid-base homeostasis remains as an important part of future research.

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Physiology and Pharmacology of K^+ Channels

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Summary

K^+ channels are diverse group of ionic channels which play a role in the broad spectrum of more or less specialized cellular functions including establishing of the resting membrane potential, electrical excitability of the membrane, control of synaptic efficacy and of heart beat, cell-cell communication, secretion, mobility and cell proliferation. Resting membrane potential apparently exists in all mature animal and plant cells, its maintenance is a prerequisite for cellular homeostasis and can thus be considered to be one of the basic characteristics of the living cells. There are over 30 different K^+ channels which have been characterized biophysically up to now. Four of them, inward rectifier, delayed rectifier, Ca^{2+}-activated and ATP-dependent K^+ channels are apparently responsible to a great extent for the regulation of above mentioned functions. The heterogenity of K^+ channels has made it difficult to purify these channels for biochemical studies. A number of workers have used channel blockers such as tetraethylammonium (TEA), apamin and other toxins as agents to help distinguish different K^+ channels in a given cell. However, the affinity for TEA is usually low and specific high affinity ligands for the most important K^+ channels are lacking. Generally these pharmacological separations are most secure when the K^+ channels are also separable on the grounds of their physiological properties.

Plasma membrane transport systems

According to the membrane theory of Bernstein the cells are surrounded by a membrane selectively permeable to K^+, Na^+ and Cl^- ions (Hodgkin and Katz, 1949) which are freely distributed in the free cellular water. Ions have a tendency to diffuse across the cell membrane from sites of higher concentrations to lower concentration. Transmembrane concentration gradients are maintained by pumps and other carriers which transport ions actively against their concentration gradient.

As regards the fact that charged ions cannot cross the lipid bilayer of the plasma membrane, since the conductance of a phospholipid bilayer is extremely small when compared to the conductance of the usual biological membrane, transport proteins spanning the thickness of the lipid bilayer and forming ionic channels had to be proposed.

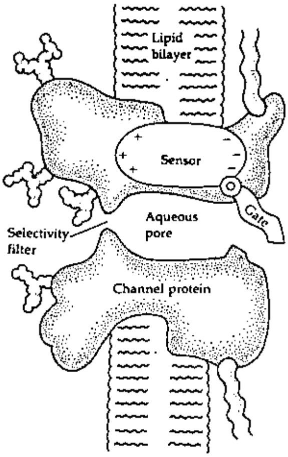

Fig. 1. Voltage-dependent ionic channel, a hypothetical model (Hille, 1984). The channel is drawn as a transmembrane macro-molecule with a hole through the centre. The functional regions, selectivity filter, voltage sensor and gate are deduced from electrophysiological experiments but are not yet confirmed by structural studies.

At present, it is well established that ionic channels for Na^+, K^+, Ca^{2+} and Cl^- ions are protein macromolecules forming aqueous pores equipped with many selective devices such as selective filter, voltage sensor and with gating mechanism (Fig. 1). An essential element in the functioning of a channel is the rearrangement of gating structures in response to changes in the electric field (voltage dependent channels) and/or to binding of an activator molecule (chemically activated channels). This process is responsible for a conformational change in the channel-forming protein leading to opening or closing of the channel.

There is a number of different electrically and/or chemically activated channels in excitable as well as in non-excitable tissues (Hille, 1984) which can be analyzed and quantified biophysically using voltage-and patch-clamp techniques developed by Sakmann and Neher in 1976 (Sakmann and Neher, 1983). Specific high affinity ligands serve as a tool for biochemists who have recently provided the complete amino acid sequences of numerous channels such as Na^+ channel, Ca^{2+} channel, acetylcholine-activated channel. Studies identifying genes encoding K^+ channels are, however, rare.

In parallel with the ion channels there are additional transport mechanisms in the resting membrane mediating ion fluxes across the membrane: Na^+, K^+ pump, Ca^{2+} pump, Na^+-Ca^{2+} exchange, $Na^+/K^+/Cl^-$ cotransport system, Na^+-coupled contransport of sugars and amino acids, etc. All these mechanisms can be classified as carrier-like transport systems. Generally, carrier transport is considered to be an active transport system energized by ATP hydrolysis and/or by ionic concentration gradients.

Carriers and channels can be distinguished on the basis of kinetic criteria. The rate of passage of ions through one open channel during excitation is in the range of 10^6 ions per second but the rate of active transport mediated, for example, by Na^+,K^+-ATPase is suggested to be 300 K^+ ions per second per enzyme molecule. Nevertheless, the carrier and channel mechanisms are not exclusive possibilities. Either conformational change facilitates the transport of ions through the carrier forming a pathway which can, but need not necessarily, be of the aqueous pore type. Either carrier may be considered as a limited example of a channel with multiple conformational states.

Resting membrane potential

The relation between the resting membrane potential (RMP) and ion concentrations is described quantitatively by the Goldman-Hodgkin-Katz (G.H.K.) equation :

$$V_m = \frac{RT}{F} \ln \frac{p_K[K^+]_o + p_{Na}[Na^+]_o + p_{Cl}[Cl^-]_i}{p_K[K^+]_i + p_{Na}[Na^+]_i + p_{Cl}[Cl^-]_o}$$

where V_m is the membrane potential, R and F are the gas and Faraday constants respectively, T is absolute temperature, p_{Na}, p_K and p_{Cl} represent the passive permeability of the membrane to potassium, sodium and chloride ions in the steady state and i and o represent their intracellular and extracellular concentrations, respectively. The G.H.K. equation is based on the assumption that there is zero net current flow across the membrane and also zero net current attributable to ionic pumps, so that there is a constant electric field through the membrane.

Generally in all eukaryotic cells p_K and p_{Cl} are high while p_{Na} is relatively low. For example, in skeletal muscle p_{Na}/p_K is usually less then 0.01. The intracellular concentration of K^+ is several times higher than that of extracellular fluid but the concentrations of Na^+ and Cl^- are always lower intracellularly than outside. There are also other ions which are distributed according to their electrochemical equilibrium, for example H^+ and Ca^{2+} However, intracellular H^+ is effectively buffered by cytoplasmic buffering systems and the resting permeability for Ca^{2+} is normally so low that it is hardly measurable, these ions therefore cannot contribute directly to the RMP unless they are coupled to fluxes of the main electrogenic ions (K^+, Na^+ and Cl^-).

Membrane permeability to potassium can be calculated from the G.H.K. equation by measuring the membrane potential under sudden changes in external K^+ concentration. The effect of changing the solution can be determined only in the short period during which there is no alteration in intracellular K^+ concentration. The permeability is directly proportional to membrane conductance and in practice, the difference between these two terms is merely a question of terminology. "Permeability" is used when refering to a membrane characteristic and "conductance" is used in relation to the ion which carries the current. Conductance can also be calculated according to Ohm's law when current response to applied voltage is measured. The membrane resistances of different cells range from 10 to 10^6 Ω cm^{-2}. This broad range of membrane resistance implies that the conductance differs markedly from cell to cell, together with the variations in RMP (Table 1).

The G.H.K. equation predicts a number of ways in which the RMP can be altered. For example, increase in intracellular Na^+ or Cl^- or decrease in intracellular K^+ would cause depolarization and decrease in p_K or an increase in p_{Na} or p_{Cl} would also additionally cause depolarization. Intracellular compartmentalisation and ion binding to intracellular proteins should also be considered when RMP changes are attributed to changes in the intracellular concentrations of ions.

The resting transmembrane movement of K^+ is regulated by K^+ channels which allow more or less passive diffusion of K^+ across the membrane, by ATP-driven Na^+, K^+ pumps and by $Na^+/K^+/Cl^-$ cotransport systems. The electrogenic Na^+,K^+ pump and $Na^+/K^+/Cl^-$ cotransport are carrier-like transport systems which apparently do not directly contribute to the membrane conductance and may contribute to the RMP depending on the metabolic state of the cell. The type of K^+ channel which is mainly responsible for the resting membrane K^+ permeability has not yet been recognized for certain but inward rectifying, Ca^{2+}-activated and ATP-dependent K^+ channels are likely candidates. Other channel types such as delayed rectifier, transmitter-activated and stretch-activated K^+ channels are rather involved in specialized membrane functions.

Table 1. Examples of resting membrane potential of different cell types measured with microelectrodes and/or using tritiated triphenylmethyl phosphonium ion distribution (*)

Cell type	RMP (mV)
skeletal muscle	
frog sartorius	-94.0
rat diaphragm	-78.6
mouse diaphragm	-75.3
human intercostal	-78 to -87
liver of mouse*	-41.1
enterocytes of rabbit*	-53.1
human red blood cells*	-10 to -20
human platelets*	-48.1
human lymphocytes*	-70.0
neuroblastoma cells of mouse	-72.9
Rana pipiens eggs	-55.0
Xenopus laevis eggs	-19.3

Inward rectifying K^+ channel

The direction of resting K^+ conductance was discovered by the finding that K^+ permeability of the membrane is about 100 times higher for inward currents going into the cell than for outward currents going out.

The inward rectification channel has been directly documented by the patch-clamp technique but not yet been isolated biochemically. A study of surface membrane vesicles derived from rabbit skeletal muscle showed that the calculated K^+ channel density in the resting membrane is about 5 channels per μm^2. The model of the inward rectification channel suggests that there is an internal blocking cation or particle either present in the intracellular solution or held at a constant concentration at the cytoplasmic surface of the membrane, which is displaced by K^+ moving in through the channel from the outside (Armstrong, 1975).

The inward K^+ conductance also depends on the extracellular K^+ concentration, being lowered with a decrease in extracellular K^+. It may be regulated both by divalent cations and locally by fixed surface membrane charges, since the K^+ conductance increases as the pH of the external solution is lowered. It is supposed that ionization of channel proteins induces conformational changes and thus regulates channel permeability.

The ionic selectivity and pharmacology of the resting inward rectifier is separable from other K^+ channels : the inward rectification is blocked only by very high concentrations of tetraethylammonium (TEA), but is not inhibited by 4-aminopyridine. The inward rectification shows no Rb^+ permeability while external Ba^{2+}, Cs^+, Na^+ and Li^+ ions have a blocking action on the inward K^+ current during extreme hyperpolarization (Table 2).

Table 2. Agents blocking K^+ channels involved in the resting K^+ permeability.

K^+ channel	blocking from the outside	blocking from the inside
Inward rectifier	TEA, Cs^+, Rb^+, Na^+, Ba^{2+}	H^+
Delayed rectifier	TEA, Cs^+, Ba^{2+}, H^+, 4-aminopyridine, dendrotoxin	TEA, Cs^+, Na^+, Li^+, Ba^{2+}
Ca^{2+}-activated	TEA, Cs^+, apamin	H^+
ATP-dependent	?	ATP, ADP

Not only the physical nature but also the physiological meaning of inward K^+ conductance is not clear. Apparently it cannot serve to balance the loss of K^+ during the impulse activity of excitable tissues since this is effectively accomplished in a short time by the Na^+, K^+ pump. It also cannot play any role in the recovery of the potential from any state of depolarizations not only because of uncertainities about the voltage-dependence but also because its direction is exactly the opposite of that which is required electrically. It is assumed that the regulation of RMP over short time intervals is different from that in the steady state and that inward rectification may provide a long-term determinant of resting membrane potential.

Ca^{2+}-activated K^+-channel

Calcium-induced changes in K^+ permeability were originally described in human erythrocytes incubated in the absence of glucose and with glycolysis inhibited. The increase in the resting membrane permeability in this case was attributed to a rise in intracellular Ca^{2+} since ATP depletion causes inhibition of plasma membrane Ca^{2+}-ATPase and cessation of active Ca^{2+} efflux. The Ca^{2+}-dependence of K^+ permeability has been confirmed in many cell types, for example in molluscan neurones injected intracellularly with Ca^{2+}, on *Amphiuma* red cells when the extracellular Ca^{2+} was increased, on human red cells by using the Ca^{2+} ionophore A 23187, and on metabolically damaged frog skeletal muscle where intracellular Ca^{2+} increases as a consequence of inhibited Ca^{2+}-transporting mechanisms in organells.

The existence of Ca^{2+}-activated K^+ channels has been directly demonstrated in a variety of cells including neurones, skeletal muscle cells, cardiac cells in culture and red blood cells by the patch clamp technique. The Ca^{2+}-activated K^+ channel has a high unitary conductance of 100 - 200 pS. It is outwardly directed, mediating K^+ efflux and is sensitive to both extracellular K^+ and intracellular Ca^{2+}. The channel is voltage dependent but cannot be opened by depolarization alone but by the simultaneous binding of Ca^{2+}. In rat skeletal muscle cells in culture there are two different classes of Ca^{2+}-activated K^+ channels with different pharmacological properties. One class of channel is inhibited by tetraethylamonium while the other class of channel is blocked by apamin, a bee venom polypeptide, and is resistant to TEA. Both types of channel are resistant to aminopyridines (Table 2). The Ca^{2+}-activated K^+ channel of erythrocytes is stimulated by calmodulin, an endogenous Ca^{2+}-binding protein, and the calmodulin antagonist, trifluoperazine, can block the Ca^{2+}-dependent increase in K^+ permeability in a sarcolemmal preparation.

The activation of Ca^{2+}-dependent K^+ channels by micromolar concentrations of Ca^{2+} is accompanied by membrane hyperpolarization. In cells which are not metabolically exhausted and where a Ca^{2+} pump is active, this hyperpolarization is transient as the Ca^{2+}-activated K^+ channels close spontaneously within about 30 sec when the Ca^{2+} pump responds to an increase in intracellular Ca^{2+}. Another possibility to explain transient activation of Ca^{2+} -dependent K^+channel is that the increase in intracellular Ca^{2+} causes a decrease in intracellular pH as mitochondria take up divalent cations in exchange for H^+ and the acidification of cytoplasma can inhibit Ca^{2+}-activated K^+ channels by competition between Ca^{2+} and H^+ for the binding site. It is therefore assumed that under physiological conditions almost all Ca^{2+}-activated K^+ channels are closed unless the concentration of Ca^{2+} needed to activate the channels is submicromalar so that they may be spontaneously active to some degree. This latter situation has been found in mouse myeloma cells where half-maximal concentrations for K^+ channel activation is 30 nM Ca^{2+}. In other cases the Ca^{2+}-activated channels are supposed to contribute to the resting membrane potential only in metabolically exhausted cells when intracellular concentration of Ca^{2+} is above a physiological level.

The hyperpolarization induced by metabolic poisons may be also due to activation of ATP-sensitive K^+ channels, which are sometimes observed more commonly than Ca^{2+}-activated K^+ channels (see latter). It is improbable that the only role of Ca^{2+}-activated K^+ channels would be to provide a link between metabolism and membrane permeability. Regarding the fact that Ca^{2+} is released from the organells into the cytoplasm under membrane depolarization, the Ca^{2+}-activated K^+ channel might also contribute to the slowly activated K^+-conductance changes during the recovery from the action potential in excitable cells. Another possible role for the Ca^{2+}-activated K^+ channel arises during development of muscle cells when an increase in intracellular Ca^{2+} parallels the increase in the resting membrane potential. It is suggested that the differentiation is accompanied by the appearance of high-conductance Ca^{2+}-activated K^+ channels (Fig. 2).

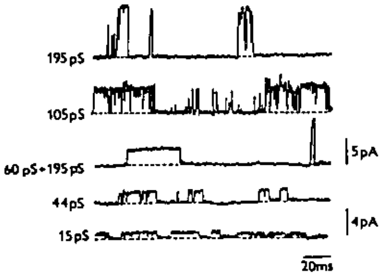

Fig. 2. Typical patch current recordings showing the activity of five K^+ channel types found in cultured chicken muscle cells. There are differences betwen myoblasts and myotubes in the percentage of incidence of individual channel types. High-conductance K^+ channels are most frequently to be observed in myotubes, but they are rare in myoblasts where low-conductance K^+ channels predominate (Zemková *et al.*, 1989).

ATP-dependent K^+ channels

Recently it has been shown using the patch-clamp technique that cardiac cells, pancreatic B cells and frog skeletal muscle contain K^+ channels which are sensitive to intracellular ATP (Table 2). These channels are outwardly directed, insensitive to $Ca^{2+}$and they are distinct from the K^+ channels associated with the ATP receptors in mammalian sensory neurones which are stimulated by ATP. ATP-sensitive K^+ channels are inhibited by ATP, they are stimulated by diazoxide and the hormone somatostatin. They are opened when the intracellular ATP decreases below 1 -2 mM but are closed at higher ATP concentrations. In skeletal muscle ATP-sensitive K^+ channel opening is influenced by membrane potential, so that it is partly inactivated by hyperpolarization. But in pancreatic B cells these channels are reported to be insensitive to membrane potential. Channel conductance decreases with reduction in K^+ concentration on the inner side of the membrane. Its unitary conductance is 48 - 60 pS which is lower than the unitary conductance of Ca^{2+}-activated K^+ channels.

The mechanism of action of ATP is not yet known but it is believed that ATP closes channels without being metabolized since ADP has almost the same effect. It has therefore been stated that ATP apparently increases the chance of the channel entering the closed state. The density of ATP-sensitive K^+ channels in skeletal muscle is reported to be as high as or even higher than that of the voltage-dependent K^+ channels involved in delayed rectification and to be higher than that of Ca^{2+}-activated K^+ channels in pancreatic B cells, but their physiological significance is not clear. In normal cells the ATP concentration is high (3 - 5 mM) and, at least in skeletal muscle, it is maintained stable by creatine phosphate and creatine kinase. This means that under normal physiological conditions these channels should be blocked by intracellular ATP and make no contribution to the resting membrane potential. It is believed that the primary role of the ATP-sensitive K^+ channels is to sense the intracellular ATP levels and to prevent both ATP depletion and irreversible changes in energy metabolism. A secondary function of these channels may be to participate in the regulation of resting membrane potential by cellular metabolism in metabolically exhausted cells where hyperpolarization is a familiar phenomenon, until now ascribed only to the increase in intracellular Ca^{2+} concentration.

Delayed rectifying K^+ channel

In voltage-clamped squid giant axons the total membrane potassium permeability declines almost linearly with membrane hyperpolarization. In skeletal muscle the total K^+ permeability also depends substantially on membrane potential. Voltage-dependent membrane conductance has been observed not only in excitable tissues where it has been extensively studied, but also in egg cells and in erythrocytes. The voltage-dependent K^+ conductance is apparently identical with the delayed rectification which is slowly activated by depolarization during action potential generation and which is directed outwardly i.e. mediates K^+ current going out from the cell. The delayed K^+ conductance can be blocked by TEA and related ammonium salts and by 4-aminopyridine and in special cases by dendrotoxin (Table 2). The selectivity sequence of this conductance is K^+, Rb^+, Cs^+, Na^+, Li^+, the last having a very low permeability.

The K^+ channel involved in delayed rectification has been identified in sarcolemmal vesicles, prepared from frog skeletal muscle by enzymatic treatment, as a K^+ channel with a unitary conductance of 15 pS. A similar low conductance channel of 18 pS has been identified in red blood cells. In squid axon the delayed rectifying K^+ current is the major outward current which is mainly responsible for the repolarizing phase of an action potential but in non-excitable tissues the function of these channels is still unclear.

The delayed rectifier in skeletal muscle is activated by depolarization to -40 mV, this voltage-dependent K^+ channel is therefore assumed not to contribute to the resting membrane potential. In the red blood cells this channel is also not considered to play a role in the regulation of RMP but to buffer the plasma K^+ concentration and to regulate plasma volume since the red blood cells RMP is determined mainly by Cl^- ions. Outward rectifying K^+ conductance in B lymphocytes can be modulated by second messengers and increases by interleukin suggesting the role for these channels in stimulated proliferation.

Transmitter-modulated K^+ channels

There is a group of K^+ channels in the nervous system which are modulated by neurotransmitters such as acetylcholine, serotonin and gamma-aminobutyric acid. In experiments on sensory neurones of *Aplysia* it has been demonstrated that a single class of K^+ channels is modulated in opposing direction by distinct neurotransmitters acting through distinct second messenger systems. The first second messenger system which has been recognized, and which received wide attention in neurotransmitter action, was the cAMP cascade : however, it is now clear that several other second messenger pathways play major roles in the nervous system, including cGMP and the products of phosphatydilinositol breakdown such as inositoltriphosphate (IP_3) and diacylglycerol, the activator of protein kinase C. In sensory neurones serotonin causes prolonged all-or-none closures of K^+ channels that are active at the resting potential and whose gating (opening and closing reaction) is relatively independent of voltage and is insensitive to internal Ca^{2+} concentration. Support for a role of cAMP comes from the finding that direct injection of cAMP or direct application of the catalytic subunit of purified cAMP-dependent protein kinase into the cell also closes single serotonin-stimulated K^+ channels.

It is supposed that the substrate involved in channel modulation is either the channel itself or another membrane protein adjacent to the channel. In smooth muscle cells and hippocampal neurons, epinephrine leads to an increase in K^+ current through a cAMP-dependent mechanism. This effect is antagonized by acetylcholine. The up- and down-modulation of K^+ channel activity contributes to presynaptic inhibition and presynaptic facilitation in these neurons.

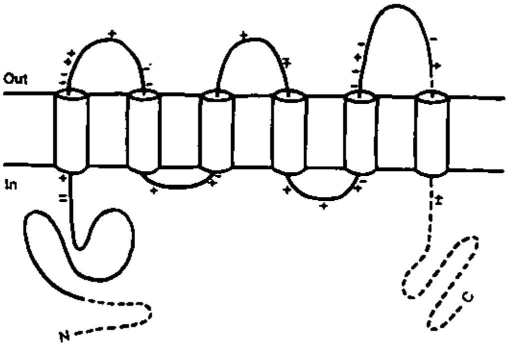

Fig. 3. Transmembrane folding model for a *Shaker* K^+ channel protein in the membrane. There are six membrane-spanning regions and the termini of polypeptide chain are assumed to be cytoplasmic. Approximate position of every charged amino acid residue in the linkers connecting the transmembrane segments are indicated. (Modified according to Tempel *et al.*, 1987).

Stretch-activated K^+ channels

Most cell membranes express stretch-activated ion channels which open with increase in membrane tension and behave as inward rectifiers. Stretch-activated channels can be further classified into two groups based on permeation properties : non-selective cation channels and K^+ selective channels. The non-selective channels are blocked by Ca^{2+} and other divalent cations including Zn^{2+}, Ni^{2+}, Mn^{2+}, Co^{2+} and Cd^{2+}. K^+ selective stretch-activated channels which are much more permeable to K^+ than to Na^+ are blocked by quinidine, Cs^+ and Ba^{2+}. A complete kinetic analysis of stretch-activated channel gating has only been done for chick myotubes where the gating energy was proposed to be a quadratic function of applied pressure. The channels have been found in a variety of cells : oocytes, red blood cells, hair cells, dorsal root ganglion neurones and epithelia cells. It is assumed that these channels play a crucial role in volume regulation but in muscle cells the stretch activated channels may be the mechanoelectrical transducing elements responsible for the initiation of stretch-induced contraction.

Expression of channels in oocytes

On the basis of the electrophysiological analysis of *Shaker* (a Drosophila gene) mutant, the *Shaker* locus has been cloned which encodes a structural component of voltage-dependent fast transient outward K^+ channel with properties of delayed rectifier. This hypothesis has been confirmed by expression studies in frog oocytes injected with *Shaker* DNA. The complementary DNA sequence predicts and integral membrane protein of about 70 kDa containing several membrane-spanning sequences (Fig. 3). The diversity of K^+ channels may be generated by alternatively spliced transcripts.

Conclusion

Potassium channels have been described mainly with respect to their function in excitable cells (Kolb, 1990) where different voltage-dependent K^+ channels define the shape and duration, time dependence and firing pattern of action potentials and may be involved in alterations in synaptic efficacy and learning. Since the K^+ currents are mainly inhibitory and responsible for repolarization, an increase in the K^+ conductance depresses electrical excitability. In non-excitable systems such as pancreatic B cells (insulin secreting cells), hepatocytes, renal epithelial cells and leukocytes K^+ channels are also involved in specific physiological functions. In pancreatic B cells, the rythmic electrical activity evoked by glucose is closely involved in regulation of insulin secretion and depends on variations of the K^+ permeability. In hepatocytes, the membrane K^+ permeability determines the rate of voltage dependent membrane transports of amino acids and glucose. In the nephron K^+ channels play a role in regulation of K^+ secretion together with the Na^+, K^+-ATPase. In many other cells K^+ channels are required for activation of cell proliferation, are involved in hormone-activated increase in protein synthesis, interleukin-2 production, thymidine incorporation and volume regulation. Comparison of single K^+ current properties in different tissues cannot help with final K^+ channel classification until the channels are not cloned and expressed, and the channel structure is not determined. The genetic approach is now in full progress and this combined electrophysiological and biochemical approach swould yield a valuable classification of the K^+ channels with respect to their contribution to the specific function of the cell concerned. It would provide a practicable way to improve our understanding of the physiological function of K^+ channels.

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Therapeutic Implications of Alterations in Endogenous Potassium Concentrations for Organ Functions

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Summary

This report briefly summarizes the advance in our knowledge of physiology of potassium regulation including the pathophysiological aspects of alterations of potassium homeostasis. This review focuses on the interaction of hypo- and hyperkalemia with drugs effects and on the drug interactions that can result in hypo- or hyperkalemia, as well. The paper deals with the most frequently used drugs (diuretics, antibiotics, hormones, mediator-like drugs, laxatives, cardiovascular drugs, non-steroid anti-inflammatory drugs) induced hypo- and hyperkalemia and with their interactions. It is especially important for clinicians to be aware of these drug-induced disturbances of K^+ homeostasis to avoid the unexpected complications.

1. Introduction

In the past decade, information has been accumulating on the occurence of drug-induced disturbances in potassium homeostasis and the influence of hypo- or hyperkalemia on the effects of drugs. The relationship between the alteration of potassium homeostasis and the actions of drugs are important because the drug-used different electrolytes disturbances appear to be a great part of unexpected iatrogenic disorders (Rado, 1987). Based on the excellent comprehensive recent reviews (Rado, 1987, 1989; Tannen, 1990) in this review we are shortly summarizing the physiology of potassium regulation and clinical sequelae of hypo-, hyperkalemia and focussing our interest to drug-induced potassium disorders and the drug-drug interactions in altered potassium homeostasis.

2. Potassium homeostasis and physiology of potassium regulation

In a normal, 20-year old man, total body content (TBK) is 58 meq kg^{-1}. This value is dependent on sex, age and muscle mass. About 90% of TBK can be found in the intracellular space and 1.4% in the extracellular fluid water compartment. The majority of intracellular K^+ is located within muscle, the remainder is in other organs and erythrocytes (Tannen, 1990). Potassium concentration in plasma (serum) corresponds to its concentration in extracellular fluid. Normal serum potassium concentration ranges from 3.5 to 5.0 meq l^{-1}. Hypokalemia is defined as a state in which K^+ concentration is below the normal range, while in hyperkalemia there is a rise above the normal range. Hypo- or hyperkalemia do not necessarily reflect a parallel change in intracellular potassium concentration. However changes in the intracellular potassium concentration are usually paralelled by alterations in serum concentration.

2.1. Normal dietary intake

Potassium homeostasis is regulated by dietary potassium intake, by elimination mechanism 90% by kidney (both are regarded as "external balance") and by the factors ensuring the maintenance of unequal distribution of K^+ between the intracellular and extracellular space ("internal balance"). The mechanisms responsible for K^+ regulation are listed in Table 1.

2.2. Factors affecting transcellular distribution

The intracellular K^+ content is regulated by a pump-leak mechanism. The Na-K pump catalysed by the enzyme Na-,K-ATPase ensures the transport of K^+ uphill into the cell exchanging for sodium from the cell into the extracellular space. The exit of K^+ from the cell is regulated by passive forces, leak mechanisms. The chemical gradient is greater than the opposing electric gradient (cell interior negative) and chiefly determines the membrane potential (log K_i/K_e). The leak process (K^+ exit into the extracellular space is opposed by the electrical gradient and favored by the chemical gradient) is regulated by the permeability characteristics of the membrane. The permeability of the membrane to K^+ is determined primarily by ion selective K^+ channels. Different types of K^+ channels exist in various tissues. The activity of K^+ channels is influenced by mediators, hormones and modulated by a variety of intracellular signaling mechanisms, including calcium, magnesium, ATP, cyclic AMP and guanine regulatory, proteins, (Greger, 1987; Rosati, 1986; Armstrong, 1986; Weiss, 1987; Findlay, 1987; Sasaki, 1987).

Table 1. Physiology of potassium regulation

2.1. Normal dietary intake
2.2. Factors affecting transcellular distribution
2.2.1. Acid-base alterations
  pH
  Bicarbonate
2.2.2. Pancreatic hormones
  Insulin
  Glucagon
2.2.3. Catecholamines
  β Adrenergic system
  α Adrenergic system
2.2.4. Aldosterone
2.2.5. Osmolality
2.2.6. Cellular K^+ content
2.2.7. Exercise
2.3. Renal regulation of potassium excretion
2.3.1. Plasma K^+ concentration
2.3.2. Flow rate
2.3.3. Sodium
2.3.4. Transepithelial potential difference
2.3.5. Anions
2.3.6. Adrenal hormones
  Aldosterone
  Glucocorticoids
2.3.7. Acid-base status
  Systemic pH
  Ammonia
2.3.8. Catecholamines
2.3.9. Antidiuretic hormone
2.4. Response to chronic manipulations of dietary K^+

The factors that modify the transcellular distribution of K^+ can act by influencing either the pump or the membrane permeability (function of K^+ channels). The most important factors that can modify the transcellular distribution of K^+ are considered in the following discussion:

Blood pH. Acidosis enhances K^+ exit from cells and tends to increase serum potassium concentration, while alkalosis acts in the opposite way.

Insulin. Data from studies of humans and experimental animals demonstrated that insulin deficiency impeded cellular uptake of K^+, resulting in hyperkalemia, while insulin excess promoted cellular K^+ uptake (DeFronzo, 1980; Silva, 1981; Sterns, 1981). The mechanism whereby insulin promotes K^+ uptake is not clear. Some data indicating that insulin hyperpolarizes muscle, increases Na^+ efflux and K^+ influx and stimulates Na-K-ATPase activity suggest the direct stimulative effects of insulin on the Na-K pump (Moore, 1973; Clausen, 1977; Zierler, 1985). Other investigators could not confirm this hypothesis (Stark, 1981). There are results which suggest that the stimulation of Na^+-H exchange by insulin may interact with alteration in Na-K pump activity (Moore, 1981; Rosic, 1985). It is clear, however that insulin-mediated K^+ uptake is independent of its effects on glucose uptake. Plasma potassium concentration directly affects pancreatic insulin release. An increase in plasma potassium stimulates insulin secretion, while low potassium content inhibits it. As insulin in turn stimulates cellular K^+ uptake resulting in alteration of plasma K^+ level, thus a potassium-insulin regulatory feed-back mechanism operates, modulating plasma potassium concentration (Bia, 1981).

Catecholamines. Catecholamines are important modulators of the distribution of potassium between the intracellular and extracellular fluid compartments. Circulating catecholamines as well as adrenergic nerve activity can influence cellular uptake (Silva, 1981; Tannen, 1983). β-adrenergic agonists promote cellular K^+ uptake by a cyclic AMP-dependent activation of Na-K pump (Silva, 1981). This effect is mediated by β_2-receptors, except in myocardium, where β_1 -receptors are responsible for this action (Brown, 1983; Ellingsen *et al.* 1987). Nonselective beta-blocking agents inhibit cellular K^+ uptake under basal conditions and also influence the stimulatory effects of β-adrenergic agonists (Vincent, 1985) In contrast to β-adrenergic stimulation, α-adrenergic agonists increase plasma potassium concentration by promoting hepatic potassium release and modifying muscle uptake (Bia, 1981; Vincent, 1985).

2.3. Renal regulation of potassium excretion

The regulation of potassium excretion is largely dependent on those factors that modify potassium secretion and /or reabsorption at distal nephron sites. Among these factors (Table 1) our interest was focused on adrenal hormones.

Aldosterone. Aldosterone is one of the most important hormones in regulation of potassium turnover. Aldosterone increases electrogenic sodium reabsorption and K^+ secretion by the cortical collecting tubule, stimulating the Na-K-pump activity (Thier, 1986). There is a renal interaction between aldosterone and potassium. Potassium directly influences aldosterone secretion in adrenal cortex. Thus in relation to aldosterone there is also a regulating feedback system. High plasma K^+ level stimulates aldosterone secretion and this results in an increase of urinary K^+ excretion, returning plasma K^+ concentration toward normal (Tannen, 1983) However, there are some observations in vivo suggesting the extrarenal effect of aldosterone on K^+ transcellular distribution, but direct aldosterone mediated tissue uptake of potassium has not been demonstrated.

Glucocorticoids. Glucocorticoids also stimulate potassium excretion and this effect seems to be independent of an action on mineralocorticoid receptors (Thier, 1986).

3. Hypokalemia

Hypokalemia can be manifested without a concurrent change in intracellular K^+ content (modifying the K^+ distribution across the cell membrane) and can be accompanied by cellular depletion as well. As potassium ions play a key role in the cell function hypokalemia causes complex and sometimes severe clinical manifestations.

3.1. Clinical symptoms of hypokalemia

A great part of the clinical symptoms of hypokalemia issues from abnormalities in membrane potential which determine the function of excitable tissues. Beyond the resting membrane potential, the threshold for provoking an action potential and certain parts of the repolarization phase of action potential are also determined by the relationship between the intra- and extracellular K^+ concentration. Therefore the most significant clinical manifestation of hypokalemia is its effect on cardiac, skeletal and smooth muscles. The clinical symptoms of hypokalemia are characterized by cardiac, neuromuscular, renal, fluid and electrolyte and endocrine phenomena.

In this paper we are dealing only with those clinical manifestations of hypokalemia which might be important from the point of view of hypokalemia-drug interaction. Hypokalemia can alter the cellular effect of a drug and thus it can modify its therapeutic effect.

Cardiac phenomena include the following :

predisposition to digitalis intoxication
abnormal electrocardiogram
ventricular ectopic rhythms
cardiac necrosis

Predisposition to digitalis intoxication. Hypokalemia potentiates the effects of cardiac glycosides on cardiac conductivity and can provoke digitalis intoxication. Hypokalemia predisposes to cardiac glycoside intoxication because the affinity of ouabain for the Na-K-pump is increased by a low external K^+ concentration and also because of the decrease in skeletal muscle ouabain binding sites induced by K^+ depletion (Clausen, 1986).

Abnormal electrocardiogram. Hypokalemia causes typical changes in the electrocardiogram, including flat T wave, depression of ST segment and prolongation of QT interval.

Ventricular ectopic rhythms. Hypokalemia increases the susceptibility for ventricular fibrillation and sensitizes the myocardium to epinephrine induced arrhythmias. It is not clear that hypokalemia directly accounts for development of arrhythmias or potentiates only catecholamine effect. Hypokalemia seems to be a risk factor in clinical circumstances where patients suffer ischemic heart disease or are subjected to anesthesia.

Hypokalemia can modify the potency of some antiarrhythmic agents. Lidocaine does not act on the maximal rate of rise and on the repolarization phase of cardiac action potential in low or normal external potassium concentration. The explanation of this ineffectiveness of lidocaine is that lidocaine mainly binds and acts on the inactivated sodium channels and under physiological or hypokalemic condition very few sodium channels are in the inactivated state (Kecskeméti, 1991).

Skeletal muscle phenomena. Muscular weakness, fatigue, cramps, the restless leg syndrome, paralysis and rhabdomyolysis can be observed with the degree of potassium depletion (Tannen, 1990). These disturbances are due the consequence of the alterations of skeletal muscle membrane functions induced by hypokalemia. The membrane potential is decreased and the number of Na-K pump units is diminished (Knochel, 1982).

Endocrinological effects. Hypokalemia increases plasma renin and decreases aldosterone level, modifies the number and affinity of angiotensin II receptors on adrenal and vascular tissues. This diminished sensitivity to the pressor effects of angiotensin II results in a decreases in systemic vascular reistance and blood pressure. The pressor response to vasopressin is also depressed in hypokalemia. Hypokalemia lowers the blood pressure in both normotrensive and hypertensive animals (Tannen, 1990). The most important endocrinological disturbances associated with potassium defiency is the development of glucose intolerance which results from decreased insulin secretion.

3.2. Drug-induced hypokalemia

Many drugs frequently used in clinical practice can be implicated in potassium regulation and induce hypo,-or hyperkalemia. Drugs can induce hypokalemia by causing potassium depletion (negative external balance) and by enhancing cellular potassium uptake (change of internal balance). Mechanisms responsible for drug-induced hypokalemia and the currently identified drugs are seen in Table 2.

Gastrointestinal potassium loss. Hypokalemia can occur from gastrointestinal losses (diarrhoea, vomiting) via several complementary mechanisms. Any drugs causing vomiting or diarrhoea can induce hypokalemia. Clinically this phenomenon is most often seen in patients abusing laxatives or purgatives. The clinical setting (symptoms, laboratory values) of these patients sometimes mimic Barter's syndrome (pseudo-Barter syndrome) (Rado, 1987).

Relatively inadequate potassium intake. During the therapy of severe anemia hypokalemia can be developed as a result of a demand for potassium to support cell growth which exceeds the amount of potassium intake.

Table 2. Drug-induced hypokalemia

Mechanism	Drug
1. Potassium depletion	
1.1. Extrarenal origin	
1.1.1. Gastrointestinal potassium loss	laxatives
1.1.2. Relatively inadequate K^+ intake	drugs used in the therapy of severe anemia (Iron, B_{12})
1.2. Renal potassium loss	
1.2.1. Diuretics	a. carbonic anhydrase inhibitor b. thiazide compounds (chlorothiazide, hydrochlorothiazide, bendroflumethiazide, chlorthalidone, etc.) c. loop diuretics (furosemide, ethacrinic acid muzolimine, piretanine, bumetadine) d. osmotic diuretics, mannitol, glucose
1.2.2. Antibiotics	a. penicillin, carbenicillin, nafcillin, etc. b. aminoglycosides : gentamycin, tobramycin
1.2.3. Hormones	a. steroids (glucocorticoids, mineralocorticoids) b. drugs with steroid-like effects : liquorrice-glycirrizid acid, carbonoxolone
1.2.4. Miscellaneous drugs	levodopa, gossypol, cisplatin
2. Change of K^+ transcellular shifts (redistribution)	
2.1. Glucose (through insulin)	
2.2. Hormones, mediators	a. insulin and oral antidiabetics b. aldosterone and other mineralocorticoids (DOCA, fludrocortisone, etc.) c. beta-adrenoceptor agonists (epinephrine, isoproterenol, salbutamol, prenarterol, etc.)
2.3. Miscellaneous drugs	barium ingestion, B_{12}, theophylline, toluene intoxication, calcium channel blockers

Potassium depletion of renal etiology

Diuretics. As sodium and potassium are reabsorbed in parallel diuretics decreasing sodium reabsorbtion in the proximal tubule and the thick ascending limb of the loop of Henle, where potassium reabsorbtion also runs on, will simultaneously increase potassium excretion. In addition to their above-mentioned effect, diuretics also promote potassium secretion (carbonic anhydrase inhibitors). The question is open about what magnitude of diuretics-induced potassium loss is clinically important (Tannen, 1990, Rado, 1989). Moreover, the necessity, the form and quantity of potassium supplementation or sparing are also widely discussed (Tannen, 1987; Rado, 1989). Of interest and potential therapeutic importance, some diuretics and diseases (myocardial infarction) cause magnesium depletion .As the ability of potassium to enter cells is influenced by magnesium, supplementation with magnesium might be important in the therapy.

Antibiotics. Large doses of penicillin or penicillin derivatives (ampicillin, nafcillin, carbenicillin, ticarcillin, amoxicillin) and cephalexin result in renal potassium loss. Increased renal potassium excretion results from their poorly resorbable negatively charged property. Aminoglycosides result in both potassium and magnesium loss.

Hormones. A syndrome of mineralocorticoid excess (hypertension with hypo-kalemia) was observed using nasal spray containing a high dose of mineralocorticoid. Carbenoxolone is an effective anti-ulcer drug with mineralocorticoid activity. True licorice contains glycirrihizic acid, a potent mineralocorticoid. As chewing tobaccos contain true licorice their use result in the development of a clinical syndrome very similar to primary hyperaldosteronism (Brass, 1982).

Miscellaneous drugs. Levodopa (L-DOPA) during the treatment of Parkinson's disease causes increased potassium excretion (Brass, 1982). Using cisplatin both hypokalemia and hypomagnesia can be observed.

Change in the redistribution of potassium

Hormones and mediators. Insulin, catecholamines and in a lesser degree, aldosterone all increase the potassium entry into the cell and result in hypokalemia. Excess insulin occurs in two clinical settings. First in healthy patients applying acute glucose load and secondly in the diabetics patient given exogenous insuline. The increase in endogenous catecholamine release accompaning severe acute pathologic condition (acute myocardial infarction, head injuries, open heart surgery) also causes transient hypokalemia. Hypokalemia has been reported after the administration of non selective beta-adrenergic agonists (epinephrine, isoprenaline) and selective beta$_2$-agonist (salbutamol, terbutaline, fenoterol) for the therapy in asthma and premature labour.

Miscellaneous drugs. These drugs result in hypokalemia by different mechanisms. Theophylline enhances the release of catecholamines and insulin and directly increases cyclic AMP. Barium induces hypokalemia by specifically blocking the channels for potassium exit from cells. Calcium channel blockers inhibit calcium-activated K^+ channels resulting in a decrease in cellular K^+ efflux.

4. Hyperkalemia

Hyperkalemia can occur in conditions that cause potassium retention and as a result of a variety of endogenous and exogenous factors that can modify the redistribution of potassium across the cell membrane. Glucagon and somatostatin (by inhibition of insulin secretion) and catecholamines with high alfa-receptor activity which are the most important endogenous substances result in hyperkalemia by inhibiting K^+ uptake or enhancing K^+ efflux. Potassium retention results from either increased potassium intake or diminished renal potassium excretion. This latter is the determinant mechanism. Under these circumstances clear-cut increases in cellular potassium content have not been demonstrated, presumably because retention of a relatively small quantity of potassium results in life-threatening hyperkalemia.

4.1. Clinical sequelae of hyperkalemia

The most important manifestations of hyperkalemia similarly to hypokalemia result from aberations in membrane polarization of excitable tissue. The membrane is depolarized because the ratio of K_i/K_e is decreased. The major clinical manifestations of hyperkalemia result from this depolarization. The most prominent and sometimes severe symptoms of hyperkalemia occur in the heart.

Cardiac symptoms. Hyperkalemia induces typical alterations in the electrocardiogram. The T wave becomes peak and tented, P-R interval and QRS complex are prolonged. In very severe, life-threatening hyperkalemia P wave is no longer recognizable and either ventricular fibrillation or arrest follows. These signs result from the impaired cardiac conduction by hyperkalemia. The hyperkalemia-induced depolarization inactivates the fast sodium channels but tends to activate the slow Ca-channels. The slow Ca^{2+}-

dependent action potentials evoked by these latter channels are responsible for a certain type of arrhythmias. Such slow response action potentials can be observed in cardiac preparations obtained from patients submitted to open-heart surgery (Kecskeméti, 1985).

Neuromuscular effects. Paresthesia, weakness and flaccid paralysis characterize the presence of hyperkalemia.

Endocrinologic manifestations. The endocrinologic effects including increased aldosterone, insulin, glucagon and catecholamines secretion, do not result in clinical problems.

Hemodynamic effects. High potassium intake lowers blood pressure both in hyperkalemic animal models and human. This action is attributed to a decrease in peripheral vascular resistance. High potassium diet, independently of antihypertensive action may protect against the development of stroke.

4.2. Drug-induced hyperkalemia

The drugs that frequently induce hyperkalemia and their mechanisms of action can be seen in Table 3.

Potassium containing drugs and foods

The most frequent sources of exogenous potassium are the various potassium supplements (both oral and parenteral) or salt substitutes. Extensive statistical study demonstrated the incidence of hyperkalemia in elderly patients with renal insufficiency; in those receiving potassium both orally and intravenously; in those receiving potassium in combination with diuretics; in patients receiving high-dose intravenous injection of potassium-penicillin (Rado, 1987).

Table 3. Drug-induced hyperkalemia

Mechanism	Drug
1. Via potassium containing drugs, foods and fluids	Potassium chloride, citrate, etc. Penicillin. Blood transfusions
2. Via suppression of renal potassium excretion	
2.1. Aldosterone antagonists	spironolactone, canrenone, K canreonate
2.2. Pseudoantagonists	triamterene, amiloride
3. Via selective hypoaldosteronism	
3.1. Renin suppression	a. non-steroid anti-inflammatory drugs b. cyclosporine c. beta-adrenergic agents
3.2. Angiotensin suppression	converting enzyme inhibitors
3.3. Inhibition of aldosterone biosynthesis and secretion	heparin, calcium chanel blockers
4. Change in redistribution of potassium	
4.1. Suppression of insulin secretion	somatostatin, glucagon (?)
4.2. Hyperosmolality	hypertonic saline and glucose
4.3. Adrenergic activity	beta-$_2$ antagonists, alfa agonists
4.4. Na-K ATP-ase inhibition	digitalis
4.5. Depolarizing agents	succinylcholine
4.6. Ion exchange	arginin infusion
4.7. Rhabdomyolysis inducing agents	narcotics and sedatives
4.8. Other cell lysis inducing agents	chemotherapy
4.9. Increased leak of K^+ and renal failure	fluoride, amphotericin

Suppression of renal potassium secretion

Aldosterone and *Pseudoantagonists.* Potassium sparing diuretics acting on the distal tubules all inhibit K^+ secretion, although their mechanisms of action differ. Spironolactone, canrenone, K^+ canrenoate act as competitive mineralocorticoid antagonis, while, amiloride, triamterene impair potassium secretion by an aldosterone-independent action. Hyperkalemia is the most frequent adverse effect of these drugs.

Drug-induced selective hypoaldosteronism

Many drugs can result in hypoladosteronism and hyperkalemia by different mechanisms.

Renin suppression. Non- steroid antiinflammatory drugs (indomethacin, ibuprofen, naproxen, fenoprofen, piroxicam) can cause clinically significant hyperkalemia by inhibiting the renin-angiotensin-aldosterone system. The underlying mechanism presumably relates to inhibition of the prostaglandins-mediated stimulation of renin secretion. In addition to producing hypoaldosteronism, they interfere with renal potassium secretion and inhibit cellular potassium uptake by preventing insulin secretion. Beta-blocking drugs can decrease renal renin release and tend to increase serum potassium level. Hyperkalemia has been reported in patients with immunosuppressive agent, cyclosporine. It causes a hyporeninemic hypoladosteronism syndrome and impairs potassium excretion.

Angiotensin converting enzyme inhibitors (Captopril). These drugs cause hypoaldosteronism by reducing angiotensin II level. Significant hyperkalemia has been observed only in patients with abnormal renal function. Coadministration of converting enzyme inhibitors with diuretics causing potassium loss decreases the magnitude of the potassium deficit.

Inhibition of aldosterone biosynthesis and secretion. Heparine blocks aldosterone biosynthesis by inhibiting enzyme .18-hydroxylase. Hyperkalemia has been produced with doses of 20000 unit/day. Calcium channel blockers can inhibit aldosterone secretion but hyperkalemia has not been reported because these drugs also enhance cellular potassium uptake.

Change in redistribution of potassium across cell membrane

Suppression of insulin secretion and *Hyperosmolality.* Suppression of insulin secretion is the main mechanism by which somatostatin and glucagon induce hyperkalemia.

Adrenergic activity. Alfa agonist, phenylephrine decreases cellular potassium uptake and tends to induce hyperkalemia. Beta-blockers chiefly selective beta$_2$ blockers preventing the enhancing effect of catecholamines on cellular potassium uptake can increase plasma potassium concentration. Beta-blockers may heighten and prolong the exercise-induced or other drug-induced hyperkalemia. Therefore in these cases the use of beta-antagonists must be disregarded or the administration of selective beta$_1$-blocker is recommended.

Na-K-ATP-ase inhibition. Cardiac glycosides inhibit Na^+-K^+ pump activity and result in increase of extracellular potassium and intracellular sodium concentration. Therapeutic dose of cardiac glycosides causes small increase in serum K^+ concentration. Hyperkalemia has occurred with overdose with these drugs and severe hyperkalemia usually causes mortality.

Depolarizing agents. The depolarizing muscle relaxant, succinylcholine increases K^+ efflux of muscle cells. The risk of hyperkalemia can be accentuated in patients undergoing anaesthesia. Increase in susceptibility to narcotics and to increased sympathetic activity can be observed.

Rapid necrosis of large numbers of cells releases potassium and causes severe hyperkalemia. The treatment of leukemia, lymphoms with chemotherapeutic drugs has been reported to cause hyperkalemia.

Increased K^+ efflux. Rapid infusion of amphotericin has caused hyperkalemia and ventricular arrhythmia by increasing potassium efflux from the cells. Fluoride by enhancing potassium efflux and by renal effect causes hyperkalemia and hypocalcaemia. Between these two ionic disturbances, there is a potent synergism that results in ventricular arrhythmias.

5. Conclusion

Potassium homeostasis is regulated by both factors that determine K^+ intake and renal excretion ("external balance") and by those that ensure the distribution of potassium between the intracellular and extracellular space ("internal balance"). Disturbance in either of these two regulatory sytems results in hypo,-or hyperkalemia. Hypo-and hyperkalemia modify the effects of different drugs and many drugs induce hypo,- or hyperkalemia, as well. Diuretics, mineralo- and glucocorticoids, beta-adrenoceptor agonists are the most important drugs which induce hypokalemia, while K^+-sparing diuretics, non-steroid antiinflammatory drugs, cardiac glycosides, beta-receptor antagonists, angiotensin-converting enzyme inhibitors frequently cause hyperkalemia. It is therefore important with any disturbance of K^+ homeostasis to consider carefully the rationality for a drug therapy and assess the relative risk and benefits of treatment.

Acknowledgements

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Potassium Concentration in Beverages as a Guidance for Potassium-Threshold Levels in Drinking Water

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Summary

The EC Directive on the quality of water for human consumption has established for potassium a guide level of 10 mg l^{-1} and a minimum admissible concentration (MAC) value of 12 mg l^{-1}. There are obviously no health-related reasons for the determination of such low limit values in drinking water, since the potassium concentrations in beverages are substantially higher (e.g. fruit juices contain up to 2270 mg l^{-1}). The aim of this contribution is to point out this discrepancy. In this connection, it is important to consider the significance of potassium in physiological processes, including the probability of dietary potassium deficiency or excess and other health effects like the possible influence on blood pressure. The levels of potassium found in the food chain clearly show that beverages including tap water still represent 13.5% of the daily potassium intake and have no health relevance in relation to the total potassium intake through solid foods. In conclusion, it would be unsound from the viewpoint of nutritional medicine to take the potassium concentrations in beverages as a guide for the corresponding level in drinking water. The same applies to the determination of a limit value for potassium itself.

Key words : potassium; health effects; food chain; occurrence; daily intake.

1. Introduction

Directive 80/778/EEC on the quality of water for human consumption is intended for use by the member states as a basis to harmonize their legislation, and thus to ensure the safety of drinking water supplies in the whole community (1). This EC Directive establishes for potassium a guide level of 10 mg l^{-1} and a maximum admissible concentration (MAC) value of 12 mg l^{-1}. WHO and USEPA do not consider this parameter (2,3).

For potassium and certain other substances, there is obviously no health-related, and thus, no uniform principle for the determination of limit values. In addition, according to Article 9 of Directive 80/778/EEC deviations from the limit value are permissible in the cases of potassium and some other substances such as magnesium and sulphate, if necessary for geogenic reasons. In this connexion, values have been determined only for sulphate for reasons of health. With regard to infants, the content of sulphate should not exceed 500 mg l^{-1} because of its laxative effect (4).

The determination of an admissible limit value for potassium of 12 and 50 mg l^{-1} drinking water, respectively, (5) is of no importance for health due to its low share in the total potassium intake. Levels of more than 12 mg potassium l^{-1} would be objectionable only if this would indicate fecal contamination. In such cases, the potassium content in drinking water would be higher than the sodium content (6). Apart from that, there is neither a physiological nor toxicological justification for such a low limit value for potassium (7). As is generally known, many beverages which are recognized as being wholesome contain distinctly higher potassium concentrations than drinking water.

Therefore, the objective of this contribution is to point out this discrepancy. First of all, I would like to consider, for a better understanding, the significance of potassium in the human organism, in particular with regard to the health effects of a potassium deficiency or excess, before treating the subject proper, i.e. the occurrence of potassium in beverages, in order to show the value of this element in the food chain in relation to an unnecessarily low limit value of potassium in drinking water.

2. Significance of potassium

2.1. Physiology

Potassium is essential for normal growth and existence. Total body potassium amounts to about 2000 mg kg^{-1} body weight, that is about 140 g for the average adult. At least 95 per cent of this is intracellular, occurring in cell water at a concentration of 150 mM (5.9 g l^{-1}), more than 30 times the concentration at which it is found in plasma and interstitial fluid (3.5 to 5.5 mM). This compartmentalisation of potassium is maintained by the energy-dependent so-called sodium pump (8,9). This process is fundamental to the cellular uptake of molecules against electrochemical and concentration gradients, to the electrophysiology of nerves and muscle, to acid-base regulation, and to the maintenance of normal blood pressure (10,11).

More than 90% of ingested potassium is absorbed from the gastrointestinal tract, but higher or lower intakes are not reflected in fluctuations in plasma potassium concentrations because the kidney can regulate potassium balance. Potassium is lost from the body in urine and gastrointestinal secretions, whereas only minimal amounts are excreted in sweat. To maintain normal body stores and a normal concentration in plasma and interstitial fluid, an intake of about 1600 mg per day may be needed. Therefore, the estimated minimum potassium requirement of healthy persons over 18 years was fixed at up to 2000 mg per day (12,13).

2.2. Potassium deficiency and excess

Potassium deficiency arising from an inadequate dietary intake is unlikely because of the ubiquity of potassium in foodstuffs. The most important cause of deficiency is excessive losses, usually through the gastrointestinal tract or the kidney. Large alimentary potassium losses may occur through prolonged vomiting, chronic diarrhoea, or laxative abuse. The most common cause of excessive renal loss is drug-induced, especially by diuretic agents. Some forms of chronic renal disease and metabolic disturbances can also lead to severe potassium loss. The chief symptoms of potassium deficiency are muscular weakness and mental confusion. The effects on cardiac muscle are reflected by electrocardiographic changes characteristic of impaired polarization which may lead to arrhythmia and cardiac arrest. Similar functional changes in the intestinal muscle can cause paralytic ileus; this leads to abdominal distension, which may be an important early sign of potassium deficiency, especially in children. Since potassium is an important component of lean tissue, potassium deficiency can impair growth in children, in particular in those recovering from protein-energy malnutrition.

The effects of potassium excess are only reported as a result of sudden enteral or parenteral increases of potassium intake to levels about 250 mg kg^{-1} body weight (18 g) for an adult. Such an excessive dose may induce acute intoxication (hyperkalaemia) which may also cause sudden death by stopping the heart. As long as renal function is normal it is almost impossible to induce potassium excess on habitual dietary intakes (1.6 to 5.9 g d^{-1}). Intake from drinking water represents less than 1 percent of the total daily intake. In individuals with impaired renal function, adrenal insufficiency or liver cirrhosis, the threshold for acute toxicity may be lower, at 80 to 100 mg kg^{-1} body weight (14,15).

In the case of patients with disturbances of the potassium balance, constant control of the serum potassium level and of the potassium intake via food (vegetable food rich in potassium!) are necessary. The contribution of potassium from drinking water to the total potassium intake has to be ignored also under this aspect so that there is no reason for the determination of a low limit value for potassium in drinking water from the viewpoint of health (7).

2.3. Other health effects

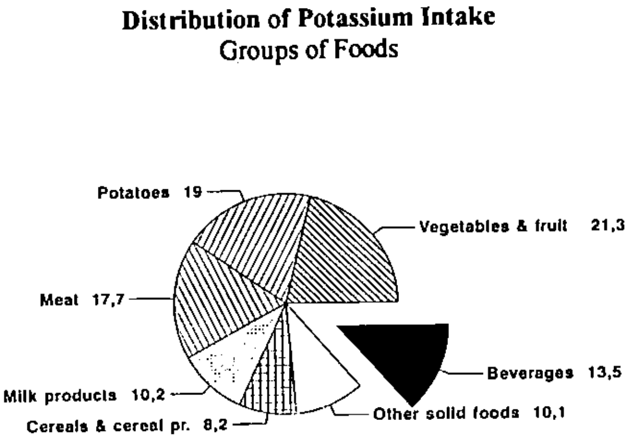
There is considerable evidence that dietary potassium exerts a beneficial effect in hypertension, and recommendations for increased intake of fruit and vegetables (16) would raise the potassium intake of adults to about 3.5 g per day. In the Intersalt study, urinary potassium excretion, an assumed indicator of potassium intake, was negatively related to blood pressure as was the urinary Na:potassium concentration ratio (17). Increasing potassium intakes to above levels achievable with customary diets reduced blood pressure in normotensive and hypertensive individuals and increased urinary sodium loss (18,19). Although some studies contradict these findings, a meta-analysis of published reports suggests that such observations are valid (20).

3. Occurrence in the food chain

It was accepted that, in the evaluation of the health effects of any inorganic constituents, all routes of exposure had to be considered when deciding upon a value for drinking water (2,31). Occurrence of potassium in the food chain includes solid foods, beverages and drinking water.

3.1. Solid foods

Among the solid foods, potassium is particularly abundant in vegetables, potatoes, fruit (especially bananas) and cereals. High concentration of potassium is also found in meat, fish, some milk products and egg (21,22,23,24). Consuming a mixed western diet, the reported average intakes of potassium were in the range of 2.8 to 4.5 g/day (24,25,26,27,28). For example, in the Federal Republic of Germany (before 1990) women and men consumed a total amount of 3.2 and 3.77 g potassium/day, respectively (27). The mean percentage contribution of food commodity groups to the mean daily potassium intake is given in Fig. 1. The main sources of potassium were vegetables and fruit (21.3%), potatoes (19%), meat (17.7%), milk products (10.2%) and cereal products (8.2%). All solid foods together contribute about 87% of the potassium supply.


Distribution of Potassium Intake
Groups of Foods

Data from Ernährungsbericht 1988

Fig. 1. Main sources (%) of the daily potassium intake per capita.

3.2. Beverages

As shown in Fig. 1, beverages including tap water still represent 13.5% of the daily potassium intake. However, to get more precise information about the contribution of various beverages to the intake of this element, it is important (i) to know the different potassium concentrations in beverages in comparison with drinking water, and (ii) to have more data about the consumption of various alcoholic and non-alcoholic beverages by adults in detail.

Table 1. Potassium Concentration in Different Beverages (mg kg^{-1})

	Mean	Range	Reference
Tap water	2.2	(0.1-40.3)	(7)
Mineral water	21.2	(0.9-322)	(7)
Coffee	880	-	(21)
Tea	170	-	(21)
Milk	1570	(1440-1780)	(23)
Fruit juices	1570	(1060-2270)	(23)
Soft drinks	67	(0.1-462)	(29)
Beer, light	380	(320-440)	(23)
Wine, white	820	(660-920)	(23)

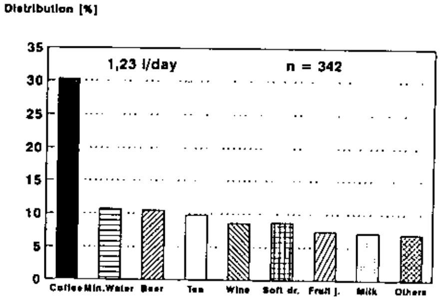
Table 1 indicates the means and ranges of potassium concentrations in different beverages and tap water. The highest mean levels (1570 mg kg^{-1}) were found in natural fruit juices and milk. By contrast, soft drinks like Coca Cola or fruit-flavoured drinks contained relatively low levels of potassium (mean value 67 mg kg^{-1}). The great variation in the latter depends on the kind of preparation. Fruit-flavoured drinks prepared from concentrate had a higher potassium content than those prepared from crystals (29). In comparison with soft drinks, coffee or tea infusions contained more potassium. In the case of coffee the mean potassium content will depend on the time of infusion. After 20 minutes infusion, the potassium concentration increased to 1100 mg kg^{-1} (21).

The alcoholic beverages, especially wine and beer, have also substantially higher mean levels of potassium (820 and 380 mg kg^{-1}) in comparison with drinking water (2.2 mg kg^{-1}).

However, data on composition of beverages say only little about the actual burden in humans. Therefore, a second step in any nutritional or health evaluation relating to the contributions of non-alcoholic or alcoholic beverages to the daily intake of potassium must be to estimate the consumption of beverages by adults.

For this purpose, the results of a representative inquiry involving 723 women and men aged 17-90 were used (30). According to this inquiry, women consumed altogether 1.23 l day^{-1} of beverages (Figure 2). 30% of the total consumption was coffee, whereas the share of alcoholic beverages was altogether 19%. The consumption of mineral water (11%) by women was higher as compared to fruit juices and milk with 7% each.

Consumption of Beverages
West German Women

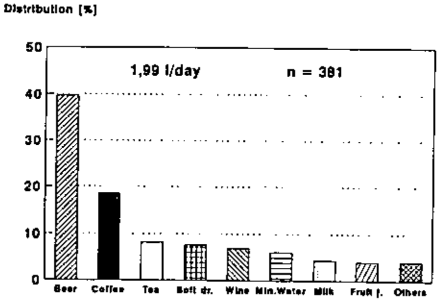


Data from Diehl & Elmadfa (1986)

Fig. 2. Share of various groups of beverages in the total consumption of West German women.

Men consumed altogether more than women, i.e. 1.99 l day^{-1}. In this case, the higher consumption was due to alcoholic beverages (Figure 3). As can be seen, men in western Germany prefer beer which comprises 40% of the total consumption of beverages. In Czechoslovakia, there is probably a similar drinking behaviour, whereas in France more wine than beer and in the United Kingdom, mainly tea is consumed (31).

Consumption of Beverages
West German Men



Data from Diehl & Elmadfa (1986)

Fig. 3. Share of various groups of beverages in the total consumption of West German men.

For this evaluation, the amount of potassium provided by each beverage was calculated by multiplying the considered content of the element (cf. Table 1) by the estimated average consumption of each beverage group (cf. Figs. 2 and 3).

As a result of these calculations, it can be determined that in the case of women, in the first line coffee accounts for about 42% of the total potassium intake via beverages (Fig. 4). In spite of the low consumption of fruit juices and milk, they contribute about 18% because of their high content of potassium. The alcoholic beverages, wine and beer, still provide 17%. Contrary to this, the potassium intake from tea (2.6%) or from the other beverages (1.9%) which include all soft drinks, mineral water as well as drinking water, has practically no importance for the total potassium intake of women from drinks.

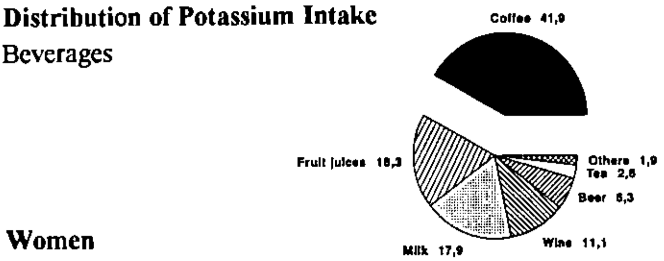


Fig. 4. Percentage of the contribution of various groups of beverages to the average daily potassium intake of women in Germany.

As concerns men, alcoholic beverages provide altogether 39%, coffee, 31%, milk, 13% and fruit juices, 12% of the total potassium intake from beverages (Fig. 5). The contribution from tea (2.6%) and other beverages (1.7%) such as soft drinks, mineral water and drinking water is negligible.

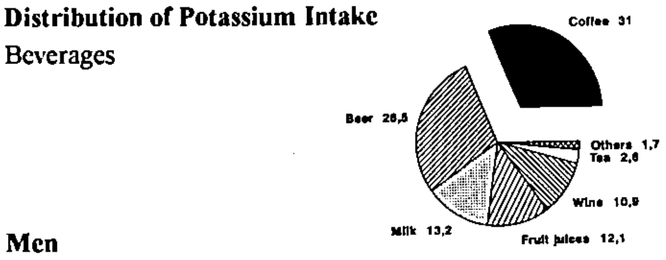


Fig. 5. Percentage of the contribution of various groups of beverages to the average daily potassium intake of men in Germany.

These results are in accordance with a study performed in France which reveals that alcoholic beverages (wine, beer) formed 35% of the daily consumption of beverages and thus represented an essential source of potassium from beverages also in France. Altogether, the share of potassium from beverages in the total potassium supply was given as 12% (32).

3.3. Drinking Water

When calculating the contribution of tap water to the total potassium intake, the various routes of water consumption have to be considered (Table 2).

Table 2. Survey of Human Water Intake Routes

Route	Mean estimated quantity (% of total)
Local Tap water (drinking water, coffee, tea, soup, water for boiling, baking etc.)	60
Non-local drinking water (beer, soft drinks)	10
Non-drinking water (milk, wine, citrus juice, meat, vegetables)	30

Data from Zoetman & Brinkmann, 1975.

The amount of the local tap water consumed directly as drinking water was, on average, only 12 ml day^{-1} for women and men in the above-mentioned inquiry (30). This low average value was due to the fact that ca. 10% of the interviewed persons said they drank tap water. 800 ml day^{-1} was the highest amount consumed. In contrast to this, a maximum consumption of 2875 ml and 2750 ml day^{-1}, respectively, were recorded for coffee and tea (30).

In order to consider all deviations adequately, a total consumption of 2 l day^{-1} is generally taken as a basis when exposure to a substance is considered (31). Therefore, if the average or maximum concentration of potassium in drinking water (2.2 and 40.3 mg l^{-1}) determined in the Federal Republic of Germany were taken as a basis, only 4 and 80 mg potassium would be incorporated via this route. For this reason, the contribution of drinking water to the total potassium intake (3770 mg day^{-1}) should be ignored from the viewpoint of nutritional physiology. It is, on an average, only 0.1% (7). The share of potassium in the total potassium intake may increase to 13.5% from beverages (cf. Fig. 1). Finally, this amount of potassium from beverages has no health relevance as compared with the contribution from solid foods.

4. Conclusions

In consequence of the nutritional and health evaluation of potassium in water and the levels found in beverages and solid foods, the MAC value for potassium in drinking water is unnecessarily low. From the point of view of nutritional medicine, a health relevance cannot be derived as an argument.

Although the contribution of potassium from beverages such as milk and fruit juices is considerably higher, it is, however, of minor importance in relation to the total potassium intake through foods.

For this reason, it would be unsound from the viewpoint of nutritional medicine to take the potassium concentration in beverages as a guide for the corresponding level in drinking water and the same applies to the determination of a limit value for potassium itself.

References

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Coordinator's Report on Session 3

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The interest of an agronomist in a session devoted to potassium in the food chain is twofold :

1. Knowledge of K requirements of man and influence of K on health;
2. Determination of the possible impact of K fertilization of crops on man's health.

It is important to answer these questions in order to determine whether present K fertilizer treatment of crops should be modified.

The role of potassium in the plant is well known. The function of more than 60 enzymes depends on optimal K^+ concentration in the cytoplasm. An important role is also attributed to potassium in maintaining water balance in the plant. Indeed, plants suffering from K deficiency are usually considered more drought susceptible, more liable to frost damage and less resistant to the effects of salinity. K fertilizer is also considered to have moderating effects with respect to plant diseases. Plants which are well supplied with potassium are less sensitive to fungal and bacterial diseases and also to pest infestations. From an agronomic point of view therefore there is no reason to limit K fertilizers unless there is a harmful influence on man or the environment.

We learned from the papers presented in this session that total body potassium accounts for 2 g kg^{-1} body weight, i.e. about 140 g on average for an adult man or woman. According to R. Grossklaus, the minimum need for man has been established as 2000 mg per day in order to maintain normal body reserves and a normal K^+ concentration in plasma and interstitial fluid. Additional K intake does not seem to present any disadvantages. The amounts which are not required are eliminated mainly by the kidneys but also by gastro-intestinal secretion. Kecskeméti and Grossklaus even mention the beneficial effect of a high potassium diet for people suffering from hypertension. Indeed high potassium intake lowers blood pressure.

Professor Anke stated that intakes by adults vary between 1875 and 5625 mg day^{-1} K in the USA and Germany. In a group of people in Germany, he noted average intakes of 2500 and 3200 mg day^{-1} K for women and men respectively. An exhaustive investigation of K in foods and beverages showed very important differences in the K content of foods.

Those rich in lipids (butter, cheese, sausages) are poor in K while many vegetables (cabbage, lettuce, potato), coffee, fruit juices and milk are K-rich. As a result, the quantities absorbed by man seem to depend mainly on diet and not on the fertilizers applied to crops.

However, Grossklaus points out that an EEC guideline (80/778) sets the maximum admissible concentration (MAC) of drinking water at 12 mgl^{-1} K whereas the WHO does not suggest such a threshold level for K, as it obviously has no relevance to health. According to Grossklaus, mineral waters contain on the average more than 20 mgl^{-1} K; consequently, many of these should be considered undrinkable according to the EEC directive. Grossklaus also reminds us that the intake of K^+ in drinking water is only about 0.1% of total daily intake and, consequently, the MAC for K in drinking water is unjustified. Possible faecal contamination in drainage, ground and drinking water should therefore be detected by factors other than the simple determination of K as a tracer element.

Professor Kecskeméti noted the therapeutic implications of alterations in endogenous K^+ concentration. Potassium deficiency involves a weakening of the skeletal and cardiac muscles. In serious cases, it can even lead to cardiac arrest and death. It was also pointed out that deficiency can affect a child's growth. Potassium deficiencies (hypokalemia) ean be caused by insufficiency of K in the diet but, generally, they are the result of excessive loss through the gastro-intestinal tract (vomiting, chronic diarrhoea) or kidney. Sudden, excessive intake of K can also induce poisoning (hyperkalemia) which affects the heart and can cause sudden death. However, according to Grossklaus, as long as the renal functions are normal, it is almost impossible to induce potassium excess with the normal diet. Hyperkalemia is due to strong retention of potassium, generally caused by a reduction in renal potassium excretion. According to Prof. Kecskeméti, several drugs (diuretics, antibiotics, hormones, laxatives, cardio-vascular drugs) affect retention and elimination of potassium and can cause hypo- and hyperkalemia. It seems, therefore, that disturbances in K- homeostasis of humans have no connections with the amount of K fertilizer applied to crops.

H. Zemková and G. Rechkemmer both described systems ruling the transport, compartmentalisation and homeostasis of potassium in the human body. Over 90% of potassium is found within the cells at a concentration thirty times higher than that in the extra-cellular fluids (plasma and interstitial fluid). K^+ concentration in the extracellular fluids is kept within narrow limits by a regulatory mechanism. Different K^+ channels ensure the passage of this ion through the lipid bi-layer membrane of the cells which cannot normally be crossed by potassium ions. According to Zemková, these channels are protein macromolecules forming pores equipped with many selective devices. The high K^+ concentration in the cell is maintained by K^+ pumps and other carriers which transport ions actively against their concentration gradients. Potassium is absorbed in the gastro-intestinal tract, whereas elimination is the concern mainly of the renal system. However, about 15% of potassium is eliminated faecally, mainly in the colon. In the case of renal insufficiency, K^+ elimination in the colon seems to increase and can, in this manner, partly compensate for renal insufficiency.

In conclusion, we may state that potassium is essential to maintain animal physiological functions. K^+ intake by humans depends mainly on the diet. A high diet in K has no harmful effect. It has even been observed that a high K intake is recommended for people suffering from hypertension.

As agronomists, we conclude that a reduction in K fertilizer usage just for ecological or health reasons, as recommended for phosphorus and nitrogen, is in no way justified. The limits on potassium content of drinking water fixed by the EEC have no sound basis and are unjustified. They create confusion for the consumer and incite him to consider potassium as a harmful element whereas the information given by the scientists proves the contrary.

Chairman of the Session 4

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Session 4

K Requirements in Different Land Use Systems

The Role of K in the Amelioration and Sustainability of Ecosystems

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Summary

The consumption of commercial fertilizers in Czechoslovakia has recently been at a satisfactory level, generally suited to cropping intensity and local soil conditions. Small differences in rates between regions, farms and fields, caused significant differences in soil K contents and thus significant changes in K content in biomass.

Determinations of CEC and cation saturation indicate satisfactory K status but also significant variation between regions, farms and fields. K contents were high in arable, hop-yard and orchard soils. At the same time certain areas were characterised by low soil K. The main reasons for differences in soil K status are unreasonably heavy use of manures (cattle slurry always applied to the same fields), arbitrary rates of K fertilizer and unreasonable practices of reserve K fertilization. Mg saturation of the CEC shows little variation but is usually low, indicating a need for Mg fertilization. Long-term trials in Czechoslovakia show that for maintenance of necessary production, soil fertility and reasonable K content in soils, 60-90 kg K per ha per year is necessary, the exact quantity depending on local soil conditions and intensity of biomass production.

Introduction

Potassium has recently received a great deal of attention due to its importance for plant development (biochemical aspects, crop yield and quality, etc.) and its relationship to other nutrients, mainly cations, its behaviour in soils and its influence upon soil properties and the ecosystem as a whole.

Quite unambiguously, even if not fully clarified is the activity of potassium in the most important processes in plants. K has a significant effect on osmotic pressure and thus on the water transport in plants, on photosynthesis and assimilate transport and on the activity of many enzymes and enzyme systems (Mengel, 1984). Very many authors state a positive influence of K^+ on the health conditions of plants (well reviewed by Perrenoud, 1990), and on improving technological properties, production quality, etc.

Relatively good agreement in the literature could be found on the quantity of potassium necessary for safeguarding the vital plant functions. Mostly it has been stated that a content of 2.0-2.5% of K in leaf dry matter is satisfactory and that higher contents do not cause a significant increase in important processes, but can even cause some disharmonies, mainly in the relationship to other cations. Higher and more luxurious uptake of K may cause limitation in the uptake of Na, Mg, Ca and minor nutrient cations.

Our efforts therefore should be directed to creating conditions guaranteeing a sufficient uptake of K for photosynthesis and other plant functions and preventing the possibility of luxury consumption with possible negative effects in production, including reduced fertilizer efficiency. Data were published showing that higher K uptake increases the uptake of nitrates (Królovic, 1984). Our results however do not confirm this (Balik, 1992). It is obvious that there is a reversed tendency. Increased uptake and utilization of NO_3^- N in plants causes an increase in K uptake (Kirkby, 1968).

High mobility of K in a plant and its activity in the soil solution determine the principles of K nutrition and fertilization. The main source of potassium for plants is soil potassium bound on soil colloids and present in soil solution. The relationship between the quantities of the cations H^+, K^+, Na^+, Mg^{2+} and Ca^{2+} in solution and on the solid soil components is mainly a function of ion exchange processes and is governed by the convertibility of bound cations on the soil complex. The quantity of a single cationic species on the colloid complex can be different and mutual relationships can cause significant changes in plant uptake and plant growth. Our efforts must be to stabilize suitable quantities and ratios of cations on the sorption complex, thus creating conditions suitable for harmonious plant nutrition. The K supply should be 2-5% of the CEC (Gedrojc, 1955, Large, 1971, Baker and Amacher, 1981). Potassium should be present in the soil solution in a quantity of 0.5 me per liter, i.e. ca. 20 mg K in 1000 ml solution.

In view of the fact that K can be leached from the root zone, the rate of its release from the solid soil phase is very important. Such release depends not only on the quantity of exchangeable potassium, and on the soil sorption capacity, but also on the type of clay minerals (Grimme *et al.*, 1971, Kuchenbuch and Claasen, 1985).

Differences in potassium demands among crops and in accumulation of potassium in their tissues can lead to large differences in potassium recycling during the production of different crop species. For instance, clover, sugar beet, potatoes, and some vegetables withdraw large quantities of potassium from the soil.

Comprehensibly, if such crops are well represented in a crop rotation, the need for K fertilization increases. In contrast, when cereals dominate, the export of potassium from the agro-ecosystem is small. A large part of K absorbed is concentrated in the straw, which remains on the field or returns to the soil in the form of manure.

Trends in potassium supply in Czechoslovakia

Table 1 gives the most important data on N, P_2O_5 and K_2O consumption in the form of fertilizers in the period 1956-1991. It is evident that K uptake was high and in the eighties reached an annual level of 85 kg K_2O per ha. Czechoslovakia was regarded as one of the countries having the highest K fertilizer consumption (Von Peter, 1979). Such a high level of consumption can be caused by the low production of manures of low K content.

In any case, during the period of the highest K fertilizer consumption, the supply of K exceeded K consumption by crops. The data in Table 1 show that the K supply stagnated in later years and that a downward trend started in the period 1987-1989. The supply of K originally outweighted that of N and the ratio K_2O : N fell under 1 as a result of unchanged consumption of N fertilizers.

High rates of K fertilizers caused a gradual decrease in acreage having a low supply of soil K (Vostal, 1992).

Economic problems of farming, changes in land ownership and insufficient attention by politicians led to a very severe decline in fertilizer usage, mainly of P and K in 1991 and again in 1992. It has become obvious that the evident discrepancy between K uptake and K supply will, if it continues, lead to a serious decline in soil fertility.

Table 1. Nutrient consumption and ratios in industrial fertilizers in the CSFR.

Years	kg per ha agricultural land per year			Ratio $N:P_2O_5:K_2O$
	N	P_2O_5	K_2O	
1956-60	16	18	30	1 : 1.1 : 1.80
1973-74	66	54	81	1 : 0.84 : 1.22
1982-85	96	76	85	1 : 0.79 : 0.88
1987-89	99	67	64	1 : 0.68 : 0.65
1991	46	11	8	1 : 0.24 : 0.17

K representation on sorption complexes

To attain a harmonious plant nutrition, attention was paid to cationic supplies on sorption complexes and the levels of sorption capacity. Soil analyses for CEC and for levels of Ca, Mg, K and occasionally Na in sorption complexes were made (Matula, 1984, Vanek, 1984). Some results are given in Table 2. Significant differences in the presence of cations and in sorption capacities among production areas and enterprises, can be observed. From the given data it is evident that there are considerable differences, mainly in potassium.

Table 2. Results of CEC analyses and presence of cations in CEC-arable soils of selected agricultural enterprises.

Enterprise	Value	CEC meq kg^{-1}	% CEC		
			Ca	Mg	K
Dobrá Voda (sugar-beet-producing region)	x range	179 160-201	88 52-90	4.6 2.3-6.7	3.5 1.7-5.1
Hlusice (sugar-beet-producing region)	x range	215 168-322	76 51-90	5.2 3.9-8.0	3.9 1.9-14.3
Cechtice (potato-producing region)	x range	118 40-251	47 32-90	2.6 0.8-10.3	7.9 2.9-24.9

The higher K saturation of sorption complexes in the potato-growing region were due to the naturally high K reserves in these soils and the lower K uptake by plants. High levels of K saturation were found in hop yard soils

(Table 3). It is evident that the older the hop-yard the higher is the soil K content. The gradual increases in soil K contents can be ascribed to intensive use of manures and fertilizers.

Table 3. CEC values and presence of cations on sorption complexes in selected hop-yard soils.

Enterprise	Value	CEC meq kg^{-1}	% CEC Ca	 Mg	 K
Polepy	x range	264 155-398	80	12.3 7.2-15.6	8.8 3.4-18.0
Cítov	x range	210 175-258	80	26.2 13.6-45.0	6.7 4.5-10.0
Nová Vea	x range	142 108-179	80	6.8 4.4-9.3	6.7 2.8-10.8
Pavlíkov	x range	181 151-290	80	6.7 3.3-9.2	6.6 3.2-11.7

Table 4. CEC values and presence of cations on sorption complexes in soils of 2 apple orchards (Holovousy).

Orchard	Depth of sampling cm	CEC meq kg^{-1}	% CEC		
			Ca	Mg	K
1	0-12.5	113	80	5.9	7.6
	12.5-25.0	113	80	4.7	5.2
	25.0-37.5	134	80	4.9	3.9
	37.5-50	127	80	5.2	2.7
2	0-12.5	126	57	7.0	9.3
	12.5-25.0	118	42	5.3	5.1
	25.0-37.5	120	57	7.5	3.6
	37.5-50	138	61	9.1	2.0

Analyses of orchard soils (Table 4) show that the soil K contents were evidently influenced by fertilizer use. Because of surface application, the K contents are highest in the topsoil. The % K saturation is mostly adequate at a depth of over 25 cm and there are no problems in the Ca nutrition of the apples.

The data presented confirm the necessity of establishing suitable cationic ratios in the sorption complexes, and at the same time direct attention to the other cations, mainly Mg. They also show the necessity for greater differentiation in K fertilization of some crops. Evaluation of soil K content and K saturation showed very different values not only between regions, farms and soil types but between and within fields also.

The main reasons for these variations are :

- unreasonably high application of farm manure and slurry to the same fields or part of fields. Potassium in farm manure has often not been taken into account in making fertilizer recommendations;
- rates of K fertilizer have been arbitrary and not related to plant uptake and soil reserves;
- application of maintenance K dressings at intervals (e.g. 1 year in 3) to soils of low sorption capacity;
- long-term use of high K compound fertilizers increasing the K reserve in soils;
- uneven spreading of fertilizers.

Long-term experimental results

Experimental data of the Central Control Agric. Inst. (Trávník and Pokora, 1990, 1991) show that increased K fertilization in sugar-beet producing region has no marked influence on crop yield (Table 5). K uptake was higher than needed for maximum yield on all treatments including K. Soil K content (Figure 1) was significantly lower when no K fertilizer was applied and it can be taken that soil K content in this high production area can be stabilised by using annual dressings of 90 kg ha^{-1} K.

The potato growing area is characterized by a lower soil fertility level, and adequate fertilization therefore increases yields by more than 40% (compare treatment 1 and treatments 4, 5, 6 in Table 6). About 60 kg ha^{-1} K increases yield on most sites but there is no further increase from higher rates.

Table 5. Annual production of dry matter and K consumption in long-term experiments in a sugar beet producing region (average of 4 sites at the Central Control Agric. Inst.), in the period 1972-1989. Cereals occupied 50%, alfalfa 22% and sugar beet 22% in crop rotation of the experiment.

Treatment	Fertilization	Dry matter yield, t per ha	Annual input kg K per ha	Consumption kg K per ha	Difference
1	0	9.62	0	142	-142
2	Manure	10.12	48	154	-106
3	Manure + NP	11.77	48	178	-130
4	Manure + NPK1	11.64	108	193	-85
5	Manure + NPK2	11.59	138	201	-63
6	Manure + NPK3	11.59	166	208	-42

Dose of N was 99 kg N per ha per year in fertilizers.

Dose of P was 35 kg per ha per year in fertilizers.

Table 6. Annual production of dry matter and K consumption in long-term experiments in a potato producing region (average of 9 sites at the Central Control Agric. Inst.) in the period 1972-1989. Cereals occupied 50%, clover 22% and potatoes 22% in crop rotation of the experiment.

Treatment	Fertilization	Dry matter yield, t per ha	Annual input kg K per ha	Consumption kg K per ha	Difference
1	0	6.52	0	92	-92
2	Manure	7.07	48	103	-55
3	Manure + NP	9.05	48	130	-82
4	Manure + NPK1	9.30	109	143	-34
5	Manure + NPK2	9.36	133	149	-16
6	Manure + NPK3	9.32	163	152	+11

Dose of N was 96 kg N per ha per year in fertilizers.

Dose of P was 34 kg per ha per year in fertilizers.

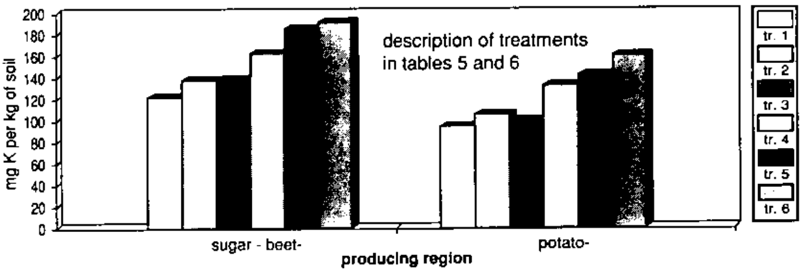

Fig. 1. Available soil K contents after harvest (Data of Central Control Agric. Institut).

Conclusion

Long-term trials in which the contents of available nutrients in soils were monitored, show that for optimum production and quality of agricultural products and for maintenance of adequate K contents in soils it is necessary to supply the soils annualy with 60-90 kg K per ha of arable land with respect to the local conditions and productive intensity.

At the same time it is necessary to maintain a correct balance of cations on the sorption complex and to differentiate fertilizer use according to plant uptake and K reserves in soils.

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Potassium in Ecosystems, with Emphasis on the US

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Introduction

The aspect of K in the ecosystem of primary interest has to do with man and food and fiber production. Secondarily, the environmental aspects come into play. The importance and management of crop nutrients provided by fertilizers in food and fiber production during the last half of the twentieth century cannot be underestimated, with potassium playing a major role. There are those who believe nitrogen and world population growth are closely linked (Smil, 1991), but because of N-K and P-K, especially in N_2 fixation, relationships in plant nutrition, be assured that K plays a key role in that link.

From an agricultural-ecosystem standpoint it is important that a more complete accounting of the nutrient inputs and outputs (flows) or dynamics be made and understood if one is to improve and sustain various ecosystems. Researchers and producers in China with their ecological systems approach to agriculture (Xie and Hasegawa, 1985 [emphasis on K], and Luo and Han, 1990) probably come as close to any country in achieving such an accounting in producing food for their nearly 1.2 billion population, although soil erosion is still one of their major problems in terms of nutrient losses. China now uses more fertilizer nutrients than any other country (IFA, 1991).

In most production systems in developed countries, the overriding role of K based on environmental concerns should be to improve nitrogen-, phosphorus- and water-use efficiencies. Environmentally, nitrogen and phosphorus are the nutrients of most concern in the eutrophication of lakes[1], estuaries and coastal zonal areas, and nitrate-N is of concern in

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[1] It needs to be remembered that peat bogs were formed through a natural eutrophication process that occurred over millions of years, and that oil, coal and lignite deposits that are now being exploited are a result of that process.

groundwater. With the growing interest in the causes of 'Red Tides' and associated organisms and toxicities in coastal waters (Culotta, 1992), efforts to further decrease N and P in sewage and agricultural runoff and erosion will increase.

Regarding nitrate-N in groundwater, a recent U.S well-water survey indicates that it is much less of a problem than had initially been thought (Fedkiw, 1991). Bacterial contamination is a far greater problem in drinking water than nitrate. There is also evidence that nitrate-N in surface water in rivers, even in regions of high N-use that are tiled, has not materially changed from periods when the use of fertilizer N was extremely low in the mid 1940s (Keeney and DeLuca, 1992).

Water year-in and year-out in the U.S. is the most limiting factor in crop production. That is undoubtedly the case in much of the rest of the world. To give an idea of how limiting water is, in high-yield maize and soybean production, irrigation increased the five-year average yield of maize by 8.78 t ha^{-1} (Flannery, 1985) and average yield of soybean by 2.35 t ha^{-1} (Flannery, 1989). In irrigation studies in North Carolina, Anderson (1991) found irrigation increased the seven-year average yield of maize by 5.68 t ha^{-1}. Average maize yields in the state of Washington, mostly irrigated, are as high as 10.98 t ha^{-1}. Cooper *et al.* (1992) found soybean yield increases of nearly 3.7 t ha^{-1} with subirrigation of soybeans (40.6 cm watertable). Potassium has had a major role in increasing the water-use efficiency, and contributes greatly to the yield of all crops.

In this discussion it is my objective to present a perspective that looks primarily at K in our crop production ecosystem, and consider relationships that may be useful for improving and sustaining K availability. Some of the policy and management changes occurring in the U.S. that are interacting in that system will also be discussed. To do that requires some historic reflection, and a look at the present and the future as well. Much of the emphasis will be on U.S. production agriculture, although ideas for K use in other ecosystems and the future will be discussed.

Some Background-U.S. Agriculture

Nutrient Use

As in many regions of the world, there were and are soils that can produce little until nutrient additions, such as K, have been applied. Such was and is the case in some areas of the U.S.. Nutrient use in the U.S.

started increasing during the 1940s, because food was badly needed during World War II and the period of recovery that followed, especially in Europe and Japan. By 1950 the N, P and K use was 1.06, 0.82 and 1.00 million tons, respectively. Nutrient use continued to increase until the late 1970s and early 1980s. Phosphorus use peaked in 1977 at over 2.23 million tons, while nitrogen (N) and potassium use peaked in 1981 at 10.82 and 4.76 million tons, respectively, which was 10.2, 2.7 and 4.7 times the 1950 use. Since then nutrient use has been down or unchanged, being 10.4, 1.64, and 3.75 million tons of N, P and K, respectively, in 1991 (Fertilizer Statistics).

Because of improved fertility management, yields of most crops in the U.S. have continued to increase without increased nutrient use. Also, millions of hectares of less productive, environmentally sensitive land has been removed from production by various programs. Therefore, nutrient-use efficiencies for crops, except for wheat, have been increasing (Wallingford, 1990). The reason nutrient-use efficiencies for wheat has not shown increases is that nutrient use was so low, that yields could not be increased until use increased.

The total estimated annual N, P and K inputs from fertilizers, animal manures, sludge and crop residues in the U.S. are shown in Appendix Table A. These values can be compared to the estimated annual nutrients lost to runoff, eroded soil sediments and removed by crops (output). Based on a 'nutrient balance' the estimated annual deficits in millions of tons of nutrients amount to -4,069.4 for N, -715.8 for P and -56,507 for K based on total losses. These losses are obviously less when only soluble or "available" nutrients are considered, as is shown.

During the 1970s, because of increased fertilizer-P and K use, soil test levels in various states were increased. In data from the state of Iowa, one can observe the increases in P and K soil test levels over three time-periods (Table 1). This indicates that soils were being improved. If soil test K levels of a field are adequate, for most crops there will be little crop response to additional applied K. Large areas of soils of the semi-arid Great Plains contain very high levels of K, and thus show little response to K fertilizers unless chlorides are deficient.

Table 1. State average phosphorus and potassium soil test levels during three periods of time in Iowa (Killorn *et al.*, 1990).

Summary period	Soil test* P test	Soil test* K test	Sample number
	mg kg^{-1}		
'74-'79	24	126	75,000
'80-'85	31	144	62,000
'86-'89	33	160	61,140

*Bray P_1 or ammonium acetate extraction used.

Crop Production Trends

From the late 1800s through the 1930s average yields of most crops in the U.S. increased little. By the late 1930s hybrid maize had been developed and plant breeding programs were beginning to pay off. Lime, manure, and fertilizer phosphate and potash use were increasing alfalfa and legume yields so that more N was being fixed symbiotically. However, even for crops grown on the high organic matter soils of the Midwest, nitrogen was often the most limiting nutrient. Much of the early research was on phosphorus. More potassium and phosphorus fertilizer resources were discovered and developed. Ammonium nitrate and anhydrous ammonia became available following World War II. Nutrient use started increasing more rapidly during the 1950s. Also, the first herbicides came into use during the late 1940s. The benefits of technology and plant breeding began increasing crop yields, which are still trending upward.

In Europe the benefits of the combined technology on small grain yields over time is perhaps best documented from long-term research data from the Rothamsted Experiment Station (Johnston, 1989, 1992), as well as in the average yields being achieved by regions. According to A. van Diest, wheat yields of over 8 t ha^{-1} are common in western Europe. In the U.S. the benefits of soil fertility can be observed over time in the research data from 'The Morrow Plots', initially established in 1876 at the University of Illinois (Odell *et al.*, 1984; Runge *et al.*, 1990). After 109 years the average yield of continuous maize without any applied nutrients for the past 31 years was 2.79 t ha^{-1}. These medium-textured soils were formed under tall prairie grasses (mollisols) and were initially high in organic matter capable of mineralizing considerable N, P and S. For the same period where manure, lime and phosphate (MLP) were applied the maize yields averaged 5.73 t

ha^{-1}. By adding lime (L), fertilizer-N, P and K treatments to the MLP treatment, the continuous maize yields averaged 9.12 t ha^{-1}. The improved mineral nutrition increased maize yield by 6.33 tons or 3.27 times. When soybeans replaced oats in the rotation, average maize yields were increased to over 9.88 t ha^{-1} for the MLP + LNPK treatment. However, one must remember that on a given field only half the area would be in maize each year.

What have been the yield trends in U.S. agriculture? By evaluating the pre-technology average yields of the decade of the 1930s and comparing them with the averages for the decade of the 1980s, one can appreciate the changes that have occurred. Data for maize, soybeans and wheat are shown in Table 2a.

Table 2a. Comparison of average yields for the pre-technology-decade of the 1930s and the decade of the 1980s for U.S. maize, soybeans and wheat, increases and 1992 predicted yields*

Crop	Average 1930s decade yield	Average 1980s decade yield	Increase	Predicted '92 yield
	t ha^{-1}			
Maize	1.56	6.64	5.08	7.61
Soybeans	1.08	2.04	0.96	2.41
Wheat	0.72	2.41	1.69	2.49

*USDA Crop Production Statistics.

During the decade of the 1980s, wide swings in yields were caused by two serious droughts in 1983 and 1988. However, it is of interest that the coefficient of variation (CV) in maize yields, under much lower levels, during the decade of the 1930s was greater (15.7 %) than that for the decade of the 1980s (14 %) under higher yields. The largest decade-average increase in maize yield came during the '70s, which was 1.66 t ha^{-1} above that for the '60s. The decade-average yields for the '80s was 4.26 times or 326 percent greater than for the '30s for maize, 1.89 times or 89 percent greater for soybeans and 3.35 times or 235 percent greater for wheat. Without an adequate level of soil and/or fertilizer K, those yields would not have been achieved.

1992 projected harvested areas for the major crops are as follows: Maize, 29.2 million ha; Soybeans, 23.5 million ha; Wheat, 25.5 million ha; Sorghum, 5 million ha; and Cotton, 4.6 million ha. Because of higher yields in general, adequate grain supplies can be produced on fewer hectares, and environmentally sensitive soils can be set aside in the governmental Conservation Reserve Program. It has been projected that if yield levels were at 1938-1940 levels, the U.S. would have to be farming an additional 169 million ha (Miller and Larson, 1990).

With the previously mentioned increases in yields have come parallel increases in dry matter or biomass left in the fields by crop residues. Unless hay, straw or residue are removed from fields, for example, as maize stover, an amount of dry matter (and the nutrients it contains) will be left in the field essentially equal to the dry matter removed with the grain, not to mention the greater root mass of a well-fertilized crop. From a crop utilization standpoint it is a very wasteful practice not to use half of the dry matter the crop accumulated during the season. However, if these residues are removed from fields, there is a dramatic change in the environmental K balance in the ecosystem, and a decrease in the residue cover left on soils, exposing the soil to greater erosion. On many soils that were initially low in organic matter, biomass additions from higher yields produced by proper fertililization have increased soil organic matter levels, and improved nutrient cycling and soil productivity. This tends to increase the cation exchange capacities of soils, but potassium held by these charges is relatively loosely bonded, which may increase K availability. However, it should be remembered that this may also increase the susceptibility of K to leaching (Lucas, 1982). With higher yields on soils with adequate subsoil K levels, greater biomass surface deposits tend to increase soil surface K levels over time (Motavalli *et al.*, 1992a, b).

With moldboard or chisel plowing crop residues are mixed back into the soil, but in no-till systems they stay on the soil surface and K is leached from the residue and tends to remain there as if it had been top dressed. Initially it was thought that on most soils, because of the residue-moisture-temperature-aeration relations, the K at the residue-soil interface may not be as available as once thought. This may be true in ridge-till maize systems too (Allan *et al.*, 1992; Darst and Murphy, 1992).

In the state of Minnesota maize yields from 1950 to 1991 were found to be increasing at an average rate of 119 kg ha^{-1} yr^{-1} (1.9 bu/ac/yr). However, the average rate of increase was 150 kg ha^{-1} yr^{-1} (2.4 bu/ac/yr) if the drought years, such as 1983 or 1988, were removed from the regression determination (Baker, D. G., personal communication, 1991). Thus, when one speaks of sustainability in ecosystems and crop production, one should think in terms of sustainable growth. That is especially true for less developed countries, which are facing large annual population increases. These countries, in fact, are showing remarkable abilities to increase yields through use of fertilizer nutrients and technology.

Nutrient Uptake For High-Yielding Crops

Plant analysis plays a key role in determining nutrient uptake (Munson and Nelson, 1990). However, in determining nutrient uptake one has to use care, because sampling is usually at a single time, often at about the time the crop approaches maturity. For K, which is often lost from the crop before maturity, one may miss the maximum uptake needed to produce a given yield if sampling is not done at several growth stages up to physiological maturity. As yields have increased, the total uptake of nutrients of various crops has continued to increase. Efforts in maximum yield research have given an idea of the uptake needed for some relatively high yields. These measurements do not include the nutrients that are in the root systems, which some believe to account for an additional 10 percent of that in the aerial portion of the crop. However, nutrients in roots do remain in the soil and become a part of the cycling nutrient system. The total aerial nutrient uptake for a number of crops under high yield levels is shown in Table 2b:

Table 2b. Total nutrient uptake by crops.

Nutrient	Total nutrient uptake in kg ha^{-1}				
	1) Maize 2) Yield t ha^{-1}		3) Soybeans 4) Yield t ha^{-1}		Potato 5) Yield
	19.3	21.2	6.79	5.38	66.8 t ha^{-1}
N	386	434	614	460	140
P	68.6	94.8	64.6	37.8	28.8
K	368	424	402	232	269
Ca	59.4	n.e.*	185	80	23.4
Mg	47.7	n.e.*	63	35.8	25.8
S	40.3	n.e.*	36	n.e.*	n.e.*
B	0.92	n.e.*	0.09	n.e.*	0.10
Cu	0.86	n.e.*	0.13	n.e.*	0.07
Fe	16.2	n.e.*	7.1	n.e.*	1.8
Mn	7.6	n.e.*	1.2	n.e.*	0.32
Zn	3.93	n.e.*	0.83	n.e.*	0.19

* not estimated

1) Flannery, 1986a

2) Flannery, 1984

3) Flannery, 1986b

4) Henderson and Kamprath, 1970

5) Rosen *et al.*, 1991

Table 2b. (cont.) Total nutrient uptake by crops.

Nutrient	Total nutrient uptake in kg ha^{-1}				
	Alfalfa 1)	Soft white winter wheat 2)	Winter wheat 3)	Hard red spring wheat 4)	
	Yield t ha^{-1} (hay)	Yield t ha^{-1}	Yield t ha^{-1}	Yield t ha^{-1}	
	24.1	8.16	11.02	4.1	3.79
N	731	177	261	130	123
P	66	48.5	42.8	11.4	16
K	532	134	247	216	134
Ca	301	23	43	14.6	16
Mg	64	14	24	n.e.*	17
S	64	11.4	34	18	n.e.*
B	n.e.*	n.e.*	n.e.*	n.e.*	n.e.*
Cu	n.e.*	0.034	0.056	0.034	n.e.*
Fe	n.e.*	n.e.*	n.e.*	n.e.*	n.e.*
Mn	n.e.*	0.4	0.9	0.006	n.e.*
Zn	n.e.*	0.28	0.37	0.25	n.e.*

* not estimated

1) Kansas State University

2) Koehler, personal communication

3) Brown, 1986

4) Malzer, 1992

By dividing the total uptake of a nutrient by the measured unit of yield, one can determine the input:output relationships for the different nutrients. These values may be viewed as the internal nutrient requirement of the crop or the amount needed to grow a unit of yield or ton of grain, beans or forage. By taking the reciprocal of those values, one can determine the output or yield per unit of input for each nutrient. These can be useful values in determining if hybrid or variety A is really more efficient in nutrient use than hybrid or variety B. In looking at the yields of given hybrids or cultivars under given soil test levels it certainly appears that they have differing capacities to recover both soil and fertilizer nutrients, as will be discussed later.

There is interesting evidence that over relatively wide ranges in yield levels and environments, in general, if one considers the nutrient uptake per unit of yield for N, P and K, they appear to be reasonably stable. In other words, the crop has an internal requirement or it takes a given amount of each nutrient to produce a unit of yield. For maize for grain yields that ranged from 5 to over 21 t ha^{-1}, the mean values (n = 13) were 20 kg N, 3.66

kg P and 18.5 kg K per ton of grain produced (Runge *et al.*, 1990). The coefficients of variations (CVs) were 5.18 % for N, 15.5 % for P and 10.1 % for K. For soybeans in which the bean yield ranged from 2.35 to 6.78 t ha^{-1} the mean values (n = 12) were 88.3 kg N, 7.55 kg P and 40.7 kg K per ton of beans produced (Runge *et al*, 1990). The CVs were 10 and 20 % for N and P, but 30 % for K. which may reflect a greater variation in growth stages at which uptake measurements were made.

As nutrients other than K are applied and yields are increased, K uptake by the crop increases rather dramatically. Malzer (personal communication, 1992) has provided data on MN 73167 a variety of spring wheat, which clearly shows the close relationship between N and K uptake (measured at soft dough stage of development) as yields are increased by applying N (see Table 2c).

Table 2c. Effect of N-rate and yield on nutrient uptake of wheat (Malzer, 1992).

		Nutrient uptake				
N rate	Wheat yield	N	P	K	Ca	Mg
kg ha^{-1}	t ha^{-1}	kg ha^{-1}				
0	2.67	57	13	58	7	8
67	3.87	99	17	101	12	13
134	4.02	125	17	133	17	16
		% increase				
	50	119	31	129	143	100

When N is applied to a system that does not contain either adequate soil reserves or receive adequate rates of fertilizer-K, yield drop rapidly, within a few years. In a ten-year study with continuous no-till maize conducted in Maryland, Bandel (1990, personal communication) obtained average yields of 4.66 t ha^{-1} yr^{-1} when only N was applied. When adequate K was applied with the N, yields averaged over 9.87 t ha^{-1} yr^{-1}. Adequate K and other nutrients increase yields and N recovery and stabilize yields at higher levels. Even though the yields of the treated plots in this study the first year were essentially equal, by the sixth year, the 179 kg N treatment was yielding less than the control plots. The unfertilized treatments produced an average yield of only 2.26 t grain ha^{-1} yr^{-1}. The grain produced per kg N was increased from 26 kg grain kg^{-1} N for N alone to 55.2 kg grain kg^{-1} N, a factor of 2.13, with adequate K. Based on N uptake calculations, the N efficiency was increased over 83 % (Munson and Runge, 1990). It took about 84 kg K ha^{-1} yr^{-1} to maintain optimum yields in the system used.

Nutrient Removals Per Unit of Production

Grain or forage analyses can be used to determine nutrient removals per unit of yield, which in the long run become extremely important for maintaining soil productivity and sustainable growth in production to realistically face the future. Considering maize in which the yields ranged from 5 to over 23 t ha^{-1}, the mean nutrient removal values (n = 15) for grain were 12.9 kg N t^{-1}, 2.79 kg P t^{-1} and 3.41 kg K t^{-1}. The CVs were 6.2 percent for N, 12 percent for P and 20 percent for K. With newer single cross maize hybrids, these values might be lower and show more variation in the future. For soybeans in which the yields ranged from 2.68 to 7.96 t ha^{-1} (n = 16), the N, P and K removals per ton of beans produced were 55.6, 5.42 and 15.2 kg, respectively. CVs were 6.1 % for N, 12 % for P and 5 % for K.

For cropping systems involving maize and soybeans in areas where only one crop per year is obtained, the K removals in two years amount to 100 kg K ha^{-1} when maize yields average 11.29 t ha^{-1} and soybean average 4.03 t ha^{-1}. In research on the better soils of Indiana, Li and Barber (1988) reported 25-year average yields of over 9.4 t ha^{-1} for maize and 3.9 t ha^{-1} for soybeans. For a maize-soybean-wheat-maize rotation they found that in the long term, the most profitable rate of potassium use required 349 kg ha^{-1} K every four years or 87 kg ha^{-1} yr^{-1} (the most profitable rate of phosphorus was met by applying 110 kg ha^{-1} P every four years or 28 kg P ha^{-1} yr^{-1}). For soils that fix K, more frequent applications are desirable. In some regions farmers are obtaining three or more crops a year. In others, they are obtaining three crops in two years. This management places increased stress on soils and fertilizer K levels needed for sustainable growth in production.

Effects of Long-term Cropping on Subsoil K

Initially many soils in the U.S. had fairly adequate levels of soil potassium. With the improved yield levels resulting from increased nitrogen and phosphorus use, more soils developed K deficiencies. Also, where the same crop has been grown year after year, as is the situation with cotton in some regions, subsoil K depletion appears to becoming an increasing problem. Also, the development of higher-yielding cotton varieties, having a high K demand during fruiting has increased "K-stress". Currently two strategies are being used to overcome the situation. Deeper placement and vertical distribution of applied-K is being researched and suggested for cotton (Tupper and Ebelhar, 1992). Foliar applications of K each week during 'fruiting' is also being used with good success when petiole K indicates deficiencies (Snyder *et al.*, 1991). This has been the case in Arkansas and other areas of the southern U.S.

It turns out that progressive states take into account the subsoil levels of pH, P and K and consider them in making nutrient recommendations. By only sampling the surface 15.24 cm, erroneous answers may be obtained. For example, in K rate-alfalfa studies initiated in 1985 in Minnesota and then discontinued, six years later maize was planted on the plot area. Observations indicated serious K deficiencies developed on some of the plots. The results of the diagnostic work are shown in Table 3.

Table 3. Effects of three annual K applications to alfalfa, followed by an oat crop on subsequent K soil tests and maize yields during the fifth year. Waukegan silt loam (Schmitt *et al.* 1991).

K- application		K- test		Maize yield
Annual	Total	Initial 1985	1990 0-15 cm	
kg ha^{-1}		mg kg^{-1}		t ha^{-1}
0	0	100	53	0.38
116	349	-	61	4.64
232	698	-	62	10.10
464	1394	-	87	11.29

It is obvious from the soil test levels and maize yields that the normal depth of soil sampling did not reflect the level of available subsoil K that resulted from the K rates previously applied on this experimental site (Schmitt *et al.*, 1991). (Some of the benefits may have been derived from greater N-fixation by alfalfa and from improved K availability).

In areas with coarse-textured, low-CEC soils, low in K, for high production systems sidedressed K is recommended to help carry the crop through the season. In some areas, by applying adequate rates of deficient nutrients other than K, surface K soil test levels will actually be increased over time, because of increased quantities of K deposited through the crop residues (Motavalli *et al.*, 1992a, b).

Another aspect of the K nutrition problem involves the high-K-fixing soils, such as those found in California (Cassman *et al.*, 1991). Very large application of fertilizer K have to be made to assure that crops such as cotton have adequate levels of K to meet the periods of high demand during fruiting and fiber production. In the California ecosystem, the K deficiency is complicated by Verticillium wilt (V. dahliae). Field studies indicate that the K deficiency can also be "cured" by soil fumigation (Weir *et al.*, 1992), which increases cotton petiole K concentrations and increased the average cotton lint yields by 662 kg ha^{-1} yr^{-1} over a three-year period. In the earlier K fertilization-cotton research, there was a tendency for slightly higher yields when manure was part of the K source. The results can be compared in Table 3a. Regarding K sources, data from Minnesota on maize indicates essentially equal results for equal rates of K from organic or inorganic sources (Table 3b, Moncrief *et al.*, personal communication).

It is of interest that in the U.S. livestock manures could only account for 13 % of the K needs (Follett *et al.*, 1987). The main point to remember is that different K sources readily substitute for one another, and it makes little difference whether the K is provided by crop residue mulches, animal manures or K fertilizers (Xie and Hasegawa, 1985). Each source needs to be credited and properly used as a resource in the production package.

Table 3a. The effects of previous accumulative K input and recent organic and inorganic K sources on three-year average yields of lint cotton (Cassman *et al.*, 1991).

Previous K input KCl '85-'87	Recent K input '88-'89	Cotton lint yield (average '87, '88, '89) K source	
		Manure-organic	KCl-inorganic
kg ha^{-1}		kg ha^{-1}	
0	0	1080	1097
360	120	1242	1141
720	240	1301	1226
1440	480	1401	1326

Table 3b. The effects of equal rates organic and inorganic applied of K and of tillage systems on maize yields. Timula silt loam (Moncrief *et al.*, personal communication).

K source	Maize yield Tillage system	
	Chisel plow	No-till
	t ha^{-1}	
Soil	5.83	5.14
Soil + Manure	8.34	8.09
Soil + Fertilizer (KCl)	8.72	8.03

Anion Aspects of Long-Term K Use

An aspect of K fertilization that needs to be considered in drier regions has to do with associated anions, such as chloride. Initially, in some mid-continent areas, chloride may be deficient, as appears to be the case in the northern Great Plains area of the U.S. (Fixen, 1992). It has been found that 67 kg ha^{-1} of chloride in the top 30.5 cm of the soil profile is adequate for wheat. However, if KCl continues to be applied in semiarid areas, chlorides will accumulate, just as sulfates will. Under such conditions, one becomes concerned with those crops and cultivars of some genera that are sensitive to chlorides. Researchers in Georgia and Arkansas, for example, have found that some varieties of soybeans are sensitive (sometime referred to as 'includers') to higher levels of chlorides. Studies with maize indicate that it appears to exclude chloride, and shows a low sensitivity.

Shift to Crop Residue Management, Reduced Tillage Systems

The U.S. has from 127 to 129 million hectares (314 to 319 million acres) planted to its principal crops each year.

Not all of this area is erodible, or environmentally sensitive, but by the end of 1994 all farmers that participate in federal government commodity price support programs will have to have a conservation plan for their farms and have it implemented. Under this 'conservation compliance' plan some 54.6 million hectares (135 million acres) of highly erodible land will likely be in some form of crop residue management, reduced tillage system, to decease water runoff and soil erosion. (Over 14.2 million hectares - 35 million acres with a goal of 42 million - of environmentally sensitive land has already been removed from production through the U.S. Conservation Reserve Program. That land will be kept out of production for a period of 10 years. In the Acreage Reduction Program farmers usually remove their least productive land first). Because residue management is the fastest way to decrease runoff and erosion, it undoubtedly will be combined with a greater movement to no-till.

Effect of Tillage and Residue Management on Nutrient Losses

The type of tillage and crop residue management definitely has an effect on soil and nutrient losses. Laflen (1982), working in Iowa, obtained data shown in Table 4, which indicate the effects of tillage and residue cover on soil and nutrient losses on a 7 % slope of about 70 m length. In going to no-till systems of residue management, it appears that the reductions in nutrient losses will be much greater for N and P than for K. The fact that K is soluble and readily leached from crop residues, would indicate that where both runoff and soil erosion is controlled, K losses will be decreased, unless soils are very sandy or coarse- textured and losses occur due to leaching.

Table 4. Effect of tillage on crop residue cover and soil and nutrient losses (Laflen, 1982).

Tillage	Residue cover %	Soil loss t ha^{-1}	Nutrient losses N	P	K
			kg ha^{-1}		
Fall plow	3	25.8	98.6	38.0	19.0
Fall chisel	35	4.9	22.4	7.8	7.8
No-till	80	0.56	6.7	1.1	9.0

There is evidence that no-till and heavy residues left on the surface of soils may in the long run increase preferential movement of nutrients through the soil profile. However, earlier studies in fine textured soils did not indicate very much movement of K through the soil profile (Munson and Nelson, 1963). In three soil series in which percolate ranged from 10.2 to 23 acre-inches, K loss varied 2.8 to 5.6 kg ha^{-1}. In other studies on fertilized maize, average nutrient losses in drainage water in kg ha^{-1} yr^{-1} were: 14.1 kg N, 0.29 kg P, 1.49 kg K, 195 kg Ca and 105 kg Mg. These losses tend to parallel Barber's mass flow-diffusion results on the manner in which nutrients move to roots (Barber, 1984). In most soils N, S, Ca and Mg would move to roots by mass flow, and accumulate, while P and K move by the much slower mechanism of diffusion. In coarse-textured soils K losses are greater, but very dependent upon soil pH, especially for soils having pH dependent charges, as well as the method of application and source of K applied.

Method of Nutrient Application and Tillage Affect Nutrient Losses

Baker and Laflen (1983) studied erosion and nutrient losses when fall nutrient applications of 31 kg N, 35 kg P and 80 kg K per hectare using different methods of application and/or tillage following soybean harvest which left 5.7 t ha^{-1} of surface residue, that covered 82 % of the surface. The slope of the land was just over 4 %. Diammonium phosphate and potassium chloride were the sources of the nutrients. The results are summarized in Table 5, following two rains totalling 183 mm. Surface nutrient application without tillage produced the highest K loss, while chisel plowing following application produced the lowest loss of K. Considering the 80 kg rate of application and an initial 153 mg kg^{-1} K soil test, these losses are relatively low.

Table 5. Effects of method of fall-fertilizer application and of tillage on soil erosion and N, P and K losses following a soybean crop and two simulated rains (Baker and Laflen, 1983).

Nutrient treatment	Soil erosion	Nutrient losses		
		NH_4^- & NO_3^-N	PO_4-P	K
	t ha^{-1}	g ha^{-1}		kg ha^{-1}
Control	0.54	313	97	3.8
Spoke inj.*	0.56	239	90	2.9
Surface	0.64	984	414	5.9
Chisel	0.72	124	95	0.9
Disk	2.31	488	320	3.1

*Injection was to a depth of 5 cm every 20 cm in rows 76 cm in width. Other treatments were surface applied and then tilled. The measurements were made during October (fall).

Effect of Tillage System on K Availability

Early studies by Schulte and his colleagues at the University of Wisconsin clearly indicated that reduced tillage decreased K availability, and that higher levels of soil test K were required for of no-till than were needed for equivalent yields under moldboard plowing or conventional tillage (Table 6). One of the major effects of no-till in northern regions is a decrease in soil temperature. There is also a moisture-conserving effect of residues due to increased infilration and a decrease in evaporation, as well as lower K loss due to erosion on sloping soils.

Table 6. Influence of tillage and K soil tests on maize yields. Plano silt loam (Schulte, personal communication).

K soil test	Maize yield Tillage		Difference in yield
	No-till	Moldboard plow	
mg kg^{-1}	t ha^{-1}		
67	6.71	8.53	1.82
112	8.03	9.34	1.31
156	9.03	9.85	0.82
200	9.85	10.22	0.37
Yield increase	3.14	1.69	

Results of Rehm (1991) in Minnesota indicate that with ridge-till systems, even on soils testing 145 mg kg^{-1} K, banding K in the ridge is producing very profitable yield increases, and the responses are hybrid-dependent, varying from 502 to 1380 kg ha^{-1}.

More K Required With Soil Compaction

Soil compaction with larger combines and equipment is part of the changing scene of agriculture. Loaded combines during harvest, especially under wet conditions can seriously compact soils. Studies by Bundy, Lowery, and Wolkowski in Wisconsin produced data clearly indicating that increased levels of soil test and fertilizer K could help overcome the effects of soil compaction. Sidebanded, row-place K was particularly effective for maize (Table 7).

Table 7. The effects of soil compaction and sidebanded row K on maize yields (Bundy *et al.*, personal communication, 1986)

Soil compaction	Maize yield		Yield increase
	Without K application K soil test: 102 mg kg^{-1}	Sidebanded K application 37 kg ha^{-1}	
tons	t ha^{-1}		
4.54	8.28	10.16	1.88
8.16	7.15	9.53	2.38
17.24	6.96	9.97	3.01

Hybrids and Varieties Respond to K Differently

Differential varietal responses to K on the same soils and environment have been observed over the years. Parks (1985) has discussed this interaction for a number of crops. It is not always apparent as to why these differential responses occur. In some cases it may be due to different root densities or, with legumes, because of differential effects on nodulation. The work of Rehm was mentioned earlier. He found that on a soil with a 145 mg kg^{-1} K test, two maize hybrids yielded nearly the same, while a third hybrid was 1.38 t ha^{-1} greater. For the highest responder the yield was increased 1.38 tons by 74 kg ha^{-1} of K banded in the ridge, while for the highest yielder the yield was increased 0.63 t by the 37 kg K rate.

Table 8. Maize hybrids response to increasing amounts of sidedressed K* (Tsai, personal communication, 1991).

	Maize yield Hybrid			
Sidedressed K	B73 x PA91	B37 x A632	P3732	Difference
kg ha^{-1}	t ha^{-1}			
0	13.5	11.0	10.4	3.1
93	14.8	10.5	10.2	4.6
186	15.5	10.3	10.3	5.2
Response	2.0	-0.7	-0.2	

* Soil K = 164 mg kg^{-1}; N 134 kg preplant ammonium-N plus 134 kg sidedressed with K at 7 weeks. Plant population 59,3094.

Unpublished research of Charles Tsai at Purdue University indicates how differently maize hybrids may respond to increasing amounts of K sidedressed applied with 134 kg of ammonium-N, 7-weeks after planting (Table 8).

The K treatment increased the yield of B73 x PA91 cross by 2 tons above a high yield level, while the yield of B37 x A632 was decreased 0.7 tons. Note how the differential in yield among the hybrids increased with K rate. In this research the timing of increased K availability is being studied. The hypothesis is that the sidedressed K with ammonium-N will increase the channeling of photosynthate to the ears or physiological "sinks" and prevent 'cannibalization' of leaf N, keeping leaves active longer and resulting in a higher yield. This research has been criticized because of the relatively low plant population used. The concept appears to be effective for some hybrids.

Earlier research conducted in Alabama and Tennessee indicated how differently soybean varieties respond to K. In the Tennessee research 55.6 kg ha^{-1} K increased the yields of McNair by 517 kg, Forrest by 739 kg and Essex by 1.58 t ha^{-1}.

Terman working at the Tennessee Valley Authority with the Soils and Fertilizer Research Branch found that the varieties Bragg and Dare responded differentially to K on a soil initially testing very low in K. A summary of the results is shown in Table 9.

Table 9. Soybean yield-level and response to K, as influenced by variety (Terman, TVA).

K rate	Soybean yield Variety		Difference
	Bragg	Dare	
kg ha^{-1}	t ha^{-1}		
0	2.42	3.22	0.80
75	3.06	4.04	0.98
150	3.39	4.76	1.37
Increase	0.97	1.54	

K Interactions with Rainfall and Water

As indicated earlier, in many production systems water, either too little or too much, limits yields. In general, by far the overriding problem seems to be too little water, but tiling or drainage can also be a serious problem in some areas. For example, millions of hectares of farm land are tile-drained in portions of two high production states, these being southern Minnesota and north central Iowa. There should be little doubt that water should be treated as a nutrient, and that it interacts in a very special way with K^+ and certain other monovalent cations, such as Cs^+, Rb^+, and Li^+. We have known for some time based on enzyme activation research that these elements have a special role in plant metabolism, as well as stomate control, but new research has been reported that could indicate a possible special 'structural' role of K with water (Chem. & Eng. News, 1991). Based on research with Cs^+ there are indications that these metal ions can be encaged in a stable clathrate, containing 20 molecules of water. Perhaps this relationship may relate to the apparent 'water-conserving' effects of K under lower levels of soil moisture.

My first observations and thinking about K and water relationship occurred in studying data of Lawton (1945) in which the effects of nutrient application (NP vs NPK), soil moisture (15 %, 25 % [field capacity], and 40%) and aeration on maize growth and nutrient uptake were evaluated.

The data indicated that the highest dry matter yields (shoot + roots) of maize were obtained with the lowest level of soil moisture (15 %) with the NPK treatment, and that increasing soil moisture to 25 % and 40 % dramatically decreased yield and increased the Ca + Mg: K ratios (meq per 100 g or cmol kg^{-1} basis). When K was added to the NP treatment at 15 % moisture, dry matter yields were increased from about 34 to nearly 37 g/pot and the Ca + Mg: K ratio was increased from about 0.4 to 0.8. When K was added to the NP-aerated treatment, at 40 % moisture the yield per pot was increased from 26 g to 45.5 g and the Ca + Mg: K ratio was decreased from 1.38 to 0.49, indicating the importance of adequate K and aeration on K uptake, Ca + Mg: K relations and K in soil-plant-water relations.

Results of early research on K indicated how K concentration in the soil and water interacted to influence K movement to crop roots, with diffusion usually being the dominating mechanism (Barber, 1984). This research on maize clearly indicated lower responses, but higher yields, when soil moisture was adequate. Results have shown largest responses to applied K when crops are under drought-stress for both maize and soybeans (Johnson, 1985). See Tables 10 and 11.

Table 10. Effect of K rates and relative rainfall on soybean responses (Johnson, 1985).

K rate kg ha^{-1}	K soil test mg kg^{-1}	Soybean yield		Difference
		High rainfall	Low rainfall	
		t ha^{-1}		
0	64	3.78	2.01	1.77
93	100	4.22	3.24	0.98
186	120	3.89	3.29	0.60
Increase		0.44	1.28	

Table 11. Maize yields as influenced by adequate rainfall and low rainfall between seasons and response to K (Johnson, 1985).

Annual K kg ha^{-1}	Maize yield		Difference
	Adequate rainfall	Low rainfall	
	t ha^{-1}		
0	10.22	5.00	5.22
46	10.22	7.09	3.13
93	10.47	7.59	2.88
186	10.22	8.09	2.13
Increase	0.25	3.09	

K soil test = 81 mg kg^{-1}

Consideration for Tropical and Subtropical Ecosystems

As mentioned earlier, in some ecosystems without K applications, and often adequate amounts of lime, N, P and other essential nutrients, there can be little crop production. In the Amazon region of Peru, results have shown that with a slash and burn agriculture, the K, Ca, and Mg from the burned wood is essentially all taken up by crops or leached within three years. There are some 1600 million ha of Oxisols and Ultisols in the world, of which 680 million are potentially arable. Some 200 million ha of these soils are in Latin America's Cerrado region in Brazil and the Llanos region of Colombia and Venezuela. Because of the relatively low exchange capacity of the soils, and their fragile nature, nutrients, such as K, Ca and Mg, along with N, P, S and micronutrients, must be managed carefully and provided on a continuous basis (Munson, 1982). If only N and P are used, which are usually the nutrients initially the most limiting, results will be disappointing.

China currently uses over 18.5 million tons of fertilizer N, while only using 2.27 million tons of P and 996.8 thousand tons of K (IFA, 1991). Of course, they use night soil, manures and crop residues, as well as some imported fertilizer K, but in many areas they are short of K. However, it is apparent on many crops that they must pay closer attention to K in their ecosystem in order to improve N efficiency and continue to improve their yields. That is especially true if they plan to effectively use the increasing amounts of N they are producing and applying.

New Developments

Research is underway to test the use of plastic tubes placed just over 30 cm below crop rows (one could think of this as a variation of trickle irrigation). These tubes can be used to infuse water and nutrients into the system based on the stage of growth and projected yields. These tubes can also be used to periodically aerate the soil. Thus far the results of Jay Johnson, Ohio State University, indicate that very high yields of maize and soybeans can be achieved, grown no-till, with little effect on the environment as far as N losses are concerned.

Fewer researchers are exploring way of making the crop production package per unit area larger. Undue attention is being given to environmental issues, because that is where the research dollars are. However, more attention is now being given to cropping systems and managing cropping sequences to obtain a higher return per unit area per unit of time. This requiring closer nutrient management in both research and on the farm operations.

Grid soil sampling (with a global positioning system) and testing enables the nutrient test results to be translated into nutrient recommendations for know positions in the field. The results can be put on a computer chip, with the encoded geo-positioning information, placed in an 'on-board computer' in the cab of new variable-rate and nutrient-combination field applicators. The applicator can then move across the field applying different rates and nutrient combinations based on the test results [2]. This new technology has

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[2] Workshop on Research and Development Issues in Soil Specific Crop Management, April 14-16, 1992, Minneapolis, MN. For the publication contact Dr. W. E. Larson, Soil Science Dept., University of Minnesota, St. Paul, MN 55108 USA

certain advantages where large variations exist within fields, and for smoothing out nutrient level differences over time. It also is more applicable for larger rather than smaller fields. However, in general, broadcast nutrient applications are less efficient than those placed or timed based on stage of crop development or conditions. It will be interesting to see if this same technology can be applied to band or row applicators. As agriculture becomes more environmentally aware, the industry will move more to site-specific soil and crop management. This should improve the use of K in ecosystems, further increasing crop yields and improving N, P and water use- efficiencies.

From an environmental standpoint, the tailings left by the production of K fertilizers is causing problems in Canada. When K was produced in the arid southwest in the U.S. they were not a problem. However, when you have up to 300 millions of tons of high sodium tailings influencing productive land, people become concerned. Schultz and Rutland, 1992, have recently addressed these concerns and have estimated that the impact of effectively managing the byproduct salt and process wastewater will likely cost between US $11 to $21 per ton of K_2O or US $6.7 to $12.6 per ton of product in Canada. The idea of 'dumping' tailings into rivers as has been done in Europe is no longer a viable option, and probably should never have been done.

Technology is available for extracting K from ocean waters. As we achieve nuclear fusion and energy becomes a non-issue, energy-nitrogen-potassium oceanside production sites can be established that will use hydrogen from electrolysis for the N production, and extract K and perhaps Mg from the ocean.

Conclusion

There are so many aspects to K and mineral nutrition in the ecosystem, one can only touch on a fraction of them. However, I hope that this discussion has brought out some of the points that may be helpful to the reader in more effectively evaluating the need for and use of K in assuring sustainable growth in agricultural production, so that lack food will not be a factor limiting the nourishment, health or welfare of the people of the world. Some of the relationships involving environmental issues are very complex. We must examine and sort out the issues that are important, from those that are only 'smoke and mirrors' and being used to generate research funds and complicate actions and policy decisions.

World nutrient use is currently at about 78.8 million tons of N, 16.4 millon tons of P and 22.1 million tons of K (IFA, 1991). There is little doubt that K use worldwide will have to increase, but in some areas in some countries with high K soil tests for a few years, we can exploit or use those resources as part of wise management. However, finally adequate K must be used, in balance with that cycling in the system and being introduced from various sources.

APPENDIX

Table A. The annual U.S. input of N, P and K from fertilizers, animal manures and crop residues, and the losses (output) due to eroded sediments and removal by major crops (Follett *et al.*, 1987; Miller and Larson, 1990; and Wallingford, personal communication, 1992).

Nutrient source	**INPUTS** Nutrients added-1,000 tons N	P	K
Manures	808.9	588.8	1,127.6
Crop residues	2,986.5	396.4	3,131.3
Sewage sludge	297.6	190.5	34.0
Fertilizers	10,141.6	1,812.5	3,753.1
Total	14,234.6	2,988.2	8,046.0

	OUTPUTS-1,000 tons		
	Nutrients lost due to eroded sediments	Nutrients removed by 20 major U.S. crops (based on the average of 5-year running means, 1985-1989)	Total
N Total	9,494	8,810	18,304
Available	1,744		10,554
P Total	1,704	2,000	3,704
Available	34.1		2,034.1
K Total	57,920	6,860	64,780
Available	1,158		8,018

NUTRIENT INPUT - OUTPUT = DEFICIT or SURPLUS-1000 tons		
Based on total inputs - outputs		
N	P	K
-4,069.4	-715.8	-56,734
Based on available inputs - outputs		
N available	P available	K available
3680.6	953.1	28

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Need of K Fertilizers in Tropical and Temperate Forests

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Summary

K deficiency, K fertilizer requirements and results of experiments are reviewed. K nutrition is deficient mainly on peat soils in northern countries, on sandy soils from glacial or fluvioglacial deposits (for instance in northeastern Germany, northeastern USA and southern Québec), calcareous shallow soils particularly under Mediterranean climate, and strongly weathered ferrallitic soils in the tropics. There are no common methods for soil analysis and soil analysis interpretation; the different techniques used according to ecological conditions are briefly reviewed. Foliar diagnosis is probably very useful and sure, but wide gaps in knowledge remain for many species, namely broadleaves.

Introduction

Foresters have for long used fertilizers in order to improve timber production or, more recently, tree health. Usually, P and N have been found the most effective. K was more rarely a key element for increase in growth for the probable reason that it is very mobile in ecosystems. It is easily released from clay minerals like biotite, phlogopite and illite and not strongly held by kaolinite or organic matter ; it moves easily from colloids into the soil solution and thence into plant roots. Turnover between foliage and soil is rapid. More than half the return of K from the forest canopy to the soil is via throughfall ; little N or P is returned in this way. Annual uptake of K exceeds accumulation in wood and foliage, indicating very active cycling (Table 1). Thus, despite the fact that the trees' K demand is quite high, this is more easily satisfied than those for N, which is dependent on mineralisation of soil organic matter, or P, which is generally strongly held by soil colloids. Nevertheless, under a range of soil conditions, it has proved useful to apply K along with N and P in order that the two later exert their maximum effect ; it can even be an "essential element" in its own right.

Hereunder the main conditions where K may be a primary or secondary growth limiting nutrient are reviewed.

K as a limiting factor in northern and temperate forests.

In afforestation of peat soils with *Pinus contorta, Picea sitchensis, Pinus silvestris,* K fertilization is essential together with P fertilization, as shown in many experiments in Scandinavian countries (Holmen, 1967; Heikurainen, 1967; Braekke, 1977); Scotland, Ireland (Dickson, 1972). An application of 50 to 150 kg ha^{-1} K_2O in addition P or NP fertilization may double height growth (Franz and Baule, 1962).
The positive effect of K_2O fertilizers may last for 10 to 20 years.

There are strong K deficiencies in Europe and North-America on sandy soils developed from glacial deposits. Many papers were devoted to the effects of K fertilization on *Pinus silvestris* or *Quercus rubra* plantations under such conditions in northeastern Germany (Heinsdorf, 1966; Seibt *et al.*, 1969; Krauss, 1967a and 1967b; Baule, 1974; Trillmich and Uebel, 1970). In several cases K fertilization is inefficient if Mg is not added together with K (Brüning, 1961, 1963, 1967). In this area soils where K fertilization is beneficial are characterized by a K concentration in A_1 horizons lower than 0.4 % after calcination and digestion in boiling 0.1 N HCl, or 0.11 % after digestion without calcination (Fiedler and Nebe, 1963) or a total K concentration lower than 800 mg kg^{-1} after HF digestion (Krauss, 1967b; Heinsdorf, 1966; Brüning, 1967). On these poor sandy soils K fertilization may protect *P. silvestris* from damage by the caterpillar *Rhyacyonia buolliana* (Baule, 1968).

In Koo *et al.*, 1970 in Korea observed a similar effect in *Pinus densiflora,* in which, after a fungus attack, growth is strongly enhanced on K plots in comparison with controls.

Table 1. Nutrient cycling in two forest stands : a beech stand *(Fagus silvatica)* (Ulrich, 1973) and a spruce stand *(Picea abies)* (Nys, 1987), in kg ha^{-1} yr^{-1}

	Beech			Spruce		
	N	P	K	N	P	K
	kg ha^{-1} yr^{-1}					
Annual immobilization in wood	14	2.6	7	16	1.4	8
Quantity of elements in the annual foliage growth	90	6.0	27	60	5.2	21
Annual uptake	69	7.8	48	71	5.4	35
Returning to soil						
by litterfall	55	4.8	17	54	3.5	7
by throughfall	1	0.1	24	0	0.5	20

In northeastern America, on sandy soils from glacial sediments, growth of *Picea abies* and *Pinus resinosa* is increased by K fertilization (Stoeckler and Arneman, 1960; Leaf and Berglund, 1971; Kawana *et al.*, 1969; Gagnon, 1965; Gagnon, 1969). Responses to K fertilization correlate with K extractable in boiling HNO_3 (White and Leaf, 1964). The efficient rate is 160 kg ha^{-1} K_2O (Kawana *et al.*, 1969); the effect of K fertilizer is long lasting in spite of the high mobility of this element in such soils : 39 years after fertilization, thanks to the good cycling of K in the forest ecosystem, K concentrations in throughfall, stemflow and exchange complex are still higher in the fertilized plots than in the controls (Shepard and Mitchell, 1991); this has been substantiated by a lower Rb/K ratio in fertilized plots : 12 years after fertilization 25 % of K content of the needles came from the fertilizer (Stone, 1981). In southern Québec, under about the same ecological conditions, K deficiency is thought to play a role in the dieback of sugar maple stands where the leaf K concentration is lower than 0.55 % (Bernier and Brazeau, 1988). Operational fertilizations are already being carried out.

In southern Germany, K concentrations in needles of declining Norway spruce stands on paragneiss soils is only 0.47 % today while it reached 0.62 % in 1964. This decrease indicates that needle loss and yellowing in these stands might be linked with a deterioration of mineral nutrition (Hüttl and Zöttl, 1985).

In conifer plantations of western Europe, while P applied alone improves growth, P + K is more effective. Some examples from France are given in Table 2.

Table 2. The effect of P with and without K on tree characteristics measured in four French tree fertilization experiments. C : control. S.T. : basal area(1). Circ. : circumference at breast height. +, ++ : significant at 5 %, 1 % level versus control.
(1) : sum of the stem areas at 1.3 meter height.

Experiment name and ecological conditions		Age yr	Measured feature	C	P	P + K
Langle : humic acid brown soil on granite Massif Central	Douglas fir	21	Circ. cm	70.6	77.4^{+}	84.0^{++}
Forêt de Boulogne : podzolic soil on sandy sediments - Sologne	Corsican pine	18	Circ. cm	30.9	33.4	35.3^{+}
Razès : humic brown podzolic soil on granite Calluna heathland - Massif Central (Bonneau, 1983)	Norway spruce	17	S.T. $m^2\ ha^{-1}$	9.3	17.2^{+}	20.8^{++}
Barcus : brown leached soil on silt, Pays Basque (Maugé, 1969)	Douglas fir	5	height m	-	1.1	2.5

In calcareous or high Ca or Mg saturated soils Ca-K or Mg-K antagonisms are known to hamper K nutrition. K deficiencies were identified by Krapfenbauer (1969) on soils developed from dolomite or serpentine. The recent forest decline gave clear examples of such situations. For instance, in the Luchon area, in the Pyrenees, severe yellowing in white fir (*Abies alba*) has been described; foliar analysis showed that this yellowing is associated with K concentrations as low as 0.25 % in the current year needles (Cheret *et al.*, 1988). K deficiencies, associated with high Ca and Mg and low N and P concentrations, have been disclosed on slightly calcareous soils in the Bavarian Alps (Laatsch, 1967a), in the Jura, in the northern French Alps, and on eutrophic soils on basalt in the Massif Central. For instance the mean K concentrations in first year needles of Norway spruce or white fir in the Jura are 0.40 % and that of the second year needles 0.32 % in yellowing stands while they are 0.55 % (first year) and 0.50 % (second year) in healthy stands (Bonneau, 1989).

K nutrition in Mediterranean areas.

In the Mediterranean regions, soils are often shallow and become very dry in summer. Repeated cycles of drying and wetting lead to varying K fixation and K release in the clay-layers; soils are often rich in Ca or even contain free calcium carbonate in the fine fractions. These conditions are unpropitious to K nutrition. Laatsch (1967b) showed that Aleppo pine plantations in Spain suffer from severe K deficiency on middle-shallow soils rich in Ca, with high capacity for fixing K, but still containing enough humus to guarantee young plantations good N nutrition. The K and N concentrations in current year needles were respectively 0.3 and 1.5 %, while on deep soils K concentration reached 0.8 % with a N concentration of 1.4 %. However K fertilization was inefficient in those middle-shallow soils because of their high K fixing capacity. On clayey sands, in the Mamora forest (Morocco), Lepoutre and Mandouri (1976) found that P fertilizer had little or no effect unless accompanied by K. In the south of France, in the Arques experiment (Carcassonne area) a Corsican pine plantation on a calcareous soil rather poor in K (2.5 m.e. kg^{-1} in the A$_1$ horizon) showed a very good response to K fertilization applied 1, 2, 3 and 10 years after planting (55 g of K_2O per young tree as K_2SO_4) as shown in table 3. K concentration in the first year needles, was 0.51 % in the control plots in 1976, 13 years after planting (Guitton *et al.*, 1988). However K deficiencies and effects of K fertilization are not always the rule in Mediterranean regions : for instance in Provence, to the north of Toulon, on a shallow but rather K rich soil (10 m.e. kg^{-1} in the A$_1$ horizon), without free calcium carbonate in the fine fractions, *Abies cephalonica* showed only a slight and short lived response to K fertilization; the K level of the first year needles was very good in 1986, 18 years after planting : about 1 % in all treatments including control (Guitton *et al.*, 1988).

Table 3. Effect of fertilizers on Corsican pine - (Arques experiment)

Treatment	Height in 1986 13 yr cm	Height increment 1979-1986 cm
Control	155	103
P	217 $^{+}$	151 $^{+}$
K	255 $^{++}$	161 $^{++}$
PK	215 $^{+}$	152 $^{+}$
NPK	259 $^{++}$	176 $^{++}$

\+ : significant result at 5 % level
++ : significant result at 1 % level

K nutrition and fertilization in tropical areas.

There have not been so many fertilizer experiments in tropical and subtropical areas as in northern or temperate regions but some of them give evidence that K deficiencies are rather frequent. In four pine species (*P. Elliottii, P. taeda, P. palustris* and *P. clausa*), on sandy soils of central Florida, Bengtson (1976) found K concentrations lower than 0.35 % associated with effects of potassium fertilization on height growth. McKee (1978), in preliminary glasshouse experiments, showed that *P. Elliottii* responded to K fertilization on imperfectly drained soils of the southeastern part of the U.S.A. Fertilization of *Pinus caribaea* plantations in the Sao Paulo State in Brazil must include K (Simoes *et al.*, 1970). The same species, in Tanzania, showed a better survival rate if K was added to N + P fertilization (Kalache, 1983). In Benin (West Africa) several tree species (*Eucalyptus camaldulensis, Leucaenia leucocephala, Casuarina equisetifolia, Acacia* spp) suffer from K as well as N and P deficiencies a few years after planting (Drechsel and Schmall, 1990). But Zöttl (1980) mentioned needs for B, N and P fertilization only, in forestry plantations of Colombia.

Good examples of responses of pines to K fertilization were obtained in afforestations in Madagascar (Malvos and Bailly, 1979; Malvos, 1980; Malvos *et al.*, 1982; Rampanana, 1984). Many experiments have been made in this country, the most detailed in the Haut-Mangoro afforestation area near Mouramanga, on ferrallitic (lateritic) soils. Four sites have been studied: two (A and B) on old yellow fluvioglacial sediments, B with an indurated clayey horizon at 60 cm depth, one (C), on eroded soils derived from migmatites(1), and one (D) on recent sandy fluvial deposits. All these soils are acidic (pH 4.5 to 5.0), rather poor in organic matter and very poor in P_20_5 (10 to 20 ppm. by Truog method, 0.001 to 0.07 ppm of water extractable P_20_5, 575 to 1,860 ppm of total P_20_5). P_20_5 levels vary little between sites. The level of exchangeable K, extracted by ammonium acetate, is higher in upper horizons of sites A and C (about 1 meq kg^{-1}) than in sites B and D (0.05 meq kg^{-1}). Deep horizons are poor : 0.05 meq kg^{-1} on sites A, C and D, and 0.02 meq kg^{-1} on site B. Besides, a strong Zn deficiency has

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[1] Metamorphic rock made up of a mixing (migma in Greek) of gneissic and granitic masses

been found on site C. Fertilizer experiments were set up at planting time or several years after, with rather small quantities, 50 kg ha^{-1} K_2O and 70 kg ha^{-1} P_2O_5, applied around plants. All plants were grown in nursery beds inoculated with mycorrhizal fungi. The main results can be seen in table 4. K effects were the strongest in sites B and D where the soils were the poorest in exchangeable K, and greater than P effects. On site C, K and P effects were about the same but growth remained rather poor because the soil was stony and dry. On site A, the richest of the four sites, K effect was small when fertilizer was applied at planting time, but better if applied several years after : K concentrations in the first year needles, sampled in the dry season (July), were very low in the control plots (0.15 - 0.17 %) and increased up to 0.20 - 0.25 % in K fertilized plots. The effect of the initial fertilization lasted about ten years, but decreased later and K deficiencies appeared again in fertilized plots.

Table 4. The effects of P and K singularly or in combination with each other on growth (growth increment over control) of trees grown in the Haut-Mangoro afforestation area in Madagascar (Malvos *et al.*, 1982).

	Effect of P in absence of K	Effect of K in absence of P	Effect of K in presence of P
Site A			
- Fertilization at planting; effect after 9 years	+ 15 %	+ 5 %	+ 5 %
- Fertilization several years after planting	+ 3 %	+ 10 %	+ 25 %
Site B			
- Fertilization at planting; effect after 9 years	+ 20 %	+ 50 %	+ 30 %
Site C, with Zn fertilization			
- Fertilization at planting; effect after 4 years	+ 20 %	-	+ 15 %
- Fertilization several years after planting; effect after 3 years	+ 30 %	+ 3 %	+ 25 %
Site D			
- Fertilization at planting; effect after 5 years	+ 10 %	+ 50 %	+ 35 %

It was shown that 8-year-old pine accumulated 91 kg ha^{-1} K_2O if fertilized with K and P and 54 kg ha^{-1} if fertilized with P but without K (not including roots). Thus almost all K applied was consumed by the end of 8 years. It still might increase growth by internal recycling, but K deficiencies appeared again later on, because the soil was not able to sustain this growth and K became more and more diluted in the tree biomass. As a matter of fact these soils do not contain more than 200 kg ha^{-1} of exchangeable K, or 400 kg ha^{-1} of K extracted in 10 minutes by 0,5 N boiling HNO_3 (White and Leaf, 1964). These quantities are very small when compared with the needs of a fast growing stand.

These results give a good illustration of the extreme impoverishment of some tropical soils, in which the very small K reserves are probably in the form of felspars, which weather very slowly, and clays are mainly kaolinit.

Diagnosis of K fertilizer needs in forest soils.

Soil analysis.

Extraction of exchangeable K by N ammonium acetate is the most frequently used method, but estimates of the critical value (below which K fertilizer is effective) vary much according to the literature. These values differ from one tree species to another. For non high demanding species, such as pines, this critical value seems to be very low, for instance 0.26 meq kg^{-1} in Florida for *P. Elliottii* (C.R.I.F.F., 1980). But Stoeckler and Arneman (1960) estimated that 0.5 meq was the threshold value. This value seems to be more realistic and to correspond rather well with the results of the experiments in Madagascar, where *P. kesiya* showed very strong responses to K fertilization with 0.25 meq kg^{-1} of exchangeable K in the upper soil horizons.

In more humic soils of temperate climates and for more demanding species such as *Picea abies*, the critical value is probably much higher ; on the basis of our own experiments we propose 4 meq kg^{-1} in A_1 horizons and 1 meq kg^{-1} in mineral horizons. These values are in good agreement with those proposed by Süchting (1943).

Other authors proposed more drastic extraction methods, like 0.5 N boiling HNO_3 for 10 minutes (White and Leaf, 1964). Fiedler and Nebe (1963) proposed a critical value of 4 g kg^{-1} of K extracted from A_1 horizons by 6N boiling HCl for one hour after calcination, or 1.1 g kg^{-1} extracted without previous calcination. Brüning (1967) and Heinsdorf (1966) suggested using total K extracted by HF with a critical value of 800 mg kg^{-1} for *Pinus silvestris*. Zech (1968) proposed a critical value of 5000 kg ha^{-1} of total K in calcareous soils. The exchangeable Mg/K ratio is probably important : for instance in the A_1 horizon of soils in the Luchon area (Pyrenees) where white fir suffer from K deficiency, the Mg/K ratio is above 2; this ratio is lower than 2 in the Vosges, where Norway spruce and white fir are Mg deficient (Bonneau, 1989) (fig. 1).

As a whole it seems that there is no universally accepted method so far, and that the NaTPB method has not been used in forestry. Progress might be achieved by researching in this direction.

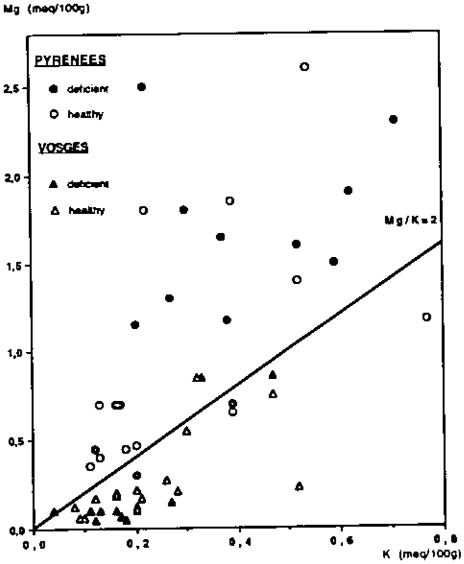

Fig. 1. Exchangeable Mg and K concentrations in the A_1 horizons of Pyrenean soils (with K deficient white fir) and Vosgian soils (with Mg deficient white fir or Norway spruce).

Foliar analysis.

Foliar analysis probably is a better diagnostic tool if one takes care to correctly sample needles or leaves. Literature in this field is tremendously abundant and an exhaustive review is impossible. For temperate tree species, one can find very useful and complete documentation in Fiedler *et al.* (1973) and Baule and Fricker (1969).

Pine species are probably the least demanding. *P. kesiya* can grow well with a K concentration in first year needles of about 0.3 % (Malvos *et al.*, 1982). For *P. Elliottii* the critical value below which K fertilization has a positive effect is 0.35 % (Bengtson, 1976) and is the same for *P. radiata* in Australia (Raupach and Hall, 1974). Healthy and well growing *P. halepensis* in Spain has a K concentration of 0.7 % while it is clearly deficient at 0.3 % (Laatsch, 1967b). *P. silvestris* seems to be more demanding : the deficiency threshold is 0.35 %, the critical level about 0.40 - 0.45 % and the optimum concentration 0.45 - 0.50 % (Fiedler *et al.*, 1973). The K/Ca ratio is important for this species : Hofmann and Müller (1971) reported a linear correlation between K/Ca and height growth : height at age 70 was 16 m for a K/Ca ratio of 1.2, and 27 m for a K/Ca ratio of 2.0. Norway spruce is probably a little more demanding than Scotch pine : according to our own experiments (Bonneau, 1972, 1983) the optimum concentration in the first year needles might be about 0.6 %, but some authors define a lower optimum value, at about 0.45 - 0.50 % (Zöttl, 1990) with a critical level for fertilization efficiency at 0.40 %, and a deficiency threshold at 0.25 % (Burgtorf, 1968 *in* Fiedler *et al.*, 1973; Zech, 1968 *in* Fiedler *et al.*, 1973). According to Keller (1966), a K/Ca ratio lower than 0.3 on clayey calcareous nursery soils corresponds to clear K deficiency and the deficiency-symptoms disappear at a K/Ca ratio higher than 0.5. Douglas fir and larch are less known species with regard to K nutrition; however their optimum K concentration in needles is probably a little higher than that of Norway spruce, perhaps 0.7 (Van Goor, 1971; Höhne, 1968 *in* Fiedler *et al.*, 1973). According to Zech (1968) deficiency symptoms appear in larch on calcareous soils at a K concentration lower than 0.3 %.

According to Bernier and Brazeau (1988) many declining stands of sugar maple have less than 0.55 % K in the leaves while a normal value is about 0.9 %. In the west of France natural seedlings of *Quercus petraea* grow well with about 0.6 to 0.7 % of K in the leaves in August. Other deciduous trees do not grow satisfactorily at such K concentrations : optimum levels are at least 1.3 % for birch (Trillmich and Uebel, 1970) and poplars (Sheedy and Vallée, 1981) but according to Van der Meiden (1962) the optimum value is as high as 2 %.

Conclusion

Obviously everything is not known about needs for K fertilization in forestry. The soils in which K nutrition is most clearly limited are :

- peat soils in northern countries;
- sandy soils on glacial or fluvioglacial deposits;
- calcareous and shallow soils mainly in Mediterranean areas;
- strongly weathered ferrallitic soils in the tropics.

Besides these major K deficient areas, K may be a very useful fertilizer together with P in many temperate and tropical soils. Soil analysis is not very useful as a guide to K fertilizer requirement; it is unlikely, or perhaps impossible, that any one method of analysis and interpretation from among the many which have been tried can be proposed for general use. An obvious reason is that plant available and reserve K occur in very different forms according to variation in geological, soil and climatic conditions.

Foliar diagnosis may offer a safer way but, while many forest species have been reasonably investigated in this respect, we are still far from an adequate knowledge of many others (mainly broadleaved species), both in temperate and tropical areas where the major effort has been devoted to pines.

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Potassium Requirements of Fast-growing Tropical Tree Plantations

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Summary

A literature review has been conducted to compile data on K nutrition and K requirements (for above ground biomass production) of fast-growing tropical tree plantations. The paper focusses on *Tectona grandis, Eucalyptus sp.* and *Pinus sp.* Potassium nutrition has been successfully characterized by foliar analysis. Deficiency of the considered species is indicated by leaf values of K < 2-6 mg g^{-1} (*T. grandis*), < 3 mg g^{-1} (*Eucalyptus sp.*) and < 1.3-2.0 mg g^{-1} (*Pinus sp.*). Optimum supply needs foliar concentrations of 5-25 mg g^{-1}. Teak has the highest demand while pines need the lowest concentrations.

Likewise, the annual K requirements of teak are highest among the considered species, followed by eucalyptus. The data vary greatly and generally tend to increase with the age of the stands (up to about 25 years). Site fertility, water supply, fertilization, and use of biocides also explain part of the variability. Recorded data range up to 555 kg ha^{-1} a^{-1} K for teak, vary from 7.7 to about 25 for *P. caribaea*, and reached about 180 kg ha^{-1} a^{-1} K in an intensively fertilized *P. radiata* stand. Up to 50% of the K requirements of a forested site may be due to understorey uptake of K.

Up to 70% of the K requirements are supplied by internal retranslocation. Mineralization of K from litter plays an important role for K supply, too. In the early stage of a forest plantation, however, the soil K is the major source to cover the stand requirements.

Introduction

The total above ground nutrient requirements of forest trees as expressed in kg ha^{-1} a^{-1} are considered to be the quantities necessary for annual increments in branch and stem biomass plus the amount required for the replacement of the foliage within one year (Switzer and Nelson, 1972). The requirements for substitution of the root biomass have to be considered additionally when talking about the total nutrient requirement of trees. It has to be assumed that root litter production is at least as high as annual leaf litter fall (Fabiao *et al.*, 1985). Since, however, the data base on below ground biomass, element stores and root growth dynamics is very weak, this paper is confined to the K requirements of the above ground biomass production. Additionally, canopy leaching of nutrients has to be substituted by uptake. Although this quantity returns to the soil it has to be added to the annually required amount of nutrients. In order to evaluate the nutrient requirements of a forested site the nutrient demands for understorey biomass production have also to be taken into account (Turner and Lambert, 1983).

A rough first estimate of the annual nutrient requirements (R_r) of forest stands from literature data may be derived by deviding the total stock of nutrients at the time of harvest (S_r) plus the amount of nutrients recycled to the soil via litter fall and canopy leaching (L_r) by the duration of the rotation period (T_r) (Eq. *I*).

$$R_r\ (kg\ ha^{-1}\ a^{-1}) = \frac{(S_r + L_r)(kg.ha^{-1})}{T_r(a)} \qquad (I)$$

Requirement data derived in this way will then provide average values neglecting, however, the significance of the specific dynamics of the annual nutrient demands during the forest plantation cycle. According to Miller (1984) the nutrient requirement can be considered in three distinct phases. In phase I, prior to canopy closure, the young trees have high nutrient requirements. The major nutrient source in this phase is the soil. During the second phase, retranslocation of nutrients within the tree becomes the main source. Finally, in phase III, the growth rate of the trees declines, nutrients are fixed in organic soil layers or are depleted from the soil (see also Attiwill 1979).

Thus, if data are available it will be more convenient to estimate the annual nutrient requirement on a database collected during a growth period or at least during vegetation periods where the requirements differ less (mean annual periodic requirements). Substituting the suffix *r* (rotation) by *a* (annual) and *p* (periodic) Eq. *I* turns into:

$$R_{a,p}\,(kg\ ha^{-1}\ a^{-1}) = \frac{(S_{a,p} + L_{a,p})(kg.ha^{-1})}{T_{a,p}(a)} \qquad (II)$$

According to the mass balance equation the annual nutrient requirements can also be calculated as the sum of annual uptake (U_a) plus annual internal redistribution of nutrients before litterfall (Re_a):

$$R_a\,(kg\ ha^{-1}\ a^{-1}) = U_a\,(kg\ ha^{-1}\ a^{-1}) + Re_a\,(kg\ ha^{-1}\ a^{-1}) \qquad (III)$$

Potassium requirements of fast growing tropical trees have been calculated from literature data by means of one of Eq. *I* - *III*, depending on the available data base. Before reviewing the requirement data, it is useful to give first some general rules for the diagnosis of the K demand and also, to evaluate the K nutrition status of tropical trees.

Diagnosis of potassium demands

The visual approach to identify the nutritional status of trees by specific deficiency symptoms is rapid and inexpensive. Thus, there have been attempts to provide special guides for diagnosis (Drechsel and Zech, 1992). Since K belongs to the phloem mobile nutrients symptoms of deficiency will in general, with some exceptions, first show on older plant tissue. With respect to K, Drechsel and Zech (1992) established the following diagnostic criteria for eucalyptus, pines and teak :

Eucalyptus sp.: Symptoms are first localized in younger leaves, leaves are not abnormally discoloured, but margins and veins of the leaves are dying off. Leaves of seedlings are smaller than normal, often whith crinkled surfaces and margins. Branching is pronounced, giving a bushy, round-topped appearance. However, the deficiency symptoms described are not always in agreement and are not very clear for K (Schönau and Herbert, 1989).

Pinus sp.: Older needles are affected, after tip yellowing the needle tips turn brown-reddish, the transition of the discoloured needle tip to the green basal part is smooth, not distinct. Sometimes needles appear bluish-green.

Tectona grandis: Older leaves show well marked interveinal chlorosis, the margins of the leaves appear scorched. Younger leaves show wrinkled surfaces, the leave margings curl inwards.

Visual symptoms, thus, may be useful in qualitative diagnosis. However, they are often readily apparent only after the deficiency has resulted in reduction of growth (Mead, 1984). Another disadvantage is that multiple mineral deficiencies make diagnosis difficult. Thus other techniques are required to get both early and precise information about the nutritional status of trees. One of these techniques is foliar analysis.

Potassium foliar values of tropical trees

The tree foliage nutrient concentration is an indicator of the nutritional status of a plantation since it integrates the soil nutrient availability over a certain period of time and also reflects actual changes when comparing foliage of different ages. Thus, foliar analysis reveals a powerful tool to assess the nutritional status of plants (e.g. Lambert, 1984; Mead, 1984; Zech, 1984; Bergmann, 1986). Recently, Drechsel and Zech (1992) have summarized the usefulness and limitations of foliar analysis and have given technical implications with respect to sampling, analysis and interpretation of data.

Drechsel and Zech (1991) have reviewed foliar nutrient levels of broad-leaved tropical tree species. The authors observed K-deficiency symptoms at K foliar concentrations less than 1.0 to 2.9 (5.7 for *Terminalia superba*) mg g^{-1}. Potassium leaf concentrations of 1.8 to 9.2 mg g^{-1} were considered to be low and values from 3.1 to 30.0 mg g^{-1} were classified as intermediate. The broad range reflects first of all differences in the demand of species. The environmental conditions may, however, also vary the need for nutrients. With respect to K the relation to soil water availability has often been demonstrated (e.g., Larsen 1983). Zech (1986) observed symptoms of K deficiency (2.0 in foliage from the lower crown to 7.6 mg g^{-1} K in tissue from the upper crown) in leaves of poorly growing *T. grandis* in Ivory Coast. However, only slightly higher foliar values (5.3 to 7.0 mg g^{-1} K) were observed in vigorous *T. grandis* at a second site in Ivory Coast. The autor attributed growth differences to higher water supply at the better site.

The leaf position also affects the concentration of K. E. g., Lamb (1976) showed that K leaf concentrations of *E. deglupta* were highest in upper crown distal tissue compared to lower crown and proximal positions. Evans (1979), however, found no inner-crown variability of K concentrations in *Gmelina arborea* trees. This may be attributed to relatively high K concentrations from 11.0 to 16 mg g^{-1} K, which do not force the tree to translocate K into younger and unshaded tissue.

The variability of K within the same crown position further depends on site conditions. Lamb (1976) observed lower coefficients of variation of the leaf concentrations of *E. deglupta* during the dry season compared to the wet season.

Differences in differently old foliage are also affected by the soil supply of K. The higher the available soil pool the lower is the difference between differently old tissue.

A summary of K foliar levels in leaves of teak, eucalyptus and pines as compiled from data of Drechsel and Zech (1991, 1992), Herbert and Schönau (1989), Zech and Kaupenjohann (1990), Zech and Drechsel (1992), Zech *et al.* (1990, 1991) is given below :

	K concentrations (mg g^{-1})		
Species	Deficiency	Low	Intermediate/Optimum
T. grandis	2 - 6	4 - 9	7 - 24
Pinus sp.	1.3 - 2.0		- 10
Eucalyptus sp.	< 3	2 - 6	5 - 15

As a general rule it can be stated that younger trees need higher K foliar values, and younger tissue needs higher K concentrations than older material. Young leaves of various *Eucalyptus sp.* e.g. contained up to two times more K per unit of dry matter than old foliage (Lambert, 1984).

Potassium requirements of various tropical tree species

The efficiency of within-stand nutrient use which was defined by Vitousek (1984) as the amount of organic compound produced per unit of nutrients tends to be principally higher in tropical than in temperate forests. Generally, evergreen species need less nutrients compared to deciduous trees. The former species group has developed a very efficient internal nutrient-conserving mechanism, which enables high productivity even on low fertility soils (Miller, 1981). The species which will be considered in this paper are *Tectona grandis, Eucalyptus sp.* and *Pinus sp.*. Other species have also, however less extensively, been studied (see e. g., Moore *et al.*, 1967; Langkamp and Dalling, 1983), and will thus not be considered further.

Potassium requirement data for a good quality ***Tectona grandis*** stand are given by Nowoboshi (1984). The K requirement in this study increased during stand development from 22 kg ha^{-1} a^{-1} K for a one-year-old stand to 555 kg ha^{-1} a^{-1} K for a 15-years-old stand. The expected annual biomass increment of this highly productive stand was 85 t ha^{-1} a^{-1} at an age of 15 years. From the teak ecosystem store data presented by Hase and Foelster (1983) it can be calculated (using Eq. *I*) that one-year-old teak required 96 kg ha^{-1} a^{-1} K, 4-years-old trees needed 39, 6-years-old ones 38, and 9-years-old teak required 120 kg ha^{-1} a^{-1} K. Increasing clay content of the soil increased the K requirements in this study (e. g., 4-years-old trees required 39 kg ha^{-1} a^{-1} K on soil containing 8 % of clay while 4-years-old trees on 19 % clay soils required 95 kg ha^{-1} a^{-1} K). Kaul *et al.* (1979, cit. in Hase and Foelster, 1983) reported significantly lower annual K requirements of a 38-years-old teak stand. Using Eq. *I* an annual average K requirement of 87 kg ha^{-1} a^{-1} is estimated.

Potassium requirement data of ***Eucalyptus sp.*** range from about 20 to 60 kg ha^{-1} a^{-1} K. Attiwill (1979) found that the total demand of K of a 40- to 70-years-old *E. obliqua* stand varied between 31 and 36 kg ha^{-1} a^{-1} K. The requirements were supplied by biochemical cycling to about 30 %, biogeochemical cycling (55 %) and uptake from the soil (according to the concept of Switzer and Nelson, 1972). This study also showed that the contribution of soil to K supply decreased with increasing age of the forest.

Turner and Lambert (1983) investigated nutrient cycling within a high-productivity 27-years-old *E. grandis* plantation. Their data show that about 50% of the K requirement of the stand was due to understorey biomass production:

Component	Biomass increment (t ha^{-1} a^{-1})	K concentration of leaves (mg g^{-1})	K requirement (kg ha^{-1} a^{-1})
Tree	24.3	6.45	55.7
Understorey	4.9	13.4	49.4

Madeira and Pereira (1990) have studied the productivity of *E. globulus* as affected by fertilization (N/P/K/Mg/Ca) and irrigation. The K requirements for the above ground biomass production were calculated according to equation II:

Treatment	Biomass increment ($t\ ha^{-1}\ a^{-1}$)	K concentration of leaves ($mg\ g^{-1}$)	K requirement ($kg\ ha^{-1}\ a^{-1}$)
irrigated and fertilized (IF)	25.0	6.2	55
irrigated (I)	15.7	6.0	33
fertilized (F)	12.7	6.0	45
control (C)	9.0	6.4	33

Fertilization increased biomass production (by about 40 %) and also the K requirements. Irrigation, however, increased biomass production by about 100 % over the control while the total K requirement remained constant. The K use efficiency (units of biomass produced by one unit of K) was thus increased from 273 (C) and 282 (F) to 476 (I) and 455 (IF); this is in accordance with the knowledge about the general physiological functioning of plants (Mengel and Kirkby, 1987).

Besides fertilization, biocide use may also affect the K requirements of stands. E. g., the potassium accumulation rate (calculated according to Eq. *II*) of a 7- to 9-years-old *E. grandis* stand was 35.7 kg ha^{-1} a^{-1} K for control trees, 39.6 for NPK-fertilized trees and 46.5 for the fertilized and weedicided plus insecticided stand (Birk and Turner, 1992).

The annual K requirements of ***Pinus sp.*** range from 5 to about 25 kg ha^{-1} a^{-1}. Data from several case studies are given below. Mean annual requirements calculated according to Eq. *I* generally increased with increasing age of the plantations while mean annual periodic requirements (Eq. *II*) seem to peak at a plantation age of about 10 years.

P. caribaea, Egunjobi and Bada (1979), Eq. *I**)			
Age	Biomass increment ($t\ ha^{-1}\ a^{-1}$)	K concentration of needles ($mg\ g^{-1}$)	K requirement **) ($kg\ ha^{-1}\ a^{-1}$)
6	10.3	7.2	20.9
10	13.4	7.5	25.8

*) Equation used to calculate K requirements;

**) K requirement for litter fall was not determined

P. caribaea, Kadeba (1991), Eq. *I*, Eq. *II* in parenthesis			
Age	Biomass increment (t ha^{-1} a^{-1})	K concentration of needles (mg g^{-1})	K requirement (kg ha^{-1} a^{-1})
5	3.6 (3.6)	6.3	7.7 (7.7)
7	7.2 (16.2)	6.5	15.1 (33.7)
9	8.7 (13.7)	5.7	17.3 (24.7)
11	9.6 (13.6)	6.4	16.7 (14.1)
15	10.8 (14.0)	5.8	18.8 (24.8)

P. caribaea, Chijioke (1980), Eq. *I*			
Age	Biomass increment (t ha^{-1} a^{-1})	K concentration of needles (mg g^{-1})	K requirement (kg ha^{-1} a^{-1})
6	11	3.4	7.7

P. patula, Singh (1982), Eq. *I*			
Age	Biomass increment (t ha^{-1} a^{-1})	K concentration of needles (mg g^{-1})	K requirement (kg ha^{-1} a^{-1})
8	2.2	3.9	4.7
10	5.2	5.2	17.2
17	5.5	4.6	14.8
34	11.2	4.9	21.5

Turner and Lambert (1986) studied the biomass and nutrient turnover of a 30-years-old P-fertilized *P. radiata* stand :

Treatment (kg ha^{-1} P)	Biomass increment (t ha^{-1} a^{-1})	K requirement (kg ha^{-1} a^{-1})
0	11.2	63
25	19.4	123
50	27.6	153
75	30.9	152
100	32.4	179

Fertilization of the poor quality stand increased the tree biomass production by about three times. Accordingly, the K requirements for biomass production increased by the same rate. In contrast, understorey biomass production as well as understorey K uptake decreased with increasing P application, presumably due to increased competition in the treated plots.

Soil fertility is generally one of the major factors explaining the variation in the nutrient contents of the stand biomass (Drechsel and Zech, 1992); both soil nutrient and water supply play a role.

Support of the K requirements of tropical forest plantations

Internal supply

Trees accumulate relatively large quantities of nutrients as their biomass increases. This internal pool provides a forest with an opportunity for some independence from external nutrient supply (Van den Driessche, 1984). Retranslocation satisfies an important proportion of the trees' nutrient requirements especially during growth stage II, as defined in the introductory chapter. The potential of K retranslocation may be illustrated simply by decreasing K concentrations during ageing of tissue as shown by Ashton (1975) by the example of *E. regnans* leaves. Immature leaves contained 12.5, 1st year leaves 11.3, 2nd year leaves 5.7 and fresh litter only 2.9 mg g^{-1} K of dry matter. Retranslocation data which have been directly taken from or were calculated on the data base of the cited papers are given below:

Species/age	Retranslocation (kg ha^{-1} a^{-1} K)	% of foliage content	Reference
E. grandis/27	31.6	(57)	Turner and Lambert 1983
E. obliqua/45-60	12.8	70	Attiwill *et al* 1978
E. obliqua/75	20.8	70	Attiwill *et al* 1978
P. elliottii	9.3	84	Maggs 1985

In principle the contribution of retranslocation to K requirements for seasonal growth should be related to the proportion of K in potentially retranslocatable pools (foliage) versus immobile pools (wood). Since the proportion of K in foliage related to K in wood decreases with tree age the relative contribution of retranslocation to K supply should decrease with stand age. Fife and Nambiar (1982) thus stated that substantial amounts of nutrients can be retranslocated in young trees. The authors showed that about 40 % of the K requirement for seasonal growth was supplied by retranslocation in 32 months old P. radiata. However, Miller (1981) suggested that retranslocation becomes an important factor after the stand has developed well into post-canopy closure phase. Indeed, Turner and Lambert (1983) found that in 27-years-old *E. grandis* 57 % of the annual K requirement for above-ground biomass production was due to retranslocation.

According to the concept of first-level and second-level nutrients (Miller *et al.*, 1979) the potentially mobilizable K in a plant can be considered as a source which compensates for inadequate soil supply. However, this compensation mechanism is restricted to overcome seasonal fluctuations of nutrient availability only.

External supply

K is added to soils by **atmospheric inputs** via dry and wet deposition. Generally, it has to be assumed that forested areas receive more aerosols from the atmosphere than do open fields. According to data cited by Chijioke (1980) the K input by precipitation into tropical forests ranges from 9.5 to 17.5 kg ha^{-1} a^{-1}. Additional data are given below :

Region	Forest type	K deposition (kg ha^{-1} a^{-1})		Reference
		with rainfall	under canopy	
Ghana	natural forest	17.5	237.2	Nye 1961
Australia	*E. obliqua*	2.0	13.4	Attiwill 1966
Australia	*P. radiata*	1.3		Turner and Lambert 1986
Australia	*E. grandis*	6.1	27.2	Turner and Lambert 1983
	P. radiata	7.6		Steward and Kellmann 1982
Australia	E. obliqua	4.2	15.4	Guthrie *et al.* 1978

Nye (1961) and Attiwill (1966) attributed the difference in K deposition between above and below canopy to K leaching whereas there was some evidence that rain wash of dust deposits did not contribute significantly. Ulrich (1983) has proposed a canopy model to distinguish mathematically between nutrient leaching and rain wash from the standing vegetation on the basis of rainfall and throughfall deposition.

The transport function of rain water in relation to the element cycle of the forest ecosystem has, therefore, two major components: first, the addition of nutrients (deposition) from external sources, and second, a circulation of elements within the ecosystem (leaching). The proportion of leaching/deposition is thus important with respect to the nutrient supply of the ecosystem.

Weathering of K-containing soil minerals is a further important source of K supply. The rates of K release from soil minerals vary greatly and depend on clay mineralogy and on the pedogenetic status of the soil profile :

Soil	K release (kg ha^{-1} a^{-1} K)	Reference
Krasnozem overlying granite	8.9	Attiwill 1981
Basalt soil	17.6	Le Maitre 1976
Alluvial sandy loam:		cit. in Attiwill 1981
1000-years-old	6.0	Hase and Foelster 1983
5000-years-old	1.2	Hase and Foelster 1983

Mineralization of K from litter fall returns K into a plant available pool. Collins (1977) has reviewed litter-fall data available from West African forests. Total litter production ranged from 1.6 to 15.3 t ha^{-1} a^{-1} and increased with both, annual rainfall and decreasing latitude. The annual total litter fall of natural *Eucalyptus* forests has been reviewed by Briggs and Maher (1983) and is given to vary from 3.4 to 5.8 t ha^{-1} a^{-1}, 20 to 80% of which is leaf litter. The total annual litter fall of coniferous forests in N.S.W., Australia, varied from 3.95 to 5.64 t ha^{-1} a^{-1}, and the amount of K in the fallen litter was 6.2 to 12.9 kg ha^{-1} a^{-1} (Spain, 1973). Fertilization increases the litter production and as shown by Miller *et al.*, (1976), it may increase both the amount of K in litter (7, 20, and 21 kg ha^{-1} a^{-1} for treatments with no, 168, and 504 kg N, respectively) and the amount of K released by crown leaching (3.2, 6.2, 8.5 kg ha^{-1} a^{-1} for the N fertilizer range as above).

Potassium which has not been retranslocated to younger leaves prior to litter fall of older leaves has to undergo the process of litter decomposition before it becomes plant available again. The cycle of nutrient deposition to the soil via litter fall, mineralization of nutrients und subsequent uptake is called the biogeochemical cycle (Switzer and Nelson, 1972). The amount of K in this cycle depends on both the quantity of litter production and the K concentration in the litter. The K concentration in leaf litter of trees tends to be independent of the species rather than to be a function of the K supply of the soil (Sharma and Pande, 1989). K concentrations in leaf litter of *Pinus*, *Eucalyptus* and *Teak* as reviewed by Sharma and Pande (1989) range from 1.4 to 9.0 g kg^{-1}. The K concentration of twig material is only about half that of leaves (Sharma and Pande, 1989).

Jordan (1989) justified the generalization that decomposition rates are higher in the tropics as long as the sites examined along the tropical-temperate gradient have comparable moisture regimes and soil fertility. Several studies suggest that in the tropics pine litter generally decomposes more rapidly than in temperate regions, however, the rates of litter breakdown and humus incorporation in tropical pine plantations are apparently much smaller than in broad-leaved species (Chijioke, 1980, Kadeba and Aduayi, 1985). Litter turnover is also influenced by soil fertility and water supply (Lamb, 1985). Some data on litter production and K returns to the soil by various species are given below :

Species/age	Litterfall ($t\ ha^{-1}\ a^{-1}$)	K ($kg\ ha^{-1}\ a^{-1}$)	Reference
Pinus caribaea/7-10	6.0	13.6	Egunjobi and Onweluzo, 1979
Pinus caribaea/9-11	3.7	7.3	Kadeba and Aduayi, 1985
Pinus elliottii/16	6.5	4.5	Maggs, 1985
Pinus patula/16-20	6.2	9.0	Lundgren, 1978
E. botryoides woodland	7.5	12.7	Lamb, 1985
E. grandis/27	6.8	9.8	Turner and Lambert, 1983
E. gummifera woodland	5.4	8.1	Lamb, 1985
E. obliqua/45-60	3.6	5.5	Attiwill *et al.*, 1978
E. obliqua/70	5.5	8.9	Attiwill *et al.*, 1978
E. regnans/23)	3.1	3.4	Ashton, 1975
E. regnans/220	2.7	2.4	Ashton, 1975
E. signata/E. umbra forest	6.4	6.0	Rogers and Westman, 1977
Tectona grandis/8	9.0	71.0	Egunjobi, 1974
Tectona grandis/25	6.0	30.9	Nwoboshi, 1981

*)Leaf litter

The ability of forests to maintain large amounts of easily soluble nutrients in circulation is thought to explain the high productivity even on relatively poor soils. Harvesting of timber, however, is a net output of nutrients out of the system and could result in depletion of the site with the ultimate effect that the soil will no longer produce satisfactory timber crops; this has already been pointed out in the 50ies (Rennie, 1955).

Thus, **fertilizers** are frequently used as an external nutrient source to overcome deficiencies. Several studies have evaluated the usefulness of fertilizers in tropical forestry. The importance of fertilization of fast growing plantation forests has been impressively demonstrated by the example of curing the second rotation decline of *P. radiata* in South Australia (Woods, 1990). Quantitatively most frequently used are N and P fertilizers. A response to K, however, has been demonstrated on many sites after N and P deficiencies had been corrected. E. g., Grant (1989) showed that the total volume of a 10-years-old slash pine stand increased by 110 % over the control as a result of applying 50 kg ha^{-1} K at planting. Herbert and Schönau (1989) and Schönau and Herbert (1989) have reviewed the result of fertilizer experiments on Pinus and Eucalyptus, respectively. Several of the cited studies showed a significant response to K fertilization. Potassium response is primarily a function of site quality. Thus, K fertilizer demands have been observed to be related to the geological reserves of soil parent material. Whitemore (1989) speculates that the need of nutrient substition of plantation forests may be systematically different on non-rejuvenating and rejuvenation soils, i.e. broadly between plains and hills.

Recorded response appears to occur mainly on soils derived from rocks inherently low in K and when the effective rainfall is marginal (Schönau and Herbert, 1989). Potassium response also depends on tree age. By the example of *P. patula*, Herbert and Schönau (1989) showed that K volume response increases up to about 5 years of tree age and then declines again. However, on soils derived from geological formations low in K-bearing minerals, or in drier areas K-application is recommended at planting, with a K:P ratio which should generally not exceed 1 (Schönau and Herbert, 1989). Since the K demand is highly dependent on soil supply the rates of optimum K fertilization for older trees show a wide range. For *Pinus* doses up to 340 kg ha^{-1} K are recommended (Herbert and Schönau, 1989). High K demands like these were needed at sites in Madagascar, which have been shown to be very low in K-supply (Bailly *et al.*, 1974; Malvos *et al.*, 1983; Malvos *et al.*, 1989). The majority of K-demanding sites, however, will require K application rates ranging from 10 to 50 kg ha^{-1} for *Pinus* and from 5 to 40 kg for *E. grandis* (Herbert and Schönau, 1989).

Mika and Moore (1990) showed that N fertilizer effects on growth of Pseudotsuga menziesii were dependent on the K supply of the trees.

Suboptimal K was expressed in a reduced degree and duration of N fertilizer responses.

Intensive management such as a combination of fertilization and weed control may further increase wood production. Birk and Turner (1992) showed that one year of NPK-fertilization in combination with weed control resulted in almost as much above-ground biomass of a 9-years-old *E. grandis* stand as 6 years of fertilizer input. Fertilizer plus weedicide plus insecticide input over 6 years, the most intensive treatment of this trial, increased the standing biomass more than twice over the control from 133 t to 274 t ha^{-1}. Biocide application increased the recovery of applied K from about 5 to 16 %.

Timing of forest fertilization operations needs to be considered in relation to the stage of the stand development, climatic conditions and other silvicultural practices (Ballard, 1984).

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Losses of Potassium Through Runoff Erosion and "Slash and Burn" Agriculture

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Summary

The effects of several management practices in intensive agricultural systems on soil physical conditions are reported. Particular attention is given to the effects on the alteration of the pore system in soil. The strong alteration of the soil pore system sometimes takes the form of soil degradation phenomena such as compacted soil structure or soil surface crusting, which lead to a strong increase of surface runoff. Intensive conventional tillage is principally responsible for soil structure degradation in the long-term, but other management practices, such as irrigation, if adopted in a non-rational way, can also cause damage, sometimes severe, to soil structure. In hilly areas the direction of tillage and wheel traffic is a fundamental element in the prevention of soil degradation. It has been demonstrated that reduced management practices can contribute most appropriately to the maintenance of favourable soil conditions and the prevention of soil structure degradation.

K-losses are closely related to the structural conditions. Adopting reduced management practices is therefore an essential contribution to reducing such losses (especially those arising from runoff and erosion) and avoiding environmental hazards.

Slash and burn, both in forestry and in agricultural systems, and above all in hilly environment, is the most dangerous practice because the losses caused by runoff of nutrients, particularly potassium, can be very relevant. In the burnt areas the ashes are easily transported by runoff due to greater hydrophobicity and degradation of soil surface.

Introduction

Long-term intensive arable cultivations have several effects on soil physical properties, particularly on soil structure, with resulting effects on soil erodibility and crop yields. The need to check the degradation of soil structure has caused farmers to consider reduced tillage management as an alternative to conventional tillage, in order to reduce the environmental impact of modern agriculture. Abandoning traditional farming rotations and adopting intensive monocultures, without applications of farmyard manure or organic materials to the soil, has decreased the soil organic matter content with evident degradation of soil structure. Another important change in modern arable land management has been an increase in the size, weight and power of agricultural machinery. The resulting soil porosity conditions are often unfavourable for crop growth (Pagliai *et al.*, 1983; 1984; 1989).

Soil structural conditions strongly influence soil chemical and biological properties and in many cases are limiting factors in crop yield. Soil fauna is strongly reduced where soil physical properties are poor. However, when soil structure is good, turnover processes in soil will increase the availability of soil nutrients and also improve the efficiency of mineral fertilizers.

A major factor responsible for the degradation of natural resources is accelerated soil erosion. It is estimated that accelerated soil erosion has irreversibly destroyed some 430 million hectares in various countries. That is about 30% of the present cultivated land area of the world (Lal, 1988).

Burning is one of the most convenient, and thus commonly used, practices for the removal of plant residues in agriculture and forestry, and for the management of natural vegetation. Beneficial effects which have been known to man for centuries are often attributed to the increased availability of plant nutrients. Harmful effects on the other hand may be associated with losses of organic matter and transport of nutrients in the smoke during fire or as a result of increased erosion or leaching following burning (Kanna and Raison, 1986; Goh and Phillips, 1990).

This paper focuses on how intensive cultivations and "slash and burn" management practices alter, in the long-term, the soil environment and the resulting soil nutrient status, with particular attention to potassium.

Effects of different management practices on soil structure

Soil nutrient resources are naturally depleted by crop uptake, and farmers make provision for their restoration by applying fertilizers, manure and crop residues to the soil. However, the effectiveness of such restoration depends on soil structural conditions.

Soil structure is one of the most important properties affecting crop production because it influences the depth to which roots can penetrate, the volume of water which can be stored, and the movement of water, air, nutrients and soil fauna. Management practices strongly influence soil structure because they modify many parameters, such as soil organic matter, soil water content, soil aggregate stability, soil porosity, soil crusting and soil compaction. The quantification of soil structure can be carried out by the complete characterization of soil porosity which now is possible due to the increasing use and availability of the techniques of image analysis, which allow the measurement of porosity in thin sections or impregnated soil blocks, prepared from undisturbed soil samples (Pagliai *et al.*, 1983; Pagliai, 1988; Ringrose-Voase, 1991). This micromorphometric method, even though analysing pores larger than 30 μm in 2-dimensional pictures only, supplies useful information about the complexity of pore patterns in soils, which cannot be obtained with commonly used methods such as mercury intrusion, water retention and nitrogen sorption. Parameters such as pore size distribution, pore shape and relative position of aggregates and pores are very important for evaluating induced modifications of soil structure, e.g., by different management practices.

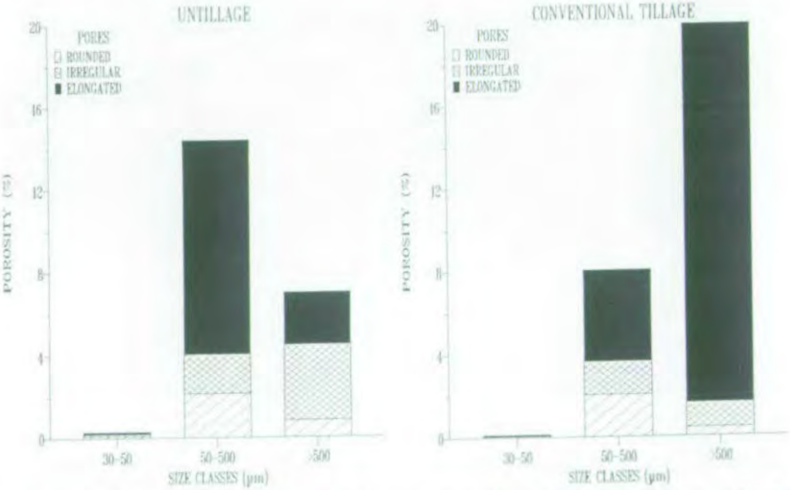

Fig. 1. Pore shape and size distribution, according to either the equivalent pore diameter for rounded and irregular pores or the width for elongated pores, in the Ap horizon of a clay loam soil under two different management practices.

In a long-term field experiment established in 1978 on a clay loam soil (Vertic Xerofluvent) under viticulture in the Po Valley (Italy) (Pagliai *et al.*, 1983), in which zero-tillage and conventional tillage were tested, total porosity, measured by means of image analysis on thin sections, was always and significantly higher in the conventionally tilled soil, but the proportion of pores ranging from 30 to 500 μm, which are considered to be the most important both for root growth and for maintaining a good soil structure (Greenland, 1977), was higher in the zero-tilled soil (Fig. 1).

The better pore system in the untilled soil was strictly related to the biological activity of the soil. Sequi *et al.* (1985) and Pagliai and De Nobili (1992) found that enzyme activity was higher in untilled soils and was positively correlated with porosity ranging from 30 to 200 μm. In the conventionally tilled soil the continuity of elongated pores (50-500 μm) was strongly reduced and the stability of surface soil aggregates was lower than in the untilled soil. This leads, as a consequence, to the formation of a surface crust (Fig. 2), as a result of raindrop impact, with strong reduction of water infiltration and an increase in surface runoff and erosion (Pagliai *et al.*, 1983; 1984; Pagliai, 1987).

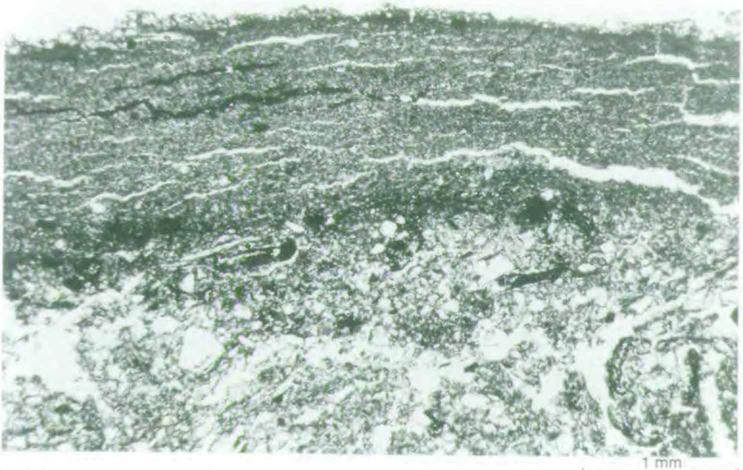

Fig. 2. Microphotograph of a vertically oriented thin section from the soil surface of a conventionally tilled clay loam soil. The presence of a surface crust is very evident. In this compacted layer, which is formed by fine soil material, the few pores are very thin and oriented parallel to the soil surface without continuity in a vertical sense and, therefore, useless for water infiltration. The picture was taken under plain light, so the pores appear white.

Similar results were also obtained in a loam soil representative of the land along the Tyrrhenian coast (Italy) cultivated to grow autumn-sown wheat, in which minimum tillage and chisel ploughing were the most appropriate tillage practices in maintaining favourable porosity and preventing surface crust formation in the soil. The porosity was more homogeneously distributed in the Ap horizon, and the proportion of continuous elongated pores ranging from 50 to 500 μm was greater than in the conventionally ploughed soil (Pagliai *et al.*, 1989).

Another aspect strictly connected with soil structure degradation and the risk of erosion is soil compaction due to the traffic of agricultural machinery. Experiments on a sandy loam soil have demonstrated that wheel traffic of agricultural tractors caused a strong decrease in soil porosity (3-4 times) in the compacted topsoil with respect to the adjacent uncompacted areas (Pagliai *et al.*, 1988). The recovery of soil structure in the compacted areas is very low and in many cases erosion phenomena start from these compacted areas (rill erosion).

It is evident from the data cited that, on intensively cultivated lands, reduced cultivation practices appear most appropriate for the maintenance of favourable soil conditions and for the prevention of run-off and soil erosion.

The adoption of reduced management practices is fundamental in hillside environments. In these areas the direction of tillage and the direction of soil compaction caused by the use of agricultural machinery play a very important part. This aspect was studied on a sandy clay loam soil in a hillside area of the Pliocene formation near Bologna (Italy) in which three management practices (contour, diagonal and downhill ploughing) and winter and spring crop rotation were tested (Rossi Pisa *et al.*, 1986). The total porosity was higher in the downhill-ploughed soil but the proportion of pores ranging from 30 to 500 μm - the most important in terms of water movement and root growth - was higher in the contour and diagonally ploughed soil (Fig. 3). Soil water content showed the same trend, i.e. it was higher in the contour-ploughed soil. In the downhill-ploughed soil most of the porosity was represented by large (>500 μm) elongated pores oriented parallel to the soil surface and therefore useless for water infiltration.

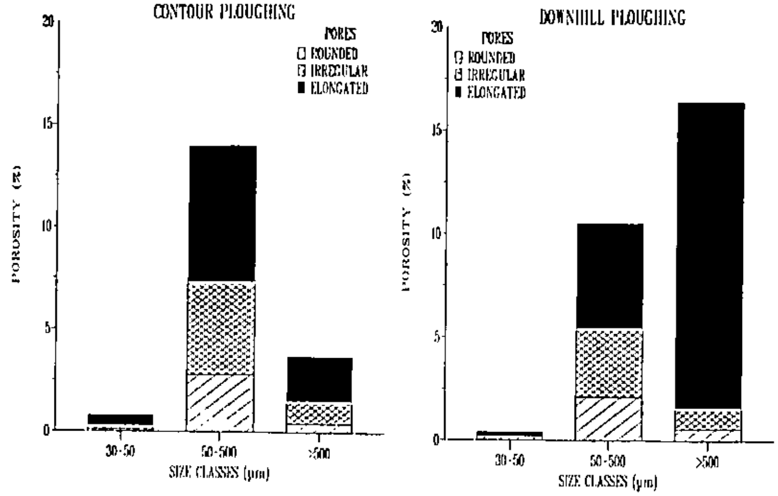

Fig. 3. Pore shape and size distribution, according to either the equivalent pore diameter for rounded and irregular pores or the width for elongated pores, in the Ap horizon of a sandy clay loam soil under two different directions of ploughing.

Relationships between soil structural conditions and K losses due to runoff and erosion

The effect of the different tillage methods on soil erosion was also assessed in the latter cited field experiment (Rossi Pisa *et al.*, 1986). The average slope on the experiment was 11%. Some characteristics are listed in Table 1. The experiment was laid down in 1983 and loss of soil by erosion, expressed as t ha^{-1} $year^{-1}$, was measured in 1985 with the following results: Contour ploughed: 0.17; Diagonally ploughed: 0.21; Downhill ploughed: 0.32. Even though these data showed that the erosion was lower than expected according to the evaluation reported in the literature in similar environments (Chisci and Spallacci, 1984), they clearly demonstrated that in the downhill-ploughed soil erosion was double that in the contour-ploughed soil. The particle size of the eroded material showed great differences between the downhill-ploughed soil and the soil ploughed in the other two directions (Table 2). Since texture did not show great differences in the field experiment, it could be stressed that in the downhill-ploughed soil runoff was able to transport coarse materials even with rain of low intensity as was the case of the period considered. In the soil of the other two directions of ploughing the high percentage of clay found in the eroded material and the lower percentage of sand seemed to indicate a lower intensity of transportation by runoff (Meyer, 1985). The surface compaction in the downhill-ploughed soil, which was illustrated, as already said, by the presence of a platy structure, i.e. elongated pores oriented parallel to the surface, was responsible for the lower water infiltration and, consequently, for the increase in soil erosion. Such an increase was positively related to K losses, which were approximately twice larger in the downhill-ploughed soil than in the soil ploughed in the other two directions.

Table 1. Some characteristics of the soil samples from the Ap horizon of the experimental field.

Sand, 200 μm-2 mm (%)	65.1
Silt, 2-200 μm (%)	10.5
Clay, <2 μm (%)	24.4
Organic matter (%)	1.57
Total N (%)	0.78
$CaCO_3$ equivalent (%)	6.0
Total P (% P_2O_5)	1.6
Available P (ppm P_2O_5)	35.1
Total K (% K_2O)	3.3
Exchangeable K (ppm K_2O)	112.9
pH (H_2O)	8.0
C.E.C. (meq/100 g)	38.5

Table 2. Soil losses, particle size of the eroded material and K losses from the experimental field.

	Direction of ploughing		
	Contour	Diagonal	Downhill
Rainfall (mm)	580.6	580.6	580.6
Time of rainfall (h)	388	388	388
Soil losses (t ha^{-1} $year^{-1}$)	0.17	0.21	0.32
Particle size			
Sand (%)	17.7	24.5	45.4
Silt (%)	6.8	2.0	11.4
Clay (%)	75.5	72.5	43.2
K_2O losses (kg ha^{-1} $year^{-1}$)	0.58	0.69	1.02

Chisci and Spallacci (1984) have presented much data on nutrient losses by leaching, runoff and erosion in the Italian hilly environment and some of their data on soil hydrological behaviour and erosion, obtained from a field experiment with different crops and soil tillage methods, are summarized in Table 3. This field experiment was carried out for many years on a loamy clay soil (Vertic Xerochrept) formed on clay sediment of marine origin, at Vicarello (Pisa), in the hilly area of the central Apennines. From these data it appears that nutrient losses by runoff and erosion are generally low. In fact, soil losses due to sheet and rill erosion appear relatively small under normal agricultural practices and the resultant amounts of nutrients exported by such processes are also small. However, even though erosion processes were not very pronounced, the losses of K_2O, for example, were much higher in the conventionally tilled soil. In this experiment the authors also found that the environmental hazard in this soil was much higher for nutrients lost by leaching than by runoff and erosion. In fact, they reported that K_2O losses by leaching were 9.22 and 9.61 kg ha^{-1} year^{-1} in grassland and in wheat on minimum tillage, respectively and 15.69 kg ha^{-1} year^{-1} in wheat on ploughed soil. This was probably due to the particular hydrological behaviour of the studied soil, where there was a high seepage through cracks. Also in this case it was confirmed that management practices, which cause soil structural degradation, strongly influence soil nutrient behaviour and status.

Table 3. Soil losses and nutrient losses by runoff and erosion for a loamy clay soil in the hilly area of Tuscany (modified from Chisci and Spallacci, 1984).

	Grassland	Wheat on minimum tillage	Wheat on ploughed soil
Rainfall (mm)	700	700	700
Runoff (mm)	4.3	25.2	33.0
Soil losses (t ha^{-1} year^{-1})	0.02	0.20	1.40
Total N (kg ha^{-1} year^{-1})	0.05	1.09	1.87
Total P_2O_5 (kg ha^{-1} year^{-1})	0.08	0.50	2.87
Total K_2O (kg ha^{-1} year^{-1})	0.30	1.56	5.16
Organic matter (kg ha^{-1} year^{-1})	0.26	2.64	18.48
$CaCO_3$ (kg ha^{-1} year^{-1})	2.23	22.30	156.10

In other experiments described by the same authors (Chisci and Spallacci, 1984) on clay soils of different hilly areas in the central Apennines they reported more severe soil erosion under continuous cultivations. Soil losses ranged from 2.6 to 30.6 t ha^{-1} year^{-1} and K_2O losses from 3.9 to 100.4 kg ha^{-1} year^{-1}. The authors stressed that these values of soil and nutrient losses could be strongly reduced when adopting contour ploughing, minimum tillage, alternation with meadow or pasture.

Intensive continuous cultivation is not the only cause of soil structure degradation; other management practices like irrigation are also important, especially in the longer term. Pezzarossa *et al.* (1991) found that in a peach orchard near Verona (Italy) soil porosity of the surface layer was decreased during the irrigation season and that the decrease was significantly greater when irrigation was by impounding than under sprinkler-irrigation due to a reduction in elongated pores. The latter was associated with a lower water content in surface soil and reduced root density. The larger amount of water applied in this system caused progressive soil compaction resulting in decreased porosity and structural degradation.

Study of soil structure conditions in the interrows (Xiloyannis *et al.*, 1992) showed that porosity (especially elongated pores) decreased from the inlet from the irrigation canal to the end of the interrow (Fig. 4). This caused decreased water infiltration and, under these conditions, 30% of applied water was lost by runoff. Table 4, reporting chemical composition of water at the inlet from the irrigation canal and at the end of the row shows clearly that runoff along the interrow transported nutrients, particularly nitrogen and potassium. Table 5 gives the amount of nutrients lost in this way. There was considerable loss of potassium, amounting to 25% of the quantity applied as fertilizer (150 kg ha^{-1} year^{-1} of K_2O).

Sprinkler irrigation consumes only half the amount of water needed for impounding and causes no evident damage to soil structure so the loss of water by runoff is negligible but, unfortunately, this method is more expensive and complicated for the farmer; it is used only by the more enlightened and environmentally conscious farmers. Efforts should be made to persuade others to adopt sprinklers but this will not be easy.

This experiment also confirmed that management practices are mainly responsible for soil degradation and, consequently, for nutrient losses. This conclusion was also reported by Pieri and Oliver (1986) in their studies on the assessment of K losses in tropical cropping systems. They stressed that losses of K from the soil were not significant under natural vegetation, such as savannah grassland or forest, but became so when the soil underwent cultivation. The main reasons for this were the change in the water cycle in the surface soil and the resulting changes in root exploration.

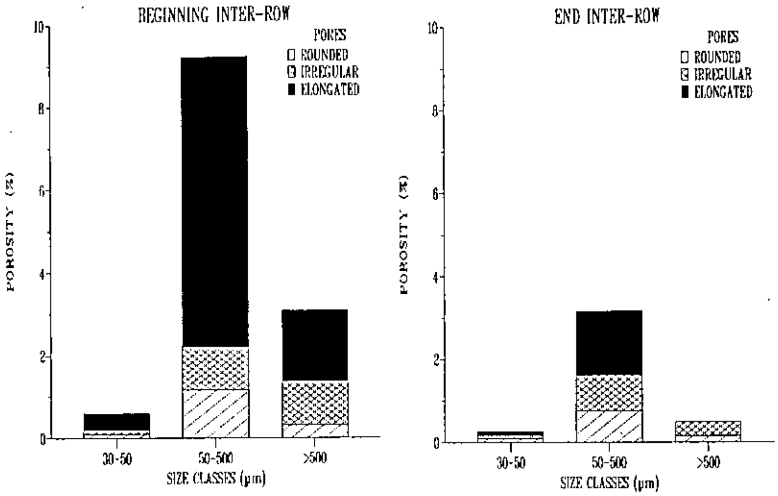

Fig. 4. Pore shape and size distribution according to either the equivalent pore diameter for rounded and irregular pores or the width for elongated pores in the Ap horizon of a sandy loam soil under peach orchard irrigated by impounding. Porosity measurements refer to the beginning of the inter-row (near the irrigation canal) and to the end of the inter-row.

Table 4. Chemical characteristics of the water at the exit of the irrigation canal (1) and at the end of the inter-row (2) in a peach orchard field experiment under irrigation by impounding.

	1	2
pH	7.5	7.0
Electrical conductivity (mmhos/cm at 25 C)	2.25	2.92
Salinity (ppm)	140	190
NH_4^+ (ppm)	0.63	1.84
NO_3^- (ppm)	1.82	6.58
K_2O (ppm)	2.66	22.68
P_2O_5 (ppm)	1.05	2.45
Na^+ (ppm)	5.01	4.60
Cl^- (ppm)	17.7	21.3

Table 5. Runoff and nutrient losses for a sandy loam soil of a peach orchard field experiment irrigated by impounding.

Irrigation water applied (m^3 ha^{-1} $year^{-1}$)	6160
Runoff (m^3 ha^{-1} $year^{-1}$)	1848
Total N (kg ha^{-1} $year^{-1}$)	11.0
Total K_2O (kg ha^{-1} $year^{-1}$)	37.1
Total P_2O_5 (kg ha^{-1} $year^{-1}$)	2.6

Effect of "slash and burn" on soil structure and soil nutrient losses

Fire has often been considered as a characteristic phenomenon for the forest ecosystems in the Mediterranean area and its effect on the vegetation has been the subject of many studies (Kruger *et al.*, 1983). In recent decades the frequency of fire has increased throughout the Mediterranean area. In the same period accelerated soil erosion has become an increasingly serious problem in this area. It is generally attributed to changes in hill slope runoff characteristics, resulting from changes in the vegetation cover and in the topsoil characteristics brought about by man, mainly through intensive agriculture, deforestation and ever increasing forest and shrub fires. This is one of the major processes causing land degradation and leading to losses of nutrients.

The increase in availability of plant nutrients after burning is commonly recognized as a beneficial effect of this management practice. Marion *et al.* (1991) demonstrated that the concentrations of nutrients in the ashes were much higher than those in the topsoil. Giovannini *et al.* (1990) showed that the effect of burning and heating of soil caused an increase in both exchangeable and water-extractable cations, such as K, Ca and Mg. Therefore, nutrient concentrations in the topsoil increased after burning with beneficial effects on plant growth. However, such a situation is extremely vulnerable, especially in hilly environments, because even light rain following burning is sufficient to cause nutrient loss by runoff and erosion. The fire not only alters the chemical properties of the topsoil but also the physical properties. The destruction of organic matter by burning causes a loss of soil aggregate stability and this may lead to a collapse in soil structure with a reduction in soil porosity. Fig. 5 shows an example of soil structure in the topsoil before burning. The presence of both dark amorphous organic matter and plant remains associated with pores is very evident. Fig. 6 shows an example of a degraded soil structure in the topsoil after burning. The porosity appears strongly reduced, the elongated continuous pores are very few in number, if any, and most porosity was represented by spherical pores (vesicles) formed by carbon dioxide liberated by the combustion of organic matter. These pores are isolated in the soil matrix and produce a "vesicular structure" which is unstable and transitory (Pagliai *et al.*, 1989). The presence of such a poor structure together with a subsurface hydrophobic layer strongly reduces water infiltration with a consequent increase of surface runoff, which is more dangerous the steeper the slope of the land is.

Sevink (1988) and Sevink *et al.* (1989) found that following forest fire in the Mediterranea area, the ectorganic horizons were partially or completely destroyed, while the hydrophobicity of the mineral layer was often preserved. From these results it was inferred that hill-slope runoff and erosion would strongly increase after fire. These results were in agreement with those of Giovannini and Lucchesi (1983) and Giovannini *et al.* (1987) in agricultural systems. The results of these authors indicated that burning crop residues over many years generally reduced organic matter content, polysaccharides, and water-stable aggregates, all factors associated with soil erodibility. These studies have also demonstrated that on the burnt area a water-repellent layer is formed below and parallel to the soil surface. The subsurface layers, in which the fire had accumulated translocated hydrophobic materials, kept these hydrophobic substances quantitatively unaltered, but they appeared more strongly cemented, because the translocated organic matter, far from remaining inactive, could react, complexing polyvalent metals and expanding the organometallic cements. The resulting condition has been reported to cause an excess of soil erosion and water runoff.

The results of the studies of Sevink *et al.* (1989) on the effects of fire in forested areas and prescribed burning on runoff using rainfall simulation experiments in the typical Mediterranean forests, clearly showed that runoff strongly increased after fire (Table 6). The runoff reached the highest values in burnt plots and was greatly influenced by the hydrophobic behaviour of the uppermost mineral soil. In these studies the authors stressed that fire leads to the partial or complete destruction of the ectorganic layer, and to the release of elements contained in it. They also concluded that high concentrations of N, K, Ca and Mg are to be found in the runoff water.

Table 7 summarizes the possible nutrient loss in a clearfelled logged and burned *Notofagus* forest (Goh and Phillips, 1990). These values were 1.8 to 2.5 times higher than those in the respective clearfelled logged but unburned treatments. This indicated that large proportions of the cation inputs from the ash layer were removed in solution.

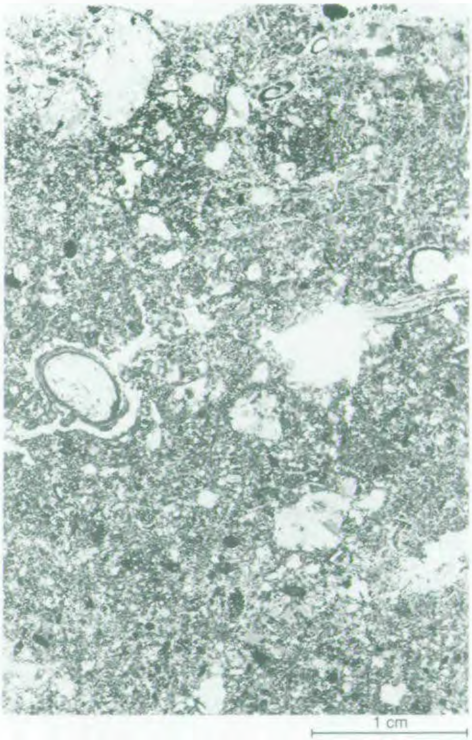

Fig. 5. Macrophotograph of a vertically oriented thin section from the soil surface of a sandy clay loam soil before prescribed burning. Large pores with plant remains and thin elongated pores are visible. The darker areas indicate the presence of amorphous organic matter. Picture taken under plain light, in which the soil pores appear white.

Table 6. Runoff results from rainfall simulation experiments under different management practices in a typical forest of the Mediterranea area (Modified from Sevink *et al.*, 1989).

Sites	Runoff coefficient
Undisturbed site	1.7
Understorey vegetation removed	13.4
Burnt site	92.6

Table 7. Nutrient losses (kg ha^{-1} $year^{-1}$) in clearfelled logged and burnt treatments from the topsoil during the first year after burning (Modified from Goh and Phillips, 1990).

Nutrients	Nutrient losses (kg ha^{-1} $year^{-1}$)	
	Low intensity burn	High intensity burn
Total N	27.3	32.0
Total P	1.30	1.42
K^{+}	35.9	42.0
Ca^{++}	19.4	27.6

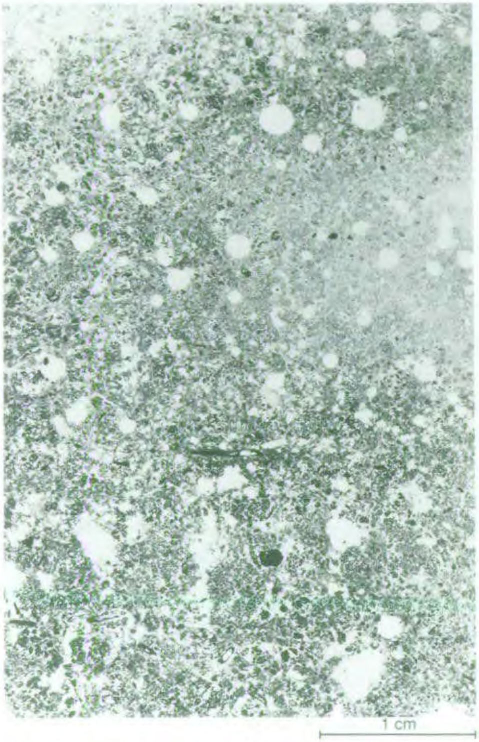

Fig. 6. Macrophotograph of a vertically oriented thin section from the soil surface of a sandy clay loam soil after prescribed burning. The presence of a vesicular structure is an indicator of degraded soil conditions. Picture taken under plain light, in which the soil pores appear white.

From all data available in the international literature it is clearly evident that among all management practices slash-and-burn causes the most dangerous environmental hazard with respect of losses of soil and nutrients through runoff and erosion. Table 8, which confirms this, shows some data reported by Pieri and Oliver (1986) as regards their studies of erosion, surface runoff and soil K depletion in Francophone Africa. The strong increase in both soil and potassium losses following the practice of burning crop residues is very evident, especially in topographies with high slope values.

Table 8. Losses of soil by erosion in a pineapple field in Ivory Coast and decline in exchangeable and total K (Modified from Pieri and Oliver, 1986).

Treatment	Slope (%)	Rainfall (mm)	Soil loss (t ha^{-1} year^{-1})	Potassium loss (kg ha^{-1} year^{-1})	
				Exch.	Total
residues burnt	4	3350	1.2	0.057	0.5
residues burnt	20	3350	69.0	3.7	32.3
residues as mulch	4	3350	0.1	traces	traces
residues as mulch	20	3350	1.0	0.06	0.5

Conclusion

The need to check the deterioration of soil structure caused by long-term intensive cultivation must be one of the most important aims of soil researchers and agronomists. The most dangerous impact of long-term intensive agriculture on soil structure is the alteration of the pore system in soil. In fact, conventional continuous tillage causes decreases in biopores and storage and transmission pores (0.5-500 μm equivalent pore diameter) normally allowing water storage, water movement and root growth. Moreover, other forms of soil degradation in continuous arable lands consist of the presence of a surface crust in many types of soils, of compaction due to wheel traffic of heavy agricultural machinery, and of formation of compacted layers along the soil profile (plough pan).

Adopting reduced management practices (reduced tillage), avoiding the downhill ploughing and reducing as much as possible the up and down wheel traffic in hilly areas, the adoption of appropriate irrigation systems, introducing crop rotation in farm planning, etc., seem the most appropriate ways of maintaining favourable soil conditions (e.g. improvement of the pore system in soil with associated better water management) and preventing soil structure degradation.

From all experiments cited in this paper it is evident that nutrient losses through runoff and erosion depend on the intensity of rainfall, the slope, the type of soil, etc., but it is also very evident that by adopting management practices that preserve as much as possible the soil structural conditions it is possible to limit nutrient losses to a level which does not cause environmental hazards.

Slash-and-burn management practices are the most dangerous in terms of environmental hazards both in forestry and agricultural ecosystems. The beneficial effects of the increase of plant-available nutrients can easily be outweighed by increased nutrient loss through runoff and erosion and the losses of nitrogen and potassium are significant. Such losses in agricultural ecosystems are both an environmental hazard and a source of economic loss because much of the fertilizer applied can be wasted.

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Potassium Concentrations in Municipal and Agro-Industrial Effluents : Data Needed for Good Fertilization Practice

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Summary

Urban areas and agro-industry produce large amounts of effluents containing plant nutrients which can be used in farming with resulting economy in fertilizer consumption. While the manurial value of these effluents, especially as concerns potassium has been the object of many experiments, little work has been done on how utilisation of these waste products may affect farm management, crops, soils and pollution of groundwater. Taking potassium as an example, methods for using effluents in farming and the data needed for defining good fertilization practice are discussed in the light of nutrient supply, crop needs and effects on top soil and subsoil. Lysimeter studies and field trials have been used to estimate the nutritional value of the potassium in effluents, losses by leaching, K-enrichment of soils and crops and the effects of antagonisms between K, Mg and Na. The chief ways of using effluent potassium (direct spreading of low-concentration effluent, or elaboration of concentrated manure) are examined. Maximum permissible rate of application for the crop under reference, frequency of application in relation to cropping system and the need for corrective fertilizer application to correct nutrient balance are important aspects.

Introduction

Urban and industrial effluents have a definite agricultural value on account of the nutrients they contain. They can safely be used unless there is a risk of chemical toxicity or a heath risk in case they contain pathogens. However, usage must obey two rules : i) It must be consistent with sound fertilizer policy and ii) it should not lead to pollution of the soil or groundwater. It is easier to obey these rules if the effluents are of uniform composition.

The fertilizing value of elements applied in effluents has been much studied (Ibrahim *et al.*, 1988; Morizot, 1986, Nielsen *et al.*, 1989; Nogales *et al.*, 1989; Steward *et al.*, 1984; Wong, 1990) but insufficient attention has been given to effects on farm management, and effects on soils and crops (Delas *et al.*, 1985).

It is necessary to understand the various constraints related in the first place to their composition and then to the nature of soils, which, on account of their physical, chemical and biological properties play an important part in purification and which affect cropping systems and ensure recycling of nutrients throught the crop.

Using effluents as a source of plant nutrients results in economy in inputs in two ways : saving in the cost of nutrients, mainly nitrogen, phosphorus and potassium, contained therein, and economy in energy consumption. For manufacture of fertilizers, 1.7, 0.33 and 0.26 TEP are needed, respectively, for a ton of N, P_2O_5 and K_2O.

Origin and state of potassium in plants

Potassium is contained in relatively high concentrations (1 to 3 % in dry matter) in all plants; somewhat less than nitrogen but considerably more than phosphorus and calcium. Table 1 gives, for selected crops,maximum uptakes of potassium by crops which can range from 50 to over 450 kg ha^{-1} yr^{-1} according to crop and yield. Some plant organs like sugarbeet roots, potato tubers and grapes are particularly rich in potassium and when treated in the factory give effluents which are K-rich. Unlike nitrogen and phosphorus, potassium is not a constituent of essential organic compounds (carbohydrates, protein, lipids). It is important in regulating various aspects of growth and development via enzyme systems. It is widely distributed through the plant, very mobile and occurs in the ionic form especially in intracellular liquid so that it is easily released when plant materiel comes into contact with water, as happens in many agro-industrial processes.

Table 1. Uptakes and removals of potash (K_2O) by the principal crops on Champagne chalkland. Expressed as kg per ton product and kg ha^{-1} (Villemin *et al.*, 1990).

Culture	Target yield t ha^{-1}	Plant part	Product harvested kg t^{-1} K_2O	Immediate requirement kg ha^{-1} K_2O	Maximum uptake kg ha^{-1} K_2O	Removal in grain kg ha^{-1} K_2O
Wheat	9	Grain	6.0	10	350	54
-		Straw	16.5			149
Barley/Oats	8	Grain	7.0			56
-		Straw	19.0			152
Maize	8.5	Grain	5.0	15	200	43
Sugar beet	80	Roots	3.5	13	450	280
Potato	40	Tubers	6.0			240
Sunflower	3.5	Seed	16.0			56
Winter rape	4	Seed	11.0	15	350	44
Lucerne	14	Forage	30.0	15	450	420
Peas	2.5	Grain	14.5			36

Effluents as a source of potassium

The increasing amounts of town and industrial effluents pose several problems of storage, decomposition and utilisation. In some situations the effluents can be used directly on farms near to where they originate and farming can profit from their contents of N, P, K, Ca, Mg, S and sometimes, trace elements. This offers overall economy (energy used in fertilizer manufacturing) and direct savings in fertilizer cost to the farmer. Nevertheless, the manner in which effluents are used should be consistent with good farming practice (Muller and Ledain, 1992).

Firstly, it is important to know as accurately as possible the composition of the effluent which should be stated in terms of minimum content and variability.

Urban wastes occur in two forms :

- Solid wastes which are treated by incineration or composting, or simply dumped. Only composted wastes have any importance for agriculture.

- Liquid wastes which are usually treated in sewage plants which produce purified water drained to water courses plus sluge which can be used on the land.

Agro-industrial wastes are principally liquid : residual water, originating in the washing of produce with various by-products from factory processing. They comprise mainly the following :

- Sugarbeet : beet tops with some leaves from cleaning, residual water from distillation, sugar extraction and refining, and concentrated lyes.
- Potatoes : mainly washing water.
- Lucerne : composition of by-products depends on whether or not drying is accompanied by protein recovery.

In Champagne-Ardenne, these three industries alone produces yearly 2,7 millions m^3 effluent which can safely be used on 4300 hectares farmland without risk to soils or groundwaters (Dutil et Muller, 1979; Muller et Ledain, 1992).

- Wine : various wastes originate in vinification and distillation of residues from vinification (filter press effluent, lyes from vinification, composted marc).
- Various other wastes arise in the food-processing industry from : cider, cider distillation, brewing, fruit and vegetable processing (carrots, peas, beans, sweet corn, etc). Generally speaking the volume of these locally is not very large and is easily absorbed by farms. Additional effluents originate in the dairy industry.

Table 2 gives mean potassium contents (as K_2O) in selected agro-industrial effluents. The values show great variation and cannot be used as standard. Some control of effluent composition by the factory is possible and the effluent should be sampled for analysis at regular intervals depending on how great the variation is.

As would be expected, potassium content is most variable and depends both on the crop being processed and the manufacturing process. Sludges obtained by decantation are usually low in K_2O (<1 %) (dairy, cheese-making, urban wase). Washing water and water used for moving produce in the factory can be quite high in potash (up to 5% K_2O) (beet factory, starch manufacture, distillery). Solid or semi-liquid sludges from concentration processes without washing can show very high values (> 10 %) (press mud, vinification dregs). In some cases these can be considered organic manures (concentrated beet distillery dregs which contain nearly 7% K_2O).

Table 2. K_2O content of urban and agro-industrial waste products.

Origin	Nature	State	%	$g\ l^{-1}$	‰ K_2O		Reference
			Dry matter	Solid	mini	maxi	
Beet factory cleanings	Leaf and collar	solid	17.0			6.12	Elev. Bovin 01/85
Beet factory distillery	Residual water	liquid		4.5		1.80	Muller, 1992
Beet factory distillery	Concentrated lyes	liquid	60.0		70.00	75.00	Beghin-Say, 1991
Beet factory	Residual water	liquid		120.0	0.60	1.20	Muller, 1992
Cider	Crude effluent	liquid		2.5		0.07	Dutil, 1982
Cider	Decanted effluent	liquid		0.3		0.12	Dutil, 1982
Cider distillery	Lyes	liquid		3.0		1.20	Dutil, 1982
Vegetable preservation	Residual water	liquid		0.1-1.5	0.02	0.18	Dutil, 1982
Abattoirs	Residual water	liquid		3.3		0.48	Dutil, 1982
Fruit distillery	Lyes	liquid		30-50	0.96	1.12	Dutil, 1982
Potato starch	Residual water	liquid		7.0		1.20	Muller, 1992
Cheese manufacture	Residual water	liquid		2.0-1.5	0.18	0.24	Dutil, 1982
Dairy	Residual water	liquid		0.5-2.0	0.05	0.96	Dutil, 1982
Lucerne drying	Residual water, no protein recovery	liquid		0.2-0.3	0.03	0.04	Muller, 1992
Lucerne drying	Residual water, protein recovery	liquid		0.8		0.25	Muller, 1992
Knacker's yard	Sludge	sludge		3.3		0.48	Dutil, 1982
Town sludge	Stabilised aerobic sludge	liquid	6.0		0.30	0.90	Dutil, 1982
Town compost	Mature natural compost	solid	72.6		2.96	4.66	SCPA Aspach, 1992
Wine press effluent	Mud and washing water	liquid			0.02	1.32	CA 51 (*)
Wine press effluent	Mud only	liquid			0.64	8.74	CA 51 (*)
Wine distillery	Lyes wine	liquid		3.5		2.30	Dutil, 1982
Wine distillery	Fresh lyes	sludge	25.0			3.90	Morisot, 1986
Wine distillery	Residual water	liquid		2-160	0.60	4.00	Muller, 1992
Wine distillery	Old lyes	sludge	69.0			6.10	Morisot, 1986
Wine distillery	Lyes	liquid		116.0		12.90	Dutil, 1982
Wine distillery	Composted marc	solid	68.0			19.10	Morisot, 1986

(*) CA 51 = Chambre Agriculture Marne, 1992.

Agricultural value of potassium applied in effluents

Usage of effluent has be considered as a part of the fertilizer programme on the farm and, for this, the following characteristics must be known as they will determine when and how often effluents are applied (Dutil and Muller, 1979) :

- Mineral composition, especially nutrients but also elements not useful to crops which may or may not be toxic and mobile in the soil.
- How the effluent material may be altered in the soil type on which it is applied. This implies knowledge of soil properties and how they may affect the availability of nutrients in the material so as to estimate to what extent the effluent may satisfy the crop's requirements as regards both quantity and nutrient balance (Dutil, 1986).
- Whether or not the soil may fix or liberate the nutrients applied.
- What crops will subsequently occupy the site and their nutrient requirements.

Advice on using effluents is based on :

- Maximum rate of application of effluent for crop and site;
- Frequency of the effluent application;
- The effects of the effluent on soil nutrient reserves which may call for adjustment of the fertilizer programme.

This imposes certain constraints not unrelated to potassium content.

In the case of urban waste water (Table 2), it is usually nitrogen which may vary from 20 to 70 mg l^{-1} or P_2O_5 (17 - 27 mg l^{-1}) which determines the maximum permissible rate of application, since potassium content is always low. The reverse applies to water effluent from agro-industry in which potash often exceeds 1200 mg l^{-1}. If the soil has a sufficiently high potassium-buffering capacity, some excess over immediate crop needs is admissible since excess potassium not lost by fixation or leaching will be available for the succeeding crops.

Little work has been done to evaluate the fertilizer equivalent of potassium in effluents. Motavalli *et al.* (1989) suggested a value of 70 % as a result of their experiments. This figure for plant-available potassium is not greatly different from that usually adopted for potassium in fertilizer (80 %) assuming 20 % to be lost though leaching or fixation (Villemin *et al.*, 1990). Comparison of K_2O balances (manures less removals) with changes from initial level in soil exchangeable K_2O content in three medium-term exprcriments on Champagne chalkland gives a linear regression with a slope near 0,3 (Figure 1).

There are other soil constraints, important among which are soil-water relationships. Soil acts as a physical filter, and mineral and organic particles in the effluent may be retained on the soil surface when, if there is much suspended matter, there is a risk of surface waterlogging with the consequence of increased runoff. Soil water retention capacity should be sufficient but not excessive in order to avoid too rapid movement of mobile elements. Clay and organic matter in the soil are concerned in ion fixation and liberation. According to the degree of saturation of the exchange complex there will be simultaneous fixation and exchange of ions (Ca^{2+}, K^+, Mg^{2+}, NH^{4+}) and movement of ions which are not fixed (NO_3^-, Cl^-, SO_4^{2-}) or those less strongly held (Na^+). These are the physico-chemical properties of the soil which, in conjunction with the quantity of water in the effluent and in rainfall regulate the movement of nutrients in the soil, especially of potassium.

Prediction of optimum K-nutrional conditions for crop yield and quality depends on so many factors that it is impossible to fix a norm applicable to all situations. However, the norm expressed as the desirable level of availability for the most demanding crops in the rotation is useful. Exchangeable potassium is a useful indicator of availability as has been demonstrated in many field experiments (Quemener, 1985). It is important to have knowledge of response to a single high rate of potassium as is often applied when effluents are used.

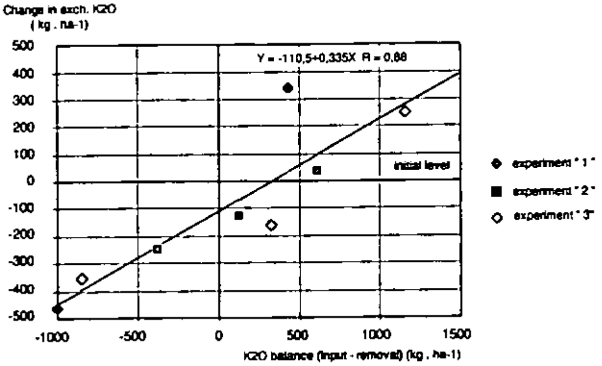

Fig. 1. Comparison of K_2O balance (manures less removals) with changes from initial level in soil exchangeable K_2O content. Three medium-term experiments on Champagne chalkland. Experiment "1" : Somme-Vesle 1977-86; expt. "2" : Saint Jean sur Moivre 1968-90; expt. "3" Herbisse 1981-85 (Villemin *et al.*, 1990).

Exchangeable potassium is also an indicator of potassium availability for comparison of the K-balance over a period of some years (application in manures and fertilizers, less removal in harvested crops) with change in soil potassium content (Figure 1). In order to maintain soil potassium at its initial level it is necessary to apply rather more potassium than that removed, the more so the less the degree of K saturation.

Table 3. Spreading of residual water from beet factory, beet-wheat rotation. Potash balance over four seasons : 1977-1981. Lysimeter experiment on rendzina over chalk. Expressed as kg.ha^{-1} (INRA Châlons sur Marne).

	Effluent application			
Treatment	NIL	80 mm Once	80 mm Twice	160 mm Twice
	kg.ha^{-1} K_2O			
INPUTS				
Rain	8	8	8	8
Fertilizer	624	0	0	0
Effluent		2355	5021	9674
Total	**632**	**2363**	**5029**	**9682**
OFFTAKES				
Harvest	192	162	282	362
Drainage	86	82	163	478
Total	**278**	**244**	**445**	**840**
BALANCE				
Inputs-Offtakes	354	2119	4584	8842
Removed at harvest	30.4%	6.9%	5.6%	3.7%
Removed in drainage	13.6%	3.5%	3.2%	4.9%
Stored in soil	56.0%	89.7%	91.2%	91.3%

The soil's capacity to store potassium is important as demonstrated by the resuts of parallel experiments in lysimeters and in the field to assess the effects of massive K application in sugarbeet factory effluent waters. The experiments lasted four years on a chalk soil under a beet-wheat rotation. Effluents were applied once or twice in the autumn preceding the sugarbeet crop. Table 3 shows the K balance for the four cropping seasons in the lysimeter experiment in which the different inputs (rain, fertilizer and effluent) and removals (drainage and crops) could be precisely measured. The difference between application and removal represents the amount stored in the soil and this was almost proportional to the inputs. The proportion stored in the soil ranged from 56 % with an application of 625 kg ha^{-1} K_2O to 91 % when 9682 kg ha^{-1} was applied. The results of the field experiment presented in Table 4 confirm those of the lysimeter experiment.

Table 4. Spreading of residual water from beet factory, beet-wheat rotation. Comparison of inputs (rain + fertilizer or residual water) and crop removals. Results of 4 years of field experiments on rendzina overlying chalk. kg.ha^{-1} K (INRA* ASAE Châlons sur Marne; ASAE = Association for monitoring of soils receiving residual water from crop processing industries in Champagne-Ardenne).

	Effluent application			
Treatment	NIL	80 mm Once	80 mm Twice	160 mm Twice
	· kg ha^{-1} K_2O			
Inputs	296	1899	4146	8170
Offtakes	79	118	214	302
Fraction removed	26.7%	6.2%	5.2%	3.7%

The experiment yielded some information on leaching losses on chalk soil. In both lysimeter and field experiments losses in drainage for an annual mean rate of application of 160 kg ha^{-1} amounted to 13,5 % of the amount applied, or around 20 kg ha^{-1} yr^{-1} K_2O. Though the proportion leached diminished as the rate of application increased (Table 3) the amounts lost in leaching can become relatively high at high of application; 40 kg ha $year^{-1}$ for an application of 5 t K_2O and 120 kg $ha^{-1}.year^{-1}$ for 9.6 t. The results in table 5 show that leaching losses of potassium are much less than those of other major elements under these conditions. The proportion of potassium lost by drainage ranged in an small interval from to 61 % of the inputs in bare soil to 73 % under permanent grass, that is a situation very different than for nitrate. Excessive application of potassium could adversely affect ground water quality. The maximum permissible level for K in water, as fixed by the EC, is 12 mg l^{-1}.

Application limits in relation to crops are dictated on the one hand by the immediate crop demands and on the other by crop removals which will determine the variation in soil stock. Crop potassium needs are estimated from crop K contents during growth or at harvest. Table 1 gives the K contents of different plant parts which may or may not be removed from the field. Clearly, there can be large differences between amounts removed at harvest and maximum crop contents during growth. Uptakes show little difference between maximum and immediate requirements. Maize yielding 8.5 t ha^{-1} grain has a maximum requirement of 200 kg K_2O, lucerne (14 t ha^{-1} dry matter) and beet (80 t roots) have maximum requirement of 450 kg ha^{-1} K_2O. Removals at harvest on the other hand depend very much on the fate of crop residues (straw, etc). Little K (40-50 kg ha^{-1}) is removed in grain so, if straw is left in the field, K removal is small. Much the same applies to rapeseed and sunflower. When straw is removed, removal by wheat increase from 54 to 149 kg ha^{-1} K_20. For beet, potatoes and lucerne, removals are very high and can reach 420 kg ha^{-1} K_20. in the case of lucerne. There is, of course, a direct relation betwen crop yield and K removal.

Table 5. Mean annual potash balance as related to soil cover. Lysimeter experiment on rendzina overlying chalk kg ha^{-1} K (INRA Châlons sur Marne).

Soil cover	Bare soil	Permanent grass	Rotation beet-wheat
Period	1973-88	1973-88	1977-81
Volume drained (mm)	294.0	2.4	161.0
K_2O input (I)			
Rain	2.4	2.4	2.4
Fertilizer	0.0	0.0	187.6
K_2O removed (R)			
Crops	0.0	0.0	58.0
Drainage	16.0	19.0	26.0
Balance (I-R)	**-13.6**	**-16.6**	**106.0**

There are problems when potassium applied in effluent is much in excess of crop requirement. If soil potassium is raised unduly, leaf-and root-K contents in sugar beet increase as indicated in Table 6, though above 500 ppm exchangeable K plant K content increases only slightly. Removals of potassium can be greatly increased without there being any increase in yield.

If potassium application is greatly above crop requirement, K will accumulate in the soil and it may be necessary to reduce the frequency of application and to correct the K/Mg ratio in the soil. The relation between K and other elements, such as Na, should also be mentioned, and it is therefore essential that effluent analysis should be complete in order to fully assess its agricultural value.

Vigilance must be exercised in controlling potassium enrichment of the soil which may result in luxury consumption. This may have positive effects on crop quality (Villemin *et al.*, 1991) but can also have adverse effects though ion antagonism (Dutil, 1978).

Table 6. Variation in K content of sugar beet leaves and roots related to exchangeable K_2O content of soil 0-20 cm) (INRA* ASAE Châlons sur Marne).

Plant material	Exchangeable soil-K (‰ K_2O)				
	0.25	0.32	0.49	1.021	1.642
	% K_2O of dry matter				
Roots	0.80	1.21	1.58	1.59	1.77
Leaves	5.00	5.73	7.40	8.08	7.17

Alternative ways of using potassium-rich effluents

Effluents may be used with or without pre-treatment by concentration or extraction of materials with fertilizer value. The first is the less costly and perhaps preferable as it return large amounts of water to the environment (Dutil and Muller, 1979; Muller and Ledain, 1992). The second is seldom used except in the case of concentrated sugar beet factory distillery effluent. This is essentially an organic fertilizer which can be used in the same way as conventional fertilizer; this product can be modified by adding a calcium supplement for use on land with a lime requirement. When potassium concentration is high it may be praticable to extract the potassium and market it as sulphate or bicarbonate of potash.

Town or agro-industrial effluent should be used only with some precautions and with understanding of the effects it may have on the soil. In consideration of the function of the soil as a purifier, it is necessary to determine the essential kinetic parameters dependent on the nature of the effluent, soil and climatic conditions and cropping systems. Application must be considered in the light of the whole crop rotation. Rates must be consistent with immediate crop need and nutrient balance. Part of the nutrients in the effluent will be taken up by the crop and removed from the soil, and nutrients not taken up may be leached by winter rains and can pollute the groundwater. The following must be defined :

1. Maximum permissible rate of application, usually expressed as mm water, in the light of the three following conditions as they apply to potassium and other elements :

a) allowing some storage, but not too large or permanent, in the soil;

b) adjustment according to the potassium balance. If the soil is not K-retentive, the total of K applied in the effluent + fertilizer together with the supply from the soil should equate the K need of the first crop to be grown.

c) if the soil retains potassium, the rate of effluent to apply should be calculated in the light of the K requirement of the whole rotation.

2. Frequency of spreading effluent, which is determined by crop removal of the nutrient applied in the largest quantity between applications, by other fertilizer applied and by losses through leaching and fixation as applied to the whole rooting zone (topsoil + subsoil) :

$$\begin{array}{c} \text{K applied in effluent} \\ + \\ \text{K from soil} \\ - \\ \text{Loss by leaching and fixation} \end{array} = \begin{array}{c} \text{Removal in crop} \\ + \\ \text{Change in soil K} \end{array}$$

A pratical example would be the application of potato starch factory effluent containing 1200 mg l^{-1} K_2O and of which, in order that N supply for the immediate crop should not be excessive, the rate of application is limited to 80 mm. Comparison of inputs and offtakes of potassium will determine the interval between effluent spreadings and/or the rate of fertilizer supplement to be applied for the 8-year rotation beet - wheat - beet - wheat - oats - lucerne - wheat - wheat for example. Crop potassium removal is calculated from the data in Table 1. If wheat straw is consistently removed, K_2O removal approximates 1900 kg ha^{-1}, a figure which is reduced to 1600 if straw remains in the field. According to the situation, it is possible to calculate either the frequency of effluent spreading or the need for supplementary potash if the frequency of application is dictated by another limiting factor. Like that, the manner in which effluent is used should be consistent with good farming pratices.

We can say in conclusion that the use of effluents in farming rests upon some simple propositions first mentioned by a French agriculturalist, Bernard Palissy, in his "Traité des sels divers et de l'agriculture" published in 1563, from which we may quote :

- *To maintain the fertility of the soil it is necessary to return to it that which has been removed in the harvest.*
- *Human and animal excrements should be rendered to the soil for they are forms of substances contained in harvested crops.*

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Replacement of Sodium in Home and Industrial Uses by Potassium : Importance and Possibilities

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Summary

Treatment of waste water is made necessary both by the ban on discharge of effluents into the sea and rivers and in order to satisfy the needs of an increasing population. Treatment aims to eliminate pathogens and organic matter and to precipitate heavy metals; soluble salts are not removed. Domestic and industrial use of water results in an increase in salinity principally due to the use of sodium chloride in water softening. The average annual increase in salinity in Israel is 170 mg Cl l^{-1} per head (about 17 kg NaCl per head). The SAR is raised by 2.5 units and this leads to sodium enrichment of soils which impairs soil quality. The high sodium content of softened drinking water may be detrimental to human health. The increased salinity of sewage effluents is a significant item in the salt balance. It would be possible to reduce the SAR of effluents and so limit salinity build-up by substituting potassium for sodium in water softening and other processes. The Israeli Environment Ministry and the Dead Sea Works are jointly sponsoring a project in this field.

Waste water recycling

Recycling of waste water is becoming a common practice all over the world, especially in arid or semi-arid regions.

One reason for this is the increasing demand for water. In Israel, more and more water must be diverted from agricultural to urban use. The allocation of water for irrigation can be maintained only by using waste water. Waste water recycling in the agricultural sector is increasing in many countries: the USA, Egypt, China and others. Urban re-use of waste water is also spreading. Several cities in Japan and in the USA are already using properly treated waste water for residential irrigation or for toilet flushing.

The use of properly treated waste water for irrigation is environmentally sound. Waste water applied to soil is purified by the uptake of nutrients by plants, by biodegradation and through adsorption on soil colloids. Thus, irrigation of dry or wetlands is a common method of treating waste water.

The re-use of effluents imposes several requirements. Efforts are made at the source to prevent the inclusion of toxic wastes and heavy metals in industrial waste water. Effluents for use in irrigation should be subjected to biological, physical and chemical treatment to reduce or abolish potential pathogenic factors. However there is no treatment to reduce the levels of soluble salts. Dessalinization of effluents is a very costly operation. Thus, any increase in salinity of the water is recycled with the water. It seems that this is a major problem associated with the large-scale use of waste water.

Salinity increments in municipal sewage

There have been several studies in Israel to evaluate salinity increases arising municipal and industrial uses of water. Rebhun (1965) measured the salinity in the supply and sewage water in Haifa. He found that the average annual increase in salinity was 170 mg Cl/l, accompanied by an almost equivalent rise in sodium (115 mg/l), i.e. the added salinity consists mainly of NaCl. Several more recent studies (Feigin *et al.*, 1991) revealed an increase in electrical conductivity averaging, in several communities, 0.5 dS/m. This increase is equivalent to an increase of 175 mg Cl/l, which agrees with Rebhun's results. The average SAR of the water increased, according to these studies, from 2.5 to 5.0 SAR units.

The increase in salinity due to domestic use alone was estimated in several studies. The daily per capita body excretion of salts amounts to about 4-5 g chloride or 10-11 g total salts (Selkurt, 1961; Rebhun, 1965). The total salinity increment from domestic uses was evaluated in the USA (Metzger *et al.*, 1958) and in Israel (Rebhun, 1961), to be about 7 g chloride per capita per day. The expected increase in salinity, due to domestic uses, for an average per capita water consumption of 100 m^3 per annum should be 26 mg Cl/l as compared with the observed increase of 170 mg Cl/l. The large difference (144 mg Cl/l) is explained by the contribution of chlorides from industry.

Simovici (1988) measured the chloride discharge from 100 big factories in the Dan (Tel-Aviv) metropolitan area. She found that the annual discharge from this source amounted to 4,215 ton chlorides, equivalent to 48 mg Cl/l increment in the metropolitan waste water. This relatively low chloride increase can be explained by the fact that the study did not cover all industrial sources and by the low industrial effluent discharge in this area (about 10% of the total waste water).

Industrial sources of salinity and sodium

Industrial sources of salinity and sodium consist mainly of NaCl and NaOH (Table 1). The most important and largest source of salinity is water softening, which usually uses NaCl solution for regeneration. Simovici (1988) found that 94% of the chlorides discharged from the factories in the Dan (Tel Aviv) metropolitan area consisted of NaCl and that 63% of the total chlorides originated from water softening processes.

Commercial water softening is based upon the use of cation exchange columns. The hard water to be softened (typical water hardness in Israel is ca 400 mg/l, expressed as $CaCO_3$) flows through a sodium-saturated exchanger. When exhausted, the column is regenerated by through-washing with concentrated NaCl solution (10-20%) followed by rinsing to remove residual salts. These processes are inefficient, using on the average about 3 g NaCl per gram of removed hardness. The efficiency of the process is about 40%, i.e. the amount of NaCl used is 2.5 times the theoretical need.

The major industrial uses of water softening are in steam generation, cooling towers, laundries, textiles, etc. Moreover, it seems that water softening is increasing, both for industrial and general household purposes, especially due to the popularity of laundry and dish-washing equipment. Home water softening leads to more sparkling glassware and prevents scaling in cooking ustensiles.

Other industrial uses of sodium salts are textile dyeing processes and in flotation separation processes for food and agricultural products which use saturated salt solutions. Large quantities of NaOH are consumed for cleaning (especially in milk processing industries), textile treatment and in the food industry. It is possible to replace NaOH. An additional use, common in Israel is the NaCl treatment of all meat products as demanded by the Jewish dietary law.

Table 1. Water, NaCl & NaOH consumption in several industries.

Industry	Water consumption m3/year	NaCl consumption ton/year	NaOH consumption 48% solution ton/year
Milk processing	450,000	450	1,000
Soft drink industry	200,000	55	125
Orange & tomato processing	450,000	65	130
First stage leather processing	1,000	20	-
Textile dyeing	1,000,000	1,680	1,800

Agricultural implications of salinity and sodicity of effluents

Salinity and sodicity of soils and waters are intrinsic and typical problems in all arid and semi-arid regions. These regions are characterised by limited leaching and thus salt accumulation is common. Moreover, due to the precipitation of Ca, the soil solution is enriched with Na. The Na ion is known to cause soil dispersion with all the consequences of this - crust formation, enhanced soil erosion, limited root aeration and penetration, etc. These inherent problems may be exacerbated if, as is the case in Israel, appreciable quantities of reclaimed waste water have to be used for irrigation. It is even the case in some areas that the only water which can be made available for irrigation is reclaimed waste water. Already, waste water in Eilat at the southern tip of Israel is so saline that it cannot be used for most crops despite all that water treatment technology can do.

It is clear that limits should be set to the contribution of urban and industrial salts to Israeli waste waters.

Health aspects

Sodium is the most common extra-cellular ion in the human body and is known to affect water metabolism, regulation of extra-cellular liquids and blood pressure. High blood pressure is the most common chronic disease in modern societies with an incidence in adults of about 30%. It is more common in areas where salt consumption is high.

High Na intake tends to raise the blood pressure. Several investigators recommend a reduction in Na intake for the whole population and not only for those already affected. On the other hand, it was found that an addition of potassium seems to lead to a drop in blood pressure, when sodium intake is high. The Na/K ratio in urine is positively correlated with blood pressure.

Food is the main source of sodium. However, it is possible that in arid and semi-arid zones, where water is usually hard and water consumption is high, sodium intake through drinking softened water is not negligible. Typical Israeli water, having a hardness of 400 mg as $CaCO_3$, has when softened, a sodium concentration of 8 meq/l. For a daily water consumption of 2 l, this amounts to an intake of 16 meq Na, or almost 1 g NaCl, which can be considered high. Several investigators have found a relationship between high blood pressure and high sodium in drinking water.

Conclusions

The contributions of urban population to the total salt accumulation in Israel are very significant. The average domestic use increment is about 2.6 kg Cl per annum per capita which is unavoidable. However, the total increment is 17 kg Cl per annum per capita, mainly due to the use of salts for industrial purposes and for water softening. Almost all of this addition consists of NaCl. This addition can and should be controlled. In Israel, the contributions of municipalities and industries to the total salinity amount to 85,000 tons of chlorides per annum, which is equal to the input of salts from the Sea of Galilee - a contribution of major national concern.

The fraction of sodium in the total enrichment is high. This implies a worsening of irrigation water quality. It seems that the rising fraction of sodium in water also has consequences for human health, both directly and indirectly. The use of softened water for drinking purposes leads to a significant increase in sodium intake. The overall increase of sodium in water may lead to increased sodium concentrations in irrigated crops and thus to increased sodium intake by the population.

A possible way to counter this trend is to use potassium rather than sodium in water softening and other industrial activities.

Theoretically, potassium can replace sodium. Such a replacement has been tested in a few industries in Israel and there seemed to be no major problems. The price per unit potassium may be somewhat higher, especially since the equivalent weight of potassium is higher than that of sodium (1.28 kg KCl are needed to replace 1 kg NaCl). However, the overall expense may be reduced if more efficient ways of use can be developed. The replacement of sodium salts or NaOH by potassium will alleviate the potential damage caused by sodium. Moreover, K as a major plant nutrient will be taken up by crops and this will effectively reduce the soil salinity hazard.

It seems that the use of potassium rather than sodium in home water softeners is of special importance, due to the health risk associated with Na-softened water and to the potential health gain associated with the use of K-softened water.

The Israeli Ministry of Environment, together with the Dead Sea Works is now supporting a major Research and Development project to bring about such a transition. In addition to other related efforts initiated by the Ministry of the Environment, this will, undoubtedly, reduce the salinity load of recycled water.

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Coordinator's Report on Session 4

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In the fourth session, devoted to K requirements in different land-use systems, attention was paid both to replenishment of agro-ecosystems from which K is withdrawn in the form of produce, and to prevention of losses of K due to erosion arising from improper soil management.

In the first paper by Vanek and Balik, it was shown that generally the consumption of fertilizer-K in Czechoslovakia is at a satisfactory level, although rather wide variations in K use exist, sometimes resulting in K-induced Mg deficiency. Like in Western Europe, apparently the problem of excessive K supply in the form of cattle slurry can be the cause of unduly high levels of soil K. This once more points out the pressing need for a more efficient distribution of nutrients present in manures.

In his comprehensive treatise of the role of potassium in agricultural ecosystems, Munson rightfully stressed the importance of K in improving the efficiencies not only of water, but also of nitrogen and phosphate. In our western society, we are justifiably concerned about N and P causing eutrophication of our ecosystems. Too little attention so far has been paid, however, to the fact that often we have not created the proper conditions for plants to optimally utilize N and P supplied as fertilizers and/or manures. Frequently, these nutrients cannot be fully utilized by crops because other nutrients, like K, are not present in sufficient quantities. In other words, a more balanced supply of nutrients can be an effective safeguard against environmental pollution. Munson offered many valuable suggestions for a more judicious use of fertilizers needed to produce more food and fiber for an ever growing world population, without endangering the quality of our environment.

Trees play an important role in our European environment, and we all know that the health of our European forests is endangered. Slowly our foresters are beginning to realize that one of the most effective means of conditioning a tree against inclement factors, is to make sure that the tree is properly fed. Bonneau, in his presentation, pointed this out, but he also emphasized that our current soil testing methods, as they are geared to agricultural use, are often not suitable for making recommendations on forest fertilization. He stated that foliar analysis might be a more effective tool for improving the nutritional status of our European forests.

Kaupenjohann showed the usefulness of knowledge of foliar nutrient concentrations in tropical trees for maximum wood production. Surprisingly high quantities of K are needed for proper development of fast-growing tropical trees. Here again, attention should be given to proper soil management enabling an efficient recycling of K within the plantation ecosystem.

The hazards of slash-and-burn practices, both in forestry and agricultural systems, were also emphasized by Pagliai. From his presentation, it can be concluded that in Europe far too much tillage is practiced, and that in hilly regions the direction of tillage is usually still wrong. Soil, moving down the slope, contains large quantities of nutrients. Measures taken to reduce soil erosion serve two important purposes : in the first place, the efficiency of nutrients supplied in fertilizer form will be improved, and second, surface water will be protected from being charged with large quantities of eutrophying nutrients.

The nutritional value of effluents was the topic of the paper presented by Muller. It became clear from his presentation that under certain restricted conditions such effluents can replace fertilizers as nutrient suppliers, but that the application methods can have detrimental effects on the physical condition of a soil.

In countries with high water demands and with a high degree of hardness of the available water, the use of NaCl as a water softener can add considerably to an ever increasing salinity problem. In their paper, Avnimelech, Bazelet and Weber announced the intention of Israeli authorities to replace sodium by potassium.

When considering K in various agro-ecosystems, the ready availability and low prices of potash fertilizers in Europe and North America can easily lead to the erroneous conclusion that potassium nutrition of crops will never be a major problem. Unfortunately, the reverse is often the case in tropical countries. Many agro-ecosystems have become heavily depleted of K. For example, annually Thailand exports more K in cassava to the Netherlands alone than it imports for its entire agriculture in the form of fertilizer.

Therefore, in the future the International Potash Institute will still have the important task of convincing policymakers in Asia, Africa and Latin America to purchase the K needed for a balanced nutrition of crops required in increasing quantities to feed an ever growing world population.

Chairman of the Poster Session

Prof. Dr. H. Beringer, Secretary of the
Scientific Board of the International
Potash Institute

Posters

1. Derivation of K-Fertilizer Recommendation

Potassium Balance in Czech Agriculture

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Summary

The effect of K fertilizers over the past 30 years on the potassium balance and its influence on the concentration of available K in soil is discussed. High rates of K fertilizer resulted in a positive K balance up to 1986. The K balance has been negative since 1988. This negative balance was confirmed by results of soil tests, which indicated a fall in available K in soils in some regions in the last testing cycle.

The calculation of a nutrient balance sheet (inputs - outputs) is useful in assessing optimum rates of application for maximum fertilizer efficiency. Target yield, crop quality, soil fertility and environmental factors must also be taken into account in arriving at recommendations (Jurkin *et al.*, 1974; Jurgens-Gschwind, 1974; Hebert, 1984).

National and regional K balances have been calculated using data from the Federal Statistic Institute in Prague, the Central Agriculture Control Institute in Prague and the Czech Ministry of Agriculture.

Table 1. Potassium balance (kg K per ha) in the Czech Republic.

Years	Fertilizers	Manure	Uptake	Balance
1961-65	33,4	34,9	56,4	+ 11,9
1971-75	70,1	36,6	73,2	+ 33,5
1981-85	70,2	41,2	94,8	+ 16,6
1986	61,6	38,3	92,9	+ 7,0
1987	59,3	38,8	96,4	+ 1,7
1988	55,2	39,0	94,3	- 0,1
1989	46,4	39,5	98,6	- 12,7
1990	42,2	38,1	89,9	- 9,6
1991	6,6	32,7	89,0	- 49,7

The balance was positive until 1985 due to generous application of K fertilizer, then neutral for the next two years (inputs = outputs), but negative thereafter.

Table 2, again based on the whole country but distinguishing between arable and grassland soils, shows changes in the proportions of arable and grassland soils falling in different categories for available K (ammonium acetate/oxalate extraction after Schachtschabel, 1941). The classification into K categories takes into account soil texture indicated by the proportion of soil particles < 0,01 mm (Table 3). There was general improvement in soil K status up to 1983 (positive K balance) but the situation on the grassland was not so satisfactory with still a high proportion of soils in the low and very low categories.

Table 2. Percentage of soils in differing categories of K availability.

	Category of availability				
ARABLE SOIL					
Years	VL*	L*	M*	H*	VH*
1961-65	37,6		39,9	22,5	
1971-75	18,7		35,3	46,0	
1976-80	1,4	10,6	34,3	33,1	20,6
1981-83	1,2	8,4	32,0	35,8	22,4
1984-86	1,0	8,4	31,0	35,5	24,1
1987-89	1,1	8,1	30,0	35,1	25,7
GRASSLAND					
1961-65	62,7		24,4	12,9	
1971-75	49,8		26,0	24,2	
1976-80	7,3	18,6	25,5	23,3	25,3
1981-83	5,8	14,0	23,6	25,1	31,5
1984-86	5,9	14,3	23,4	24,7	31,7
1987-89	6,5	16,3	23,8	22,5	30,9

* VL - very low L - low M - medium
H - high VH - very high

Table 3. Classification of available soil K (mg K per kg soil) for arable and grassland soils of differing texture.

	Soil texture	K concentration				
		VL	L	M	H	VH
Arable soil	Light	<50	51-80	81-130	131-200	>200
	Medium	<70	70-110	111-170	171-250	>250
	Heavy	<90	91-140	141-220	221-330	>330
Grassland	Light	<40	41-70	71-100	101-150	>150
	Medium	<60	61-90	91-130	131-180	>180
	Heavy	<80	81-110	111-160	161-230	>230

From 1976, soil test data was compiled for different regions in the Czech Republic (Table 4) which indicates that the effect of K fertilizer application on available soil K differed between regions. This table also confirms the "Cinderella" status of grassland where available K declined in 4 out of 7 regions at the last soil test cycle whereas on arable soils there was a slight decline only in two regions.

Table 4. Mean soil available content (mg K per kg soil) by regions.

	Region*	Cycle of soil testing			
		1976-80	1981-83	1984-86	1987-89
Arable soil	MB	184	194	195	208
	SB	192	200	190	183
	WB	178	195	191	210
	NB	277	262	259	269
	EB	179	194	205	198
	SM	213	214	227	229
	NM	162	171	176	192
Grassland	MB	133	136	143	156
	SB	153	170	166	154
	WB	138	157	150	169
	NB	186	181	176	170
	EB	139	162	161	152
	SM	180	187	217	191
	NM	136	148	149	162

* MB = Mid Bohemia EB = East Bohemia WB = West Bohemia
NB = North Bohemia SB = South Bohemia NM = North Moravia
SM = South Moravia CR = Czech Republic

Table 5. Area of soils (excluding peat and young soils) of different textures in regions of Czech Republic (UZPP, Prague 1972).

Region*	Light soil		Medium soil		Heavy soil	
	(ha)	(%)	(ha)	(%)	(ha)	(%)
MB	154 473	22,1	473 703	67,8	65 788	9,4
SB	322 141	52,7	277 854	45,5	4 118	0,7
WB	162 723	30,5	358 579	67,2	7 698	1,4
NB	66 793	16,6	257 501	63,8	75 504	18,7
EB	124 151	18,0	498 235	72,2	66 153	9,6
SM	218 468	23,2	611 562	64,9	110 222	11,7
NM	60 670	10,6	477 708	83,4	33 848	5,9
CR	1 109 419	24,9	2 955 142	66,4	363 331	8,2

* See Table 4.

Conclusion

Since K fertilizer consumption has declined it can only be assumed that there will be a further decline in available K in all regions. This can be prevented by more accurate K fertilizer application based upon soil test results and K balances over smaller regions.

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Estimation of K Fixation and Release in Soils by Two Consecutive Methods

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Summary

In this paper, the theoretical and practical foundation of a simple method for estimation of potassium fixation and release is given. It allows to calculate how much K fertilizer is required to achieve the necessary exchangeable K level in soils and to estimate the relation between the rate constants of K fixation and of K release.

Introduction

There are many different methods for predicting K fixation and release in soils (Addiscott & Talibudeen, 1969; McLean & Watson, 1985). Methods, which have been proposed to estimate kinetic parameters and to determine K fixation are too complicated for routine testing and for advisory purposes, although advisors often need information about K fixation and release in a soil sample to provide the farmers with adequate instructions.

The purpose of this paper is the theoretical and practical foundation of a simple method of estimating the relation between rate constants of K fixation and of K release and the prediction of K fixation after adding K fertilizer in soil.

Theoretical consideration

We consider K fixation and release as reversible reaction between the K of the soil exchange complex (K) and the K which is fixed in the secondary minerals with expanded interlayers (K_{fixed}) :

$$(1)\ K \underset{k_2}{\overset{k_1}{\rightleftharpoons}} K_{fixed}$$

where k_1 is the rate constant for fixation; k_2 is the rate constant for release.

If K is the exchangeable K then its rate of change with time is determined by the two first-order reactions of fixation and of release, i.e.

(2) $dK/dt = k_2 * K_{fixed} - k_1 * K$

We consider a case when initial steady state of exchangeable K is disturbed by adding some K fertilizer (K_{added}). The initial steady state at the moment $t = 0$ is characterized by the exchangeable K content K_0 and the fixed K content $K_{fixed(0)}$. The steady state after adding K is characterized by the exchangeable potassium K and fixed potassium K_{fixed}. Mass conservation equation for this case will be

(3) $K_0 + K_{fixed(0)} + K_{added} = K + K_{fixed}$

Substituting K_{fixed} in the equation (2) by its value derived from the equation (3), we have

(4) $dK/dt = - (k_1 + k_2) * K + k_2 * (K_0 + K_{fixed(0)} + K_{added})$

Since we have $dK/dt = 0$ at the steady state, the new steady exchangeable K content after adding K fertilizer may be calculated from

(5) $K = B * (K_0 + K_{fixed(0)} + K_{added})$

where

(6) $B = k_2 / (k_1 + k_2)$

In this way, we derive a parameter (B) which characterizes the relation between the rate constants of K fixation and of K release (eqn 6) and determines part of the exchangeable K in the total amount of the K (added, exchangeable and fixed) (eqn 5).

The next mathematical calculation provides a simple method for estimation of B - values from the exchangeable K contents obtained in two consecutive extractions.

We have analyzed equation (5) for two K_{added} values: 1) $K_{added} = 0$;
2) $K_{added} = K_0$. In the first case, the steady state exchangeable K content is not changed and from equation (5), we have

(7) $K_0 = B * K_{fixed(0)} / (1 - B)$

Consider the second case as a removal of exchangeable K from the soil sample using salt or acid extract. After removal, the new equilibrium state of K fractions is established with exchangeable potassium K_1.

According to the equation (5), it will be equal

(8) $K_1 = B * K_{fixed(0)}$

K_1 may be determined in the repeated extraction from the same soil sample using the same method after the equilibrium in this sample has been reached.

From equations (7) and (8), we have

(9) $B = (K_0 - K_1) / K_0$

This means that the B-value of the soil may be determined by K extracted in two consecutive steps. Parameter B can characterize the buffer capacity of soils. According to equation 9, B can change from 0 (when $K_1 = K_0$) to 1 (when $K_1 = 0$). In the first case ($B = 0$), soil has the highest K fixation and buffer power and can maintain the initial exchangeable K level. In the second case ($B = 1$), the soil has the lowest potassium fixation and buffer power; then all added K will be in the exchangeable form.

From equations (5) and (7), we also have

(10) $K = K_0 + B * K_{added}$

(11) $K_{added} = (K - K_0) / B$

These equations are useful for advisory purposes. If we know the B value of a soil, we can predict the exchangeable K content at the steady state after adding K fertilizer (eqn 10). Using eqn 11, we can calculate how much K fertilizer is required to achieve the necessary exchangeable K level in a soil.

Experiments

Laboratory and field experiments were carried out to verify the proposed method of estimation of K fixation and K release. A condition of the suggested method is the achievement of the steady state in the soil after the first extraction. We selected wetting and drying from the factors affecting K fixation. This considerably accelerates the process of K equilibration in the soil system.

The effects of drying time and temperature were investigated in a laboratory experiment and it was found that only temperature significantly affected B. The higher the temperature, the lower is B and the higher K fixation. So we use the maximum drying temperature (occurring under field conditions) to obtain potential K fixation for a given soil. In general, therefore, the soil sample on the filter after the first extraction was air-dried (22-24° C) and the following procedure used to calculate B:

1. The determination of exchangeable K in the soil sample with ammonium acetate.
2. The drying of this sample until the air-dry state.
3. Determination of exchangeable K in the dried sample again with ammonium acetate.
4. The calculation of B value using eqn 9.

For that purpose, 13 soil samples from typical chernozems (loam soils) with different exchangeable K content were used. K fixation was determined in the soil samples by two methods : 1) using parameter B, and 2) from the exchangeable K content after addition of K fertilizer.

The square mean deviations, mistakes, model error and regression analysis coefficients were determined in order to compare the calculated and actual values of K fixation and presented evidence on the high degree of agreement between them.

A field experiment on microplots investigated 20 typical chernozem soils with the same parent material but differing in fertility. Four different crops were grown without fertilizer over four years. Various characteristics of K regime of the soils and yields recorded were subjected to correlation and regression analysis. B values correlated well with yield of barley, accounting for most of the variation, as did various K extractants.

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Importance of Texture and CEC in K Fertilization Advice

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FERTILITY DIAGNOSIS...

Theoretical basis

Exchangeable K is the most frequently used indicator of soil-K fertility. It represents a quantity of potassium which is considered as totally available for plants. Nevertheless, this availability is related to soil texture : a same quantity of exchangeable K is less available in clay soils than in sandy ones. This is explained by the exchange properties of the soil which can be formally described by an exchange equation like Gapon's one. In non-acid cultivated soils under temperate climate, the Gapon's equation can be simplified as follows :

$$\frac{K_e}{Ca_e \, or \, CEC} = k_G \cdot \frac{(K)}{(Ca)^{1/2}}$$

k_G : Gapon selectivity coefficient
K_e, Ca_e : exchangeable cations adsorbed on soil ($meq.kg^{-1}$)
(K), (Ca) : cation concentration in soil solution ($molc.l^{-1}$)
CEC : cation exchange capacity

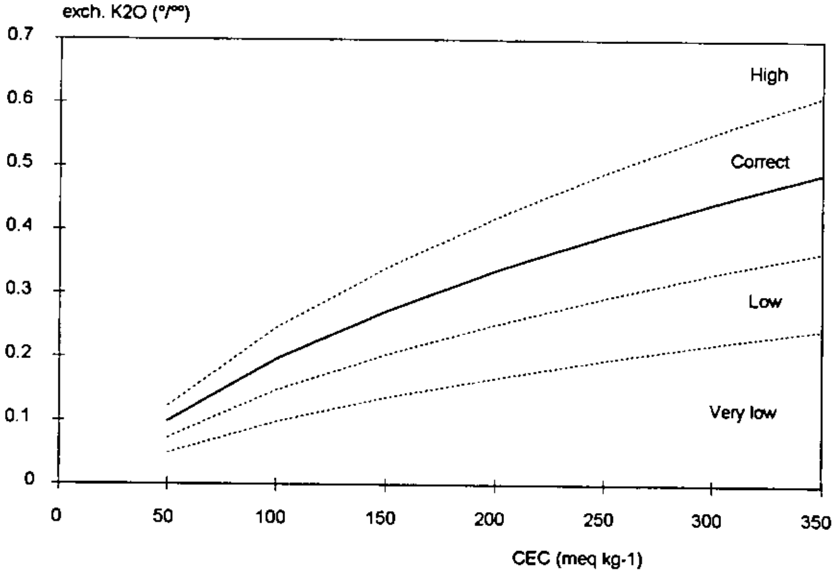
CEC is closely related to clay content, thus to soil texture. So a same amount of potassium represents a lower potassium saturation ratio in a clay soil than in a sandy one. So does the potassium concentration in the soil solution where plants take up their nutrients.

On the other hand, for a given plant uptake and a given soil-K saturation ratio, the relative decrease of the saturation ratio is less important in a clay soil, and so the K concentration in the soil solution. Thus the given K quantity will be absorbed in a shorter time in the case of the clay soil. More, a clay soil shows a higher non-exchangeable K reserve which is known to participate to the plant nutrition. These facts allow a lower saturation rate in clay soils to get the same availability.

Translation into extension

On experimental basis, a general reference curve, called norm, has been established. It gives the level of exchangeable potassium above which no response to K fertilizers can be expected, according to the texture expressed either by clay content or better by CEC.

For soils with low to medium CEC, exchangeable K saturation rate allowing optimal K nutrition has been found to be close to 3 to 4 %. For heavier soils, the norm increases less than proportionally with CEC.



Adaptation to local conditions

- **Plant influence** : it is well known that plants do not have the same demand in potassium. So the norm has to be modified according to this factor : shift to a lower value for low responsive crops, such as cereals, to a higher value for sugar beet, potato, lucerne,... which have high needs in K and some difficulties to absorb it.
- **K-reserve and K buffer capacity** : as long as soil solution potassium is absorbed by plants, exchangeable K becomes soluble and so-called non-exchangeable K is liberated in an exchangeable form. To get the same availability, a lower exchangeable K saturation rate could be sufficient in soils having high K reserves.

In the same line, some clay soils (e.g. Groies in SW of France) have a very low buffer capacity (the relationship between exchangeable and soil solution potassium). In these soils, the high yields of irrigated maize, for ex., require higher reference K levels.

- **Volume of soil** : according to the different types of soils, the quantity of earth supplying nutrients to plants can vary in a large extent : 1200 t/ha in stony calcareous soils to more than 4000 t/ha in deep loamy soils. Participation of the subsoil to the nutrition of the plant in homogeneous deep soils is a well-known modifying factor even though, generally, not in use in most of soil-test interpretation systems.
- **Influence of climatic conditions** : potassium release and fixation are highly dependent on wetting and drying cycles and influenced by the clay type and content. Translation of basic studies on that topic into extension recommendations remains very difficult.

... AND FERTILIZER RECOMMENDATIONS

When soil K is above the critical level, the soil should receive fertiliser to replace the various losses : removal in crop, fixation and leaching. Texture is an important factor for determining K leached under the root zone. Either tables or formulas give leaching values according to the clay content, the drainage and potassium buffer capacity.

When soil K is below the desired level, corrective measures are called for. Corrective requirement is calculated using the mass of soil in which the application will be diluted and a fixation coefficient. This coefficient depends on the soil type and can be calculated according to statistical formulas which are experimentally established. For example, in a loamy soil in the north of France, fixation capacity is given by :

$$\text{fixation capacity (\%)} = 0.14 \text{ CEC (meq kg}^{-1}\text{)} - 0.056 \text{ exch. } K_2O \text{ (ppm)} + 37$$
$$(r^2 = 0.79)$$

in which texture, estimated by CEC, plays a major role.

The great influence of texture at the different steps of fertility diagnosis or fertilizer recommendations can be explained by considerations about ion exchange, K-reserves (quantities and kinetics) and diffusion. These phenomena, among others, regulate potassium dynamics and behaviour in plant nutrition.

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Geographical Information Systems as a Tool for Site-Oriented Fertilizer Recommendations

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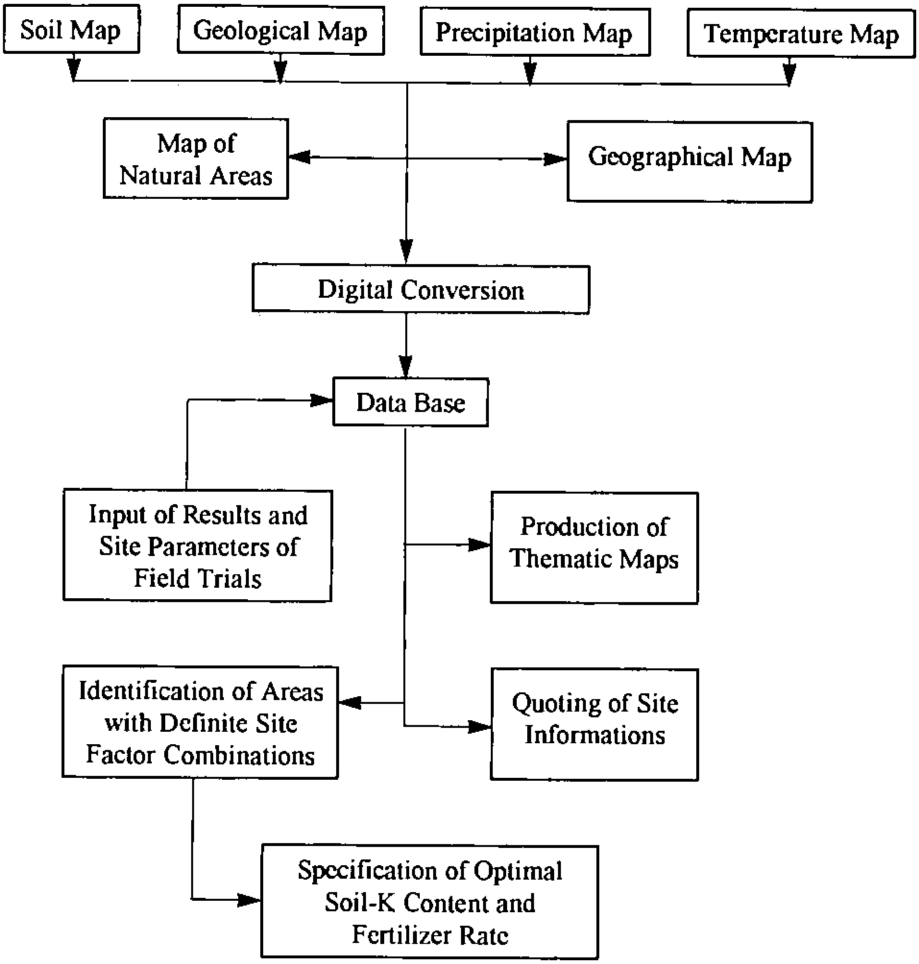
Fertilizer recommendations for potassium are normally based on the results of soil analyses and soil clay content. The plant availability and the uptake of the nutrient element potassium is, however, dependent on a number of further factors :

- effective rooting depth,
- soil water,
- temperature and air regimes,
- specific K uptake potential of the plant,
- soil texture,
- clay mineralogy,
- reserves of non-exchangeable potassium.

The varying combination of these factors on different sites results in a strong site-dependent relationship between soil K content, K uptake by the plant and optimum K fertilizer rate. It is only possible to forecast accurately the K fertilizer requirement for a given soil K content if as many as possible of these site factors are taken into account.

The result of a long-term fertilizer experiment will indicate the overall effects of site conditions on optimum K fertilization but it is impossible to evaluate the effects of single factors on the availability of K to plants. Therefore the results of a particular experiment apply only to areas characterised by the same or similar site factors as those of the site of that experiment.

In this context the Agricultural Advisory Service of Kali und Salz AG developed a computerized site information system named "KALIPROG". In this system, maps with site characteristics such as soil type, soil form, geological parent material, climatic conditions are stored in graphical data banks. By combination of information from the geographical information system with the site characteristics of a field experiment, it is possible to demarcate on a map an area or areas representative of conditions at the site of the field experiment. So, in a given area, both farmers and advisors are provided with site-specific data supported by the results of field experiments indicating the optimum fertilizer rate and soil potassium supply.



Structure of the site information system KALIPROG ®.

Methods for the Derivation of K-Availability Indices in Arable Soil

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Introduction

The aim of modern plant production is to achieve economically and ecologically optimum crop yield through appropriate fertilizer usage while making the fullest use of soil nutrients. This object will be achieved if soil nutrient content is sufficient to ensure that the yield potential is reached when only maintenance fertilizer dressings are applied (nutrient in fertilizer = nutrient removed by the crop). This is the situation when the soil falls into category C for K availability.

	Soil K category				
	A	B	C	D	E
K need	Above maintenance		Maintenance	Below maintenance	Nil

Various ways of determining available K content of soil have been tested; the standard method used in East Germany is that of Egner and Riehm. Soil test values are calibrated with K response in field experiments testing the effect of increasing K dressings. Some methods of soil analysis interpretation are discussed below.

A simple method is the graphical representation of response to K fertilizer at different levels of available soil K (Figure 1).

Another good procedure is based on the K balance. Balances are calculated for each year and treatment :

K balance (x) = amount of K fertilizer (Z) - K removed in crop (E)

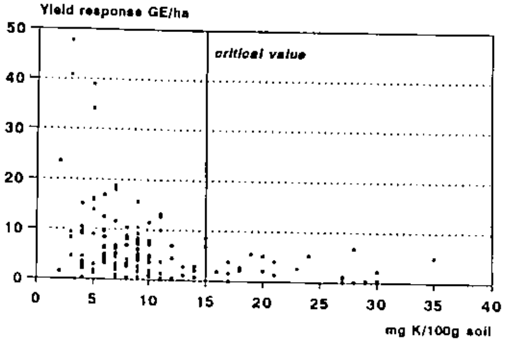

Fig. 1. Yield response caused by K application in relation to soil K content (DL-method) for loamy sand and sandy loam.
GE = cereal equivalents.

Treatments are then placed in K balance groups (Table 1) and the linear regression relating average relative yield (highest yield in trial year = 100) to soil K content (Figure 2) is calculated.

Table 1. Potassium balance classes for loam.

Balance classes	K-Balance in kg ha^{-1}*
7	$\leq$ -100
6	-99.9 to -60
5	-59.9 to -20
4	-19.9 to +20
3	+20.1 to +60
2	+60.1 to +100
1	$\geq$ 100

* K-Fertilizer minus K uptake in crops.

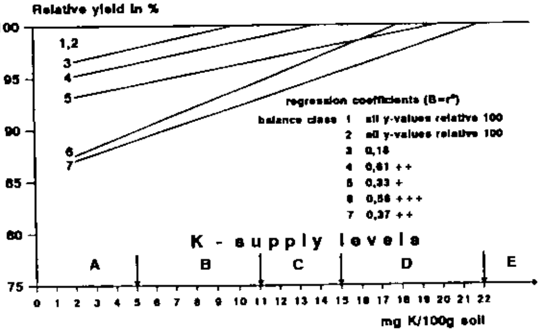

Fig. 2. Relative yields in relation to soil K content (DL-method) in the balance classes 0 to 7 (cf. table 1) for loam.
Optimum yield = 100%.

At the soil K level where the regression line for group 4 (balance -19.9 to +20.0 kg/ha K) represents attainment of the optimum yield by applying maintenance dressings (relative yield = 100) the conditions for soil K category C are fulfilled. Categories A and B are represented by balance groups 3 to 1, and categories D and E by groups 7 to 5.

The mathematical procedure for establishing optimum soil K content requires a large amount of experimental data. The basis for the calculation is the K balance (x). Yield difference (y) between treatment yield and maximum yield is also noted. Further data are shown in Figure 3.

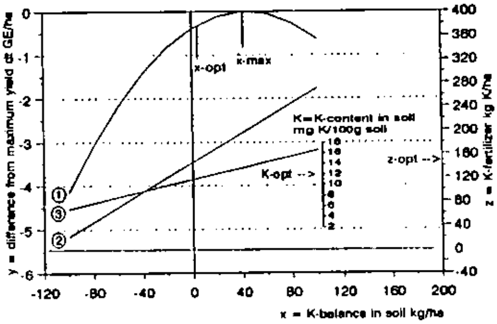

Fig. 3. Relation between K balance in soil (x), difference from maximum yield (y), amount of K-fertilizer (z) and soil K-content (K) (DL-method). Results of a long-term (8 years) field experiment with different K-values on loess-loam (average maximum yield 62,1 dt GE/ha).

The relationships of Figure 3 are expressed in the following equations where the index "opt" is a parameter for optimum yield and "max" that for maximum yield.

The example applies to loam soils.

Yield difference $y = a_1 + b_1x + c_1x^2$ (1)

Nutrient balance $x_{max} = \frac{b_1}{2c_1} = 44 \text{ kg ha}^{-1} \text{ a}^{-1}$

$$x_{opt} = \frac{b_1 - \frac{\text{fertilization costs}}{\text{crop price}}}{-2c_1} = 7.0 \text{ kg ha}^{-1} \text{ a}^{-1} \text{ K}$$

K-fertilizer $Z = a_2 + b_2 x$ (2)

(miner. + org. fertilizer) $Z_{opt} = 145.97 + 1.246\ x = 155 \text{ kg ha}^{-1} \text{ a}^{-1} \text{ K}$

K-uptake = K-removal $E_{opt} = Z_{opt} - X_{opt} = 148 \text{ kg ha}^{-1} \text{ a}^{-1} \text{ K}$

For an economically optimum yield the ratio plant uptake (E_{opt}) to amount of fertilizer (Z_{opt}) is denoted the balance coefficient (A_{opt}) and is a measure of K fertilizer efficiency.

$$A_{opt} = \frac{E_{opt}}{Z_{opt}} \ .\ 100\%$$

If $A_{opt} = 100$, K fertilizer requirement for optimum yield is the maintenance rate, i.e. fertilizer K = plant uptake. If $A_{opt} > 100$ less fertilizer is needed and if $A_{opt} < 100$ additional K fertilizer is required. In our example :

$$A_{opt} = \frac{148}{155} \ .\ 100 = 96\%$$

Determination of critical soil values

Determination of critical soil K levels calls for the use of all balance coefficients from all K response experiments (for every year) relating to the soil type. The optimal soil K (K_{opt}) corresponding with optimum yield is calculated by :

$$K_{opt} = a_3 + b_3\, x_{opt} \tag{3}$$

This value represents the soil K level needed for economically optimum yield on one soil.

The relation between the balance coefficient A_{opt} and soil K (K_{opt}) (Figure 4) for several soils in one soil group is then :

$$A_{opt} = a_4 + b_4\, K_{opt} + c_4\, K_{opt}^2 \tag{4}$$

The intersection of the regression line with A_{opt} = 100 describes the K content of the soil for soil K category C where optimum yield is obtained by applying the K maintenance dressing and is calculated from :

$$K_{opt_{A_{opt}=100\%}} = \frac{b_4}{2c_4} \pm \sqrt{(\frac{b_4}{2c_4})^2 - \frac{a_4 - 100}{c_4}}\, mg\; K / 100g\; soil$$

In the loam soil example of Figure 3 as well as on arvage of 13 long term experiments on loam (Figure 4) it is 12 mg K/100 g soil.

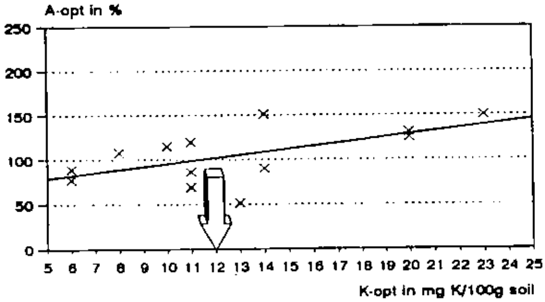

Fig. 4. Correlation between the balance coefficient for optimum yield (A-opt) and K content in soil (K-opt) (DL-method). Results of 13 yield experiments on loam.

Effect of Potassium Sulphate on the Yield and Quality of Vegetables

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Introduction

Care is needed in the choice of the forms of K fertilizer to use on vegetables; they vary in their sensitivity to chloride (Geissler, 1953). In addition they differ in their sulphur requirements. Siegel and Barsch (1962) pointed out a requirement for sulphur in tomato, finding also that under certain conditions high chloride concentration may decrease the yield of tomato. Uebel (1979) produced higher tomato yields by potassium chloride treatments in Czechoslovakia; for green pepper, however, he recommends potassium sulphate. Both forms of K have their effects on the quality of vegetables.

Materials and methods

· Requirements vary not only between crops but also between varieties. In the eastern parts of Hungary the PAZ Pallagi local variety pepper (Capsicum annuum spec. cultivar : PAZ Pallagi) and the Hungarian bred tomato varieties (e.g. : Lycopersicum esculentum spec. cultivar : Prima), are commonly grown. White radish (Raphanus sativus L. cult. Fehér vaj), sorrel (Rumex acetosa v. Hort. cultivar : PNL) and cabbage (Brassica oleracea v. capitata calt. Hajdúsági) local varieties are also common.

Small plot experiments on the above varieties were conducted on brown forest soil (weakly acidic humid sand) in the years 1990-1991. The effects of equal K_2O rates as potassium chloride and potassium sulphate were investigated at equal N and P rates (100 kg N, 54 kg P_2O_5, 250 kg K_2O/ha). The size of the plots was 20 m^2, the applications were repeated 4 times.

Results

PEPPER (1991)
(Capsicum annuum spec., cultivar : PAZ Pallagi)

	KCl	K_2SO_4	KCl	K_2SO_4
	absolute value		relative value (%)	
Yield kg/20 m^2	32.2	35.8	100	111
Fruit mass g/piece	96.3	101.1	100	105
Diseased fruit(piece/100 plant)	49.0	37.8	100	77

TOMATO (1990)
(Lycopersicum esculentum spec., cultivar : Prima)

	KCl	K_2SO_4	KCl	K_2SO_4
			relative value (%)	
Yield kg/20 m^2	62.4	80.2	100	128
Fruit mass g/piece	62.8	65.0	100	104
Refraction %	5.0	5.1	100	102

SORREL (1990)
(Rumex acetosa v. Hort. cultivar : PNL)

Harvest date	KCl	K_2SO_4	KCl	K_2SO_4
	kg/20 m^2		%	
22 June	6.4	8.9	100	139
25 July	19.7	21.4	100	109
17 Septembre	15.5	17.6	100	114
Total	41.6	47.9	100	115

Conclusions

It can be concluded that potassium sulphate applications on the tested pepper, tomato and sorrel varieties produced considerably better yields. There were no significant changes in the yields of radish (cult. Fehér vaj) and cabbage (cult. Hajdúsági), which indicate that these species and varieties are not sensitive to chloride ions.

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Effect of K Fertilizer on Yield of Maize on Meadow Soils

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Introduction

Potassium is important in plant nutrition and particularly so in its interaction with nitrogen by ensuring balanced nutrition is confirmed by results originating from the programme "National Uniform Experiments on Fertilization" which has been in progress since 1966.

Results

The results presented here refer to experiments on meadow soil in Hajdúböszörmény in which maize was grown in 3 rotations :

A. Pea - wheat - maize - maize;
B. Wheat - maize - maize - wheat;
C. Continuous maize.

The soil is high in organic matter (4.2%), fertile and similar to meadow chernozem but on account of hardness (Arany's hardness number 52) and other properties placed in the group of typical meadow soils. AL-soluble P_2O_5 40 mg kg^{-1}, Al-soluble K_2O 130 mg kg^{-1} on control (no P or K fertilizer) plots.

Treatments compared were factorial combinations of increasing rates of N, P and K fertilizers (totals of 20 or 40 treatments according to the experiment). Average yields and responses to K over 11 years from selected treatments applied to the 3 rotations in one experiment are listed in Table 1. Higher rates up to 250 kg ha^{-1} N, 200 kg ha^{-1} P_2O_5 and 200 kg ha^{-1} K_2O were also tested.

The mean yield increase from applying 100 kg ha^{-1} K_2O was 1.67 t ha^{-1} but there was only a slight and statistically insignificant further response to 200 kg ha^{-1} K_2O. The optimum rates of K fertilizer appear to be 100-200 kg ha^{-1} K_2O for maize grown in rotation and 120-150 kg ha^{-1} for maize in monoculture. However, applying K fertilizer above these rates contributed to increasing the level of soil K. AL-soluble K_2O and P_2O_5 contents reached 170-180 mg kg^{-1} and 300 mg kg^{-1} respectively when P and K fertilizers were applied at the highest rates (Figure 1). The relatively slight effect of K fertilizer in raising AL-soluble soil K is ascribed to the presence of smectites in this meadow soil.

Interaction of K with NP fertilizer was quite evident (Table 1) both when maize was grown in rotation and in monoculture, but the crop seemed more sensitive to K shortage in monoculture as shown by comparison of the response surfaces in Figure 2. In that case maximum yield in the absence of K was 7.9 t ha^{-1} from 111 kg ha^{-1} N with 75 kg ha^{-1} P_2O_5 while when K was applied maximum yield was 3 t ha^{-1} higher from the combination 192 kg ha^{-1} N, 122 kg ha^{-1} P_2O_5 and 100 kg ha^{-1} K_2O. This was a most striking feature of the results.

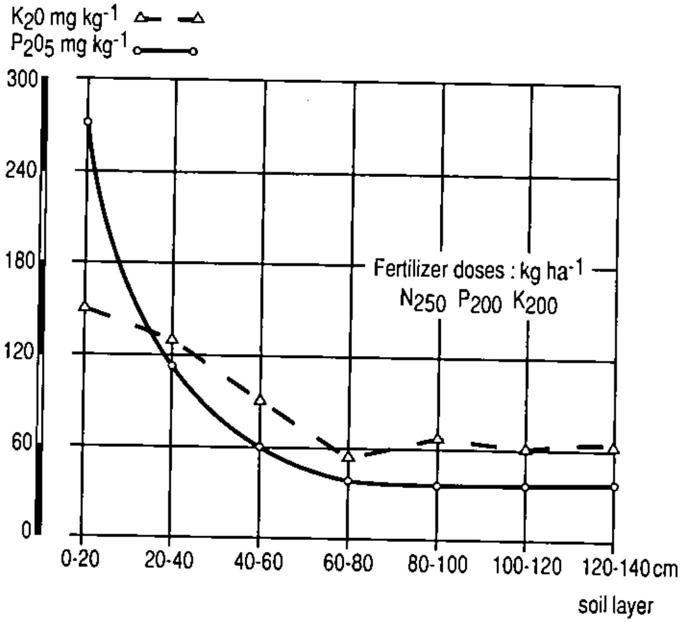

Fig. 1. Content of AL-soluble P_2O_5 and K_2O in the 0-140 cm soil layer.

Table 1. Yields (t ha^{-1} grain) of maize grown in rotation and monoculture and responses to N, P and K fertilizers. Mean of 11 years (1981-1991).

kg ha^{-1} N	Maize yield (t ha^{-1})			
	kg ha^{-1} P_2O_5			
	0	50	100	mean
Grown in rotation (average of rotations A and B)				
No K applied				
50	8.1	9.5	9.7	9.1
100	8.4	10.0	9.6	9.3
150	8.5	10.4	10.3	9.7
mean	8.3	10.0	9.9	
100 kg ha^{-1} K_2O applied				
50	9.0	11.5	11.2	10.6
100	9.9	11.7	12.5	11.4
150	9.9	12.2	12.2	11.4
mean	9.6	11.8	12.0	
Response to 100 kg ha^{-1} K_2O				
50	0.9	2.0	1.5	1.5
100	1.5	1.7	2.9	2.1
150	1.4	1.8	1.9	1.7
mean	1.3	1.8	2.1	
Grown in monoculture (rotation C)				
No K applied				
50	7.4	9.5	8.8	8.6
100	7.9	9.1	9.9	9.0
150	7.9	9.7	9.6	9.0
mean	7.7	9.4	9.4	
100 kg ha^{-1} K_2O applied				
50	8.4	10.3	10.6	9.8
100	9.6	11.5	11.7	10.7
150	8.9	11.5	11.6	10.7
mean	9.0	11.1	11.3	
Response to 100 kg ha^{-1} K_2O				
50	1.0	1.8	1.8	1.2
100	1.7	2.4	1.8	1.7
150	1.0	1.8	2.0	1.7
mean	1.0	0.8	1.8	

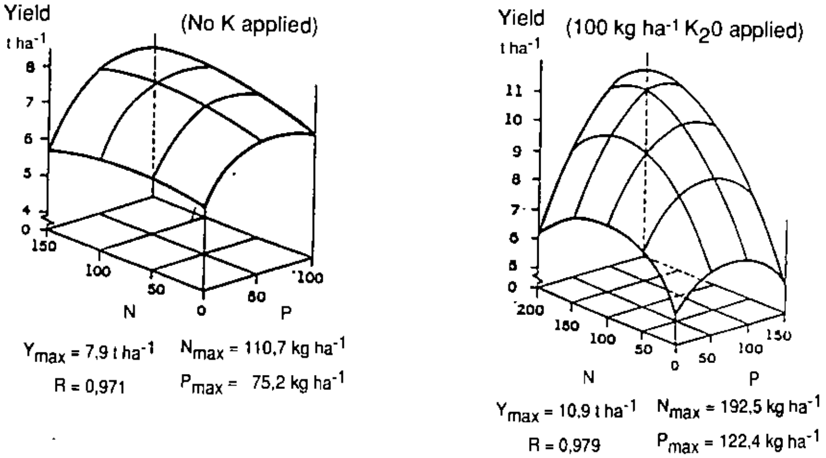

Fig. 2. Response surfaces of maize monoculture to N, P_2O_5 and K_2O (every year).

Conclusion

(1) K is important in maize nutrition resulting in considerable yield increase (ca. 1.7 t ha^{-1} grain) on average.

(2) The most important effect of K is ensuring balanced nutrition (3 t ha^{-1} increase from NPK as compared with NP).

(3) Maize is more sensitive to lack of potassium when grown in monoculture.

(4) Response to K fertilizer was greater in dry years.

(5) Optimum rates of N, P and K applied in combination can result in yields above 10 t ha^{-1} grain. The optimum rate of K fertilizer was from 100 to 120 kg ha^{-1} K_2O for maize in rotation and somewhat higher (120 to 150) for continuous maize.

(6) Applying K fertilizer above these rates gave little further yield increase but contributed to increasing the K-reserve in the soil.

Regional K-Status of Soils in Bulgaria and K-Fertilizer Recommendations to Most Important Crops

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Summary

Standard recommendations for K application to crops in Bulgaria are described. Insufficient K fertilizer is imported to cover Bulgarian needs and usage is only 42% of that recommended. A change in fertilizer policy is called for.

Introduction

The control of soil fertility and recommendations for the efficient use of fertilizers are the responsibility of the National Agrochemical System under the management of the "N. Poushkarov" Institute. Soil K status characteristics for the country are established on the basis of numerous laboratory and pot experiments and long-term field experiments in geographically representative areas of the country on the chief crops. Data from soil tests every 4 years on arable land and agricultural statistics are also used.

Bulgarian soils can be divided into 3 groups according to K status :

A. *High*-chernozems, smolnitzas, typical and leached cinnamonic forest soils, many alluvial meadow soils;
B. *Medium*-dark grey forest soils, eroded and calcareous chernozems;
C. *Low*-grey and light grey forest soils, pseudopodzolic cinnamonic forest soils, light textured acid alluvial meadow soils.

Results of experiments

K fertilizer had significant effects only on low K (Group C) soils. But even under such conditions, response to K fertilizer may be lacking if the region is arid. On others (Table 1) the effects were dependent on other factors such as yield level, weather, previous crop, etc.

Table 1. Variability in the effect of K fertilizer in long-term field trials (% increase in yield as compared with no K).

Soils	Exchangeable K mg kg^{-1} K	Crops				
		Wheat	Maize	Sunflower	Sugar beet	Fodder pea
		% increase in yield				
Leached chernozem	282	0-17	-	0	10-50	10-30
Podzolized chernozem	174	0-13	5-23	0-18	6-18	0
Calcareous chernozem	166	0	5-20	0	18-50	5-10
Grey forest soil	174	10-30	10-23	0-35	-	-
Cinnamonic forest soils pseudo-podzolic	149	0	-	0	-	0

Responses were recorded on sugar beet and maize and, in some years, on sunflower. The effect, particularly on wheat, is greater when sunflower is the preceding crop (high removal of K by sunflower stalks).

Fertilizer recommendations

These are based on results of soil tests and crop demand modified if necessary to allow for raising soil K status. It is unfortunate that there have been few if any economic evaluations of fertilizer effects. This is now essential as the country moves towards a market economy. Preliminary investigation of trial results shows that K fertilizer efficiency (kg increase in crop per kg K_2O applied) is greater at lower rates of application (60-100 kg ha^{-1} K_2O) and on fertile soils.

Table 2. Average K recommendations for the chief crops.

Crops	Average yield (t ha^{-1})	K-fertilizer rate (kg ha^{-1})
Winter wheat	4.8	53
Maize	6.9	71
Sunflower	2.1	34
Sugar beet	34.0	167
Potato (com.)	18.0	52
Country average		45

Insufficient K fertilizer is imported to make these rates of application possible and, over the past ten years, the overall K balance for Bulgaria has been negative. Average rate of application is now only 19 kg ha^{-1} K_2O compared with the 45 kg ha^{-1} recommended. This is equivalent to 32-40% of recommended rate applied to 80% of arable land. The average N:K ratio actually used (1:0.22) is far from that recommended (1:0.35) - another undesirable feature.

The results of these defects in fertilizer policy are to be seen in the changes in soil analysis results listed in Table 3.

Table 3. % arable land in different K status soils in Bulgaria (1963 to 1988).

	Exchangeable K level		
Survey cycle	Low	Medium	High
II (1963)	5.9	20.9	73.2
V (1988)	15.8	19.6	64.6

Conclusion

The national policy for the use of K fertilizer requires revision to bring it into line with the new economic conditions in Bulgaria. At present, as far as potassium is concerned, the soils are over-exploited and it is necessary to match with the demand of the market economy in order to prevent from decline in soil fertility and crop production, and to maintain the environment.

Interaction of Soil-K and Fertilizer-K on Crop Yield in Long-Term Field Experiments in Poland

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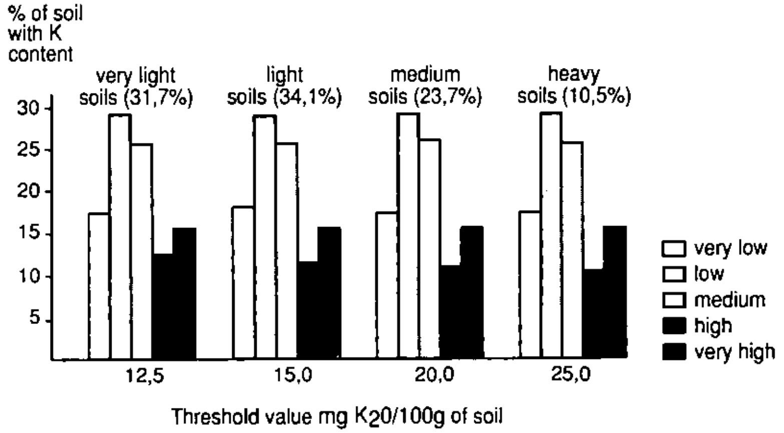
Introduction

The potassium status of Polish soils



- Most of the soils in Poland belong to sand and sandy-loam categories. The CEC of these soils is low and K fertilizers must be applied every year.
- Most of the soils are low to medium in available potassium. If soil K is below the threshold value, the rate of K applied should exceed plant uptake.
- Over the period 1975-1989, the average rate of K applied on Polish farms in fertilizers was 80 kg K_2O per ha per annum plus 35 kg^{-1} ha^{-1} in organic manures, resulting in a positive balance of 20 kg ha^{-1} $year^{-1}$ K_2O.

Methods

Long-term (12 years) experiments at 10 Exp. Stations. Rotation row crops - spring cereals - winter cereals, without FYM. Experiments were conducted in 2 series. 1976-1981 and 1983-88 on the same fields.

The layout of the experiment kg ha^{-1} yr^{-1} K applied.

Treatments 1976-1981	Treatments 1983-1988			
	0	70	140	280
kg ha^{-1} yr^{-1} K	kg ha^{-1} yr^{-1} K			
0	X	-	-	-
70	X	X	-	-
140	X	-	X	-
280	X	-	-	X

X Treatments presented in results

Results

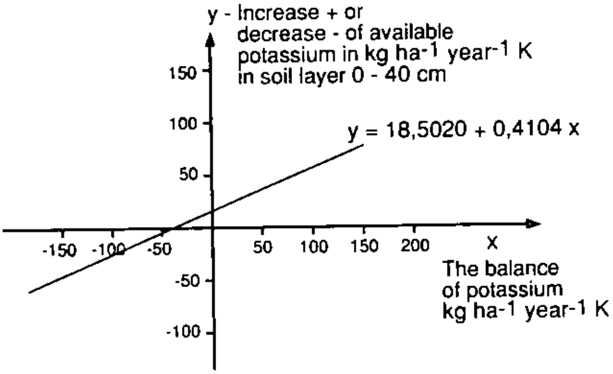
Crop yields (cereal units ha^{-1}) and K uptake

Treatment in the years		1976-82		1983-88		1976-88	
1976-81	1983-88	Cereal units ha^{-1} yr^{-1}	K uptake kg ha^{-1} yr^{-1}	Cereal units ha^{-1} yr^{-1}	K uptake kg ha^{-1} yr^{-1}	K uptake 76-88 kg ha^{-1}	Utiliz. of K %
0	0	48.7	114	46.0	75	1138	-
70	0			50.7	96	1413	65
70	70	53.8	139	56.3	117	1539	48
140	0			54.3	95	1501	54
140	140	55.5	155	59.3	142	1789	39
280	0			57.3	135	1832	41
280	280	56.0	170	60.3	174	2064	27

Potassium balance and the content of available potassium in soil

Treatment in the years		Balance of K	Available potassium 1987-88 in mg K_2O/100 g of soil
1976-81	1983-88		
0	0	-1138	4.4 low
70	0	-933	5.3 "
70	70	-699	6.8 "
140	0	-661	6.4 "
140	140	-109	9.3 medium
280	0	-152	7.3 low
280	280	+1296	15.8 high

The relation between K balance and the changes of available K in soil.



Conclusions

(1) When applied every year, K rates may be slightly lower than K uptake by plants.

(2) The relation between K balance and the changes in available potassium content in soil is linear. For 1 kg of potassium balance the content of K in 0-40 cm soil layer increases or decreases by 0,41 kg K ha^{-1}.

(3) The residual effect of potassium fertilizers applied annually for 6 years is evident at least for a further 6 years.

Hypothetical Potassium Balance Sheet for Total Area under Principal Arable Crops in Romania 1990

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Introduction

Until recently, a potassium balance sheet (KBS) for Romanian agriculture was thought to be of academic interest only because long-term field trials showed a lack of response to K fertilizer at the low to moderate yields obtained, except on some limed Luvisols in submontane depressions in the north-western parts of the country.

It was thought that the soils contained sufficient available K to support current crop yields and that therefore a temporary negative KBS would not prejudice crop yield or soil fertility. Further, the crop price/fertilizer cost ratio was not favourable.

Agronomists and soil scientists had difficulty in establishing a KBS for lack of adequate data on some input and output items.

In spite of the difficulties (some of which are due to changes since 1989 in land ownership, planning and crop production statistics), we have attempted to draw up for 1990 a KBS for the chief arable crops.

Data for the balance sheet

Inputs-*alternatively K supplies to crops*

Soil. To the unfertilized crop assumed to be up to 80% from the plough layer (SK) and less than 20% from immediate subsoil (SSK) (not evaluated) depending on rooting pattern, profile characteristics, texture and compaction. These items will not appear in the balance sheet which describes changes in K stocks in the soil.

Fertilizer. See Table 1. K in straight and compound fertilizers (KF) applied at economically justified rates for relevant target yield and soil test data.

Current official guidance is that all fertilizers, including K, should be applied at economically justified rates, ensuring maximum profit.

Manures. See Table 2. Farmyard manures (FYM) from animal husbandry assumed to contain 2-16 kg t^{-1} K_2O (Borlan *et al.*, 1983) depending on species and management.

Rainfall (RW). 3-19 kg ha^{-1} yr^{-1} K_2O, the higher values applying near industrial centres and in the hills (Vlad and Florea, 1984).

Irrigation (IW). Danube water averages 3.7 mg l^{-1} K_2O and other rivers up to 9 mg l^{-1} (Grigorescu and Florea, 1977).

Crop residues (CR) returned to the soil.

Atmosphere (D). Terrestrial and cosmic dusts estimated to contribute 0.5-5 kg ha^{-1} yr^{-1}.

Seed. This, estimated at a total of about 10 t K_2O for the whole area is not worth considering.

Outputs-*alternatively K removed by crops and losses*

In crops made up of K in marketed produce (grain, tubers, etc.) (KPY) and that in residues (straw, tops, etc.) (KSY) (Potash Export Co., Vienna, 1989).

Leaching (L) in range 5-26 kg ha^{-1} yr^{-1} K_2O (Chisci and Spalacci, 1984).

Runoff/erosion (R)

Town refuse (KTR) not used on farms totalling approx. 4600 t yr^{-1} K_2O.

Humans (KHE) losses in town sewage 12800 to 38500 t yr^{-1} K_2O for a town population of 14 million.

The two last items, do not enter into the overall balance, being included in crop removals.

The K balance sheet

for the main arable crops is then made up from :

INPUTS	-	OUTPUTS
KF+FYM+RW+IW+D		KPY+KSY+L+R

The amounts of K_2O involved are given in Table 3.

The overall K balance as based on application of fertilizer at recommended rates for 1990 was negative to the tune of about 20 kg ha^{-1} K_2O. In fact the deficit is greater since fertilizers are not always applied at recommended rates and farmyard manure is not used. Even the recommended rates would not compensate for K removed in crops.

An appreciable part of the negative balance is due to failure to return crop residues (which account for 2/3 of total crop K uptake) to the land (straw, stems, etc. used in paper mills and as animal fodder). There is also poor recovery from animal wastes (especially liquid) on intensive livestock units using imported feeds. Available supplies of FYM could cover 39% of the K output.

Consumption of K fertilizers has risen from 4.3 kg ha^{-1} K_2O in 1972 (FAO, 1988) to 27.7 kg ha^{-1} in 1990 but this has made only a minor contribution to improving the K balance.

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Table 1. Consumption of K in main agricultural crops considering the yields officially recorded in 1990.

CROP	Planted area (1000 ha)	Average yields (t ha^{-1})	Recommended economically sound rates of K_2O (kg ha^{-1} K_2O)	Total recommended requirement of K_2O from fertilizers (1000 t K_2O)	Specific consumption of main and secondary product (kg t^{-1} K_2O)	OUTPUT (1000 t K_2O)	
						Total export (KPY+KSY)	Export with secondary product
Wheat	2300	3.50	26.1	60.0	29	233.45	155.47
Barley	900	3.75	27.2	24.5	30	101.25	65.81
Maize	2900	4.50	38.6	112.2	20	261.00	195.75
Sunflower	500	1.50	8.7	4.4	80	60.00	46.80
Soybean	600	1.50	10.3	6.2	57	51.30	21.64
Sugar beet	260	20.00	15.5	4.0	6.6	34.32	12.69
Potato	350	17.50	13.8	4.9	7.7	47.16	17.68
Total	7810			216.2		788.48	515.84

Table 2. Potassium contained in animal wastes and manures (results from state owned farms, 1990).

Animal species	Number of heads (1000)	Specific content (kg t^{-1} K_2O)		Total amount (1000 t)		Total K_2O in manures (1000 t)
		Solid manure	Liquid waste	FYM	Liquid waste	
Ruminants, cattle	5939	5	16	41573	4395	278.18
Small ruminants	2450	6	-	1225	49	7.35
Horses	523	5	12.5	2615	278	16.55
Pigs	18000	4.5	2	7200	720	41.40
TOTAL						343.48

Table 3. Evaluated theoretical simplified KBS for 7,810 thousands ha of arable land under main field crops in 1990.

Inputs	1000 t K_2O	Outputs	1000 t K_2O
Recommended mineral fertilizers	216.20	with overall yield (KPY+KSY)	788.48
Animal manures	343.48	losses with infiltration water (L+R)	54.67
Rainfall (mean 7.59 kg K_2O ha^{-1})	59.30		
Irrigation water (mean 18 kg ha^{-1} K_2O yr^{-1} on 3100 .10^3 ha)	55.80		
Fallout of dust (2 kg ha^{-1} yr^{-1} K_2O)	15.60		
TOTAL	690.38		843.15

Output - input = 152.77 thousands tons of K_2O with a deficit of 19.6 kg ha^{-1} yr^{-1} K_2O.

Potassium Balance in a Crop Rotation Experiment over 18 Years

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Introduction

A widely held opinion (Cooke, 1984; Lamm and Nafady, 1973) suggests that on well buffered soils it is convenient, and as efficient, to apply heavy maintenance K dressings at intervals rather than the equivalent in small dressings to all the crops of a rotation. This opinion has been tested in the experiment described here. An earlier report (Stanchev *et al.*, 1976) dealt with P and K reserve fertilization.

Experimental results

The chief results from a long-term experiment on a slightly saline meadow soil (pH 7.2, organic matter 3.1%, total K 2.4%) are given in Tables 1 and 2, which also show the K fertilizer treatments applied. The object was to study the effect of 600 kg ha^{-1} K_2O per 6-year rotation applied either crop specifically to the 6 crops or all to the maize against a control treatment receiving no K. 3 additional treatments with 600 kg ha^{-1} K_2O also received FYM, wheat straw or pea haulm. Nitrogen and phosphate was applied uniformly at 600 kg ha^{-1} N and 400 kg ha^{-1} P_2O_5 per 6 years. Three cycles were completed (18 years).

The pattern of response to treatments (Table 1) was essentially similar as between the 1st, 2nd and 3rd rotations, hence the mean yields over the 3 rotations only are given. However it may be noted that maize yielded much higher in the third rotation (8.4 t ha^{-1} vs 5.0 on control; 11.0 vs 8.7 on K-treated) due to change to selected Bulgarian and imported types. All crops reacted strongly to K fertilizer. The response was less when all the K was applied to maize except for maize in the 2nd cycle when there was a difference of 0.4 t/ha in favour of all to maize. Except in the 1st cycle when treatment 4 on maize outyielded treatment 3 (by 0.5 t ha^{-1}) there was no additional response to K applied at over 600 kg ha^{-1}. This was probably due both to the moderate yield potential and to the modest NP fertilizer rate.

Except for treatment 4 (900 kg ha^{-1} K_2O) the K balance was negative and the levels of 2N HCl extractable K declined slightly with time on all treatments confirming Milcheva and Nikolova's (1980) observations on chernozem soils and smolnetz.

K fertilizer efficiency

The percentage utilisation of applied K calculated by the difference method by all crops over the 18 year period was as illustrated in Figure 1. It is to be noted that sharing the total K applied between all crops gave higher efficiency (compare treatment 2 with those where all the K was given to maize).

Table 1. Crop yield (t ha^{-1}) from a 6 year rotation receiving different rates of K fertilizer applied in different ways. Mean of 3 rotations (1967-1989).

Treatment	1	2	3	4	5	6	7
kg ha^{-1} K_2O applied:							
Maize	0	100	600	600	600	600	600
Other crops	0	500	0	300	0	0	0
FYM (t ha^{-1})	-	-	-	-	30	-	-
Wheat straw (t ha^{-1})	-	-	-	-	-	4	-
Pea haulm (t ha^{-1})	-	-	-	-	-	-	2[a]
Total K_2O	0	600	600	900	600[b]	600[b]	600[b]
	t ha^{-1}						
Maize	6.8	10.1	9.8	9.6	8.8	10.0	9.3
Wheat	1.6	4.9	4.7	4.5	4.6	4.9	4.3
Oat & tare hay	3.1	5.4	5.2	5.6	5.4	5.3	5.0
Wheat	1.9	3.7	3.7	4.0	3.8	3.9	3.7
Maize	6.6	10.1	9.6	9.8	9.7	9.6	9.2
Barley	1.3	3.5	3.2	3.3	3.2	2.9	2.7

[a] Dry matter

[b] + K_2O in FYM, straw or pea haulm.

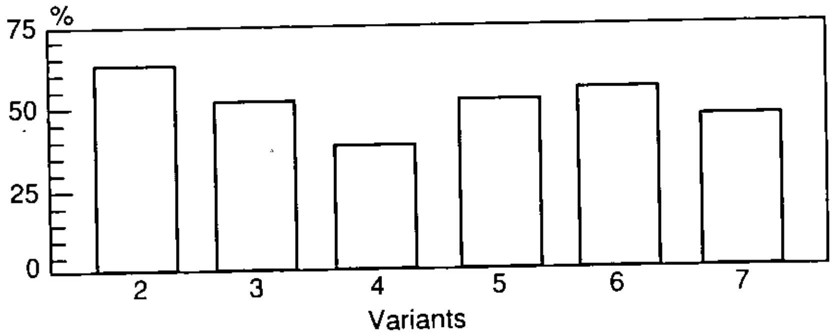

Fig. 1. Coefficient of K utilisation by crops (total for the 3 rotations).

Table 2. 2N HCl extractable K (mg/100g) in soil after 1st and 2nd rotations with (in parentheses) K balance (kg ha^{-1} K_2O).

Treatment	End of 6 years	End of 12 years	End of 18 years
1	51 (-379)	41 (-831)	na (-1328)
2	52 (-179)	45 (-444)	na (-655)
3	51 (-167)	44 (-325)	na (-448)
4	52 (+113)	44 (+223)	na (+662)
5	49 (-111)	46 (-299)	na (-455)
6	49 (-157)	41 (-343)	na (-520)
7	46 (-110)	41 (-225)	na (-355)

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Towards Unity and Clarity in European Soil Testing

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Introduction

In the Netherlands, estimates of plant-available K are traditionally obtained by extracting soils with 0.1 M HCl. Extensive field experimentation with various crops made it clear, however, that a unit quantity of HCl-extractable K is worth less in terms of plant-available K, the higher the CEC of the soil is. Consequently, the clay contents and/or the organic matter contents of heavy-textured soils and sandy soils are taken into account for correcting HCl-extractable K into plant-available K. Presently, efforts are made to simplify Dutch soil-testing procedures. A 0.01M $CaCl_2$ solution is tested for use as a universal extracting agent, encompassing all nutrients. In Czechoslovakia, the Mehlich extracting solution is used as universal extracting agent.

Experimental

Recently, H. Horakova (Dept. of Agrochemistry and Plant Nutrition, Prague Agric. Univ.) determined extractable K in Czechoslovakian soils from three experimental sites with:

a. the Mehlich extraction procedure

b. 0.01 M $CaCl_2$ as extracting agent

(work conducted at the Dept. of Soil Science and Plant Nutrition, Agric. Univ. Wageningen, The Netherlands).

Some results are shown in Fig. 1, in which the relative yields of maize are plotted against Mehlich method-extractable soil K. There appears to be a relation for the Časlav and Viglas soils, but not for the relatively heavy-textured Pohorelice soil.

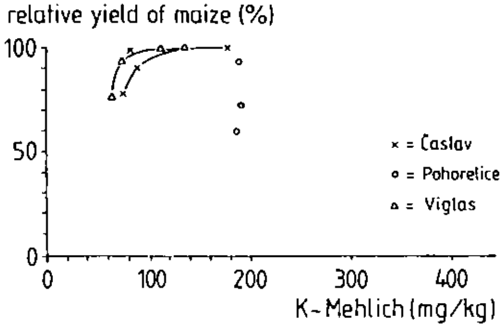

Fig. 1. Relative maize yields plotted against Mehlich-extractable soil K.

In Fig. 2, the relative maize yields are plotted against 0.01 M $CaCl_2$-extractable K. For all soils, including the Pohorelice soils, the relation appears satisfactory. However, maximum maize yield were reached at levels of extractable K which differed rather widely for the three soil types.

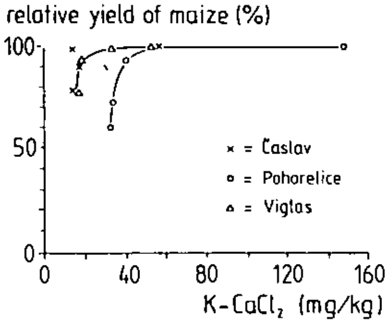

Fig. 2. Relative maize yields plotted against $CaCl_2$-extractable soil K.

It is presumed that differences in the size of the exchange complexes of the three soil types involved may be responsible for the discrepancy in optimal values of extractable soil K. In Fig. 3, the relative maize yields are, therefore, plotted against the percentages of the exchange complexes occupied by $CaCl_2$-extractable K. The values thus obtained are called K-index values, calculated as follows :

$$K-index=\frac{mg\,CaCl_2-extractable K\,kg^{-1}soil/390}{CEC(cmol(+)kg^{-1}soil)}$$

(CEC determined according to Gillman (1979) at the actual soil pH; the values found were for the Časlav soil 15, the Viglas soil 11 and for the Pohorelice soil 21 cmol (+) kg^{-1} soil).

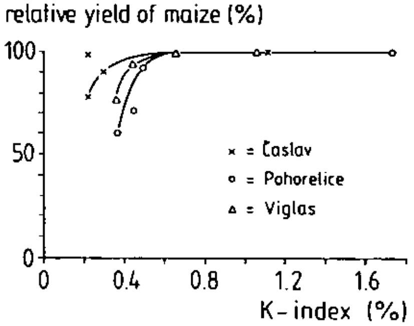

Fig. 3. Relative maize yields plotted against K-index values.

The K-index value gives an impression of the relative saturation of the exchange complex with K. It can be observed that for all three soil types a K-saturation percentage of 0.6 can give rise to maximum maize yields.

Conclusions

1. 0.01 M $CaCl_2$ appears to be a suitable extracting solution for providing estimates of plant-available soil K.
2. Expressing $CaCl_2$-extractable K as a percentage of total CEC provides a means of making valid recommendation for K-fertilizer use, irrespective of differences in soil texture.
3. The lower the percentage saturation of an exchange complex with K, the higher is the quantity of K occupying K-specific exchange sites from which it is not easily released for uptake by plants.

2. Ecological Aspects of Potassium Use

Effects of K and Mg Fertilizers in Forests on Soils Previously Used for Agriculture

Uebel, E.[*], Agric. Extension Service, MdK, Erfurt, Germany *and Chrzon, S.*, Research Institution of Forestry, Eberswalde, Germany

Introduction

Extensive farming leads to increased K and Mg deficiency in the northeastern German Lowlands. Various effects of K and Mg fertilizing have been tested.

Material and methods

Fertilizer experiments have been carried out in the northeastern German Lowlands for many years in forests on acid sandy soils of low exchange capacity and low in organic matter, developed on glacial sand. These soils have been degraded by extensive farming and the water-table is higher than average.

Results

Seedling and thicket stage (pine and other trees)

K-Mg fertilizer applied as easily soluble neutral salt in simple doses of 60-120 kg ha^{-1} K_2O and 40-80 kg ha^{-1} MgO leads to :

- rapid improvement in nutritional conditions,
- improved tree survival,
- improved tree growth (Figure 1),
- more intensive rooting (Figure 2),
- better development of mycorrhiza,
- less pest infestation,
- improved frost and drought resistance.

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[*] Member of the "Society for promotion of ecologically controlled fertilizer application" (VFD), Erfurt, Germany.

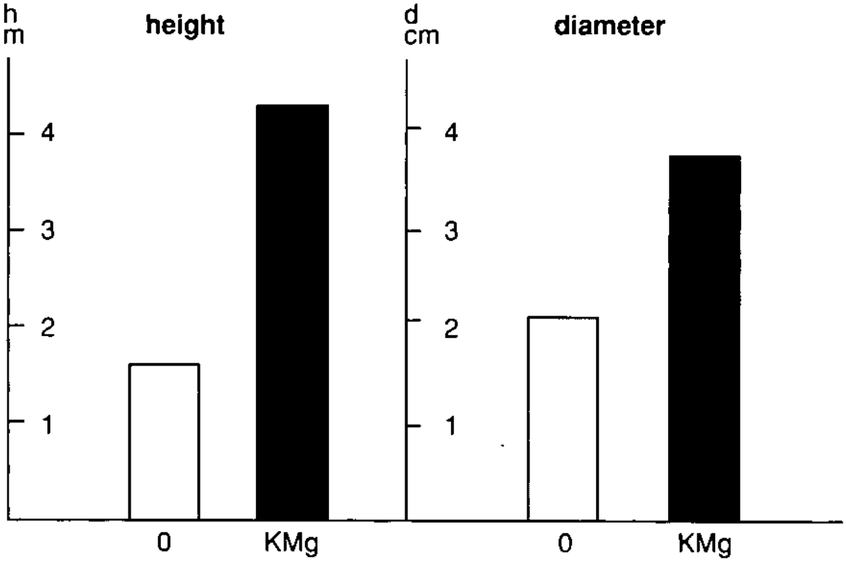


Fig. 1. Effect of KMg-fertilizer on height and diameter of 12 year old pines.

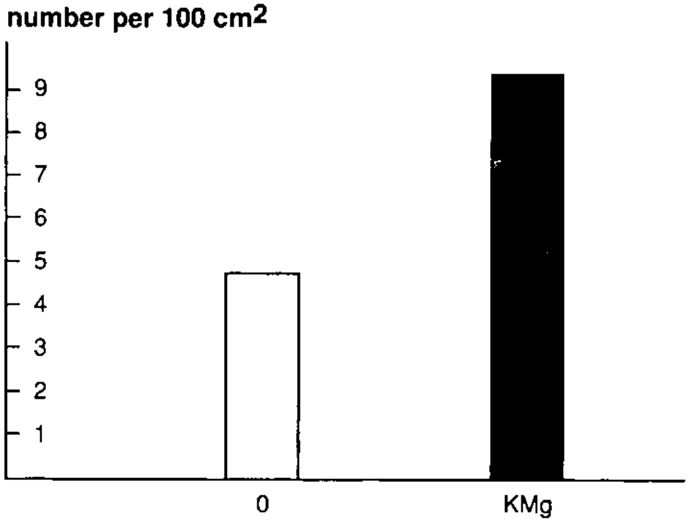
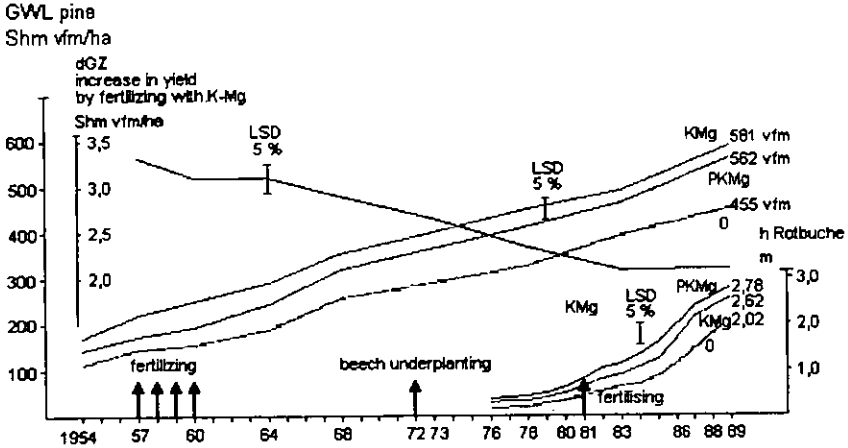


Fig. 2. Number of roots per 100 cm^2 at depth of 0 to 60 cm (pine, age 18 years).

Pole wood stage (pine)

When the effects of initial K-Mg fertilization wear off, additional freshly applied K-Mg of 90-180 and 60-100 kg ha^{-1} K_2O and MgO respectively result in :

- higher K and Mg contents in the trees,
- higher rate of growth (Figure 3),
- better rooting,
- improved health (Figure 4),
- increased accumulation and improved elaboration of soil organic matter,
- better humus quality.



GWL: total volume production.

Shm vfm: trunk wood, solid cubic meter of standing crop per hectare.

dGZ: mean annual increment.

Fig. 3. Effect of P-K-Mg fertilizer on yield of pine and height of beech.

Timber stage (pine)

With higher nitrogen inputs from the atmosphere, nutrient imbalance increases. Applying of K-Mg at this stage results in :

- a tendency to improved growth,
- improved tree health,
- increased metabolic incorporation of deposited N.

If beech is underplanted at this stage, a further application of 120 kg ha^{-1} K_2O and 60 kg ha^{-1} MgO is absolutely necessary. The following effects were observed :

- improved nutritional conditions,
- improved tree survival,
- increased growth (Figure 3).

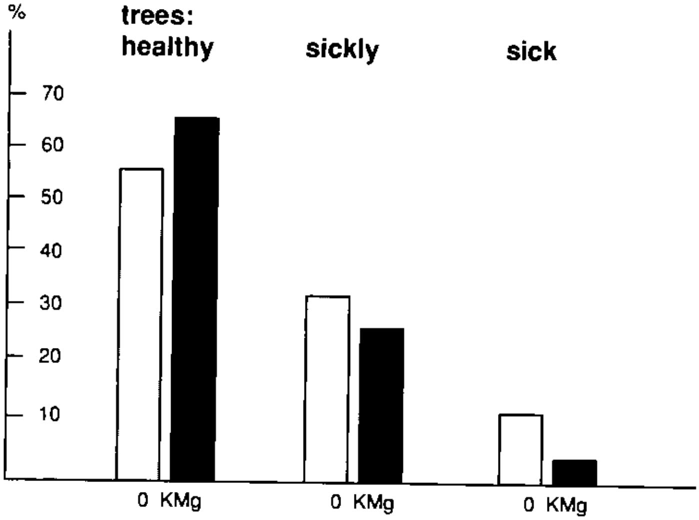


Fig. 4. Proportion of healthy, sickly and sick trees.

Conclusion

K-Mg fertilizer applied to trees on degraded sandy soils improves plant nutrition, resulting in growth and vitality and affects the whole ecosystem in various ways. Increased N from the atmosphere causes nutrient imbalance which can be corrected by applying K-Mg. Applying K-Mg improves forest stability meeting requirements for management of the environment.

Non-Traditional Use of Potash Salts

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Summary

Unique properties of potash salts are used in various branches of national economy. Production Association "Uralkali" carries on researches in directions :

- non-medical treatment of patients with non-specific chronic lung diseases and some allergic diseases.
- organisation of effective storing of perishables.
- speleoagroindustrial production of ecologically pure food-stuffs.

Underground speleohospital

Since 1977, Underground speleohospital operates in Berezniki Mine 1.

Table 1. Number of patients treated.

Years	1980-84	1985-90	1991	1992
Number	1763	2335	402	208

Table 2. Indices of the effectiveness of treatment.

Disease	% of recovery
Bronchial asthma :	
Slight severity	78
Medium severity	57.6
Asthmatic bronchitis	86.9

Surface speleohospital

In 1992, surface speleohospital for children was put into operation.

Table 3. Characteristics of air in speleohospital (8 hour period).

Light aero-ions	800-1200 e/m^3
Micro-organisms, not more than	550-800 e/m^3
Volume activity of DPR Rn	0.025 x 10^{10} meq/m^3
Content of anthropotoxins	0.01 vol %

Vegetable store-house

To decrease the losses of agricultural products when storing potash spray is used.

Table 4. Indices of storing of potato in surface store (amount of potato diseases).

Variant	Disease %				
	Dry rot	Wet rot	Phytoptora	Total	Relative to contr.
Standard storage	6.2	5.1	1.8	13.1	100
Potash spray	5.6	0.7	0.9	7.2	54.9

Table 5. Indices of crop capacity of potato after its storing with potash spray.

Variant	Number of blooming plants	Number of stems	Lenght stems cm	Yield t ha^{-1}
Standard storage	24.0	3.1	54.8	26.1
Potash spray	33.6	4.2	57.2	29.37

Salt spray decreases the vital activity of micro-organisms, creates better conditions for safe keeping of juicy products.

Rational Use of K Fertilizers in Central Russia

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Present K fertilizer usage

K fertilizer consumption has decreased over the past 4 years, the forecast for 1993 being only 2.5 million t, equivalent to about 20 kg ha^{-1} K_2O. Sandy, easily leached soils predominate and very large areas are under K-demanding crops (potato, vegetables, fodder roots, sugar beet, flax) requiring at least 50-60 kg ha^{-1} K_2O. Clearly much arable land receives no K fertilizer. We should be able to define rates of K fertilizer to supply at least the minimum K requirements of crops and which will give maximum efficiency.

Experimental results

Table 1 indicates the risk involved in underestimating the need for K fertilizer : while the effect of K in the first year was small in comparison with that of N, by the 4th year it is of the same order and later it is greater.

Table 1. Effect of N, P and K on potato yield (t ha^{-1}) on loam soddy podzol (80 ppm exchangeable K_2O).

		Year 1	Year 3	Year 4	Year 9	Average
No fert.		19.7	17.7	10.7	13.5	15.4
Effect of	N	+8.6	+6.8	+2.3	+6.1	+6.0
"	P	-0.8	+1.6	+2.6	+4.2	+1.9
"	K	+1.2	+1.5	+2.5	+7.1	+3.1
NPK		31.8	27.5	15.1	24.6	25.0

Similar results were obtained in a long-term experiment with a test of K fertilizer applied over ten years followed by test of residual effects over the next 10 years during which no K was applied. In the first period, for every 100 kg of fertilizer K_2O not taken up by crops exchangeable K_2O in surface soil increased by 7.2, 15.4 and 11.1 ppm respectively for rates of 60, 90 and 144 kg ha^{-1} K_2O applied. Every 100 kg ha^{-1} K_2O taken up by crop in the

2nd (residual test) phase decreased exchangeable K_2O by 23.5, 40.9 and 35.0 ppm. Thus depletion in K_2O had a greater effect than accretion.

In another experiment the returns from N fertilizer were on soils of different K status as shown in Table 2.

Table 2. Relative yield (69 ppm exch. K_2O = 100) of total crop fresh matter per unit N applied.

	69 ppm exch. K_2O	180 ppm exch. K_2O
Maize	100	130
Potato	100	app. 200
Oats	100	134

Recommendations

Clearly in order to sustain productivity it is necessary to maintain soil K at an adequate level to ensure efficiency of the other nutrients.

Other benefits of so doing include :

1. Improved efficiency of liming on acid soils;
2. Improved tolerance of pest and disease with economy in agrochemicals;
3. Improved drought resistance (errors in irrigation) and toleration of inappropriate sowing date;
4. Decreased uptake of heavy metals. Recent work showed that uptake of ^{137}Cs was decreased by a heavy dressing of K fertilizer (180-200 kg ha^{-1} K_2O) by 2.5 - 7,3 - 10 and 3 - 4.5 times in arable crops, grass and woody plants respectively.

However, some long-term trials have shown that on soils well supplied with K, yields may be sustained for quite a time although the K balance may be negative. Present economic circumstances in Russia suggest that there should be economy in K fertilizer usage. We have therefore tried to assess to what extent usual K fertilizer recommendations might be reduced without prejudicing crop performance. The permissible reduction depends on target yield, soil K content, K saturation and clay content. Our suggestions for permissible reduction in K application below crop K removal are listed in Table 3.

Table 3. Examples of permissible deviations from normal maintenance* K dressings applied to the rotation on soils of different properties (kg ha^{-1} K_2O).

Target yield (t ha^{-1} grain equiv.) :		<3			3-5			>5		
Clay content		<20	20-40	>40	<20	20-40	>40	<20	20-40	>40
ppm exch. K_2O	% K satn.	kg ha^{-1} K_2O								
50-100	<2	5	-10	-10	0	-5	-10	+5	0	-5
(Low)	2-4	-5	-10	-15	0	-5	-10	+5	0	-5
	>4	-10	-15	-20	-5	-10	-15	0	-5	10
150-200	<2	-15	-20	-25	-10	-20	-20	-5	-15	-20
(High)	2-4	-15	-25	-30	-10	-20	-25	-5	-10	-20
	>4	-20	-25	-35	-15	-25	-30	-10	-20	-25

* Maintenance = replacement of K removed by crops in the rotation.

K Balance and K Fertilization in Extensive Grassland Utilisation on Peat Soils

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Introduction

Peatlands in Germany are often managed extensively. In order to avoid over- or under-supply with potassium, account must be taken of the special properties of these soils (high organic matter content, poor adsorption of cations, etc.) in considering the K balance and K fertilizer requirement.

The data

The peaty layer on the experimental area was 0.8 m thick and the water table in the growing season was at a depth of from 50 to 80 cm. Summer (April to September) rainfall was 318 mm. A long-term (30 year) experiment investigated the effect of a uniform dressing of 126 kg ha^{-1} K (152 kg K_2O) on K content of herbage and soil (Kreil, Käding and Leipnitz, 1992). Other short term experiments (3-5 years) using varying rates of K fertilizer were also taken into account. Leaching of K was studied in lysimeters (Mundel, 1990) and field experiments.

Results

K balance

Results from several experiments were used to set up the K balance. High rates of K fertilizer raised herbage and soil K contents while high rates of N fertilizer reduced them due to the increased biomass production and consequent increased nutrient uptake. Figure 1 shows the additions and removals of K in herbage and estimated leaching losses for a cut sward (3 cuts per year). At a constant rate of K fertilizer K removal declined as the rate of N fertilizer was reduced and K leaching increased from 5 to 20 kg ha^{-1} K. At a yield of 7.5 t ha^{-1} dry matter about 165 kg ha^{-1} K as fertilizer is required to replace removals.

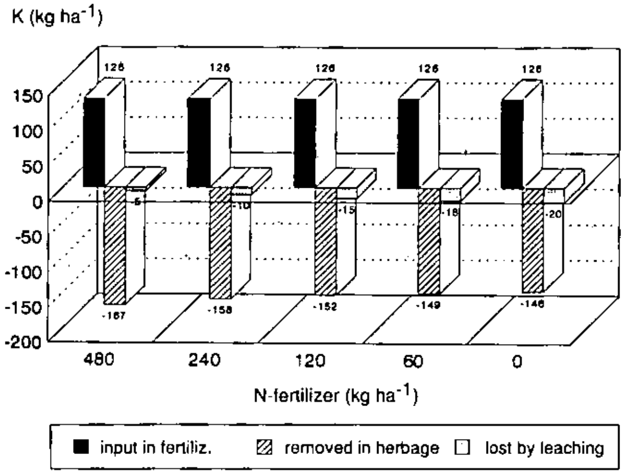

Fig. 1. K-balance under cut grass.

Under grazing, input and removal of K was determined by intensity of management (Figure 2). The negative K balance was much lower under grazing since most of the K removed in herbage returned to the soil in droppings. The higher the grazing intensity, the more K was removed but a great deal of this was returned in droppings, part of which entered the groundwater.

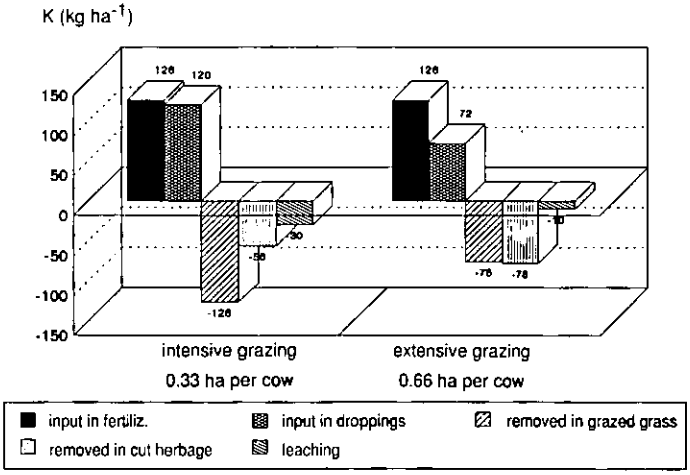

Fig. 2. K balance under grazing + cutting.

K fertilization

Ecologically appropriate K fertilization is based upon knowledge of the nutrient cycle, crop uptake and release of K from the soil. The annual K requirement is determined mainly by the yield level, method of herbage utilisation and K status of the soil (Table 1). Much less K fertilizer is needed under grazing than when all the grass is cut. Account must also be taken of the utilisation of manures (slurry).

Table 1. K fertilizer recommendations for grassland on peat soils with medium available K.

	kg ha^{-1} K (K_2O)	
t ha^{-1} dry matter	Cut	Grazed
3 - 5	85 (102)	35 (42)
5 - 7	125 (151)	50 (60)
7 - 9	170 (205)	70 (84)
> 9	200 (241)	80 (96)

Lower K soils (Class A) require a supplement of 25 kg ha^{-1} K (30 kg K_2O) while on very high K soils (Class E) the dressings should be reduced by 50% below those given in the table (Käding, 1991). In a dairy enterprise on these soils, ecological considerations demand that K fertilizer should be applied shortly before the spring flush. It is preferable to use farmyard manures on arable land where the need for organic matter is greater. Should it be necessary to apply manure to grassland, this should be done during the growing season. If the grassland is not utilised, normal fertilizer treatment should be suspended.

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Coordinator's Report on Poster Session

Beringer, H., Huensche Burg 10, 3520 Hofgeismar, Germany

The posters presented at this colloquium can be viewed from various angles :

- an ecological point of view where we ask "what are the functions and the needs for potassium and its inorganic salts in agriculture, horticulture, forestry and medicine ?"
- a planning aspect, where the problem prevails "what is the K-fertilizer balance at the field-, farm-, regional or national level, how can this balance be improved by better fertilizer distribution, by modifying the cropping system, by producing/importing more fertilizer ?"
- a scientific approach, where the main question is how the reserve of plant-available K in soils and the needs for K-fertilizer can best be determined, which improvements in methodology do exist ?

Whatever approach is chosen a quotation from Justus von Liebig (1855) should be the general guideline to all concerned about the ecosystem, to the farmer and his advisor as well as to the ecologist and policy-maker in environmental issues.

"Recycle to the soil exactly the nutrients which you have taken from it, neither more nor less. But if the land should become more fertile the question is different."

To make this clear and to reemphasize the need for unity and clarity in our scientific terminology some principles must be recalled :

- Plant roots absorb their nutrients from the soil solution. As far as potassium is concerned clay minerals and organic colloids release potassium ions rather easily from their surface charges (exchangeable potassium), but less easily or hardly at all from their interlattice positions (non-exchangeable potassium).
- If plants are to produce maximum yield they need a certain potassium concentration in the soil solution. Should they have to rely only on the admittedly large, but only slowly available potassium reserves, growth would be limited by an insufficient rate of potassium release.
- In achieving the required flux of K^+ ions towards the root the interrelationship between the quantity of available potassium and soil

moisture has to be borne in mind. Good growth can be achieved either by optimising soil moisture at a relatively low K concentration in the soil solution or when moisture is lacking by establishing higher levels of available potassium i.e. higher concentration gradients through fertilizers. Threshold levels of potassium availability can thus be defined only by taking into account clay content and the moisture regime in the rooted soil profile.

The easiest approach to an evaluation of the needs for K-fertilizers from a planning point of view is the calculation of K-balance sheets in the sense of Liebig's quotation above. Though simple and quick, such balance sheets have the disadvantage of generalizing where more differentiation would be appropriate as to the exactness of the various input/output parameters as well as to the status of soil in available nutrients on which the balance is established.

National and international nutrient balances are generally calculated by referring to statistical yearbooks giving crop area and crop yield and by assuming an average quantity of nutrient required to produce a unit of biomass. In doing so, Bogaci and Borlan, Nikolova and Vostal have calculated negative K-balances for Romania, Bulgaria and Czechoslovakia respectively, while others have presented data from long-term fertilizer experiments under different ecological and agronomic conditions (Fotyma and Czuba, Gorbanov *et al.*, Käding *et al.*, Prokoshev and Sarvari). Although these balances may have been positive in previous decades thus improving the status of K-availability, the present economic problems, especially in countries moving from centrally-planned state-farms to market-oriented private farm enterprises compel the farmers to set strong priorities in spending their limited financial resources. It is, therefore, understandable when Prokoshev tried to find the minimum level of available K down to which soils could be exhausted and to find as well the least required quantity of K-fertilizer. Though thanks to the buffering capacity of soils for P and K the application of P- and K- fertilizers can be suspended for some years, regular soil tests and yield records are essential to detect the time when crop growth will become limited by insufficient K supply. Ecologically, however, the quotation of Liebig cited above should at least be borne in mind and even be stressed where soil fertility and food production have to be raised which in most countries is still the major moral objective in crop production.

Consequently soil chemists worldwide try to define the quantity and rate of K-availability required for high yields of the various crops growing in a range of soils differing in pedogenesis and texture. Although each soil or location has its individuality groupings and generalisations are necessary.

The influence of clay content and type of clay mineral on K-availability has been reemphasized by Schneider and Villemin. In soils with <2% organic matter clay minerals more or less represent the cation exchange capacity, of which in humid, temperate regions approximately 2-4% should be saturated with K^+ ions in order to achieve K-concentrations in the soil solution between 0.05 and 0.5 mM K required for high-yielding crops. This degree of K-saturation can be lower when - as van Diest *et al.* have shown - instead of 1 M NH_4-acetate only 0.01 M $CaCl_2$ is used as an extractant with the advantage that also available nitrogen can be analysed in the soil extract.

The higher the clay content and the proportion of 2:1 clay minerals in the soil the stronger is, on one hand, the adsorption (fixation) of K, but the greater are, on the other hand, the reserves of exchangeable and non-exchangeable K in the soil. Due to the competition between clay particles and plant roots for easily available K^+ soils with higher clay content need a higher level of available K/100 g soil to satisfy the K-requirement of a crop in quantity and rate as shown also in the posters by Fotyma and Czuba and by Richter and Kerschberger. Such soils, however, also have a greater K-buffer capacity whose contribution to the actual K-nutrition has long attracted attention of soil chemists, a point to which will be referred later.

Equally interesting to the researcher as well as to the ecologist is the question as to the most appropriate method for estimating K-fertilizer efficiency. Fotyma and Czuba and Richter and Kerschberger have presented data from long-term experiments. Both groups arrive at the same conclusion: annual dressings of 140-150 kg ha^{-1} K_2O are the maintenance rate if all above-ground crop is removed from the field. By using the difference method for calculating fertilizer efficiency, Fotyma and Czuba and similarly Gorbanov *et al.*, however, conclude that with increasing rates of K-fertilizer only 65 to 27% of this fertilizer are utilised by the crop. Richter and Kerschberger, on the other hand, recommend to determine how yield response is affected by the K-fertilizer balance. By doing so, they can derive the economic annual K-balance, the optimal K-fertilizer rate and finally, by comparing K-uptake at the optimal yield level with the optimal K-fertilizer rate, they can define the so-called balance coefficient as a measure of the K-fertilizer efficiency. This is usually close to 100%. Although, definitely, not all fertilizer-K will be taken up in the year of application this method of calculation of fertilizer efficiency seems to be more ecological than the assumption (in the difference method) that plants growing at different rates of K-fertilizer absorb the same basic quantity of soil-K as the plants in the unfertilized treatment. In conclusion, neither method mirrors the real K-fertilizer efficiency and therefore the range of optimal K-availability in soil is still rather wide as demonstrated for loam soils by Richter and Kerschberger.

Why are low levels of exchangeable K sufficient for optimal plant growth in some soils, while in others higher levels are required ? This question about K-buffer capacity, about K-fluxes in dependence of clay content and the soil moisture regime has again challenged some poster-authors. In addition to the well-known, though complex, intensity/quantity relationships and potential buffer capacity of soils for K published by Beckett (1970), Karpinets has presented a new, simpler analytical approach to this problem. She recommends to extract a soil twice with NH_4-acetate. The first extraction gives the content of exchangeable K (K_0) and the second extraction after drying the soil again yields some additional K (K_1). She defines the K-buffer capacity as

$$B = (K_0 - K_1)/K_0$$

Assuming the second extraction (K_1) gives the same quantity as the first one K-buffering is very high (B=0). In her data for 20 chernozems the B value correlated with barley yield with r=0.57, which, however, was not better than after only one extraction with ammonium acetate. The explanation for this rather unexpected result may be the high K-availability in the soils investigated and their high organic matter content as well as other site specific factors.

Such site specific parameters as geological parent material, pedogenesis and soil type, topography, rainfall, temperature, etc. can now all be put together and integrated in what is called a geographical information system. Orlovius and Andres have impressively demonstrated the ecological orientation as well as the economic benefits of such new approaches in fertilizer advice. It is sincerely hoped that such ideas will be taken up and improved by many other institutions in order to extricate fertilizer recommendations from empirism and tradition.

As far as horticulture and the type of K-fertilizer is concerned, Loch and Pethö have provided evidence for K_2SO_4 being superior to KCl in some vegetables. Interestingly fruit set and harvests were slightly accelerated, while in the KCl-treatments the period of shoot growth was obviously slightly extended.

Better scientific understanding of non-agricultural ecosystems would also be highly desirable. There are several indications that forests are not only suffering from acid rain, pollutants and/or pests and diseases, but also from absolute and/or induced nutrient deficiencies. Most susceptible to the latter are forests on sandy soils with low nutrient and moisture retention as well as low pH, especially when such forests occur in areas with livestock intensity i.e. N-imissions of >40 kg ha^{-1} N. Uebel and Chrzon have provided long-term experimental evidence for the positive effects of K- and Mg-fertilizers on growth, health and yield of trees and their undercrown vegetation. As forests and their soils have vital functions for our climate, as they are essential for the protection of landscapes against erosion and as they are indispensable as filters of air and drinking water, no ecosystem should be harvested without returning the inorganic nutrients essential for its regeneration and sustainability.

At the 22nd IPI colloquium in Soligorsk, Scharf (1990) discussed the environmental aspects in the production and handling of K-fertilizers. This time an interesting poster was presented by Papulov, showing the use of salts and mines in the therapy of bronchial asthma, in the purification of air as well as in the protection of perishable vegetables and planting material. Because in industrialised countries more and more allergies are reported it will be interesting to pursue further development in this field.

"Potassium in ecosystems" is the general topic of this colloquium. For the evaluation of the problems associated with this theme there are a number of scientific criteria : we have long-term experience in soil-testing for plant available potassium, we know the critical levels for minerals in leaf/needle analysis and for K-concentration in waters for human consumption. The known threshold levels provide good guidelines, but have, however, to be modified according to geology, type of soil and landscape as well as according to the targets of the respective ecosystem and the intensity of its utilisation. Let us hope that all people will integrate their specialized knowledge into the important holistic consideration of ecosystems, their use and their sustainability.