Atoms for sustainable agriculture: Enriching the farmer's field

A look at how nuclear and isotope techniques help find ways to improve poor soils and sustain the world's crop production

by
Christian Hera

Land represents a mere 29% of the world's total area, yet provides approximately 98% of its food. Most of this land is not very fertile: only 11% is of high fertility, 28% of moderate fertility, and 61% of low fertility.

At the same time, land, nutrient, crop, and water management practices in most developing countries are quite poor. Mining, for instance, causes soil deterioration which is no less dangerous than any other form of environmental degradation. This is one reason why the protection of nutrients and water is a major concern in many parts of the world, especially in developing countries.

Efforts to minimize soil losses and replenish nutrients are essential. Many organizations are paying increasing attention to the development of an integrated plant nutrition system. The basic underlying concept is the maintenance and possible increase of soil fertility for sustaining crop production through the best use of all possible sources of plant nutrients. This approach is ecologically, socially, and economically viable.

Nuclear and related isotope techniques are an important part of such agricultural solutions. They normally are used to compliment conventional or classical techniques in agricultural research, and they provide data that other methods cannot. This article looks at how nuclear techniques have been, and continue to be, used in soil and crop research. To a significant extent, their use has been stimulated by the combined efforts of the IAEA and Food and Agriculture Organization (FAO) of the United Nations. Since 1964, they have conducted programmes through the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, headquartered at the IAEA in Vienna.

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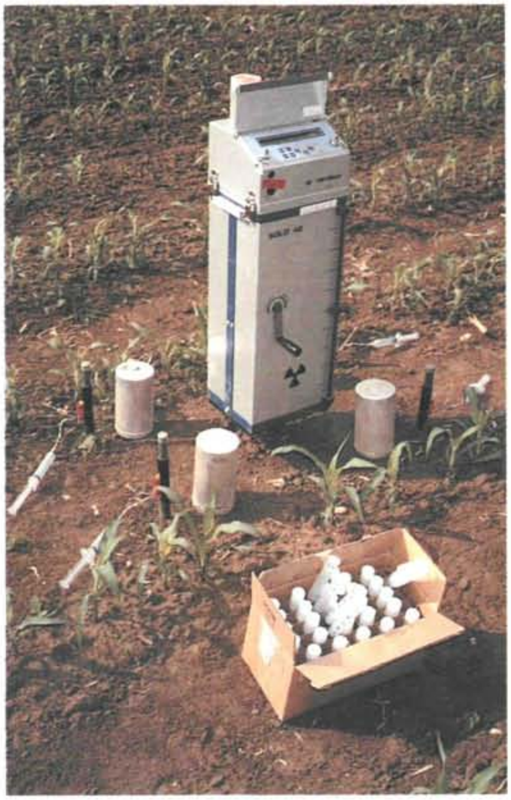
The historical perspective

Research with isotopes dates back to 1923 and the work of G.V. Hevesy, which signified the start of isotope applications in soil and crop research. Some 35 years later, in 1959, the newly formed IAEA awarded its first research contracts to Japan and the Federal Republic of Germany to support studies on the efficiency of fertilizer use. Starting in 1962, research contractors from developing countries, and agreement holders from developed countries, were integrated through IAEA co-ordinated research programmes (CRP). The first two CRPs initiated by the IAEA were also in the area of soil fertility. They focused on the application of isotopes to rice fertilization (1962-68) and on plant nutrient supply and movement in soil systems (1962-68).

Since then, dozens of CRPs have been conducted. All told over the past three decades, the Joint Division's Soil Fertility, Irrigation and Crop Production Section has had the technical responsibility for 29 CRPs. Much of the research was inspired by some of the world's top soil scientists, including Mac Fried, who became the first Director of the Joint FAO/IAEA Division, and Hans Broeshard, who headed the Agricultural Laboratory at Seibersdorf. Their pioneering efforts left their mark on soil scientists all over the world.

From the very beginning, the use of isotopes and related techniques proved to be extremely valuable for increasing the efficiency of fertilizers and optimizing plant nutrition, among a wide range of other applications. Using an isotope to label a nutrient in fertilizer or in soil, for example, is an invaluable direct method to distinguish between the amount of the nutrient that plants take up from each source.

Fertilizer studies. Over the past 30 years through activities of the Joint Division, the use of isotope techniques has largely been directed



Clockwise from above: **A neutron moisture meter used for measurements of water content in soil; IAEA Director General Hans Blix (second from left) and FAO Director General J. Diouf (centre) head a group being briefed by the author at the IAEA General Conference on the use of nuclear and related techniques in soil and crop studies; Dr. Helga Axman of the FAO/IAEA Soil Science Unit with participants at a regional training course in Ghana; participants in a 1995 regional training course in Bangkok on the use of isotopes in soil/plant relationships.**
(Credit: C. Hera, IAEA)

at studies of fertilizer efficiency for major food grain crops, such as rice, maize, and wheat. The main objectives have been to achieve higher and more stable grain yields by maximizing the uptake of nutrients from applied fertilizers and other sources, and to simultaneously reduce potential harmful environmental effects. For instance, fertilizers labelled with nitrogen-15 have been applied to a crop in different ways (sources, timing, placement) to determine and measure its uptake. The research helped scientists identify the most efficient methods of fertilizer application for different soils and climatic conditions.

In the first rice fertilization programme (1962-68), one question was the relative efficiency of different sources of nitrogen when they were applied on the surface or incorporated in the top five centimeters of soil. Field experiments using ammonium nitrate, whose two main components were labelled with nitrogen-15, were carried out in five countries. The results clearly demonstrated which component was the most effective source of nitrogen to paddy rice, and how it should be applied. The highest uptake of nitrogen was obtained when ammonium was incorporated beneath the soil. Placement had no significant effect on the utilization of nitrate.

A highly successful CRP was on maize fertilization, in which eight countries participated. Studies sought to examine the best ways of applying fertilizer in the fields, compared with the classical application of broadcast spreading on the soil surface followed by ploughing. Fertilizers labelled with nitrogen-15 and phosphorus-32 were used. Results led to the conclusion that farmers should split the amounts of fertilizer they apply and spread them in different ways (called banding) and at different times in the growing cycle.

Results were put into practice in Romania. Seeders were equipped with special devices for applying fertilizer at seeding time, and cultivators for weed control were equipped with devices for applying fertilizer at the vegetation period. They were used during maize production on an area of two million hectares. Over a period of 6 years, an average yield increase was realized of 0.62 tonnes per hectare, as compared to yields obtained through the classical fertilizer method.

The investment for adapting to the new method represents only 5% of the total value of the yield increase that can be obtained every year. The method's advantages are even greater when taking into account that it eliminates the supplementary work, and possible associated negative soil effects, involved in classical fertilizer application.

Nitrogen from the atmosphere

In spite of the abundance of nitrogen in the atmosphere (78% of all gases), it is one of the most limiting factors for crop growth. Only certain crops can directly use atmospheric nitrogen. Overcoming this limitation through the application of nitrogen fertilizer represents one of the major costs of crop production.

A process known as biological nitrogen fixation (BNF) has become a feasible alternative for farmers in both developing and developed countries. Legumes and a few other families in symbiosis with appropriate microorganisms are able to directly utilize atmospheric nitrogen through this process. It offers several advantages, including less expense, reduced pollution hazards, enhanced soil fertility, and greater protein content of crops. To realize these gains requires the proper management of nitrogen fixing systems. Nitrogen-15 isotopic techniques can provide quantitative and integrated values of nitrogen fixed in both natural and agricultural systems.

During the last two decades, several FAO/IAEA international research programmes have focused on measuring and enhancing BNF, especially symbiotic legume fixation in various systems. Current programmes emphasize the improvement of both yield and nitrogen fixation in grain legumes through an integrated multidisciplinary approach.

Results so far show large nitrogen fixation differences between the grain legumes species. For some, such as fababean, the process works rather effectively, while for others, such as common bean, it does not. These differences were persistent under a wide range of environmental conditions. Also considerable genotypic variations in nitrogen fixation between cultivars of common bean were found in different countries.

Of particular interest in BNF are nitrogen fixing trees. Studies show them to be an important component of agricultural systems. They play a significant role in restoring or increasing soil fertility and in decreasing soil erosion, and they grow well in nitrogen-deficient soils. Methods that can accurately measure factors affecting the growth of such trees under different conditions have been, and continue to be, studied.

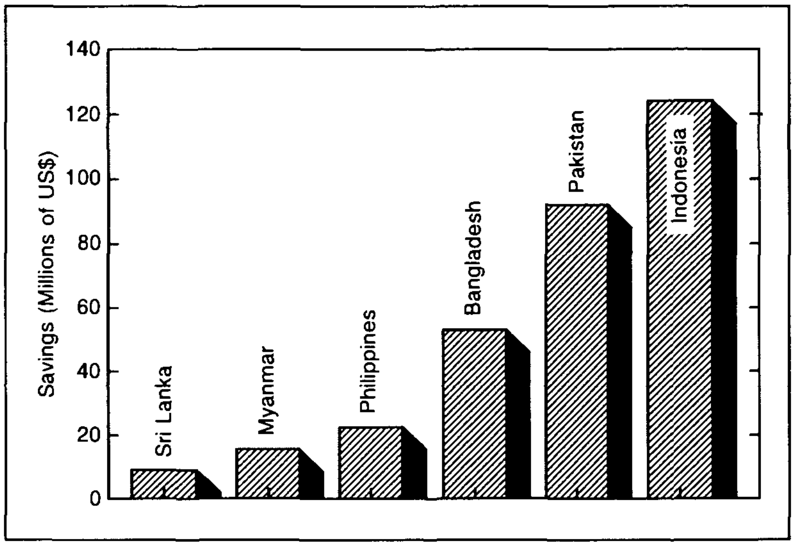
Other studies have focused on the role played by blue-green algae and their association, particularly *Azolla,* in lowland rice fields.

High yielding rice varieties linked to the "green revolution" require large amounts of expensive chemical nitrogen fertilizers. Scientists have long recognized that the aquatic nitrogen fixing *Azolla-Anabaena* symbiosis could replace at least part of the nitrogen requirement for rice. From 1984-89, a programme with financial support from the Swedish International Development Authority (SIDA) was coordinated by the Joint Division's Soil Fertility, Irrigation and Crop Production Section to investigate the benefits of using *Azolla* as a biofertilizer for rice. Scientists from nine rice producing countries — Bangladesh, Brazil, China, Hungary, Indonesia, Pakistan, Philippines, Sri Lanka, and Thailand — participated.

Although the *Azolla-Anabaena* symbiosis has been used for centuries as a green manure for rice in parts of China and Viet Nam, intensive scientific research only began after the 1973 oil shock dramatically increased the cost of nitrogen fertilizers. *Azolla* can grow very rapidly, doubling its weight in three to four days under optimal conditions. Yet before this programme began there was little evidence from field experiments to indicate whether the nitrogen accumulated by *Azolla* in the field was primarily drawn from the atmosphere or from the soil. Although there was substantial evidence to show that incorporating *Azolla* into the soil increased rice yields, only a few experiments had been done to explore the reasons for this.

With extensive use of the nitrogen-15 labelling technique, it was shown that 70% to 80% of the nitrogen in *Azolla* is derived from atmospheric fixation, and that there was no evidence of significant competition with rice for limited soil nitrogen. In fact, the most recent experiments have shown that a cover of *Azolla* floating on the surface of rice floodwater can even improve the efficiency of chemical nitrogen fertilizers. Urea is the most common nitrogen fertilizer used for rice. However, its efficiency is usually low and 50% or more can be lost to the atmosphere. Hydrolysis of urea in the water produces an alkaline reaction, and combined with the effects of algal photosynthesis, pH values over nine are commonly observed. At this pH level, ammonium is converted to the volatile gas ammonia. *Azolla* fortunately limits algal growth through shading of the floodwater. Following fertilizer applications, pH values one to two units lower were observed when *Azolla* was present.

The second effect is that *Azolla* takes up part of the nitrogen fertilizer from the water. If the *Azolla* is then incorporated into the soil, this nitrogen fertilizer becomes available to the rice along with the fixed nitrogen. In an experiment in Fuzhou, China, losses of nitrogen from a urea top dressing applied 2 weeks after transplanting were reduced from 50% without *Azolla* to 25% when the field was inoculated with *Azolla* at transplanting. Uptake of labelled fertilizer by rice was increased from 26% to 35%. In Thailand, application of urea at transplanting with and without inoculation with *Azolla* resulted in yield increases of 10% to 15% in plots with *Azolla*.



Potential savings in rice production using *Azolla* as nitrogen fertilizer

When *Azolla* was incorporated into the soil, it proved to be as good as urea as a nitrogen source for rice. Not only the uptake of nitrogen from *Azolla* was equal to that from urea but there was also the additional benefit that more of the nitrogen added as *Azolla* remained in the soil after harvest. In some of the tests, there was sufficient nitrogen available to the next crop to produce a yield increase of two to three times compared to urea, particularly when wheat followed the rice crop. Estimated savings from one crop of rice by the use of *Azolla* as a nitrogen fertilizer are substantial. *(See graph.)*

This successful programme demonstrated that a group of scientists from different parts of the world could work together, use the same critical methodology, and make rapid progress toward common goals. Since the studies were done in a wide range of environments, the results can be widely applied.

Photosynthesis and water use

Isotope techniques are indispensable in studies of photosynthesis, plant metabolism, translocation, and nutrient uptake. By exposing plants to carbon dioxide labelled with carbon-14, photosynthesis and movement of metabolites throughout the plant can be monitored using techniques such as autoradiography. Recently, carbon-13 has been increasingly employed in tracer studies because of its greater availability and the ease with which it can be measured. Moreover, as a stable isotope, carbon-13 is environmentally friendly and therefore invaluable in studies of soil organic matter and greenhouse gases. However, plants discriminate against carbon-13 during photosynthesis. Though it varies depending on the plant species, the discrimination is closely associated with a plant's ability to utilize water.

This technique can be useful for selecting cultivars of crop and tree species efficient in water use. Through one CRP, several genotypes of food crops and trees have been identified in poor soils that are highly efficient in the use of limited resources of water. In Morocco and Tunisia, genotypes of wheat have been found that are efficient in water use and produce high yields. In Sudan, provenances of the gum arabic tree *Acacia Senegal* have been identified which are highly efficient in growing in drought-prone regions. In Sri Lanka, the technique further has assisted scientists in identifying cultivars of coconut that are highly tolerant to drought and therefore eminently suitable for cultivation in the dry region of the country.

A recent research project, initiated in 1990, is investigating the effective use of scarce water resources to maximize plant productivity. The use of neutron moisture meters and other related techniques have helped assess irrigation practices and schedules. The meters were used successfully not only to measure the soil's water content but also to understand water dynamics under field conditions. Another CRP has examined the efficiency of water and fertilizer use in semi-arid farming systems. Since semi-arid zones, by definition, are deficient in rainfall, plant growth and crop yields are heavily dependent on the proper management and conservation of water. The research helped to identify measures for ensuring that crops receive an adequate amount of nutrients under such farming conditions.

Environmental protection

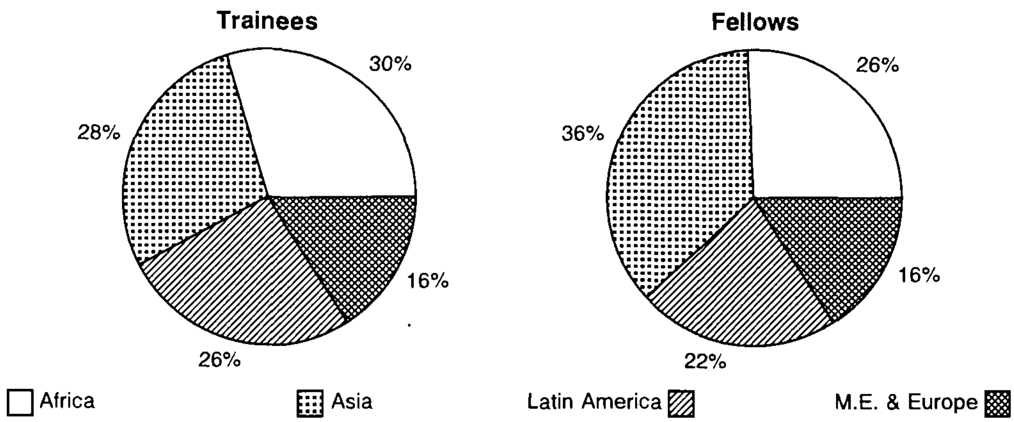
Alongside the need for improving agricultural productivity, many countries, mostly industrialized ones, share a problem of a different kind, namely the entry of nitrogen into groundwater and pollution of drinking water and lakes. In this case, there are simultaneous needs to protect existing and potential agricultural soils and nitrogen resources, and to meet the rising standards of environmental protection worldwide.

Nitrogen-15 provides a particularly powerful tool for studying the behavior of fertilizer nitrogen in the environment. With the support of Germany, the Soil Fertility Section of the Joint FAO/IAEA Division has carried out an international programme that provides key guidance for addressing problems. Based on the studies that were done, a number of conclusions were drawn. They include:

- Taking into account the prospects and time needed for developing alternative agricultural practices, conventional nitrogen fertilizer ap-

FAO/IAEA-supported training activities in soil and crop science

Hundreds of scientists from around the world have been trained through courses and events organized by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. From 1978-94, eighteen training courses were held for 345 participants from 80 countries. Another 142 scientific fellows received training during the 1962-94 period. Shown below is the geographic distribution of trainees and fellows.



Note: Data are for activities organized by the Soil Fertility, Irrigation and Crop Production Section and Soil Science unit at the IAEA Seibersdorf Laboratories plications must continue to intensify and extend for the immediate decades ahead.

- As a result of this intensification, increasing amounts of nitrogen both in native soil and added as fertilizer will be lost from the soil-plant system and find their way into the environment. Soil-nitrogen levels and contingent productivity can nevertheless be maintained by developing improved soil-nitrogen management practices.
- In some situations, the nitrate levels in ground and drinking water are likely to continue rising. A proper diagnosis of the various sources responsible for this problem should be made.
- In developing countries, the losses of fertilizer nitrogen represent those having a relatively high cost input. In the more advanced industrialized countries, on the other hand, the higher amounts utilized represent an addition to the problems and costs of environmental quality and health protection. The data generated and the information reviewed suggest that these problems can be contained by improved soil and water management in agricultural systems. In particular there appears to be a huge scope for a better exploitation of alternative nitrogen sources, such as biological nitrogen fixation in legumes and non-legumes and/or biofertilizers.
- The United Nations agencies, such as the FAO, IAEA, United Nations Environment Programme, and World Health Organization, through improved collaboration with appropriate regional and national programmes, have a vital and urgent role in implementing the required improvements and short-term research needs, and accelerating the simultaneously needed education and training.

Supporting services and activities

Several activities are simultaneously carried out to ensure the transfer of nuclear technologies for agricultural development. The Soil Science Unit at the FAO/IAEA Agriculture and Biotechnology Laboratory in Seibersdorf offers a range of research and training support.

Training courses. Annual interregional training courses on the use of isotopes and radiation techniques in studies of soil-plant relationships have been conducted at the Seibersdorf Laboratories since 1978. Each training course usually lasts 5 to 6 weeks and can be attended by 20 participants from all geographical regions. Additionally, national and regional training courses are supported.

Fellowship training. About 10 scientific fellows are trained at the Seibersdorf Soil Science Unit every year. There are two categories of fellows. Analytical fellows are accepted for a period of 2 to 3 months to learn isotope analytical techniques used in soil-plant research studies (for instance, nitrogen-15 assay techniques by optical emission spectrometry). This form of training includes technical tutoring and hands-on practical sessions. Research fellows are accepted for periods of 6 to 12 months to work on a topic within the FAO/IAEA's work programme. They receive guidance on experimental strategies and use of isotope and related techniques relevant to a particular area they will pursue upon return to their home country. They are expected to complete and write a piece of research work.

Additionally, the IAEA sponsors scientific visitors for short stays, typically for senior scientists. Other training-related opportunities for scientists of both developed and developing countries include selection as cost-free interns, cost-free experts, or associated professional officers.

Research support. Through CRPs and other mechanisms, extensive international and regional research networks have been built over the years. The FAO/IAEA Soil Science Unit provides a range of supporting services. They include the analysis of approximately 15,000 to 20,000 samples every year for projects in developing countries. Nitrogen-15 labelled fertilizers also are dispatched to participants in specific research projects. Analytical support further is provided to laboratories in developing countries receiving IAEA technical assistance and lacking suitable facilities.For routine purposes, the Unit plays a leading role in the development and transfer of nitrogen-15 assay technology used in IAEA technical assistance projects.

Quality assurance service. A recent initiative calls for establishing an international quality assurance service for nitrogen-15 analysis by optical emission spectrometry. The facilities of the Soil Science Unit will serve as the FAO/IAEA control "reference" laboratory. The service is expected to:

- ensure that the nitrogen-15 data generated by local laboratories are internationally acceptable;
- give confidence and encouragement to counterparts in their analytical procedures;
- promote regional cooperation and ensure an effective transfer of the nitrogen-15 technology to developing countries through FAO/IAEA programmes.

The service marks another step forward in global efforts to effectively transfer nuclear and isotope related techniques for beneficial purposes. It will enable developing countries to further build their expertise in applying these powerful tools for sustainable agricultural development. ❐