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IPI 60 Anniversary Issue

INTERNATIONAL
POTASH INSTITUTE
60 ANNIVERSARY 1952 2012
Optimizing Crop Nutrition

Editorial

Dear readers,

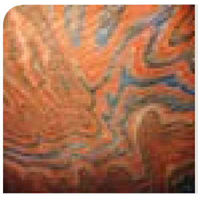
The International Potash Institute (IPI) is celebrating its 60th anniversary (1952-2012). For many decades, our agronomists and soil scientists have carried the message of "Balanced Fertilization", demonstrating and disseminating the role of potash in yield performance and quality, in stress tolerance, and in bringing greater value to the farmer. In this *e-ifc* edition, to mark the development and evolution of IPI over the years, we asked IPI members to share their views with our readers on IPI's vision and objectives.

This special IPI 60 issue highlights content from three regions which are of global importance to food production and brings a review on the molecular biology related to K^+ transport. The development of potash fertilization in China has no doubt contributed to the country's ability to significantly improve its agricultural production and food security. The science related to potash fertilization in Chinese soils is now well established. On the other side of the globe, the development of the Brazilian Cerrado has changed global agricultural production and enabled Brazil to become a significant exporter of agricultural products. Brazilian science enabled the transformation of large parts of the Cerrado from wild savanna to productive land using the best available scientific tools. Last and not least, increasing agricultural production across the vast African continent will take up much of the attention of agronomists and policymakers in the coming years. Whilst significant potential to increase yields exists, there are large gaps in scientific knowledge on Africa's soils and crops, among other constraints. These are all major issues to be considered.

By the end of 2012 we will conclude our 60th anniversary celebrations. Whilst we look back with pride on our past achievements, we are nonetheless attentive to future challenges and determined to further assist global agricultural production by continuing to conduct practical research and demonstrations for farmers and disseminate and share the knowledge gained.

We trust you find some valuable insights in this special edition.

Hillel Magen
Director



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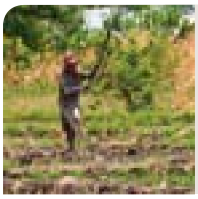

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Ore containing K in deep layers of a potash mine in Russia.

IPI 60 ANNIVERSARY

IPI Then and Now - The Story of 60 Years of Scientific Work for Balanced Fertilization with Potash

Magen, H.(1)

History

The International Potash Institute (IPI) is celebrating its 60th anniversary (1952-2012). For many decades, our agronomists and soil scientists have carried the message of "Balanced Fertilization", demonstrating and disseminating the role of potash in yield performance and quality, in stress tolerance and in bringing more value to the farmer.

IPI was founded by German and French potash producers almost 100 years after the discovery of potash-bearing salts in Staßfurt, Germany. The aim of the Institute was to *"foster the application of scientific and practical methods for the amelioration of the soil in general and the use of fertilizers, especially of potash"*. Its headquarters was located in Bern, the capital of Switzerland, and after a few months, a Scientific Board with scientists from 16 European countries was established to provide IPI with the necessary scientific guidance.

With Switzerland hosting the Institute, two distinguished politicians - Paul Chaudet and Nello Celio - who had both served as President of the Swiss Confederation, led the Institute till the 90s. Alexander von Peter, IPI Director from 1970 to 1991 reflects that "one of the assets the Institute had during these days was the open and productive exchange of views among the agronomists of the member companies, which allowed the Institute to establish missions in Africa, Asia, Latin America and more."

In 1957, after five years of IPI operation, the first new member joined the German and French founders (Dead Sea Works Ltd., a potash producer in Israel) soon followed by other potash producers in Spain, UK, GDR, USSR and Jordan. With this expansion, the Institute became the scientific hub for potash producers across Europe and the Middle East.

IPI veterans and current team

Celebrating IPI's 60th anniversary provides an excellent opportunity to hear about the Institute's past activities from previous members and leaders of IPI. During the last few months (early in 2012) I had an opportunity to meet with some of them whilst traveling to Germany and Israel.

IPI Presidents from 1970 till today (R. Gallay - not shown - was the President 1966-1970)

Paul Chaudet
1970-1977

Nello Celio
1977-1991

Erich Wyss
1991-2009

Prof. Dr. Christian Brückner
2009-today

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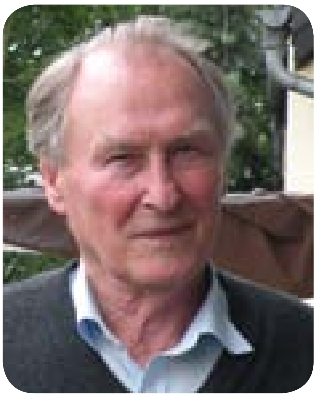
(1)Director International Potash Institute, Switzerland

Ever since his meeting Dr. Alexander von Peter in 1974, Prof. Iossif Bogdevitch from Belarus has been closely involved in IPI's work. In 1990 he was instrumental in organizing the first IPI symposium in the Former Soviet Union on "Development of K-Fertilizer Recommendations". The conference was held in Soligorsk, the city closest to the large potash deposits from which JSC Belaruskali, an IPI member, produces its potash. In the 1990s, Prof. Bogdevitch joined the IPI Scientific Committee, where he, and other leading scientists, influenced and provided valuable guidance on IPI's activities. In 1998, he became the IPI coordinator for Belarus, the Baltic States and Ukraine which, he says, was "the most satisfying time in my professional life."

Abraham Cohen and Meir Bazelet are veteran IPI coordinators, working for more than 30 years as coordinators and members of the IPI Technical Secretariat. A. Cohen joined IPI in 1971. After a few years, he was posted to IPI missions in South Africa and Latin America as an IPI coordinator, before returning to work at the head office in Bern. M. Bazelet joined IPI as a coordinator for Turkey in 1966. Later he held coordination positions in China, South Africa, Argentina, amongst others. Both veteran coordinators admit that satisfaction came predominantly from the opportunity to assist in developing sound research work on K nutrition in countries with local scientists, many of whom they stayed in contact with over the years.

Dr. Alexander von Peter served as IPI Director at the Bern headquarters from 1970 to 1992. I met him at his home in Heidelberg, and we greatly enjoyed reviewing his rich history with IPI. An economist by training, Dr. A. von Peter was always very conscious of the economical use of potash fertilizers. He recalls that the technical meetings at IPI, with so many agronomists from the member companies, always provided fruitful brainstorming. During his time as director, IPI changed its focus in activities and moved from mostly organizing symposia to active coordination in regions, which assumed that an impact in this field of operation could be gained. In 1992, after more than 20 years living in Bern, he retired and returned to his home in Heidelberg.

Marshal Tito (third from left) visits and examines potash bags at an agri exhibition in Novi Sad, 1974 (photo courtesy of A. von Peter).



Dr. Alexander von Peter.

Prof. Dr. Iossif Bogdevitch.

Abraham Cohen (left) and Meir Bazelet (right).

Dr. Adolf Krauss (center); Martha Vacano, IPI's Office Manager (left), and Hillel Magen, IPI Director (right).

Dr. Adolf Krauss served as IPI Director from 1994 to 2004. In 2002, at IPI's 50th Jubilee Symposium, he wrote that, "very early on, IPI also looked beyond Europe and established missions around the world, either on its own or in collaboration with what is now the Potash and Phosphate Institute, PPI/PPIC headquartered in the USA. The most comprehensive mission was the POTASCHEME in India (1957-1962), which had both expatriates and a large number of local staff. Other missions were founded in subsequent years in Argentina, Brazil, Peru, Uruguay, East Africa, South Africa, former Rhodesia, Hong Kong, Iran, Japan, Korea, Singapore, Taiwan, and in Montpellier, France for the Mediterranean region." During his tenure, IPI focused strongly on the term "Balanced Fertilization". Data presented in Fig. 1 shows how consumption of nitrogen fertilizers expanded in comparison to P and K, leading to severe nutrient imbalances in many regions, with ill-consequences on productivity, quality of products, declining soil fertility and environmental degradation.

Mr. Erich Wyss, former IPI President served the Institute for almost 20 years (1991-2009). This period was fundamental in forming the new identity of IPI as a result of the adjustments made at the end of the 80s following the demise of the Former Soviet Union. Mr. Wyss provided valued leadership during changing times and allowed the Institute to maintain and increase its scientific activities worldwide. He also participated in various symposia held in parts of the world, and inaugurated the IPI Golden Jubilee Congress in Basel, "Feed the Soil to Feed the People - The Role of Potash in Sustainable Agriculture", with many of IPI's research partners attending. The first Five-Year Plan (2009-2013) for IPI was completed during his service.

N. Awasthi
Coordinator East India, Bangladesh and Sri Lanka

M. Marchand
Coordinator West Asia and North Africa (WANA) and Central Europe

G. Peskovski
Coordinator East Europe

A. Shcharbakou
Coordinator SE Asia

E. Sokolowski
Coordinator China, India and sub-Saharan Africa

T. Wiendl
Coordinator Latin America

IPI Coordinators 2012.

Prof. Dr. Christian Brückner joined IPI as President in 2009. With strong support from its members, Prof. Brückner provides critical guidance for the Association as we face new challenges and opportunities. IPI's current portfolio of activities spans nine regions with research and dissemination projects led by six coordinators (see photo), overseen by the head office in Horgen, near Zurich. All coordinators are experienced field agronomists with IPI member companies. Nominated by the General Assembly of the IPI Members, IPI coordinators operate on a long-term basis in regions worldwide in accordance with the strategic framework of the Five-Year Plan.

Publications and dissemination

In the 1960s and 1970s, IPI invested heavily in producing scientific literature on the role of K in agriculture. With its first proceedings published in 1954, IPI has continued to publish new proceedings every year up to the present. All these publications have been scanned and are now available on the IPI website.

For almost 40 years between 1956 and 1995, IPI published the **Potash Review**, a collection of more than 1,000 themed scientific papers, with many of the papers dealing with potash use in international agriculture. These legacy documents were also recently made available on the IPI website, and can be searched by title, author, year and theme. Prof. (Emeritus) Uzi Kafkafi, a veteran of IPI's Scientific Committee said, "this transformation of the practical reports, published in **Potash Review** for over 40 years, is once again bringing to life the basic agronomical knowledge accumulated over almost a century of advanced agricultural research". Basic information for agronomists and growers can now be retrieved quickly and accurately with the proper references. In this new format, **Potash Review** replaces old plant nutrition books that are no longer easily accessible. In these modern times where most agricultural research centers

e-ifc No. 31, June 2012

Editorial

Dear readers,

Economics of fertilizer use has always been of high concern. "In times like the present, when farming conditions and produce markets become difficult, some advise farmers that the best way to weather the storm is to cut costs: savings can be made on the outlay on fertilizers. They say that yield increases over the years have not matched the increase in fertilizer use; that yield targets have been set too high; that, when produce prices fall, lower yields are acceptable especially as higher yields will lower prices; that it is not necessary to build up soil fertility and that advice to do so leads to over-use of fertilizers… as far as maize growing in South Africa is concerned, these ideas are false." Although this sentiment is familiar to us today, this statement from South Africa is taken from IPI's Potash Review report dating back to 1980 and much is still relevant today.

"There is no doubt of the great importance of the prices in shaping the use of fertilizers. However, of even greater importance is the dissemination of technical knowledge. The better the command of the farmers of the technique of manuring, the higher the level to which they lift the limiting-yield curve". This is also relevant, yet is a quote from IPI's Potash Review published in 1956 - now over 50 years ago.

Clearly the question of the benefit-to-cost ratio of fertilization has always been an issue, and more so during times of high fertilizer price and economic constraint. Uncertainty of the benefit from fertilization may always exist (and even just because climate is so unpredictable), so knowing more about efficient fertilizer use is crucial.

As always, reducing fertilizer rates will impact on yield. But these days, farmers can employ better tools to make fertilizer use more efficient, including using more efficient delivery systems, monitoring nutrients in soil and plant, and using remote sensing images - and decision support systems. Using these will increase the benefit-to-cost ratio of fertilizer application. And so we reach the same conclusion as in 1956 stated above: the more knowledge, the higher the limiting-yield curve can be lifted.

I wish you all an enjoyable read.

Hillel Magen
Director

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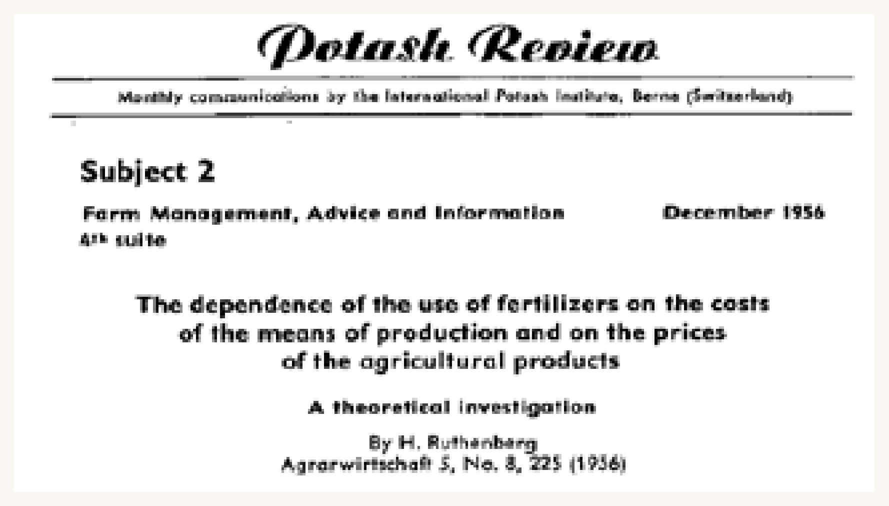


Potash Review

Monthly communications by the International Potash Institute, Berne (Switzerland)

Subject 2

Farm Management, Advice and Information **December 1956**
4th suite

The dependence of the use of fertilizers on the costs of the means of production and on the prices of the agricultural products

A theoretical investigation

By H. Ruthenberg
Agrarwirtschaft 5, No. 8, 225 (1956)

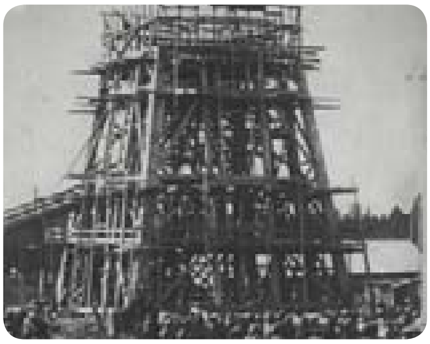
are concentrating on genetic research, such basic agronomic knowledge is neglected and the current generation of students has no real contact with the old accumulated wisdom. IPI deserves deep appreciation for the resurrection of this real basic knowledge in fertilizers and plant nutrition that otherwise would have been lost forever."

In 2006 IPI initiated a new electronic newsletter *(e-ifc)*, sent out quarterly to more than 2,000 email recipients. In each edition, three to four research items and a collation of events, new publications and an update of recently published papers with relevance to potassium fertilization are included. Edited by Dr. Ernest A. Kirkby, the newsletter provides scientific reports from IPI research projects in more than 20 countries spanning across Latin America, Europe, Africa and Asia. More than 80 research papers have already been published, and each year more are added.

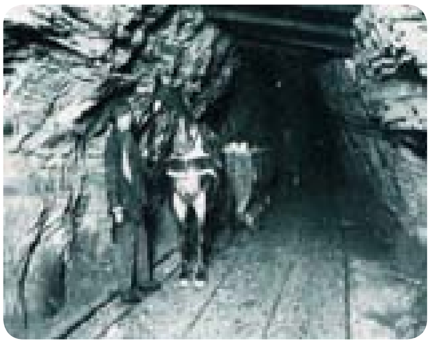
Providing "crop specific" information has been achieved by inviting eminent scientists to compile data on nutrient management for a specific crop. The first Crop Bulletin published by IPI in 1974 was on wheat, by Dr. G. Kemmler from the Büntehof Agricultural Research Center Station in Germany. More than 30 crop bulletins are now available, covering field crops, fruit and vegetables, and fiber

Early days for potash production at Dead Sea Works, Israel.
http://www.iclfertilizers.com/Fertilizers/Pages/OurHistory.aspx

Early days in Soligorsk, Belarus.
http://www.kali.by/english/history.html



1930: "Soyuzkali" decided to construct the Second Potash Mining Complex in Berezniki, later to become Uralkali's Berezniki 1.
http://www.uralkali.com/about/history/



Photograph showing the removal of ore using a horse to pull a train of wagons loaded with salt and potash. Alsace, France.
http://www.geowiki.fr/index.php?title=Les_Mines_de_Potasse_d'Alsace_au_fil_du_temps

crops, amongst others, with the Sugarcane Crop Bulletin to be released in the near future.

The need to highlight a specific issue such as fertigation, or potassium requirements of crops, led to the evolution of another series of publications known as "Research Topics", produced every two years, to which IPI invites prominent scientists to contribute on relevant topics.

IPI has not only been involved in creating scientific findings, but also in disseminating them. Recent developments in information technology provide enormous opportunities for developing new, innovative dissemination tools. IPI is developing several Apps which will run on Apple and Android systems to allow users to: view a set of pictures demonstrating the effect of potash on a large variety of crops and illustrating typical deficiency systems (K gallery); read and search through the IPI e-newsletter *(e-ifc);* or calculate nutrient removal rates from various crops. The excellent resolution, search and sharing tools makes these Apps on either Apple or Android smart phones and tablets very useful to smallholder farmers, extension experts as well as researchers.

Screen shot from IPI's K gallery App. View in App Store.

Projects and activities

Worldwide, more than fifty ongoing field experiments and demonstration plots are executed each year, together with seminars, workshops and farmers' field days. International symposia are regularly conducted in countries where we operate, to demonstrate the essential role of potassium in optimized crop nutrition to various target audiences. IPI makes a major investment in reaching out to farmers, their suppliers and advisors and believes in field-level promotion and outreach to farmers, as well as in fundamental and applied research. We also work hand-in-hand with organizations that include extension services, universities and those willing to take part in farmers' gatherings, field days, open seminars, training courses and other learning-related activities.

Potash consumption during the last 50 years (1961-2010)

The first deliveries of potash fertilizer date back to 1880 (Table 1), with high growth rates recorded during 1880-1910 when we know that some deliveries were already crossing the Atlantic from Europe to the East coast of the US. In 1935, more than 60 percent of global potash sold originated from Germany, followed by supplies from the potash mines in France, Russia, Spain, Poland, US and Israel (Fig. 2).

The potash market (and all other agri inputs) recovered after the Second World War and in 1954, total deliveries were more than 5 million mt K_2O. From 1954 to 1961 (this period is not covered by the FAOSTAT database) growth was maintained at high level, and in 1961, total deliveries reached more than 9 million mt K_2O (FAOSTAT).

From the FAOSTAT database which also covers crop and nutrient data from 1961 till today, and with supplementary data from the International Fertilizer Association (IFA), various developments can be assessed:

Table 1. Global potash deliveries in the early years 1880-1938.

Year	Potash deliveries
	-----*mt K_2O*-----
1880	69,000
1890	122,000
1900	304,000
1910	858,000
1920	914,000
1930	2,000,000
1938	2,460,000

Source: Cowie, 1951 and Turrentine, 1943.

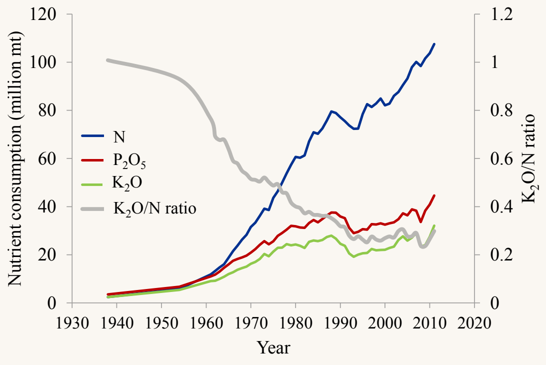


Fig. 1. N, P_2O_5 and K_2O consumption 1938-2010; K_2O/N ratio. *Source:* Cowie, 1951; FAOSTAT; and IFA for data from 1960.

- During the last 50 years, global crop production markedly grew (Table 2) with cereal production increasing by 177 percent, and some other crop groups by more than 300 percent (e.g. oil crops, vegetables and melons).
- Nutrient consumption grew steadily (Fig. 1), and that of N outstripped that of P and K (Fig. 1 and Table 2), with potash demonstrating the smallest increase of 203 percent from 1961 to 2010.
- The fall of the former Soviet Union (FSU) caused the most significant reduction in consumption of all nutrients (1988-1992; Fig. 1). Since 1992, no crisis has matched the magnitude of this time.
- The huge increase in N consumption also caused a sharp decline in the K_2O/N ratio (Fig. 1). While in the 1940-1950s, the use of N and K were similar, N use in 2010 is more than three times higher than K. Consequently the K_2O/N ratio declined sharply till after the demise of the FSU, but from the mid-90s, K_2O/N ratio has been stable (~0.28) and slowly improved. This development can be explained by the composition, or the change in growth rates, among the various crop groups: more oil crops, sugarcane, vegetables and fruit are grown in comparison to the composition in the 1960s. All these crop groups require more K than cereals.

A closer look at the development of potash consumption shows the following:

- Potash consumption grew steadily from 1961 to 1989 and from 1993 till today (Fig. 3), reaching more than 32 million mt of K_2O.
- The only period when consumption was reduced for more than one year in succession (except a single event of two years reduction in 1980 and 1981) was from 1989 to 1993, during the demise of the FSU.
- During this 50 year period, negative growth only occurred during 12 years, all of which were single year declines (except for 1980-1981 and 1989-1993).
- The average annual increase in potash consumption for the 1961-2010 period is three percent, but when separated into three distinctive periods, we see an average annual increase of 4.4 percent (1961-1988), -7.2 percent (1989-1992) and 3.22 percent (1993-today).
- This shows the resilience of consumption trends and the continued need for potash in global agriculture.

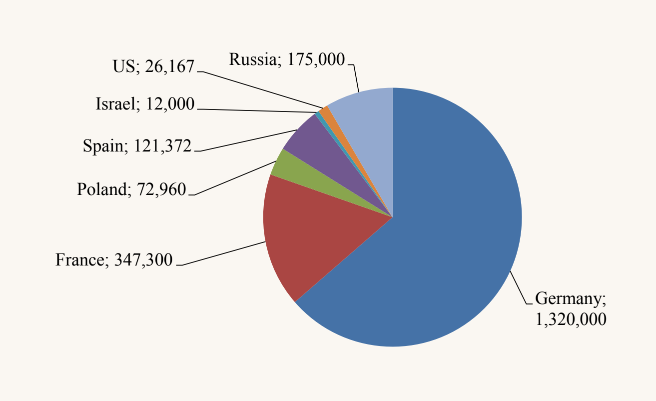


Fig. 2. Global potash sales (mt K_2O) in 1935. *Source:* Turrentine, 1943.

Table 2. Crop production and nutrient consumption (metric tonnes) during the last 50 years.

	1961	2010	Increase
	---------------*mt*---------------		*%*
Crop production			
Oil crops	25,752,797	168,444,789	554
Vegetables and melons	222,591,949	965,650,533	334
Sugarcane	447,977,518	1,685,444,531	276
Fruit (excl. melons)	175,029,853	609,213,509	248
Cereals	876,874,902	2,432,236,739	177
Pulses	40,783,485	67,652,942	66
Roots and tubers	455,331,211	727,303,077	60
Nutrient consumption			
Nitrogen (N)	11,851,000	103,700,000	775
Phosphorous (P_2O_5)	11,037,000	40,900,000	271
Potassium (K_2O)	9,068,000	27,500,000	203

Source: FAOSTAT.

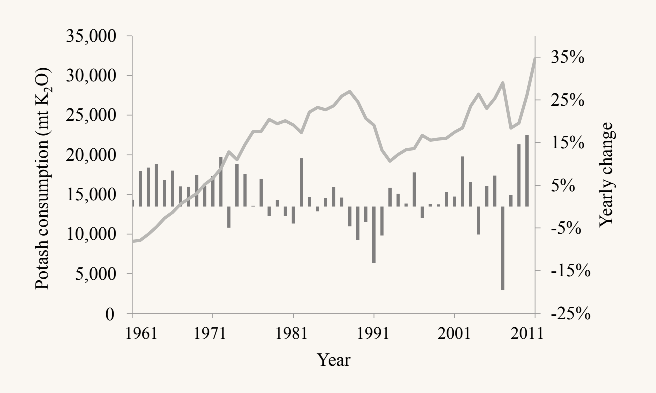


Fig. 3. Potash consumption (line, mt K_2O) and yearly change (bars, %) from 1961 to 2011. *Source:* FAOSTAT and IFA.

Members of the Board of IPI

From left to right: P. Losson, Vice President, Tessenderlo Kerley International, Belgium; I. Goldstein, Senior Vice President Marketing, ICL Fertilizers, Israel; C. Brückner, IPI President, Switzerland; O. Petrov, Director Sales and Marketing, JSC Uralkali, Russia; V. Ivanov, Director General, JSC Belarusian Potash Company, Belarus.

Conclusions and way forward

The vision of the IPI founders in 1952 is still valid today. Our principles of cooperation have lasted through many years in many regions and crises as farmers, and those who assist them, value a constant flow of science and partnerships to enable progress. Römheld and Kirkby (2010) describe the needs and prospects for research on potassium, and highlight the need for advanced and effective dissemination of knowledge. The rapid development of ICT provides many new tools to allow much faster and more effective dissemination of practical knowledge to farmers using smartphones and web connections. We, at IPI, believe that advanced dissemination is one of the first tools necessary for increasing agricultural productivity.

Römheld and Kirkby (2010) summarized and highlighted the needs for future potassium research:

- The relation between K and nutritional quality.
- Role of K in mitigating biotic and abiotic stresses (also in relation to climate change).
- The relation between K intake and human and animal health.

Other fields which require future research include:

- Developing online tools to identify in-field potash requirements.

- Developing models for better potassium recommendations based on soil, plant and environmental factors.
- Increasing the efficiency of potassium use by plants (Rengel and Damon, 2008; White, 2013, in press).

The practice of intensive fertilization to support massive food production for an increasing global population with higher dietary requirements has a short history. During the last 50 years, food production has hugely increased. However, consumption of nutrients N, P and K has been much skewed towards N, causing potassium depletion in soils and reduction in yields in many regions. Therefore, to enable closing yield gaps and allow for a much higher productivity in many regions, a significant increase in K fertilization is required (Mueller *et al.*, 2012).

Meeting the future demand for food is a huge challenge. By 2050, food production needs to have doubled, but achieving this will be very different to the past, depending on crops with a much higher demand for K than cereals, such as oil and sugar crops, fruits and vegetables, and roots and tubers. Considering the need for additional intensification, as well as environmental stewardship, soil fertility management and sustainable production, the term "Balanced Fertilization" should be revived, as one of the simplest to implement yet sound and appropriate measures farmers need to use in the future.

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For more about the history of potash and IPI go to the

IPI website

Interview with IPI Members

Vladislav Baumgertner, President and CEO
Joint Stock Company Uralkali, Russia

> **"IPI has the legitimacy, authority and mechanisms that enable it to spread its research and expertise around the globe."**

The use of fertilizers in major emerging countries is highly unbalanced, with low levels of potash application a key challenge. In China, India and Brazil, for example, application of potash is less than half the level recommended by scientists, despite almost doubling over the last ten years. In Russia, use of potash is also far below the volumes applied in the former USSR. As a result, crop yields in these regions are failing to reach their potential.

Uralkali is a veteran member of IPI. As an international organization, IPI has the legitimacy, authority and mechanisms that enable it to spread its research and expertise around the globe. The Institute can lead global initiatives, carry out research projects in different regions, accumulate the results, and come out with recommendations for the agricultural community.

At Uralkali, we aim to provide our customers with the best available knowledge on the useful characteristics of potash. In this role, we provide support for educational programmes to which organizations, such as IPI, contribute their scientific expertise. Through cooperation, we can achieve significant results in the most efficient way and together help address the global food challenge.

Today the world is developing very fast and companies and organizations need to adapt to changing realities. As an institute, IPI addresses an issue of utmost importance for the international community. The mere fact that IPI has survived over such a long period shows that it has been an effective coordinator of international efforts. I am sure that the Institute will further develop and continue making a significant contribution to global food security.

Interview with IPI Members

Isaac Goldstein, Senior Vice President Marketing
ICL Fertilizers, Israel

> "IPI research results are reliable, are adopted at local level, have the necessary local validation and have international backup."

During its 60 years, IPI has successfully pursued its mission to demonstrate the essential role of potassium in plant nutrition, contributing to a better understanding of the mechanisms and behavior of potassium in soil and plants, which has helped to improve fertilizer recommendations.

Today, however, there continues to be an acute need to build strong and stable bridges between research and extension. While the role of K in providing food security to an increasing population is fundamental, in developing countries additions of K seldom match K removals resulting in soils becoming K-deficient over time; balanced K application is urgently needed.

ICLF believes in building research-extension-private sector partnerships for dissemination of improved nutrient management practices to farmers. Supporting and educating farmers with better agronomic advice is one of our company values and this is successfully complemented by IPI activities. Through its network of coordinators, IPI reaches out to farmers, dealers, extension officers, farmers' cooperatives and foundations. By building these strong connections, IPI research results are reliable, are adopted at local level, have the necessary local validation and have international backup.

ICLF has contributed to the work of IPI, not only through financial funding, but also through the active participation of its agronomists as coordinators in various countries. ICLF agronomists, Meir Bazelet and Abraham Cohen, were actively involved in IPI from the 70s. Their work was continued by a new generation of agronomists, including Hillel Magen and Patricia Imas, who were coordinators for Argentina, India and China. Today our agronomist, Eldad Sokolowski, is the coordinator for India and China, and has the important task of initiating IPI activities in sub-Saharan Africa.

We see sub-Saharan Africa as the next challenge for IPI. Very low and stagnating yields in the region, due to low and unbalanced fertilization, prevent income generation and thus prevent the development of the agricultural sector. This inhibits rural development and may trigger migration of the labor force into urban areas in search of income and livelihoods. This vicious cycle can be stopped with the proper use of fertilizers, coupled with appropriate crop management and improved varieties and hybrids.

Through the last 60 years, IPI has created awareness, trust and confidence amongst farmers, advisors and decision-makers about the need for appropriate nutrient management, with an emphasis on potassium. IPI will continue its commitment to sustainable soil fertility, and to improving incomes in rural areas while safeguarding resources and protecting the environment.

Interview with IPI Members

Valery Ivanov, Director General
Joint Stock Company Belarusian Potash Company, Belarus

> "IPI has a track-record of acting in the best interests of member countries via an established coordination system."

In many countries of the developing world, farmers remain insufficiently aware of the benefits and strong economics of potassium application in achieving higher crop quality and yield. Agricultural extension systems are often limited and there is a lack of scientifically-based recommendations for potassium application in many key crops in some regions.

Attaining food security in all the countries of the world is achievable only through science-based cultivation techniques; balanced fertilization, as promoted by IPI, is an integral part of this. To provide the support required for achieving balanced nutrition in sustainable agriculture, all potash producing companies carry out training, often organising joint programmes with ministries of agriculture. Such activities draw on scientific results and recommendations produced by IPI studies, with the Institute active in more than 50 countries and providing information in 22 languages.

IPI has a long history of such activities, having contacts with key international and regional institutions, good standing in scientific and academic circles, and a track-record of acting in the best interests of member countries via an established coordination system. As a member of the Institute, we are pleased to be part of this great work. We are actively engaged in developing IPI's strategy, defining certain plans and objectives and increasing institutional efficiency. Among our personnel are IPI coordinators in Eastern Europe and Southeast Asia, and we use results of the Institute's work in the implementation of various agronomic projects of the company.

Interview with IPI Members

Valery Kirienko, Director General
Joint Stock Company Belaruskali, Belarus

"Our purpose, with IPI, is to offer solutions for better feeding the world."

This year, IPI celebrates its 60th anniversary. The Institute's foundation in 1952, initiated by German and French manufacturers of potash fertilizers, came out of the long-felt need to provide science-based information primarily from field experiments. Since then, world agriculture has gained extensive knowledge on issues surrounding plant nutrition and IPI has made a significant contribution to this development of agrochemistry.

In the Republic of Belarus, for example, Professor Iosif Mikhailovich Bogdevitch, a prominent scientist in the field of agrochemistry and agricultural radioecology, became a connecting link between Belarusian researchers and IPI on the role of potash fertilizers and their practical application. Prof. Bogdevitch developed the scientific groundwork of effective fertilizer utilization and soil fertility management in sod-podzolic soils. He also developed integrated computer models to assess soil fertility and provide practical measures for farmers. The work of Prof. Bogdevitch has been widely used in the educational work of international scientific and research organizations, including IPI.

The great Russian botanist and plant physiologist K.A. Timiryazev once said, "The true supporter of the peasant is not the earth, but a plant, and the whole art of the farmer consists in releasing a plant and, hence, the farmer from the earth's power." Mankind should not depend on new resources from the earth. The main direction, and essentially the only direction to develop modern agriculture, is all-round intensification and industrialization. Our purpose, with IPI, is therefore to offer solutions for better feeding the world. I would like to congratulate the International Potash Institute on the occasion of its 60th anniversary and to wish it further successes in the achievement of this noble goal.

Interview with IPI Members

Patrick Losson, Vice President
Tessenderlo Kerley International, Belgium

> “IPI acts as a catalyst to research and development, pushing its members to be the best in class.”

Correct use of potash is a classic example of sustainable intensification, improving crop yields and boosting the capacity of the crop to withstand difficult conditions, while also minimizing the environmental impact through reduced nitrate losses.

Increasing potash use in developing countries is essential, but depends on several key factors. Farmers need to be aware of how important it is to apply nutrients in the right balance, and there is also a need for logistic advice, so that farmers can access affordable, quality fertilizers at the right moment for the crops. Local authorities and other stakeholders need to understand how optimum fertilizer usage can be embedded in farmers’ business plans, and the potential of micro-credit to support fertilizer purchases.

In addressing these challenges, there is a limit to what any single company can achieve. This is where the International Potash Institute plays such an important role, combining the agronomic services of different producers for the benefit of the farming community. In China, for example, IPI has done much to create awareness of the need for potash within an optimum balance of nutrients, which has been key to achieving food security.

By joining the forces of actors throughout the indutry, including governments and NGOs, IPI acts as a catalyst to research and development, pushing its members to be the best in class. It is a perfect example of how, when industry joins forces, the total outcome is greater than the sum of its individuals.

Research Findings

History and Prospects of Potash Application in China

Jianchang Xie(1), **and Jianmin Zhou**(1)

Introduction

China is a country with a large population and limited farmland. Its population is over 1.34 billion with less than 0.1 ha of arable land per person, one-third of the world average. As a result, China is always under great pressure to guarantee food security. However, the Chinese have made a great effort to maintain a high degree of self-sufficiency, which currently stands at 95 percent. In 2011 the total annual grain yield of the country was 571 billion kilograms, representing over 400 kg of grain for every inhabitant. In relation to the total world population, China feeds as much as 20 percent of the population with only 9 percent of the arable land at its disposal. This great achievement has not only guaranteed food security and sustainable development in China, but has also made a great contribution to the stable supply of grain in the world. Fertilizer has undoubtedly played an essential and irreplaceable role in Chinese food production.

Agricultural development and fertilizer application in China

Before 1949, grain yield was very low because farmers only used manures to maintain the nutrient supply in the fields. Since that time, however, China has been producing and applying more and more fertilizers to ensure a constant, continuing increase in grain production. The present Chinese government attaches great importance to agriculture, the countryside and farmers.

Fertilizer application has continued to increase since the beginning of the 1950s. From the 39,000 mt used in 1950, an enormous rise in fertilizer application occurred, reaching as much as 3.51 Mt by 1970. Over the same period, grain yield also increased rapidly, total grain production reaching 240 Mt as compared with 132 Mt in 1950. This increase continued, with total grain yields in 1980, 1990 and 2010 of 320, 452 and 546 Mt, respectively. In 2011, the total grain yield reached 571 Mt, with a unit yield of 5.166 mt ha^{-1}, an increase of 3.9 percent compared with 2010. The increasing use of better balanced fertilizer application over eight years (from 2003-2011) allowed grain production in China to reach a new high level. These increasing grain yields from 1949 to the present day are closely correlated to the enormous rise in fertilizer consumption over the same period, as reported in Table 1.

Many scientists have questioned the possible over-use of fertilizers in recent years, even though it has resulted in increases in production of both cereal grains and cash crops. Since the 1980s there has been a gradual move towards vegetable and fruit tree planting, which in recent years has increased rapidly. These cash crops have higher economic value, but their nutrient requirements are 2-3 times higher than cereal and other staple food crops. Planting of cash crops

Table 1. Consumption of nutrients in China ('000 mt).

Year	Total*	N	P_2O_5	K_2O	Ratio $N:P_2O_5:K_2O$
	'000 mt nutrient				
1949	13				
1950	39				
1952	78				
1962	630				
1970	3,512	2,497	991	24	1:0.40:0.010
1980	12,694	9,425	2,882	387	1:0.31:0.041
1990	25,903	17,480	6,452	1,971	1:0.37:0.113
1995	35,936	22,347	9,950	3,640	1:0.45:0.163
1999	41,245	24,811	11,004	5,430	1:0.44:0.219
2010	55,617	32,000	14,000	9,500	1:0.44:0.297

*Fertilizer consumption in 1949-1962 was basically nitrogen fertilizer.

N, P_2O_5 and K_2O in compound fertilizer were calculated according to the content of the nutrient and compound amount.

Source: Li *et al.*, 2001; National Bureau of Statistics of China, 2011.

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thus acts as the primary impetus for increased chemical fertilizer input.

The planting area of staple food crops and other field crops decreased by 15.13 million ha from 1980 to 2008, while the planting area of vegetables and fruit trees increased by a total of 23.67 million ha. Over the same period, dramatic increases in the total yields of cash crops occurred, including vegetables (6.2 fold), melons and fruits (5.2 fold), oil crops (2.8 fold) and sugar crops (3.6 fold). These increases both in cash crop yields and planting area accounted for approximately 50 percent of increased fertilizer use (unpublished data). In 2010, cereal and other staple food crops accounted for 60 percent of fertilizer use, while the remaining 40 percent was applied to vegetables, fruit trees and other cash crops (unpublished data).

Input of chemical fertilizer has promoted nutrient cycling in farmland ecosystems, playing an important role in sustaining yield of food crops in China. Various other factors have also made a contribution, including use of suitable varieties, irrigation and field management, but many researchers have concluded that fertilizer input accounts for 40-50 percent of the effect.

On a world scale, since 1993 China has become the world's largest chemical fertilizer consumer, accounting for 1/3 of total use. In reviewing the history of NPK fertilizer application in China, it may be summarized that the use of N began in 1950, P in the 1960s and K in the 1970s. The application rates of chemical fertilizer in the initial stages were very low at 78,000 and 630,000 mt in 1952 and 1962, respectively, and consisted mainly of N (Table 1). Studies on the benefits of P fertilizer to crops in China began in 1960, which promoted P application.

From Table 1, it is evident there was almost no supply of inorganic K fertilizer before the 1970s, with only a small amount of K fertilizer being imported in 1972. From the mid 1970s, the application of N and P significantly increased but there was little increase in K application. From the 1980s, K application gradually increased, with the NPK application ratio of 1:0.31:0.041 in 1980 being improved to 1:0.37:0.113 (including compound fertilizer) by 1990. By 1999, K_2O consumption had risen to 5.43 Mt, and the application ratio of NPK had increased further in favor of K, to 1:0.44:0.219. The figures for 2010 show that K application (as K_2O) had dramatically increased to 9.5 Mt, and the application ratio of NPK was 1:0.44:0.297. Obviously, the NPK ratio in favor of K significantly increased over the years as did the average growth rate in grain yield, which amounted to 11.7 percent during the 30 years from 1980 to 2010.

A historic contribution has been made by Chinese researchers in furthering the application and extensive use of K fertilizer. The study of soil K was already being carried out at the Institute of Soil Science, Chinese Academy of Sciences (ISSAS) in Nanjing in the early 1950s. From then on, numerous other research, education and agricultural establishments were set up, radiating from south to north throughout the country, which supported research teams dealing specifically with potassium. The study of soil K and K fertilizer became one of the most active topics in the discipline of soil-plant nutrition and fertilizer science, which included the following areas of research interest: characterization and distribution of soil K-bearing minerals; fixation and release of soil K; content, form and availability of soil K; evaluation of soil K fertility; cycling of K in farmland; K budgets and management; and the relationship between K and crop quality as well as its effect in increasing biotic and abiotic stress resistance in crops. Together with this research, a large amount of effort was made in extension work to demonstrate the benefits of K fertilizer application to farmers.

Besides the requirement of agricultural development, close cooperation with related international organizations has further stimulated active agronomic research in K. Cooperation between ISSAS and the International Potash Institute (IPI) began at the end of the 1970s, with 12 international K symposia being convened from 1983 to the present time, and numerous field experiments aimed at optimizing K application, in more than 10 provinces, autonomous regions and cities. More recently, cooperation between the Potash and Phosphate Institute (PPI) and some other international organizations has also begun. This international cooperation, conducted by means of international symposia, publishing in international scientific journals, and carrying out field experiments and demonstrations, has benefited international academic communications and research training, as well as playing an important role in soil K research and K application on soils in China.

Contribution of K to agricultural sustainability

General situation of soil K fertility in China

The most important K source in soil is aluminosilicate minerals, which include potassium feldspar and biotite, secondary aluminosilicate minerals (such as hydrous micas or illite), and continuous weathering products such as vermiculite. High temperature and rainfall, as well as obvious wet and dry seasons, characterize southern subtropical and tropical areas in China. Through long-term weathering the parent minerals are strongly weathered. Besides kaolinite, these soils contain relatively abundant amounts of hydrargillite and hematites, and these areas are therefore typical K-deficiency regions in China. The main mineral in the middle subtropical area is kaolinite, but small amounts of hydrous micas and vermiculite are present. In the north of China, because of slow weathering and regardless of parent minerals, the soils contain large amount of hydrous micas and montmorillonite-like minerals, which have a strong exchange capacity for K in clay soil. Brown soil (Alfisols) contains large amounts of hydrous micas and vermiculite, while chernozem and chestnut soils are abundant in hydrous micas as well as montmorillonite-like minerals. The main soil mineral in the desert and semi-desert areas is hydrous micas.

A large variation in total soil K content occurs in China. The K content of the latosols in Guangxi province is the lowest, at 3.6 g kg^{-1}, while an aeolian sandy soil in Jilin province is the highest, at 26.1 g kg^{-1}, a 7.3 fold difference. Generally, the total K content in south China (except the purple soil) is low, whereas it is high in northeast and northwest areas of the country.

According to the second national soil survey of the 1980s, the readily available (exchangeable plus soluble) K distributions were characterized as given in Table 2. As shown, marked differences in K status occur between the various regions of China. Soils in which the readily available K is more than 150 mg kg^{-1} account for more than 37 percent in northeast and northwest, followed by north China at 30 percent, but less than 14 percent in central China and south China. Similarly, soils in which readily available K is less than 50 mg kg^{-1} only account for less than 3.5 percent in northeast and northwest China, but more than 50 percent in south China. With regards to slowly available K, specific ranges occur for particular soil types. In China, soil K-supply potential has been classified into seven levels, depending on the slowly available K content (Map 1 and Table 3). The map of soil K-supply potential is of benefit for a macroscopic understanding of soil K fertility, which provides a basis for K allocation and application. Table 4 shows that K-supply potential in the four provinces of Sichuan, Guizhou, Shanxi and Gansu differ significantly.

Color	K potential supply	Slowly available potassium (mg kg^{-1})	Predominant clay minerals in soil
🟨	Very low	<66	Kaolinite
🟦	Low	66-166	Kaolinite-hydrous micas
🟪	Medium-low	166-330	Vermiculite-kaolinite
🟩	Medium	330-500	Hydrous micas - Vermiculite-kaolinite
🟧	Medium-high	500-750	Hydrous micas - Vermiculite (chlorite)
🟥	High	750-1,160	Hydrous micas - Montmorillonite
🟫	Very high	>1,160	Hydrous micas

Map 1. Predominant K bearing minerals and K potential supply in soils of China.
Source: Xie and Li, 1990.

Soil K fertility is comprehensively determined by parent material, weathering degree, fertilization, plant uptake, soil erosion and soil leaching. Overall, soil K fertility gradually increases from south to north in China, which is consistent with the decrease of kaolinite and increase of hydrous micas.

Evolution of K fertilizer effect 1960-1990

The possible benefits of K mineral fertilization were considered by Lin (1989), in discussing three NPK fertilizer effectiveness experiments carried out on a national scale during 1936-1940, 1958-1962 and 1981-1983. During the first two experimental periods, K fertilizer application was without effect on yield. However, in the third experimental period (1981-1983), potash application significantly increased yield in south China, while still having no effect on most of the food crops in north China. These findings fit well with present knowledge of the soils of south China, in being inherently lower in K than those of the north, as discussed earlier.

Latosol and latosolic red soils are typically K-deficient, and were those used first in experiments to test the beneficial effects of K fertilizer. Rubber trees planted in latosolic red soil in the west of Guangdong province at the end of the 1950s commonly showed the symptom of yellow leaves, the main reason for which was proved by ISSAS to be K deficiency following two years' experiments from 1960 to 1961. In the 1960s, there was no mineral fertilizer K supply, so cement kiln dust was used instead in many experiments carried out in Guangdong, Hunan, Jiangxi and Jiangsu provinces. Data summarized by the Soil and Fertilizer Institute in Guangdong in 1973 showed that from 109 field trials in rice, yields in 90 percent of plots in west Guangdong were increased by 10-35 percent, the best effect being demonstrated in sandy and black mud fields.

Symptoms of K-deficiency in rice occurring in south China at the end of the 1970s, such as Brown Spot Disease, were found to be triggered by K-deficiency through experiments with a calcareous paddy soil in Liuzhou city, Guangxi province. K fertilizer application in south China proved to be very effective, as evident from a series of experiments in the 1970s. Corn yields increased by 21 percent in 6 experiments in 1974, and an increase of 7.9 kg corn per kilogram K_2O (agronomic efficiency of potassium; AEK) was reported by Guangxi Soil and Fertilizer Institute in 1974. Similarly, the project entitled "agricultural use and evaluation of K from Qinghai salt lake", which was organized by the Chinese Ministry of Agriculture and carried out in several provinces in south China from 1981 to 1984, showed that the application of 75 kg K fertilizer (K_2O) per hectare resulted in an AEK of 7 kg rice per kilogram K_2O.

The response of crops to K application was evident not only from the experimental sites but also from demonstration plots, the area of which gradually increased with

Table 2. Distribution of soils according to their readily available K content in the ploughed layer in different regions of China.

Region	Soil group	K content (mg kg^{-1})				
		>200	150-200	100-150	50-100	<50
		----------------------------%----------------------------				
Northeast China	Dark burozem, black soils, chernozems	19.8	17.6	39	21.0	1.7
North China	Burozem, cinnamon soils, fluvo-aquic soils	14.2	16.4	32.3	32.2	4.4
Northwest China	Catanozems, brown pedocals, gray desert soils, brown desert soils	27.7	25.1	25.5	18.3	3.5
Southwest China	Purplish soils, yellow earths	14.6	10.3	27.9	41.3	5.8
East China	Paddy soils, yellow brown earths, cinnamon soils	6.2	13.8	27.1	40.1	12.8
Central China	Red earths, yellow earths, paddy soils	1.2	12.8	21.4	56.0	9.2
South China	Latosols, lateritic red earths	2.6	3.8	9.9	33.6	52.2

Source: Xie *et al.*, 2000.

Table 3. K-supplying potential (slowly available K) in major soils of China. See also Map 1.

K-supplying potential	Level of slowly available K (mg kg^{-1})	Soil type
Very low	<66	Latosol, latosolic red soil, calcareous soil and related paddy soil (Guangxi and Guangdong)
Low	60-166	Red soil, yellow soil and related paddy soil (Hunan and Jiangxi)
Medium-low	166-330	Paddy soil around Taihu lake and Zhujiang river, sandy soil around Yangtze river
Medium	330-500	Paddy soil in Dongting lake and Ganjiang river, yellow-brown soil, boggy soil, sandy fluvo-aquic soil (Hubei, Guizhou and Sichuan)
Medium-high	500-750	Purple soil (Sichuan and Hubei), chestnut soil, meadow soil (Heilongjiang and Inner Mongolia)
High	750-1,160	Dark-brown soil, black soil, brown soil, clay fluvo-aquic soil, mountain soil (Heilongjiang, Jilin, Shanxi, Shandong, Hebei and Henan)
Very high	>1,160	Grey desert soil, brown desert soil (Xingjiang and Inner Mongolia)

Source: Xie *et al.*, 2000.

Table 4. Statistical data of slowly available K in four southwestern and northwestern provinces.

Province	Number of samples	Slowly available K (mg kg^{-1})						
		<66	66-166	166-330	330-500	500-750	750-1,160	>1,160
		--%--						
Sichuan	940	0.85	11.91	26.28	26.28	25.85	6.70	1.60
Guizhou	758	5.41	36.62	38.65	14.12	4.75	0.79	0.66
Shanxi	497	-	-	1.41	1.61	13.88	52.31	30.78
Gansu	210	-	-	-	0.95	18.10	44.76	36.19

Source: Xie *et al.*, 2000.

the support of IPI and PPI (IPNI). These demonstration areas included 1,400 ha of K fertilizer application in the Liujiazhan Plantation of Jiangxi province during 1978 to 1979 in collaboration with ISSAS, which also supported a rice demonstration in Jinhua county of Zhejiang province in 1979. Further demonstrations were carried out in Liujiang county of Guangxi in 1981 as well as a demonstration on 70,000 ha in Taihe, Jiangxi province, during 1983 to 1984. Yields increased in all the K fertilizer demonstrations and the effects were further verified by demonstration of K-based balance fertilization in Guangxi by Canpotex in 1986.

The well-established research on K in the southern part of the country has been complemented by continuing research work in northern parts of China on soil K depletion. The application of K to the K-deficient soils of north China has resulted in yield increases since the 1980s passing through three stages: no effect, minor effect and significant effect, each stage lasting around 10 years. Experiments were set up on soils with low K content in Shandong, Henan and Hebei provinces by the Soil and Fertilizer Institute of the Chinese Agricultural Academy of Sciences in collaboration with PPI in 1986, in which responses to different levels of K application were observed. As time went on, the effect of K application became more and more pronounced, the K input rate gradually increasing from the 1990s, as higher inputs of N and P raised the potential for crop yield responses to K application. 1,350 field experiments and demonstrations were designed in northeast and north China, and the results showed that yields of the main crops were significantly increased by K application when NP input was adequate. Yields of crops with high K requirement, such as cotton and sugar beet, were even increased by K application on soils rich in K. 107 experiments were conducted in northwest China (Shanxi, Qinghai, Ningxia and Xinjiang) in the 1990s, and the yields in 78.5 percent of experiments were significantly increased, by more than 5 percent, after K application. Current findings are also confirming the need for K fertilization in new varieties. The cultivation of Bt-cotton is now extending quickly in China, and it is evident that inadequate supply of K leads to premature senility and reduces yield significantly. For the long staple (fiber) cotton in Xingjiang, an adequate supply of K is very important for high quality. Thus for cotton, even in soils showing comparatively high levels of K availability, K fertilizer is needed.

The benefits of potash application to maize, the main crop grown on the cambisols of Shandong and the alfisols of Hebei in the North China Plains (NCP) were shown recently by Niu *et al.* (2011). Potash applied in various locations increased yields by 10 to 21 percent, with the strongest response in high yielding practices (HP) over conventional practice (CP; Table 5). Agronomic efficiency of K applied (AEK) to maize varied between 2 and 12 kg yield per kg K_2O applied, with the higher AEK being very profitable for the farmer (value-cost-ratio; VCR; data not shown). Higher AEK values were obtained in fields where K application was only one of the measures taken to improve productivity (high yielding systems; HP); other measures included increased plant density and optimized P fertilizer levels. K application also improved partial productivity of N (PFPN) by approx. 20 percent. In almost all locations, the partial factor productivity of K (PFPK) was higher in the HP plots. Finally, apparent recovery of K applied (REK) was higher at high K levels and in HP management systems, and increased to approx. 30 percent. This data shows that efficient use of potassium in the NCP, an area considered a few years ago as non-responsive to K, increases nitrogen use efficiency, productivity and brings economic value to the farmer.

The effects of NPK application on soil fertility and sustainable productivity through long-term experiments have also been studied in depth. The results from three long-term experiments in central China, north China and west China are shown as examples in Table 6, the soil K-supply potential differing in the three experiments. On soils with the lowest K supply potential, in Hunan province, the effects of K application remained significant for 27 years. At an upper-middle level of soil K supply potential in Henan, the effect of K application continued to be observed after 12 years' K input. The soil K supply potential in Shanxi was highest and no effect was observed after 20 years' K input.

Some other long-term experiments have shown the enormously beneficial effect of K application in seriously K deficient soils, and that the effect becomes more significant with time. For the calcareous paddy soil in Liujiang county in Guangxi province, in which total K, readily available K and slowly released K were 1.9 g kg^{-1}, 44 mg kg^{-1} and 114 mg kg^{-1}, respectively, indicative of a very low K

Table 5. Average effect of K application on maize in seven locations in the North China Plains (NCP) and efficiency indicators (adapted from Niu *et al.*, 2011). CP: conventional practice; HP: high yielding practice. The locations were in Shandong (Shuitun, Laiyang and Dajin) and Hebei (Qingyuan (3 locations) and Zhengding). K1 and K2 levels were different between locations (120 and 240; 75 and 150; and 90 and 180 kg K_2O ha^{-1}, respectively).

K treatment	Yield				PFPN		PFPK		AEK		REK	
	CP	Increase	HP	Increase	CP	HP	CP	HP	CP	HP	CP	HP
	mt ha^{-1}	*%*	*mt ha^{-1}*	*%*	------------------*kg kg^{-1}*------------------						------*%*-----	
K0	6.46	-	6.58	-	37.7	28.4	-	-	-	-	-	-
K1	7.10	9.9	7.62	15.7	41.4	32.9	81.1	87.2	7.1	11.8	0.18	0.30
K2	7.42	14.9	7.96	21.0	43.7	34.4	42.9	46.1	6.2	8.4	0.21	0.25

Table 6. Long-term effect of K fertilizer input in three different soil types.

Location	Period of experiment	Soil type	Soil K content: Total	Soil K content: Readily available	Soil K content: Slowly available	Rotation		Fertilizer rate: N	Fertilizer rate: P_2O_5	Fertilizer rate: K_2O	K effect (Comparison between NP and NPK treatment)
			g kg^{-1}	----------mg kg^{-1}----------				-----------kg ha^{-1}-----------			
Changsha city, Hunan	1981-2007	Red paddy soil	14.1	62.3	173.9	Double rice	Early rice	150	90	120	Effective immediately; the average annual yields of early rice and late rice increased by 15.2% and 17.2%, respectively, during each of the 27 years
							Late rice	180	90	120	
Fengqiu county Henan	1990-2009	Fluvo-aquic soil	18.6	82.9	797.5	Wheat-corn	Wheat	150	75	150	Effective after 12 years; the average annual yields of wheat and corn increased by 12% and 17%, respectively, from 2002 onwards
							Corn	150	60	150	
Yangling county Shanxi	1991-2010	Loess soil	21.6	200	1,500	Wheat-corn	Wheat	165	57.6	68.5	No effect in 20 years
							Corn	187.5	24.6	77.8	

Source: Data from ISSAS field experiments and other sources.

supply potential, the yield in the NPK treatment was greater by 60 percent than that of the NP treatment after 15 years (Du *et al.*, 2001). There is other evidence of the benefit of K fertilization from four year, long-term field experiments with double rice conducted in Shanggao County in Jiangxi province from 2005-2008 (Tang *et al.*, 2011). For the early and late rice, the N, P, K rates were 150, 75 and 180 kg ha^{-1}, and 180, 45 and 180 kg ha^{-1} respectively. In 2005, the early rice yield in the NPK treatment increased by 12.1 percent, and late rice yield increased by 32.3 percent, and these values were raised further in 2008, to 18.3 percent and 37.2 percent, respectively (Tang *et al.*, 2011). The results of 666 field experiments also showed that application of K fertilizer increased rice yield by 11.7 percent in 6 provinces in southeast China, the rice yield increasing by 7.5 kg per kg K_2O applied (Xie, 2000). The recent results of the IPNI China project have also shown that the agronomic efficiency of K of the main cereal crops has greatly improved, as compared with those in the 1980s (Table 7). With the extended use of hybrid rice and super rice in China, higher rice yields have been obtained requiring higher amounts of K fertilizer as well as suitable amounts of N and P fertilizer. Thus, K-deficiency has become a potentially more serious problem during cultivation while the effect of K fertilizer has become more significant.

Table 7. Agronomic efficiency of K in main cereal crops in China.

Crop	Agronomic efficiency of K: 1980-1983 Whole country	2002-2007 North	2002-2007 South	2002-2007 Whole country
	------------------------kg kg^{-1}------------------------			
Rice	4.9	7.5	7.8	7.7
Wheat	2.1	7.0	8.3	7.3
Corn	1.6	9.4	7.5	9.2

Source: IPNI unpublished data.

In recent work by Zhang *et al.* (2011), the authors analyzed K balance in wheat and maize over a 15 (1990-2005) or 18 year (1990-2008) period at five distinctive agro-ecological zones across China, with exchangeable K values from 74 to 288 and non-exchangeable from 487 to 1,764 mg kg^{-1}. Results for K balance (partial K balance; total K uptake – total K input) were negative (between -22 to -226 kg K ha^{-1} year^{-1}) in all regions except in Qiyang (Hunan), where K application was similar to removal, with additional organic manure (OM) resulting in a positive K balance. In all regions, application of only NP caused a much higher K negative balance as compared to the control, and the application of OM was mostly beneficial from the point of view of K balance. This work shows that typically used K application rates often do not offset the high K removal by the crop, and hence, K balance remains negative and affected by exchangeable and non-exchangeable K levels in the soil.

Recycling of nutrients and using alternative sources of K

As population and food production have grown in China, so too has the total amount of K removed from farmland through the harvesting of plant materials, such as grains, fruits or foliage. In order to maintain the fertility and productive capacity of the soil, this K has to be replaced, and in general, the beneficial effects of K on crop growth have been recognized in China, causing a steady increase in K consumption. However, the increase in the price of K fertilizer from the end of the first decade of the 21st century has stimulated much interest in recycling of straw and crop residues in the soil. Despite the agronomic difficulty of this practice, K levels in both are significant and can assist farmers in supplying at least part of the K requirement.

The value of K in crop residues has long been known; of the plant nutrients, K, like N, is a very easily recycled nutrient and both elements are important constituents in organic fertilizer, which has historically played an important role in Chinese agriculture. While returning straw to the field requires agronomic skills and labor, the increased cost of K fertilizer has created a real incentive for farmers and the Government to make more efficient use of this K source. Hence measures have recently been taken by the Government to promote straw recycling, thereby reducing the cost of K fertilization and protecting the environment by avoiding its burning.

A negative K balance prevails in many agro-ecological regions in China and varies from -10 to -158 kg K_2O per year (Jianmin *et al.*, 2004). The authors have drawn attention to two important sources of K that can be used: crop residues and irrigation water. A 15 year experiment near Shanghai, investigating nutrient balance using crop residues (data from Wang, cited by Jianmin *et al.*, 2004) showed that while K balance when only K fertilizer was added was at -528 kg ha^{-1} (over 15 years), the addition of straw considerably decreased the negative balance to -166 kg ha^{-1}, implying that straw alone cannot suffice crop needs and both sources (fertilizer and straw) should be used. One of the explanations for this is that adding straw, a well-documented agronomic practice, also increases the yields and hence the uptake of crops.

Jianmin *et al.* (2004; data cited from Xu *et al.*, 1998) also show that irrigation water and rain contribute K (approx. 20-35 and 5 kg K_2O per annum, respectively), but losses due to runoff and leaching are also significant. Nevertheless the total K balance taking into account all these factors is positive (net contribution) at approximately 10-17 kg K_2O ha^{-1} per year.

Clearly, Chinese agriculture is entering a period when efficient use of all resources is essential. Innovative agronomic practices and meticulous calculations of nutrient balance, taking into account gains (e.g. crop residues) and losses (e.g. leaching), are needed, in order to ensure that the productivity levels required will not cause soil depletion and reduction of soil fertility.

Prospects

The population in China is set to increase and to guarantee national food security, there is a need for chemical fertilizer application to further increase crop yields. To support rational K fertilizer application, more research should be carried out to establish a clear understanding of soil K status and cycling in crop fields. Experimental findings need to be demonstrated and passed on by extension workers and advisers to farmers, so that they become conversant with available knowledge to increase efficient K use in crop production. At the same time, mined sources of K fertilizer need to be maintained to meet the K fertilizer supply.

Improving understanding of soil K and K cycling in crop fields

A better understanding of soil K status and K cycling in crop fields is fundamental for rational K fertilizer recommendation. A number of questions may be posed in this respect. How much K in soils is available to crops? What practical methods for testing soil K are suitable for various soils and for different crops? How should K fertilizer be applied to maintain both high crop yield and soil K balance? All these issues need to be further investigated. Results from the ISSAS K research group have shown that total non-exchangeable K (NEK) values in soils are very high, averaging 40 percent of the total K in soils, with availability being determined by the release rate (Zhou and Wang, 2008). New methods are needed to classify and quantify NEK, to enable a better understanding of K status in soils. In China, NH_4OAc extracted K is the main index for both soil K availability and K fertilizer recommendation. However, the NH_4OAc method does not include soil NEK, and is thus not suitable for evaluation of K availability in soils in which NEK contributes, to a varying extent, to plant K uptake. A new method to evaluate plant available K in different soils has been established (Wang *et al.*, 2010) and its potential for general use on soils in China in relation to crop production needs to be further investigated. K fertilizer recommendations should not only aim to obtain the highest crop yield, but should also consider maintenance of soil K fertility. To achieve this target, more research in the future needs to be directed to the study of K cycling and balance, involving crops growing in the field.

Extension of soil test based fertilization for high K use efficiency

Soil test based fertilization refers to a technology of nutrient application which takes into account indigenous supplies of nutrients in soils, crop nutrient requirements and nutrient balance. This can increase nutrient use efficiency, decrease fertilizer input, and at the same time, increase yield and farmers' income.

160 million farmers from all over China benefited from a national project of soil test based fertilization, which took place from 2005 to 2010. Results from 3,000 field experiments on various crops, including rice, corn and wheat, were statistically analyzed in 2009. Yields of soil test based fertilizer treatments, compared with conventional fertilization treatments, were shown on average to be 450 kg ha^{-1} higher. Nitrogen input was lowered by 15-30 kg ha^{-1} and N, P_2O_5 and K_2O use efficiencies were increased by 10 percent, 7-10 percent, and 7 percent, respectively. According to this investigation, in the core production area in Jiangsu province,

the N, P_2O_5 and K_2O input ratio was 1:0.3:0.32 for soil test based fertilization in wheat, whereas it was 1:0.28:0.22 in conventional fertilization. The K input ratio was obviously increased through the soil test based fertilization program.

Sustaining K fertilizer supply by various means

The consumption (imports plus potash produced in China) of K fertilizer gradually increased from 1972, reaching 9.41 Mt K_2O in 2007. China ranks first in the world in K fertilizer imports, consuming 20 percent of total world production. The price of K has increased dramatically in recent years, which has not only suppressed K supply and limited agricultural application, but has also threatened national food security. Efforts have therefore been made to lessen dependence on imported K. Potash is mined in China in salt lakes, but in relatively small amounts. K production in 1980 was only 20,000 mt, but has increased rapidly and by 2005 was supplying 2.54 Mt, constituting 37 percent of the country's use. However, K is very limited in supply in China, accounting for only 2 percent of the total global resource. K production of 3 Mt K_2O per year can only be sustained for about 50 years, and there will always be a dependence on imported K.

Resources of soluble K in China are poor, but non-soluble K resources (K-rich silicon minerals) are very abundant, including feldspars and micas with K (K_2O) content of greater than 10 percent. This potential K resource includes deposits that may be more than 200×10^8 mt (K_2O). In recent years some companies have been exploring possibilities of developing K fertilizer from these non-soluble minerals. Additionally, efforts have been made to mine K resources abroad, in collaboration with foreign countries, in order to compensate for the deficiency of soluble K as a natural resource in China.

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Regional Activities/China

Research Findings

The Saga of the Agricultural Development of the Brazilian Cerrado

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Introduction

The advancement of Brazilian agribusiness, which represented 23 percent of Brazil's GNP in 2006, has been a remarkable development in the evolution of the Brazilian economy over the past three decades (Lopes and Daher, 2008). A key factor regulating this agricultural progress has been the use of adequate nutrient management techniques ensuring that Brazil is very productive. This point is illustrated by the fact that during the period of 1992 to 2011, the area cultivated with grain crops in Brazil increased from 35.6 million hectares (ha) to 48.6 million hectares (40 percent rise), with a corresponding increase in grain production from 68.3 million tonnes to 160.1 million tonnes (230 percent), and a growth of fertilizer sales from 9.3 million tonnes to 28.3 million tonnes (300 percent). These figures represent geometric annual growth rates of 1.93 percent in cultivated area, 4.77 percent in grain production, and 5.55 percent in fertilizer sales.

One of the key factors in this development has been the expansion of agriculture and beef cattle production in the Cerrado, an area regarded as unfit for farming until the beginning of the 1960's (see Map 1). Norman Borlaug, Nobel Peace Prize Laureate and known as "The father of the Green Revolution", once said that "nobody thought these soils were ever going to be productive". The Cerrado, with more than 200 million ha plays an enormous role in agricultural production, and can nowadays be considered one of the world's great breadbaskets. As the second largest Brazilian biome, the region has a rich biodiversity, which can be used for the production of food, feed, fiber, and fuel, as well as timber, medicinal and ornamental plants.

This paper presents information about the Brazilian Cerrado considering both its potential as well as its limitations, while focusing on various practices, including nutrient management necessary to overcome soil fertility constraints and achieve successful agricultural production in the region.

Map 1. South America and distribution of the Cerrado region in Brazil (marked in green). *Source:* Adapted from Lopes and Guilherme, 1994. The Brazilian Cerrado is 2.04 million km^2, 23 percent of the total area of Brazil.

The Cerrado region in Brazil

The area under Cerrado (savanna) vegetation in central Brazil occupies 2.04 million km^2 or 23 percent of the country (see Map 1). It is estimated that 50 percent of this area is adequate for agriculture whilst 66 percent could be incorporated into agriculture/livestock/forestry production. Annual rainfall ranges from 900 to 2,000 mm, usually in the 1,000-1,400 mm range, and the mean annual temperature is 22°C in the south of the region and 27°C in the north (Goedert, 1989). Most of the soils

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(3)Agronomist, PhD; Assistant Scientist, Vale Technological Institute - Mining. silvio.ramos@vale.com in this area are highly weathered Oxisols (46 percent), Ultisols (15 percent), and Entisols (15 percent) (US Soil Taxonomy; see also Map 2), presenting serious limitations for crop production in terms of low natural soil fertility. These soils are acid and are low in available nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), molybdenum (Mo) and zinc (Zn). Additionally the soils are also highly saturated in aluminium (Al^{3+}) which makes them toxic to most crop plants. These soils also have high P fixation capacities (Table 1).

Map 2. Soil map of Brazil and the Cerrado region (marked in red). *Source:* Embrapa solos.

Besides these chemical constraints there are several other limitations to agricultural production in this region (Lopes and Guilherme, 1994):

- Typically a five to six month dry season (April to September).
- Dry spells of one to three weeks during the rainy season, locally known as "veranicos", which are generally associated with high evapotranspiration rates.
- Low soil water holding capacity, even in clayey soils.
- Limited rooting depth of many crops as a consequence of Al toxicity and/or Ca deficiency in sub-surface soil layers.

These points emphasize the need for appropriate management technologies to increase potential for increased agricultural production in Cerrado soils. Despite these problems, a breakthrough in agricultural development has occurred in the region during recent decades, mainly involving food crops, pasture and perennial crops.

Until the 1970s, economic activity in this areas was based on extensive cattle raising, rice cultivation, charcoal production and logging. However, over the past 30 years, agricultural activity has shown an exceptional development. Currently about 98.5 million ha are under agricultural production including 50 million ha under cultivated pastures, 30 million ha as native pasturelands, 15 million ha utilized for annual crops, and 3.5 million ha for perennial crops and forests. The Cerrado accounts for more than 55 percent of Brazilian soybean production, with higher yields than the national average. The region also plays a very important role in the production of other key crops and provides 76 percent of cotton, 31 percent of corn, 18 percent of rice, and 22 percent of beans, with regard to national production of these crops. Agricultural cultivation has been extended recently with an increasing contribution of crops such as sorghum, sunflower, barley, wheat, and rubber, as well as fruits and vegetables for the food processing industry. For livestock, the numbers in the Cerrado are also quite significant, with 42 percent of the 176 million national cattle herd, accounting for 55 percent of Brazilian meat production (Embrapa, 2012).

The agricultural potential of this region is so significant that Dr. Norman Borlaug referred to the Brazilian Cerrado as the last great agricultural frontier of the world (Borlaug and Dowswell, 1993). Estimates suggest that annually the area could produce 250 million tonnes of grains, 12 million tonnes of meat and 90 million tonnes of perennial crops (Macedo, 1995; Lopes and Guilherme, 1994).

Table 1. Chemical properties of 518 composite samples (0-15 cm) of top-soil under Cerrado vegetation in Brazil.

Properties	Cerrado area	Properties	Cerrado area
	%		%
pH in water (<5.0)	50	Organic matter % <2.0	17
Ca $cmol_c$ /dm^3 <1.5	96	Zn mg/dm^3 Mehlich 1 <1.0	95
Mg $cmol_c$ /dm^3 <0.5	90	Cu mg/dm^3 Mehlich 1 <1.0	70
K $cmol_c$ /dm^3 <0.15	85	Mn mg/dm^3 Mehlich 1 <5.0	37
Al $cmol_c$ /dm^3 >1.0	15	N deficiency	32
Effective CEC $cmol_c$ /dm^3 <4.0	97	S-SO_4^{2-} deficiency	70
Al saturation of effective CEC >40%	79	B deficiency	60
P mg/dm^3 Mehlich 1 <2.0	92		

Source: Adapted from Lopes and Cox, 1977; and Malavolta and Kliemann, 1985.

Nutrient consumption in Brazilian agriculture and in the Cerrado region

NPK consumption has been rising steadily over the years, with a geometric annual growth rate of 4.9 percent from 1970 till 2011 (5.4, 3.82 and 5.86 percent for N, P_2O_5 and K_2O, respectively) (Fig. 1). The high demand for K relates to the crops grown in the area. Soybean – a highly demanding K crop – accounts for up to 35 percent of the Brazilian fertilizer market share, followed by corn and sugarcane, which also take up large amounts of K (Fig. 2). Over the past two decades, the use of more intense crop rotations, with the exponential rise of the no-till area in Brazil and the increased production of these high K extracting crops (e.g. soybean, corn and sugarcane), has significantly increased K removal from Brazilian soils. This is noteworthy because K plays a significant role in enhancing crop quality in Brazilian agribusiness, i.e. it improves the physical and chemical quality of sugarcane and the fiber quality of cotton. K also plays an important role in enhancing N fixation in soybean and increasing the quality of seeds.

One of the key factors leading to improved agricultural production and yield in the Cerrado region has been the increase in the efficient use of fertilizers, especially N, P and K. In 1970/71, at the beginning of the Cerrado agriculture expansion in Brazil, the average consumption of N, P_2O_5, and K_2O in Brazil was only 7.7, 11.5 and 8.5 kg ha^{-1}, respectively. The total cultivated area was 36 million ha and the production of 16 major crops (dry basis) was 52 million tonnes, with an average yield of 1.4 mt ha^{-1}. By contrast, in 2010/2011, the average consumption of N, P_2O_5, and K_2O was estimated to reach 39.9, 52.4, and 49.2 kg ha^{-1}, respectively, representing an increase of 5.2, 4.6, and 5.8 times the rate of consumption compared with 1970/71. The cultivated area reached

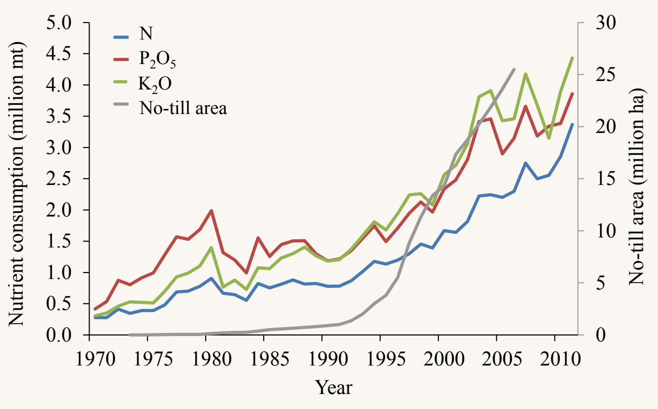

Fig. 1. Growth of N, P_2O_5 and K_2O consumption in Brazilian agriculture from 1970 to 2011, plotted together with the expansion of the no-till area in Brazil from 1973 to 2006.

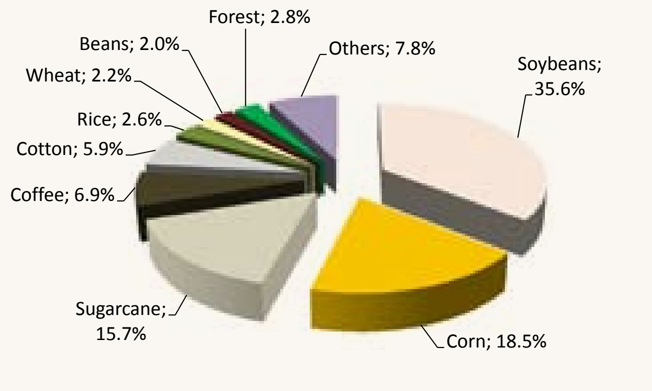

Fig. 2. Brazilian fertilizer market share by crop in 2011. *Source:* ANDA.

64 million ha in 2009/2010, with a total production of 258 million mt of 16 major crops and a yield of 4.0 mt ha^{-1}. These data represent a 1.8 fold increase in cultivated area, with a corresponding 2.9 fold increase in yield (from 1.4 to 4.0 mt ha^{-1}), leading to five times the total increase in production. The estimated area spared from this increase in yield – which has a lot to do with adequate use of nutrients – was 77 million ha of land, an area equivalent to half of the Amazon State in Brazil.

These data also reveal that K was the nutrient with the highest increase in use, especially over the two most recent cropping seasons (2010/11) in Brazil (Fig. 1). Indeed, when comparing the data for total nutrient consumption for 2011 with that of 1970, a 14.4 fold increase in K_2O consumption took place during this period, as compared with a 12.2 fold increase in N, and 9.3 fold increase in P_2O_5. This important growth in nutrient consumption has occurred mainly in the last two decades, starting with the expansion of the no-till area in Brazil and reaching 25.5 million ha in 2006, much of which took place in the Cerrado region (11.9 million ha under no-till in 2006).

That the largest relative increase in consumption was for K_2O, as compared with N and P_2O_5, is noteworthy. While contributing to an increase in production and yield of Brazilian agriculture, it has been shown that the adequate use of K in the Cerrado has many additional benefits, including reduction of water and thermal stresses, improved quality of agricultural products, increased protein synthesis, better fruit set, and higher N fixation in legumes.

Fertilization and soil management practices

Liming

Liming is an essential management practice for non-acid tolerant crops to correct low pH and Al toxicity (Table 2). The average rates of lime are 3 mt ha^{-1} (range 1 to 5), broadcast and incorporated into the soil profile as deep as possible to help increase rooting depth and, thus, tolerance to dry spells during the cropping (rainy) season. For established perennial crops, improved pastures and grain crops under no-till or minimum tillage, rates of lime are in general 25 percent of normal rates.

Since most of these low pH soils are also deficient in Ca and Mg, dolomitic lime or Mg lime are commonly recommended. The method generally used to evaluate lime needs in the region is that of an increase in base saturation, the rate of lime being determined by the following equation:

$$\text{Rate of lime (mt ha}^{-1}\text{)} = T\,(V2 - V1)/100$$

where T = CEC at pH 7.0; V2 = base saturation adequate for a given crop and V1 = base saturation at pH 7.0 (Quaggio *et al.*, 1983).

Table 2. Economic balance of the liming effect on three crops in Brazil.

Lime rate in the first year	Production increase after liming First year	 Period under review
mt ha⁻¹	--------------------*kg ha⁻¹*--------------------	
Five years of corn		
3.0	422	7,877
6.0	600	11,619
9.0	1,250	13,777
Three years of soybean		
1.5	473	1,746
3.0	513	2,357
4.5	645	2,610
Four years of cotton		
1.5	32	1,072
3.0	245	2,609
6.0	442	4,092

Source: Raij and Quaggio, 1984.

For most crops, V2 values are 50 percent and the Ca:Mg ratio must be maintained between 1:1 and 10:1, with a minimum of 0.5 $cmol_c$ Mg/dm^3 (Sousa and Lobato, 2004). The residual effects of these lime rates can vary from three to five years. Lime should be broadcast and incorporated at least 60 to 90 days before planting or fertilization.

Amelioration of subsoil acidity

In most cases the beneficial reactions of lime occur only in the incorporation layer. Low levels of Ca and Al toxicity may still restrict rooting depth in sub-surface soil layers (Lopes, 1983; Goedert, 1987). Under these conditions the application of agricultural gypsum, a by-product of phosphoric acid production, has been shown to be an efficient management practice to increase rooting depth below the surface layer (Photo 1).

It is extremely important to evaluate acidity parameters (pH, Ca and Al levels) in the surface layer (0-20 cm), and to depths of 20 to 40 and 40 to 60 cm. For perennial crops, evaluations should also include the 60 to 80 cm depth. For areas with 0.3 $cmol_c$ Ca/dm^3 or less, and/or 0.5 $cmol_c$ Al/dm^3 or more, and/or more than 30 percent Al saturation of the effective CEC in these sub-surface layers, the use of agricultural gypsum at higher rates is recommended to enable the movement of Ca down these layers and/or to reduce Al toxicity throughout the soil profile (Lopes, 1983; Lopes, 1986). The simplest soil parameter to evaluate rates of gypsum under these conditions is the clay percentage.Two approaches are most commonly used:

- Rate of gypsum (kg ha^{-1}) = 300 + (20 x % clay), developed by Lopes and Guilherme (1994), to improve the 20 to 40 cm layer.

- Rate of gypsum (kg ha^{-1}) = 50 x % clay, developed by Sousa and Lobato (2004), to improve the 20 to 60 cm layer. For perennial crops, multiply the results by 1.5.

Increase in yields from gypsum use in these soils is mainly a consequence of greater rooting depth and more efficient use of sub-soil water and nutrients. Agronomic responses from gypsum use have been reported as: 72, 59, 14, 30, and 80 percent for corn, wheat, soybean, coffee and lucerne, respectively. Significant responses have also been obtained for mango, orange and sugarcane (Sousa, Lobato and Rein, 1995). The recommended rates of gypsum are generally surface broadcast at 60 to 90 days after liming. Residual effects last from 5 to 15 years.

Photo 1. Cotton root development in depth without (left) and with (right) application of 3 mt gypsum ha^{-1}. Each square is 15 cm by 15 cm. Photo courtesy of D.M.G. Sousa. *Source:* Sousa and Rein, 2009.

Build-up of phosphate fertilization

These soils are extremely low in available P so building up phosphate fertility has been a crucial step in achieving adequate and economic yields over a short period of time. Average available soil P content is 0.4 mg/dm^3, and soil P fixation capacity is extremely high. There is a well-defined relationship between clay percentage, since most of these soils have low activity clay minerals, and application rate of P needed to build levels of soil P. In general, high clay content is related to high P fixation capacity. Consequently, fine-textured soils, such as clay loam soils, have a greater P fixing capacity than sandy coarse-textured soils. Clays of the 1:1 type (kaolinite) have a greater P fixing capacity than the 2:1 type clays (montmorillonite, illite, vermiculite). Soils formed under high rainfall and high temperatures, like Cerrado soils, contain large amounts of kaolinitic clays and therefore have a much greater P fixing capacity than soils containing the 2:1 type clay. High temperatures and high rainfall also increase the amount of Fe and Al oxides in the soil, which contribute greatly to the fixation of P added to the Cerrado soil.

Table 3. Recommended application rate for total build-up of P fertilization for the Cerrado region based upon clay percentage.

Clay	Extractable soil P level					
	Upland systems			Irrigated systems		
	Very Low	Low	Medium	Very Low	Low	Medium
%	---kg P_2O_5 ha^{-1}*---					
≤15	60	30	15	90	45	20
16-35	100	50	25	150	75	40
36-60	200	100	50	300	150	75
>60	280	140	70	420	210	105

*For acidulated phosphates: P_2O_5 soluble in neutral ammonium citrate plus water. For thermal phosphates and basic slags: P_2O_5 soluble in 2% citric acid (1:100 ratio). For reactive natural phosphates: total P_2O_5.

Source: Adapted from Sousa and Lobato, 2004.

According to Lopes (1983), for each one percent of clay, 3 to 5 kg of soluble P_2O_5 is required, generally broadcast in the first year and incorporated by disking before planting, followed by small maintenance crop fertilization to achieve the desired yield goal within three years of incorporation. More detailed recommendations for build-up P fertilization, based upon clay content, level of soil available P, under rainfed or irrigation are presented in Table 3. Higher doses are required for soils containing very low levels of soil P, as well as for soils containing higher amounts of clay. If a soil has an adequate P content, then the build-up P fertilization is not recommended.

Another common approach to gradually building up P status in these soils is to apply a little excess P_2O_5 at planting (30-40 kg ha^{-1} above normal maintenance crop fertilization). This rate should be applied for five to six years. After P soil levels reach medium to high levels, then only maintenance fertilization is used. For grain crops, sugarcane and coffee, soluble P fertilizers (i.e. single superphosphate, triple superphosphate, thermophosphate or highly reactive rock phosphates) have been confirmed as the most efficient sources for use following liming. Due to the low reactivity of most Brazilian rock phosphates, these products are usually only recommended for direct application when opening new areas with pastures of acid tolerant species (Smyth and Sanchez, 1982; Goedert and Lobato, 1984; Goedert and Lopes, 1988). Since liming reduces the agronomic effectiveness of low reactivity rock phosphates even more, lime in these cases is recommended at 25 percent of normal rates (Lopes and Guidolin, 1989).

Table 4. Recommendation of build-up K fertilization for the Cerrado region.

Extractable soil K	Interpretation	Total build-up	Gradual build-up
mg/dm^3		*kg K_2O ha^{-1}*	
CEC at pH 7.0 less than 4.0 cmol$_c$/dm^3			
≤15	Low	50	70
16-30	Medium	25	60
31-40	Adequate[1]	0	0
>40	High[2]	0	0
CEC at pH 7.0 more than or equal to 4.0 cmol$_c$/dm^3			
≤25	Low	100	80
26-50	Medium	50	60
51-80	Adequate[1]	0	0
>80	High[2]	0	0

[1] For soils with adequate level of extractable K, rates of K_2O are recommended according to expected yield.

[2] For soils with high level of extractable K, rates of K_2O of 50 percent of the maintenance fertilization or expected/estimated K extraction are recommended in the last production.

Source: Adapted from Sousa and Lobato, 2004.

Build-up of potash fertilization

Building-up levels of K is also recommended for soils with low or medium extractable K. Rates are also estimated according to CEC at pH 7.0 (Table 4). Soils with CEC at pH 7.0 of less than 4.0 cmol$_c$/dm^3 present a high potential for leaching losses (Mclean and Watson, 1985). Under these conditions rates above 40 kg ha^{-1} K_2O must be split in band applications or applied broadcast. Rates to total build-up of K fertilization for broadcast application can also be calculated to achieve 3 to 5 percent K saturation of CEC at pH 7.0 (Lopes and Guidolin, 1989).

Role of K in the growth of soybean crop

Potassium is one of the major nutrients considered essential for crop growth and yield development, even though it is not an integral component of any cellular organelle or structural part of the plant. It is the most abundant cation in plants and is associated or involved with many of the physiological processes supporting plant growth and development. Water relations, photosynthesis, assimilate transport and enzyme activation are all affected by K (Pettigrew, 2008). Furthermore, Mengel (1980) also demonstrated that the transport of amino acids is enhanced by higher K levels, especially the transport of amino acids to developing seeds.

With regard to the demand of K_2O for agricultural crops in Brazil, soybean cultivation is ranked first, due to its high cultivated area (about 25 million ha in 2012) (IBGE, 2012).

According to Sacramento and Rosolem (1998), K plays a particularly important role in the mineral nutrition of soybean since K is one of the macronutrients taken up and translocated within the crop in highest amounts. One of the more obvious visual symptoms of insufficient levels of plant K is a reduction in plant growth (Pettigrew and Meredith, 1997). This reduction in biomass occurs because soybean plants growing under K deficiency often have a marked decrease in leaf area and size (Lana *et al.*, 2002).

To achieve or maintain maximum yields, supplemental K_2O fertilization is often required, particularly in Cerrado soils. Many researchers have reported soybean yield increases in response to K_2O fertilization. Lana *et al.* (2002) found that increased soybean yield under high K fertility was due to increasing production of both total and main stem pods per plant and more seeds per pod. The positive yield response to K can also be attributed to increases in most of the yield components, e.g. the number of pods per plant (Lana *et al.*, 2002), the weight of individual seeds (Serafim *et al.*, 2012), and increased number of nodules and N fixation in some soybean cultivars (Novo *et al.*, 1999). K thus not only promotes the production of carbohydrates in the leaves but also enhances their transport to the root system for use as an energy source for nodule formation, thereby stimulating N_2 fixation (Armstrong, 1998). Moreover, in Cerrado soils, where water is a major limiting factor for successful soybean production, K may temper water stress due to its role in cell turgor control and metabolic activity.

K can play a role in quality development of many crops (Usherwood, 1985). In soybean, Tanaka *et al.* (1995) found K fertilization increases seed oil content. Soybean seeds also contain isoflavones, a group of phytochemicals thought to provide human health benefits. Yin and Vyn (2004) reported that K fertilization increased the isoflavone concentration of the seeds.

Build-up of micronutrient fertilization

The concept of building-up fertility of Cerrado soils also includes micronutrients. Micronutrient fertilizers can be broadcast to those soils with naturally low micronutrient availability (Zn, Cu, B, Mn, and Mo). When these micronutrients are at a low level, a broadcast application is recommended of: 2, 2, 6, 0.4 and 6 kg ha^{-1} of B, Cu, Mn, Mo and Zn, respectively. These rates can be split into three band applications, annually. At medium level, 25 percent of these rates are recommended on band applications. At a high level of available micronutrients, application is not recommended.

Organic matter management

The great majority of Cerrado soils contain low activity clays, medium organic matter content and very low CEC, more than 70 percent of which is due to the organic fraction. Under management systems that include monocropping, conventional tillage and use of lime and fertilizers, organic matter depletion occurs quickly and can reach unsustainable levels after a few years of cultivation. Under these conditions it is extremely important to make use of a combination of more sustainable agricultural practices to avoid rapid declines in organic matter content.

Practices such as crop rotation including improved pastures, green manure, minimum or no-tillage, cover crops, mulching in the case of small farms, manure and adequate crop residues are all important management tools. The rapid increase in no-till in the region in recent years is certainly a key factor for future sustainable agricultural development.

Maintenance fertilization

Following the build-up program, adequate and balanced maintenance programs are essential to maintain soil fertility and optimum crop production potential. Maintenance fertilization for primary micronutrients is generally based on expected yield, soil and plant analysis.

Final remarks

During the last 50 years, the Cerrado region has changed from an area once considered marginal for agricultural production to that of high agricultural productivity; an example of an agricultural revolution. A great investment in research in several agronomic areas over this period has enabled the development of a number of management strategies that has allowed the Cerrado to become one of the most productive regions in Brazil in terms of grain, beef cattle, and agro-energy production, as well as reforestation. In addition, in order to become an example of "green agriculture", a series of more sustainable management technologies have been introduced to this region in recent years including:

- Increasing use of crop rotation and cover crops (e.g. Photo 2).
- No till and/or minimum tillage: in 1990 Brazilian farmers used no-till farming for 2.6 percent of their grain crops; today it is over 50 percent.
- Integration of crop-livestock production and/or crop-livestock-forest production (e.g. Photo 3): eucalyptus is one of the species most used in commercial systems, but over 100 useful species have been identified for agroforestry systems in the Cerrado (Schorr, 2001).

Photo 2. Brachiaria as a cover crop in maize field.
Source: Courtesy of R. Trecenti.

Photo 3. Crop-livestock-forest production system.
Source: Courtesy of R. Trecenti.

We believe that harmonious coexistence of agribusiness with the rational use of natural resources in this region – aiming at a more sustainable production process – requires not only increasing research efforts on various agronomic issues but also actions to remove several logistical problems. Among the numerous factors that limit a more robust growth of agricultural production in this region, two are worth mentioning: inadequate physical infrastructure and transport. Transport and logistical issues affect not only the final price of the agricultural output, but also the supply of competitively priced inputs to agriculture which, in the case of the Cerrado region, is strategic, since sustainable production is highly dependent on an adequate supply of lime and fertilizers, among other agronomic inputs.

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The paper "The Saga of the Agricultural Development of the Brazilian Cerrado" also appears on the IPI website at:

Regional Activities/Latin America

Research Findings

Potash Fertilizers in Africa: Background, Assessment and Prospects

Wendt, J.⁽¹⁾

Introduction

The African continent will face unprecedented challenges in food production and increased pressures on its natural resources in the 21st century. Projections suggest that the African population will continue to increase well into the 21st century, from some 800 million in 2000 to 2.2 billion in 2050 and 3.6 billion by 2100 (Fig. 1). Malnutrition rates in sub-Saharan Africa (SSA) are the highest in the world, with some 30 percent of the population living in chronic hunger (FAO, 2010), a rate that has remained stubbornly high for the past two decades. Combined with a burgeoning population (both current and projected), this implies that the absolute number of undernourished people is increasing.

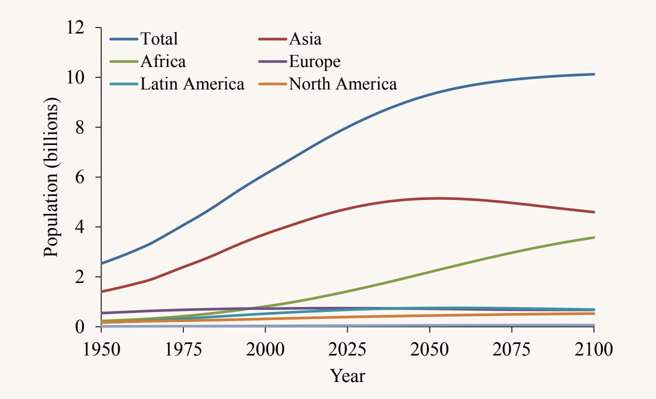

Fig. 1. Medium variant projections of population growth for various regions of the world. *Source:* Collated from UNDP, 2010.

This paper examines some of the fundamental causes of low agricultural productivity in SSA and suggests that market-driven solutions can dramatically increase food security. The role of mineral fertilizer nutrients in achieving and sustaining increased productivity is highlighted, with particular attention to potassium (K), a macronutrient of emerging interest.

In terms of this paper, the term SSA will be used to denote sub-Saharan Africa excluding South Africa. The SSA region is characterized by low agricultural productivity (production per land unit), in contrast to South Africa and Northern African countries primarily in the Sahara (Algeria, Egypt, Libya, Morocco, Sudan, Tunisia and Western Sahara).

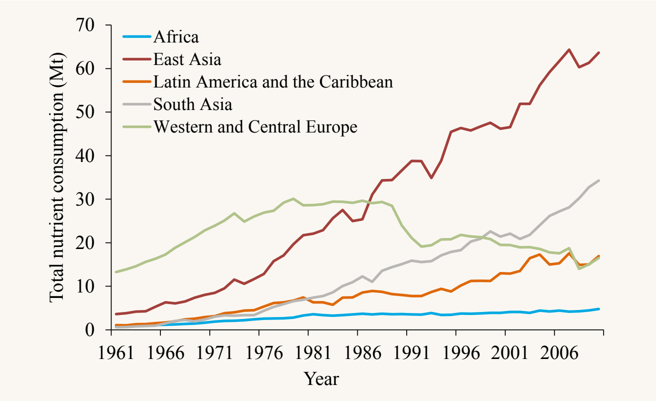

Fig. 2. Nutrient consumption (NPK) in regions, 1961-today. The term "Africa" includes North African countries, sub-Saharan Africa and South Africa. *Source:* IFA.

Agricultural development

SSA is characterized by a diversity of soil types (Map 1), agro-ecological zones (Map 2) and cropping systems, with some similarities to those of South America.

SSA largely missed the Green Revolution of the 1950s-1970s, which led to dramatic increases in productivity throughout the world due to the use of improved germplasm, mineral fertilizers, irrigation and good management practices. Mineral fertilizer use is fundamental to increasing yields and replacing nutrients removed in harvested products and loss through volatilization (i.e. nitrogen), leaching and soil erosion. The increase in N, P and K consumption in Asia and Latin America over this time was huge, while consumption in Africa stagnated (Fig. 2). Currently, some 13 percent of the world's cultivated area is in SSA, yet the region accounts for less than one percent of global fertilizer use (Fig. 3). The result is that yields in SSA have increased slowly relative to the rest of the world (Fig. 4).

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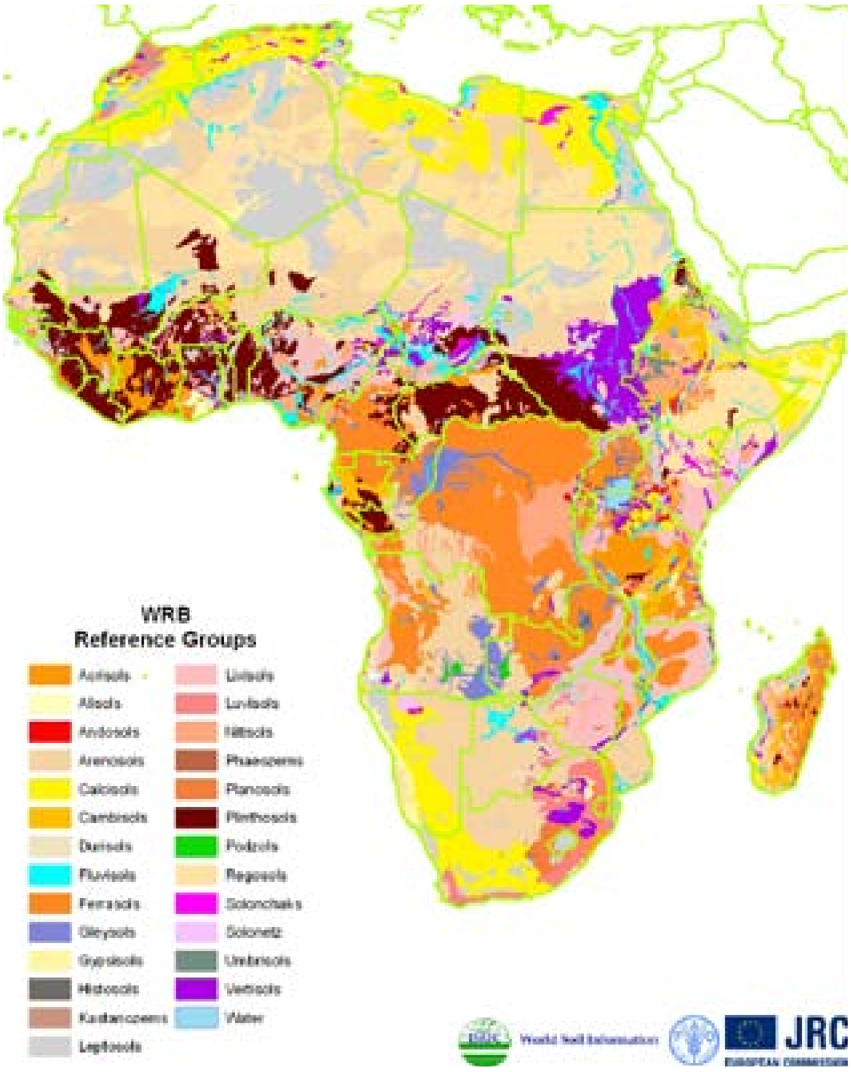
In spite of this stagnation in SSA yields, overall food production has just managed to outpace the dramatic population increases. Population in SSA increased by 370 percent from 1961 to 2010, and food energy value produced increased by 122 percent (from 1,955 to 2,380 kcal per person per day; FAOSTAT). However, this did not translate into a reduction in the percentage affected by malnutrition, as increasing urban populations consumed most of the calorie increase. The number of malnourished in SSA increased about three-fold – from 88 million in 1970 to 239 million in 2010.

Overall production increases are due largely to expansion of agricultural lands. Table 1 shows that while food commodity yields increased modestly from 1961 to 2010, total land area devoted to production of food commodities increased by 227 percent (a process known as extensification). Production increases (the product of yield and land area increases) ranged from 235 percent to 758 percent across commodity groups. Moreover, even the increase in productivity from 1961 to 2010 leaves yields per hectare well below 2010 world averages, with most commodity yields varying from one third to half of the global average (Table 1). In sum, while the rest of the world was achieving increased food security from higher crop yields generated by the use of



Map 1. Major soil types of Africa.
Source: http://eusoils.jrc.ec.europa.eu/library/maps/africa_atlas/images/COVER.pdf

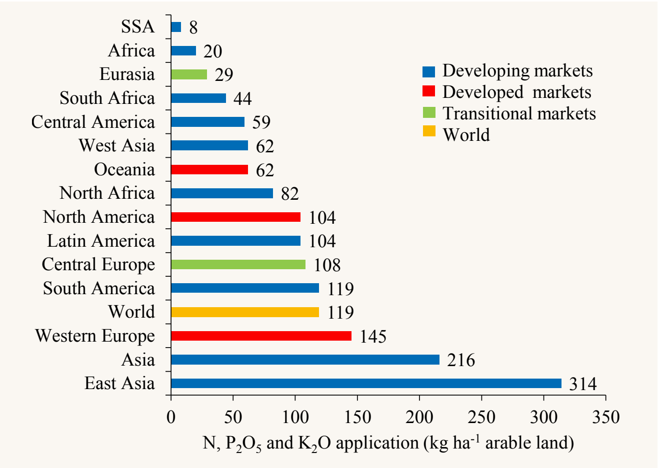


Fig. 3. Fertilizer use (kg ha^{-1}) for various regions and markets, 2010. *Source:* IFDC, derived from FAOSTAT.

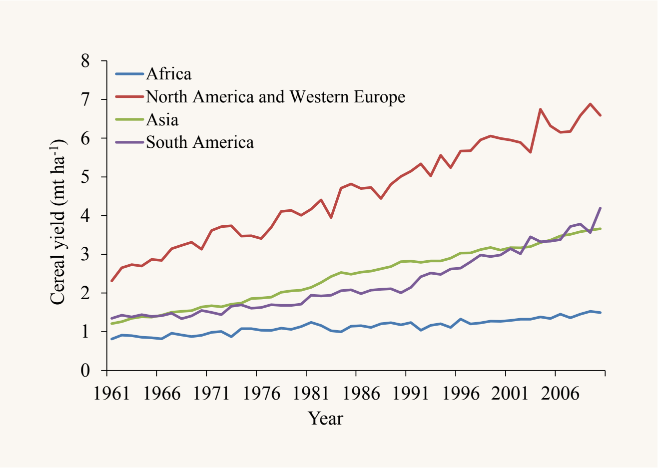
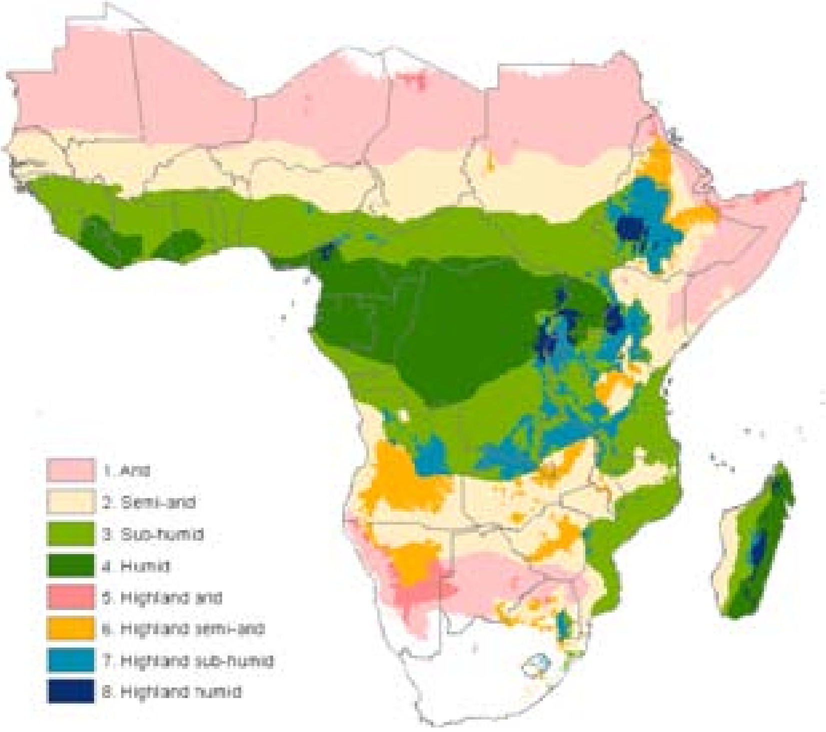


Fig. 4. Cereal yields in various parts of the world, 1961-2010. *Source:* Compiled from FAOSTAT.

improved seeds and nutrients delivered by mineral fertilizers, SSA was increasing production primarily through expansion of agricultural lands with minimal mineral nutrient inputs.

The practice of increasing overall productivity primarily through land expansion has several undesirable consequences. At farm level, low yields translate to high production costs per harvested unit. As a result of its low competitiveness, Africa's share of global agricultural trade declined from eight percent in 1965 to a paltry three percent by 2000. Low productivity also threatens other eco-systems: Henao and Baanante (2006) estimated that some 50,000 ha of forest and 60,000 ha of grassland are lost annually in Africa due to agricultural land expansion. Moreover, increasingly shorter fallow periods are inadequate for soil fertility regeneration. Poor productivity also decreases soil vegetative cover and



Map 2. Agro-ecological zones for sub-Saharan Africa based on FAO/IIASA methodology. *Source:* HarvestChoice/IFPRI, 2009.

Table 1. Changes in yield, land area and production for various commodity groups in SSA from 1961-2010, and world average yields for commodity groups, 2010.

					Change 2010 relative to 1961			
Commodity group	Year	Yield	Area	Production	Yield	Land area	Production	As proportion of food crop area
		mt ha^{-1}	*ha*	*mt*	----------------	-------%-------	----------------	
Cereals	SSA 1961	0.73	39,400,000	28,740,000				54
	SSA 2010	1.22	81,070,000	98,520,000	167	206	343	49
	World 2010	*3.23*						
Oil crops	SSA 1961	0.25	13,640,000	3,370,000				19
	SSA 2010	0.33	24,190,000	7,900,000	132	177	235	15
	World 2010	*0.63*						
Roots and tubers	SSA 1961	5.7	8,070,000	46,340,000				11
	SSA 2010	9.0	22,810,000	206,190,000	157	283	445	14
	World 2010	*13.9*						
Pulses	SSA 1961	0.48	6,090,000	2,940,000				8
	SSA 2010	0.61	20,370,000	12,470,000	127	334	425	12
	World 2010	*0.88*						
Fruits	SSA 1961	5.05	3,420,000	17,270,000				5
	SSA 2010	6.30	8,640,000	54,420,000	125	253	315	5
	World 2010	*10.92*						
Vegetables	SSA 1961	4.68	1,470,000	6,890,000				2
	SSA 2010	5.90	4,960,000	29,240,000	126	337	426	3
	World 2010	*18.98*						
Tree nuts	SSA 1961	0.61	330,000	200,000				0.5
	SSA 2010	0.72	2,130,000	1,540,000	117	645	758	1.3
	World 2010	*1.33*						
Total			72,420,000					
			164,170,000			227		

Source: Compiled from FAOSTAT.

water transpiration, which in turn results in increased erosion and nutrient leaching through the soil – thus perpetuating a downward spiral of soil fertility. Henao and Baanante (2006) warned that some 95 million ha of agricultural lands (40 percent of total African farmland) were reaching such a state of degradation that the large investments required to return them to productivity would not be economically justifiable.

Nutrient losses in Africa

Monitoring annual nutrient losses on a scale as large as Africa is a complex task that must take into account soil type (Map 1), agro-ecological zone (Map 2), topography and land use. Building on the nutrient depletion work by Stoorvogel and Smaling (1990, 1993, 1998), Henao and Baanante (2006) estimated soil nutrient balances for Africa. Inputs include fertilizers, organic residues and manures, nitrogen fixation and sedimentation, while outflows include losses from soil erosion, leaching, volatilization and crop removal.

Table 2 (derived from Henao and Baanante, 2006) shows current major sources of nutrient losses and inflows in various agro-ecological zones of Africa. Under the low yield scenario prevalent throughout most of Africa, crop removal (harvest plus crop residues) accounts for some 43 percent of N, 87 percent of P and 73 percent of K losses. (This calculation excludes the Mediterranean and arid North Africa, which are not part of SSA and receive high fertilizer inputs.) Erosion accounts for an additional 43 percent of N loss. As yields increase due to appropriate fertilization, one would expect reductions in the proportion of nutrients lost by means other than crop and residue removal.

Increased fertilizer use increases crop production (grain and biomass), thereby providing additional benefits beyond the yield increases. Because biomass in SSA is primarily used for livestock fodder or for cooking fuel, additional production increases the possibilities for a larger portion remaining on or being returned to the field. Crop residues left on the field are important in preventing the loss of topsoil, maintaining soil organic matter and recycling crop nutrients, particularly K.

Potassium availability in African soils

Given the diversity of environments in Africa, one cannot refer to K in African soils in general, but must highlight the diversity of K availability in African soils. No simple soil test exists to evaluate K availability for all soils, but ammonium acetate-exchangeable K (which correlates closely with other methods such as the

Table 2. Estimated nutrient losses and gains in various agro-ecological zones of Africa.

Region/nutrient	Annual nutrient losses (2002-2004 average)					Annual nutrient gains and inflows (2002-2004 average)						Total
	Harvest	Residues	Leaching	Gaseous	Erosion	Manure	Deposition	Fixation	Sediments	Fallow	Fertilizer	
	----------	----------	----------	----------	----------	kg ha^{-1} yr^{-1}	----------	----------	----------	----------	----------	
Humid Central												
N	-11.3	-3.4	-4.7	-9.3	-18.8	0.2	2.8	4.2	0.1	1.9	1.1	-37.2
P_2O_5	-4.2	-2.9			-1.4	0.1	0.9		0.1	1.9	0.8	-4.7
K_2O	-10.1	-3.7	-4.4		-2.9	0.3	2.4		0.1	1.9	1.1	-15.3
Humid and Sub-Humid West												
N	-16.3	-6.1	-3.2	-4.6	-18.8	1.4	3.6	4.7	0.8	0.7	2.9	-34.9
P_2O_5	-6	-2.7			-1.4	0.7	1.3		0.3	0.7	1.5	-5.6
K_2O	-12.6	-6.2	-3.3		-2.9	2.8	2.8		0.8	0.4	1.1	-17.1
Mediterranean and Arid North												
N	-31.5	-7.6	-2.7	-4.3	-17.3	0.9	1.7	3	0.7	1.3	41	-14.8
P_2O_5	-9.1	-3.1			-1.3	0.5	0.6		0.3	1.3	10.2	-0.6
K_2O	-13.3	-3.3	-3		-2.1	0.8	1.3		0.4	0.7	5	-13.5
Sub-Humid and Mountain East												
N	-17.4	-6.5	-3.6	-5.2	-13.5	1.2	2.7	3.6	0.6	0.6	7.3	-30.2
P_2O_5	-6.9	-3.2			-1	0.6	1		0.3	0.6	3.1	-5.5
K_2O	-13.5	-6.2	-2.7		-2.1	1.4	2.2		0.5	0.3	0.9	-19.2
Sudano-Sahelian												
N	-13.5	-3.7	-4.2	-7.3	-18.4	1.7	2.4	4.2	0.7	1.4	3	-33.7
P_2O_5	-5.3	-2.1			-1.4	0.8	0.8		0.2	1.4	0.7	-4.9
K_2O	-10	-3.8	-4.8		-2.5	3.1	1.8		0.4	0.7	0.5	-14.6
Sub-Humid and Semi-Arid Southern												
N	-24.4	-6.6	-5.3	-7.6	-19	1.6	3.1	4.9	0.7	1.7	23.8	-27.1
P_2O_5	-10.5	-4.4			-1.5	0.6	0.1		0.1	1.7	8.8	-5.1
K_2O	-17.5	-6.6	-3.8		-3	3	2.5		0.6	0.8	7.2	-16.8

Source: Summarized from Henao and Baanante, 2006.

Mehlich-3 or dilute acid solutions) is a commonly used method. The Booker Tropical Soils Manual (1984) highlights the various interpretations of the exchangeable K value. Deficiency limits of <0.20 meq 100 g^{-1} is the norm for Malawi, <0.25 meq 100 g^{-1} for the USA, <0.50 meq 100 g^{-1} for New Zealand and <0.15 meq 100 g^{-1} for the UK. For sandy, sandy loam and red-brown clays in Zimbabwe the critical K values are 0.05, 0.10 and 0.15 meq 100 g^{-1}, respectively. Maria and Yost (2006) report critical K norms of 0.1, 0.2, and 0.4 meq 100 g^{-1} for respective sandy, intermediate and clay soils in Mozambique.

However, potassium availability is not solely a function of exchangeable K. An exchangeable K value of 0.2 meq 100 g^{-1} represents some 78 parts per million (ppm) exchangeable K, which would equate to 203 kg of K in the upper 20 cm of a soil with a bulk density of 1.3 g cm^{-3}. This is a relatively small K quantity that would be completely depleted after two to three 5 mt ha^{-1} maize harvests with residue removal. Soils have non-exchangeable and labile (gradually available) K reserves, held primarily in 2:1 clay minerals such as smectites and illites, which are gradually released and as such buffer K supply. These minerals are generally associated with less weathered soils. Because of this buffering capacity, some soils can be cropped for many decades without depleting K reserves, particularly if plant residues, which contain substantial quantities of K, are recycled. In contrast, N and P reserves are generally depleted more rapidly, particularly with cereal crops, and crop response to N and P can often be observed without K application, whereas the reverse is less commonly true. Under conditions of low fertilizer use that prevail throughout SSA, low yields limit K removal, though notable exceptions exist, and are discussed below.

Exchangeable K levels vary widely in Africa. Kanyanjua *et al.* (2006) found exchangeable K levels in Kenya ranging from 0.2 to 1.8 meq 100 g^{-1}, and found that maize in low K soils began to show K response only after continuous cropping with N and P fertilizers. In an extensive sampling of soil types in Mozambique, Geurtz and Van den Berg (1998) found exchangeable K values in Acrisols, Arenosols, Ferralsols, Lixisols and Luvisols to average 0.98, 0.26, 0.36, 0.53 and 0.83 meq 100 g^{-1} respectively. Similar results were found by Maria and Yost (2006) in a sampling of four of Mozambique's 10 agro-ecological zones, where K levels were found to range from 0.20 to 1.7 meq 100 g^{-1}. In Nigeria, Ataga (1973) found very low K levels in sandy acid soils under palm oil production (0.03-0.11 meq 100 g^{-1}), but higher contents under soils formed from basement complex rocks (0.10-0.32 meq 100 g^{-1}). Acquaye (1973) found exchangeable K levels in Ghanaian soils ranged from 0.12 meq 100 g^{-1} on sandstones to 0.32 meq 100 g^{-1} on basic rocks (average values), and also found that plant K uptake related best to exchangeable K compared to several K indices used to measure K supply. In Tanzania, Hartemink *et al.* (1996) found K levels to be commonly below 0.10 meq 100 g^{-1} in Ferralsols and somewhat higher levels in Acrisols, where K levels averaged 0.5 meq 100 g^{-1} under secondary forest, but declined under bush fallow and continuous sisal cropping.

Decline in soil fertility indices is commonly observed under continuous cropping with no or limited inputs. In most cases, declines in soil organic matter, soil pH and exchangeable bases (Ca, Mg, K) occur together. Some examples of decline include the Tanga Region of Tanzania (Hartemink, 1997), where Ferralsols' and Acrisols' organic matter, pH and exchangeable bases declined significantly from the 1950s and 1960s to the 1980s and 1990s. Hartemink found that, in general, fertility decline in Cambisols and Luvisols was substantially less, though K decline was still considerable in these soils. Mouttapa (1973) noted that the most severe K deficiencies in Africa are in the savanna belt on sandy soils of the humid inter-tropical zone, and stated further that K deficiencies generally occur in the humid forest zone only after many years of continuous cropping, and are seldom found on Cambisols or Luvisols in semi-humid regions. Mukashema (2007) found that soil fertility indices in the Gishwati watershed in the Rwandan highlands declined over a period of 25 years under various land uses, with agricultural land degrading more rapidly than forests or pastures, and sandy acid soils deteriorating more rapidly than soils of volcanic origin. Haefele *et al.* (2004) studying soil fertility changes in Senegal for irrigated rice over 16 seasons (two seasons per year) on Gleysol and Vertisol, found that soil P dropped precipitously when only N was applied, but the exchangeable K decline was much slower. They concluded that the K buffering capacity in these soils was such that yields could be sustained for decades without K addition.

Market-driven strategies for accelerating fertilizer adoption

A seemingly obvious but often neglected fact is that farmers will adopt fertilizers only when fertilizer use is profitable. Most farmers in SSA have limited means, and are more inclined to invest in opportunities that balance the twin objectives of return and risk.

Those promoting nutrient inputs often have a tendency to direct their use to the most broadly cultivated crops – commonly cereal crops such as sorghum or maize. But these crops do not always represent the best return on fertilizer investment. In years of good production, large-scale fertilizer use can result in supply gluts at harvest, particularly in countries with low capacity to store harvest, depressing prices. If farmers are not linked to a specific market opportunity (such as a milling operation or a processor) or do not have access to warehouses to store produce until prices improve, low or even negative returns can result.

In many cases it is the less cultivated crops that can provide the best returns on fertilizer investment. As an example, leguminous crops such as groundnuts and soybeans require a relatively low fertilizer investment (often only P and K) as they fix their own nitrogen, but can result in strong returns as their value is high.

Farmers throughout Africa invest in NPK blends for vegetables, which in general offer good returns on fertilizer investments.

An additional key to accelerating fertilizer consumption is having targeted fertilizer blends. The most available fertilizers in Africa are urea, di-ammonium phosphate and NPK blends, commonly 15:15:15 or 17:17:17. Formulae best suited to specific crops are commonly not available. However, African-based fertilizer blenders are increasingly creating blends for specific vegetables, legumes, cereals and root crops. Some blends now contain secondary and micronutrients to overcome deficiencies that are limiting response to N, P and K in many environments. Until recently, secondary and micronutrients have not been available to many African smallholders. Sulfur is a commonly deficient nutrient, as are the micronutrients zinc and boron. One response to this is providing fertilizers targeted to particular crops in packages as small as 1 kg. Small quantity packages allow farmers to evaluate fertilizer response to different formulae at a small financial risk.

Combining fertilizer nutrients with other agro-inputs also generates profitable synergies. Improved seed is a key input for yield maximization. Minor investments in pesticides can often double legume yields. Herbicides, combined with minimum tillage, can drastically reduce tillage costs and weed pressure, a major cause of yield reduction, particularly in extensive farming systems where farm labor is a constraint. Addressing pests and weeds reduces farmer risk and increases the likelihood that investments in fertilizers will result in greater yields and profits.

A market-driven approach to increased productivity requires functional value chains, which is the objective of the Competitive Agricultural Systems and Enterprises (CASE) approach (Mattman *et al.*, 2011). An important element of CASE is vibrant agribusiness clusters. A cluster is comprised of all the actors required to build a profitable value chain, working together to develop a business opportunity around a specific commodity. Cluster collaborators commonly include farmers and their organizations, input suppliers, finance providers, those adding post-harvest value (processors, warehousing, packagers), marketing parties (traders, transporters and buyers) and business development services, who build capacity through technical advice. The CASE approach was successfully applied in IFDC's "Thousands to Millions" project in West Africa (2006-2010). The project succeeded in increasing fertilizer consumption by almost 100 kg ha^{-1} for some 700,000 farmers, resulting in increased production of 500,000 mt of cereal equivalents and average increases in farmer incomes of 50 percent.

Estimates of future fertilizer requirements, and conclusions

Henao and Baanante (2006) estimated that some 6.7 million tons of N, P and K ($N+P_2O_5+K_2O$) fertilizers would be required annually in SSA to reverse nutrient mining and contribute substantially to yield increases, which represents approximately 4.8 times the 2004 NPK consumption. Delegates to the African Fertilizer Summit (held in 2006 in Abuja, Nigeria) recognized that increased fertilizer use is essential to increasing yields and reversing soil fertility decline in the face of rising population. The *Abuja Declaration on Fertilizer for an African Green Revolution* (NEPAD, 2006) set a fertilizer use goal of 50 kg ha^{-1} by 2015. This amounts to more than a five-fold increase in current fertilizer use for SSA.

The African Union agreed with the tenets of the *Abuja Declaration*, and NEPAD monitors continental progress on a country-by-country basis. Market-driven initiatives show that the 50 kg ha^{-1} usage level is achievable on a broad scale, though not likely by 2015. One question that arises is how much yield SSA would realize if this goal were achieved.

For SSA to move into a more food-secure situation as envisaged by the *Abuja Declaration*, the region would need to produce yields similar to other regions, such as Central America, Western Asia, Northern Africa, Central Asia and South Africa. These regions consume an average of 53 kg ha^{-1} of N, P and K. Collectively, their yields of cereals, pulses, oil crops and roots and tubers are approximately twice that of SSA. Thus, one might roughly expect yields to double if the goals set in the *Abuja Declaration* are achieved. Doubling of yields would lessen the incentive for land expansion, dramatically increase food security and reduce production costs, increasing the competitiveness of SSA on world markets. However, it should be noted that the population of Africa is projected to triple by 2050. Fertilizer use may have to be in the order of 100 kg ha^{-1} of N, P and K by then if demand is to be met by local production. Land expansion may also play a role, but even if new lands are opened, fertilizer use on those lands will have to increase over current average use.

In conclusion, SSA must rapidly accelerate its fertilizer use to reverse environmental degradation and feed its growing population. SSA can draw upon the success of some Latin American and Asian nations which have achieved increasing yields over the past four decades with similar soils, agro-ecologies and cropping systems. Land expansion – extensification – is not a viable alternative to increasing yields through agricultural intensification, as it results in unsustainable production, low productivity and high production costs that render SSA uncompetitive on world markets.

Encouraging fertilizer use requires market-driven approaches. Agribusiness clusters have proven successful in developing profitable value chains and encouraging millions of smallholder farmers to increase productivity, with fertilizers playing a major role in yield increases. Fertilizer blenders across Africa are increasingly important in these clusters, producing blends targeted to specific crops and soil conditions to maximize returns from fertilizers. Other inputs, such as improved seeds and crop protection products, are also important in increasing productivity, are complementary to fertilizers and render fertilizer application more profitable and less risky.

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Regional activities/sub-Saharan Africa

Research Findings

Molecular Biology of K^+ Transport Across the Plant Cell Membrane: What Do we Learn from *Arabidopsis* and Rice Model Plants?

Sassi, A., I. Khan, A.A. Véry, and H. Sentenac(1)

Introduction

Potassium (K^+) can constitute up to 10 percent of total plant dry weight. It is the most abundant cation in the cytosol since it is compatible with protein structure even at high concentrations. At cellular level, this cation is used for basic functions, such as electrical neutralization of anionic groups, control of cell membrane polarization, osmoregulation and regulation of cell turgor (Clarkson and Hanson, 1980; Maathuis and Sanders, 1996). At whole plant level, K^+ is involved in highly complex and integrated functions. For instance, related to its involvement in turgor regulation, K^+ plays a role in tropisms, or guard cell movements, which allow the plant to regulate the aperture of the stomatal pores present at the leaf surface. The importance of these functions probably explains why membrane transport of K^+ has been studied more extensively than other nutrient ions, giving rise to breakthroughs and founding models, such as Epstein's dual mechanism, which proposes that membrane transport of K^+, as well as of most other ion nutrients, results from the activity of both high affinity and low affinity transport mechanisms.

Most of the present knowledge on K^+ transport in plants has been gained by studies using *Arabidopsis thaliana* as a model. It seems that the gene families involved in K^+ transport are strongly conserved across higher plant species, both in terms of family structure and gene numbers, with the exception of the HKT family, which may possess K^+-permeable members in monocots only. This difference suggests that graminaceous and dicotyledonous crops could behave differently regarding K^+ uptake and long distance transport within the plant, but the roles of K^+-permeable HKT transporters are still poorly understood.

In *Arabidopsis thaliana*, the genome encodes about 27,000 proteins. Based on current knowledge, at least 35 contribute to membrane K^+ transport (Mäser *et al.*, 2001). These membrane proteins form two families of K^+ channels, named Shaker and TPK, comprising nine and six members respectively, and two families of K^+ transporters, named HAK (or KT or Kup) and KEA, comprising 13 and six members respectively. In *Arabidopsis*, the single member from the HKT transporter family has been shown to be Na^+-selective (Uozumi *et al.*, 2000). In contrast, in rice, up to four transporters from the HKT family are permeable to K^+ (Corratgé-Faillie *et al.*, 2010). The Shaker and HKT transport systems, and at least part of the HAK and KEA systems, are located at the cell membrane. The TPK channels appear to play an essential role in K^+ transport across the vacuolar membrane. This review focuses on K^+ transport proteins active at the cell membrane and involved in K^+ uptake from the soil solution and transport within the plant.

Here we present the current model of membrane energization and ion transport in plants, and highlight some of the terminology used in this field of plant biology. Then we summarize what is currently known about molecular families of K^+ transport systems active at the plasma membrane, namely the Shaker K^+ channel family and the HAK, HKT and KEA transporter families. This is followed by a brief presentation of the roles that these systems play within the plant, in functions such as: K^+ uptake from the soil by roots; K^+ long distance transport in the xylem and phloem vasculatures; and K^+ accumulation and turgor-driven processes, like pollen tube elongation or guard cell movement, and regulation of transpirational water loss.

Energization of solute transport across the cell membrane in plants

Pioneering physiological analyses of solute uptake in roots in the 1960's and 70's led to the concept of passive and active transport (Maathuis and Sanders, 1996). Uptake of an electrically uncharged solute (e.g. glucose) across the cell membrane from the external solution into the cell is said to be active when it occurs against the concentration gradient of the solute, i.e. when the concentration of the solute is lower in the external solution than in the cytosol. Conversely, the uptake is said to be passive when it occurs down the concentration gradient, i.e. when the external concentration

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When measured in young root periphery cells, this electrical gradient is usually found to lie between -50 and -250 mV, depending on the external ionic conditions (mainly pH and K^+ concentration). Uptake is active, and thus must be directly fueled by membrane mechanisms when it occurs against the ion electrochemical potential μ, as described by the Nernst equation [$\mu = \mu_0 + RTln(C) + zF\Psi$, where C is the ion concentration, z the ion valency, Ψ the electrical potential in the cytosol, and μ_0, R, T and F have their usual meaning (standard electrochemical potential of the ion, ideal gas constant, temperature and Faraday constant, respectively). Conversely, the uptake is said to be passive when it occurs down the ion electrochemical potential. As indicated above, active transport has to be energized. This is achieved by H^+-excreting ATPases active at the cell membrane. H^+-pumping out of the cell by these enzymes, fueled by ATP hydrolysis, results in a gradient of electrical potential and pH across the cell membrane, and thus in an inwardly directed electrochemical gradient of H^+.

This electrochemical gradient, which renders "spontaneous" H^+ re-entry into the cell (i.e. exergonic), energizes the membrane and active transport activity via H^+-driven co-transport systems (as described by the Mitchell theory). Regarding K^+ uptake, this means that proteins named H^+-K^+ symporters, are active at the cell membrane, permeable to both H^+ and K^+ and couple the spontaneous re-entry of H^+ to K^+ uptake against the electrochemical potential of K^+. In other words, the spontaneous movement of H^+ within the H^+-K^+ symporter back to the cytosol is coupled to (energize) the movement of K^+ within the symporter, from the external medium to the cytosol against the K^+ electrochemical gradient. This process of membrane energization and of active K^+ uptake is depicted in Fig. 1. Of the four major cations taken up by plants (Ca^{2+}, Mg^{2+}, K^+ and Na^+), only K^+ requires high levels of active transport activity, in addition to passive transport activity depending on soil K^+ availability, with the three other cations being essentially taken up passively.

Besides this classification into passive and active transport mechanisms, mechanistic analyses have led to the division of transport proteins into two classes, channels and transporters (Stein, 1990) (in addition to pumps). When open, channels can be considered as selective pores through which substrate ions move, without inducing a change in the general conformation of the protein, while transporters undergo a cycle of conformational changes for each solute they transport. In the classical model, a transporter binds its substrate(s) onto a site facing the external solution; then, a reorientation step allows the binding site and the substrate to have access to the cytosol, into which the substrate(s) diffuse(s); then, a new conformational change allows the binding site to move back to the other side of the membrane, facing the external solution again.

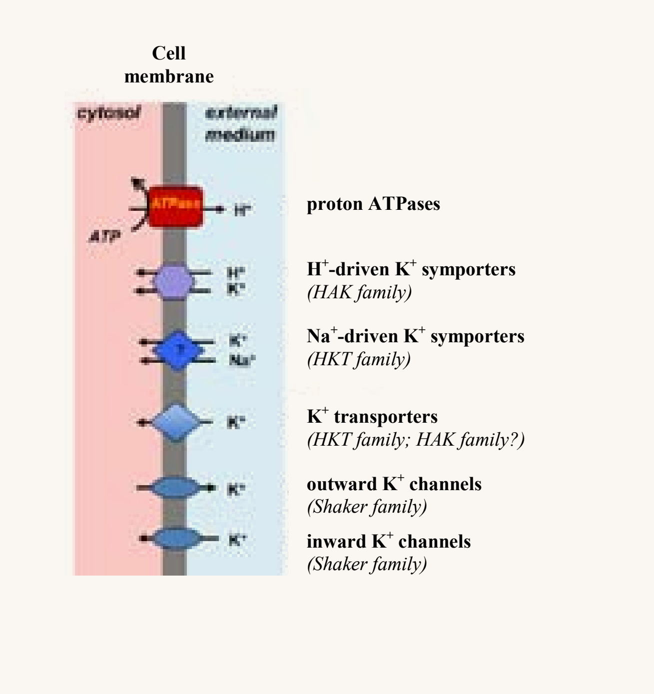

Fig. 1. Mechanisms of membrane energization and potassium transport across the plasma membrane.

The maximum velocity of transporters (up to 10^4 transport events per second per protein) is thus much lower than that of channels (up to 10^6 ions per second and protein). Taking into account energetic criteria, transporters can be divided into uniporters and cotransporters. Uniporters move their substrates down their electrochemical gradients and thus mediate passive transport, whereas cotransporters (symporters or antiporters) can move a substrate against its electrochemical gradient, by coupling this transport to another ion (e.g. H^+ in H^+-K^+ symporters).

In plants, the most extensively characterized proteins mediating K^+ transport across the plasma membrane are K^+ channels from the Shaker family. These channels mediate passive K^+ fluxes that dominate the membrane conductance to K^+ in most cell types (Lebaudy *et al.*, 2007). The HAK family, which is less characterized, comprises H^+-K^+ symporters, playing a crucial role in active K^+ uptake (Gierth and Mäser, 2007). The HKT family displays two types of transporters, the first one permeable to Na^+ only and present in both dicots and monocots, and the second one permeable to both Na$^+$ and K$^+$ and present in monocots only (Corratgé-Faillie *et al.*, 2010). The KEA family, which is comprised of cotransporters that couple K$^+$ flux to anion (Cl$^-$) flux, is still poorly characterized (Gierth and Mäser, 2007). The information currently available on each of these four families is summarized below.

Shaker K$^+$ channels

Two Shaker K$^+$ channels from *Arabidopsis thaliana*, named AKT1 and KAT1 (for *Arabidopsis* K$^+$ transport and K$^+$ *Arabidopsis thaliana*, respectively), were the first nutrient ion transport systems to be identified in plants. They were cloned in 1992 by functional complementation of a mutant strain of yeast *(Saccharomyces cerevisiae)* which was defective in K$^+$ uptake and unable to grow on physiological concentrations of K$^+$ (Anderson *et al.*, 1992; Sentenac *et al.*, 1992). Mutant yeast cells were transformed with gene (cDNA) libraries and spread on agar plates displaying low K$^+$ concentrations. Colonies showing rapid growth were picked and their transforming construct extracted and sequenced. The deduced polypeptides were found to share similarities, both at the sequence and structure levels, with animal voltage-gated K$^+$ channels, forming the so-called Shaker superfamily (Jan and Jan, 1997).

Shaker genes encode polypeptides displaying six transmembrane segments, i.e. six hydrophobic segments (of about 20 amino acids), each one spanning the cell membrane (Fig. 2A). The fourth transmembrane segment harbors positively electrically-charged amino acids and acts as a voltage-sensor rendering the gating of the channel voltage-sensitive: movements of this segment within the membrane, in response to changes in the transmembrane electrical potential gradient, result in conformational changes of the protein that favors opening or closure of the channel pore. A highly conserved membranar loop, located between the fifth and the sixth transmembrane segment, and called the P (pore) domain, forms part of the selectivity filter of the ion-conducting pore. Downstream of this hydrophobic core, plant Shaker polypeptides harbor a large cytosolic region, which comprises several domains, including a putative cyclic nucleotide-binding domain. In most Shaker channels, this cytosolic region also comprises an ankyrin domain, which constitutes a site of interaction with regulatory proteins (e.g. kinases or phosphatases) (Fig. 2A). It should be noted that a Shaker polypeptide does not form a functional channel by itself. Indeed, the functional protein has a tetrameric structure associating four Shaker polypeptides (Fig. 2B). The channel can have a homotetrameric structure, associating four Shaker polypeptides encoded by the same gene, or a heterotetrameric, associating Shaker polypeptides encoded by different genes. The heteromerization process results in increased diversity in functional properties (e.g. sensitivity to the membrane potential). In other words, with a given number of Shaker genes, the plant can generate a larger number of channel types.

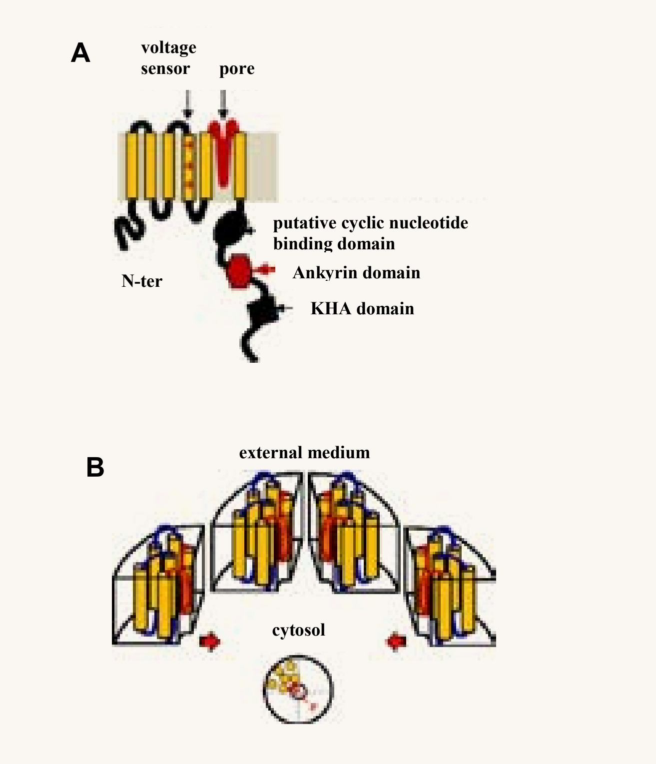

Fig. 2A. Shaker genes encode polypeptides displaying six hydrophobic transmembrane segments (displayed in yellow in the figure). The fourth transmembrane segment harbours positively charged amino acids and acts as a voltage sensor. A P domain is located (in red) between the fifth and the sixth transmembrane segment. The cytosolic region comprises several domains, including a putative cyclic nucleotide-binding domain (in black) and, in most Shaker channels, an ankyrin domain (in red), which constitutes a site of interaction with regulatory proteins. Downstream of the ankyrin domain, the KHA domain is involved in channel tetramerization (Daram *et al.*, 1997).
Fig. 2B. Tetrameric structure associating four Shaker polypeptides.

In the model plant *Arabidopsis thaliana*, nine Shaker genes are present. Five of them (KAT1, KAT2, AKT1, SPIK and AKT6) are dedicated to K$^+$ uptake across the cell membrane, two (SKOR and GORK) are dedicated to K$^+$ secretion across the cell membrane, one (AKT2) encodes a channel which allows both K$^+$ uptake and K$^+$ secretion, and one (AtKC1) encodes a channel regulatory subunit, affecting the sensitivity of heteromeric channels to voltage (i.e. to the transmembrane electrical potential gradient) (Lebaudy *et al.*, 2007). The direction of transport (uptake or secretion) through these Shaker channels depends on the channel sensitivity to voltage. Channels that activate upon hyperpolarization of the transmembrane electrical potential mediate K$^+$ uptake. They are called inward (or inwardly rectifying) channels in electrophysiological analyses. Conversely, channels that activate upon a depolarization of the transmembrane electrical potential mediate K$^+$ secretion. They are called outward (or outwardly rectifying) channels.

Comparison amongst species indicate that the structure of the Shaker gene family is strongly conserved in higher plants, in terms of gene number (e.g. nine genes in *Arabidopsis thaliana*, 11 genes in rice, ten genes in grapevine) as well as in terms of channel types (e.g. inward or outward types). Such conservation should result in easier transfer of the basic knowledge gained in classical plant models (*Arabidopsis* and, to a lower level at the present time, rice) to other plants and crop species.

HAK transporters

In plants, genes from the HAK family (also named KT or KUP by different authors) were identified by sequence homology with K^+ uptake transporters from bacteria (KUP) and high-affinity K^+ transporters (HAK) from fungi (Santa-María *et al.*, 1997; Rodríguez-Navarro, 2000; Gierth and Mäser, 2007).

Little is known about the structure of these transporters (Fig. 3). Hydrophobicity profiles suggest that they possess ten transmembrane segments and a long cytosolic loop between the second and third segment (Gierth and Mäser, 2007). So far, no region involved in ion conduction has been identified in these transporters.

The roles of these systems in plants are not yet fully understood, in particular because they do not seem to be functional at the cell membrane when heterologously expressed in *Xenopus* oocytes. Expression in yeast or *E. coli* mutant strains deficient for K^+ uptake has, however, allowed characterizing of the functional properties of some members from the HAK/KUP/KT family, belonging to groups I and II. It has been suggested that some transporters are devoted to high-affinity K^+ transport, from µM concentrations, whereas others play a preponderant role in the millimolar K^+ concentration range. *In planta*, there are indications that high affinity HAK/KUP/KT members are involved in root K^+ active uptake, in conditions of low K^+ availability, by mediating H^+-K^+ symport activity (Santa-María *et al.*, 1997 & 2000; Gierth and Mäser, 2007). This is very likely to be the case for HAK5 from *Arabidopsis thaliana* (Gierth *et al.*, 2005).

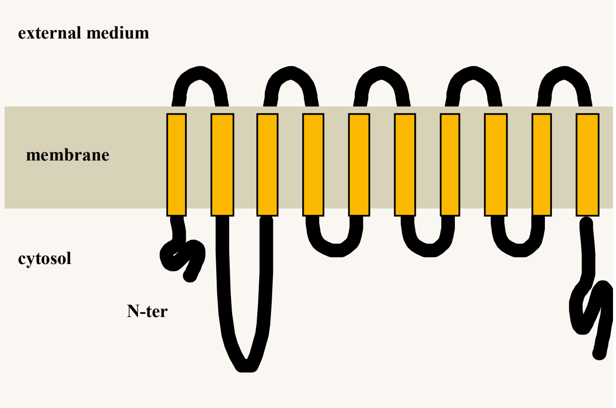

Fig. 3. Plant KUP/HAK/KT transporters were identified by sequence homology with K^+ uptake transporters from bacteria and high-affinity K^+ transporters from fungi. Based on hydrophobicity analysis, they would possess ten transmembrane segments (displayed in yellow) and a long cytosolic loop between the second and third segment. Based on genome sequence analysis, thirteen HAK genes are present in *Arabidopsis thaliana* and 26 in rice *(Oryza sativa)* (Mäser *et al.*, 2001; Amrutha *et al.*, 2007). Phylogenetic analyses indicate that four groups can be distinguished in the plant KUP/HAK/KT family (Bañuelos *et al.*, 2002).

HKT transporters

Plant HKT transporters are related to the fungal Trk and prokaryote KtrB and TrkH transporters (Durell and Guy, 1999; Rodríguez-Navarro, 2000). Fungal and prokaryote systems of this superfamily are thought to work as H^+-K^+ or Na^+-K^+ symporters, or as K^+ uniporters. In fungi, Trk transporters are the major contributors to K^+ uptake at micromolar to submillimolar K^+ concentrations, at least at neutral and basic pH (Rodríguez-Navarro, 2000). Sequence analyses have led to the hypothesis that these transporters have evolved from bacterial K^+ channels and display a transmembrane hydrophobic core structure formed of four tandemly repeated domains, each of them comprising one transmembrane segment followed by one P domain and another transmembrane segment. The four P domains line a central pore (Durell and Guy, 1999) (Fig. 4).

Phylogenetic and functional analyses identify two subfamilies of HKT transporters in plants. The first one, present in both dicots and monocots, displays transporters permeable to Na^+ only. The second one, which has only been identified in monocots so far, comprises transporters permeable to both Na^+ and K^+. It should

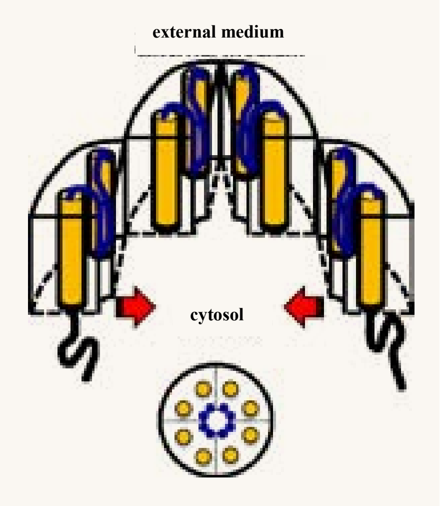

Fig. 4. The proposed topology of HKT transporters is that suggested for the whole (plant) HKT/(fungal and bacterial)Trk/(bacterial) KtrB superfamily. They display four successively arranged MPM domains, each one comprising a transmembrane segment (displayed in yellow), then a P domain (in blue), and another transmembrane segment (in yellow). The four P domains line a central pore.

also be noted that the size of the HKT family appears to be much smaller in dicots than in monocots: e.g. a single HKT gene in *Arabidopsis* or poplar, compared to ten genes in rice or each wheat genome (Corratgé-Faillie *et al.*, 2010).

HKT transporters, permeable to Na^+ only, have been shown to contribute to plant adaptation to salinity constraint. Expressed in the plant vasculature, the transporter's activity results in decreased Na^+ translocation from roots to leaves and reduced leaf Na^+ contents. Such contribution to plant tolerance to saline conditions has been evidenced both in dicots and monocots (Corratgé-Faillie *et al.*, 2010).

The role of HKT transporters permeable to both Na^+ and K^+ is still poorly understood and, thus, the physiological significance of the fact that such transporters are present in monocots only is unclear. HKT transporters from this type have been shown to be able to behave as Na^+-K^+ symporters when expressed in heterologous systems (Rubio *et al.*, 1995; Haro *et al.*, 2005) and could thus mediate active high affinity K^+ uptake. The fact that reduced availability of K^+ in the external (soil) solution results in increased expression of such HKT transporters in roots, provides further support to the hypothesis that these systems are involved in high affinity active K^+ uptake. However, all attempts to identify Na^+-K^+ symport activity in plants seem to have failed so far. Studies concerning the actual activity of these systems - and those relating to the difference in number and type of members in the HKT family between monocots and dicots - are thus highly exciting and at the forefront of scientific research.

KEA antiporters

Plant KEA (potassium exchange antiporters) are thought to function as H^+/K^+ antiporters, given their homology to proteins with this function in bacteria (Yao *et al.*, 1997). Six KEA are present in *Arabidopsis thaliana* (Mäser *et al.*, 2001), but their physiological role is so far largely unknown. In *E. coli*, KefB and KefC-mediated K^+ efflux is negatively regulated by glutathione. In the plant KEA1–3 transporters, the glutathione-binding pocket is not clearly conserved suggesting that plant KEA1–3 is regulated in a different way (Gierth and Mäser, 2007). It has been suggested that H^+/K^+ antiporters might play important roles at the plasma membrane by contributing to active K^+ secretion in the xylem sap, or regulating K^+ homeostasis by loading K^+ into vacuoles or other acidic compartments.

Root K^+ uptake from the soil solution

Information available in *Arabidopsis* identifies two systems involved in root K^+ uptake: the AKT1 Shaker channel, probably under control of the Shaker AtKC1 channel subunit and the AtHAK5 transporter (Fig. 5). Close homologs of AKT1 and AtHAK5 have been identified in other species, for instance in rice (Bañuelos *et al.*, 2002; Fuchs *et al.*, 2005; Amrutha *et al.*, 2007).

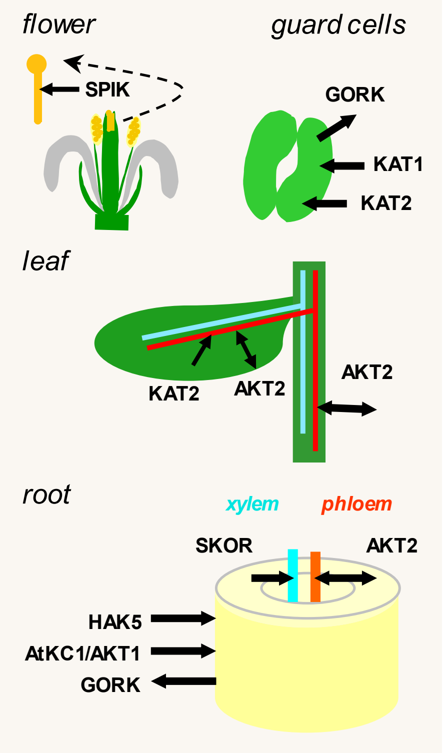

Fig. 5. Expression patterns and roles of K^+ channels and transporters in *Arabidopsis*.

Direct evidence for AKT1 contribution to K^+ uptake from the soil was obtained by using an *Arabidopsis* mutant line disrupted in the encoding gene (Hirsch *et al.*, 1998). Interestingly, AKT1 contribution to root K^+ uptake appeared to be essential for plant development only when NH_4^+ was present in the external medium. In the absence of NH_4^+, the AKT1 mutant does not display any phenotype while, in the presence of this cation, it displays decreased K^+ uptake capacity, impaired seed germination and reduced growth rate. These results led to the distinction of two components in root K^+ uptake activity, based on sensitivity to NH_4^+. The AKT1 component plays an essential role in root K^+ uptake, even from low K^+ media in the presence of NH_4^+. The non-AKT1 component is NH_4^+-sensitive, and can suffice for root K^+ uptake in the absence of NH_4^+.

K^+ transporters from the KUP/HAK family have been shown to be inhibited by external NH_4^+ (Santa María *et al.*, 2000). In *Arabidopsis*, AtHAK5 is expressed in the root epidermis and contributes to K^+ deprivation-induced high-affinity K^+ uptake (Gierth *et al.*, 2005). It could thus form part of the non-AKT1 component of K^+ uptake. It should also be mentioned that HKT transporters permeable to both K^+ and Na^+ (in monocots) are expressed in root periphery cells and could thus contribute to root K^+ uptake. However, as indicated above, the actual role of these systems is still unclear.

Long-distance transport of K^+ in plants

Reverse genetic approaches in *Arabidopsis* have revealed that activity of the Shaker K^+ channel SKOR, which is expressed in pericycle and xylem parenchyma, contributes to about 50 percent of K^+ translocation toward the shoot (Gaymard *et al.*, 1998) (Fig. 5). The other systems involved in K^+ loading into the xylem sap are still unknown.

Work on the mechanisms of K^+ transport in phloem tissues has been focused on two K^+ channels from the Shaker family, AKT2 and KAT2. KAT2 is an inward channel but AKT2 is able to mediate both K^+ uptake and K^+ secretion. This functional plasticity, and the fact that AKT2 is expressed in the phloem vasculature, both in leaves and roots, has led to the hypothesis that this channel plays a role in K^+ loading in source leaves and unloading in sink organs (Marten *et al.*, 1999; Lacombe *et al.*, 2000) (Fig. 5). At the transcriptional level, AKT2 displays CO_2-dependent light induction, suggesting that AKT2 expression in phloem tissues is regulated by photosynthates (Deeken *et al.*, 2000). Analysis of the phenotype of an AKT2 loss-of-function mutant revealed a delay in plant development and, interestingly, a 50 percent reduction in the sucrose content of phloem sap (Deeken *et al.*, 2002).

HKT transporters permeable to K^+ (and Na^+) are expressed in phloem tissues (Kader *et al.*, 2006) but their actual capacity to transport K^+ in situ in plant cells is not demonstrated, as indicated above. HKT transporters permeable to Na^+ only are expressed in plant vascular tissues and play a role in controlling/reducing Na^+ translocation towards the shoots and accumulation in leaves.

Pollen tube elongation

Although K^+ plays a major role in inducing cell turgor, only a few studies so far directly support the hypothesis that K^+ channels or transporters are involved in the control of cell growth. In *Arabidopsis*, disruption of the gene encoding the inward Shaker channel SPIK strongly impaired pollen tube development (Mouline *et al.*, 2002) (Fig. 5). SPIK mutant pollen germinated normally but elongation of the pollen tube most often aborted quickly. Tubes that succeeded in developing grew more slowly than in wild-type pollen. Since SPIK is a major component of the K^+ inward conductance in pollen, the impairment of tube development in the knock-out mutant is probably due to a deficit in K^+ uptake. This defect was shown to result in a strong decrease of pollen fitness and fertilization capacity.

K^+ fluxes in guard cells and control of stomatal aperture

Guard cell movements at the leaf surface, allowing regulation of stomatal aperture and control of water transpirational loss, are osmotically driven. An increase or decrease in turgor of the guard cells lining the pore, opens or closes the stoma respectively. K^+ and accompanying anions (NO_3^-, Cl^- and malate) are among the major solutes involved in this osmotically driven process (Talbot and Zeiger, 1996, Schroeder *et al.*, 2001). In summary, activation (by light or other signals) of H^+-excreting ATPases, active at the guard cell membrane, results in membrane hyperpolarization and thereby in activation of inward K^+ channels. This leads to K^+ influx, increased K^+ accumulation and, finally, stomatal opening. Conversely, inhibition (e.g. by the stress hormone ABA) of H^+-excreting ATPases results in membrane depolarization (further supported by activation of anion channels), leading to activation of outward K^+ channels, K^+ efflux and, finally, stomatal closure. In *Arabidopsis*, the time-constant of stomatal closure and opening are close to about ten and twenty minutes, respectively.

A single Shaker gene, GORK, encodes the outward K^+ channels active at the cell membrane in *Arabidopsis*, while five genes (KAT1, KAT2, AKT1, AKT2 and AtKC1) code for the inward channels (Fig. 5). This suggests that tight control of K^+ influx during stomatal opening is more complex and crucial than control of K^+ efflux during stomatal closure. Disruption of guard cell outward or inward K^+ channel activity (by reverse genetics approaches in *Arabidopsis*) has been shown to increase the time-constant of stomatal closure or opening by about 50 percent and 400 percent respectively (Hosy *et al.*, 2003). As expected, disruption of the outward channel activity results in increased plant transpirational loss. Disruption of the inward K^+ channel activity results in strongly reduced reactivity to fluctuations in environmental conditions, like changes in relative humidity or in internal CO_2 availability, as well as in impaired control of stomatal movements in the presence of Na^+ (even at physiological concentrations) (Lebaudy *et al.*, 2008).

Conclusion and perspectives

Considerable progress in the analysis of K^+ transport across the cell membrane in plants has been made since the initial cloning of the Shaker K^+ channels (AKT1 and KAT1) from *Arabidopsis thaliana* in 1992. Several families of K^+ channels and transporters have been identified, revealing a much more complex situation than initially thought. At the present time, the Shaker K^+ channel family has been extensively characterized, highlighting the roles of members from this family in functions such as root K^+ uptake, and K^+ secretion into the xylem sap towards the shoots or guard cell movements. Much less is known, however, about other families of K^+ transport systems. Obtaining an integrated view of K^+ transport in plants will require more effort in the analysis of functional properties and roles *in planta* of transporters from the HAK, HKT and KEA families, as well as systems active at the tonoplast, such as TPK channels.

Most studies have focused on *Arabidopsis thaliana* as a model plant but information has also been gained in other species such as rice or grapevine. In the light of known available data, knowledge obtained on the Shaker family in *Arabidopsis* is likely to be significant in helping to investigate the roles of members of this family in other species. This is particularly true as the Shaker family appears to be strongly conserved in plants, in terms of gene number, channel functional properties, as well as channel expression patterns, which are probably more complex than in other families. For instance, the HKT transporter family is very different, in terms of transporter number and functional subtypes, between monocots and dicots. Understanding the physiological meaning of such differences is a highly exciting and fundamental objective in analyzing K^+ transport in plants, especially in relation to plant tolerance to salinity.

Another major objective for future researches is to decipher the processes, at the gene or protein levels for instance, that contribute to controlling and integrating the activities of the various K^+ transport systems that the plant can express. For instance, K^+ deficiency or salinity constraint has been shown to strongly modulate the expression (transcript levels) of members from the Shaker, HAK or HKT families. At the protein level, a highly illustrative example is the identification of a CIP-Kinase and its two CBL partners that place K^+ channel activity involved in root K^+ uptake under control of cytosolic Ca^{2+} signals (Xu *et al.*, 2006).

In conclusion, although the Shaker K^+ channel family can be considered the best characterized family of nutrient ion transport systems across the plant cell membrane, important efforts are still to be made to enable further progress in this field of plant biology and to obtain an integrated view of the mechanisms and regulation of K^+ transport activities in plants. Such efforts, however, are clearly worthwhile because of the current status of the knowledge in this field, the available working hypotheses and exciting perspectives. The work is also worthwhile because of the importance of K^+ nutrition, both in terms of plant adaptation to biotic and abiotic stresses, including salinity, and biomass production.

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