Organo Científico
de la Sociedad Mexicana
de la Ciencia del Suelo A.C.

ISSN 0187-577

TERRA

Volumen 14 Enero - Marzo de 1996 Número

INDICE

"TERRA", Registro en Trámite. Organo Científico de la Sociedad Mexicana de la Ciencia del Suelo, A.C.
Volumen 14-1, enero-marzo, 1996.

ISSN 0187-5779

 Las contribuciones a esta revista deben enviarse, en original y dos copias, redactadas conforme a las Normas para Publicación en la Revista TERRA, al: Editor de la Revista TERRA, Sociedad Mexicana de la Ciencia del Suelo, A.C. Apartado Postal 45, 56230 Chapingo, Edo. de México, México.
Oficinas: Edificio del Departamento de Suelos, Universidad Autónoma Chapingo, Chapingo, Estado de México.
Teléfono: 52-595-42200 Ext. 5237; 52-595-46024
Fax: 52-595-48076

INDICE

"TERRA", Registration pending. Scientific publication of the Mexican Society of Soil Science. Volume 14-1, January-march 1995.

ISSN 0187-5779

 When submitting articles to this journal, an original and two copies must be sent to: Editor de la Revista TERRA, Sociedad Mexicana de la Ciencia del Suelo, A.C., Apartado Postal 45, 56230 Chapingo, Edo. de México, México.
Office address: Edificio del Departamento de Suelos, Universidad Autónoma Chapingo, Chapingo, Estado de México.

Telephone: 52-595-42200 ext. 5237; 52-595-46024
Fax: 52-595-48076

INDEX

EDITORIAL

Scientific Articles

Comments and Letters to the Editor

EDITORIAL

Este número de TERRA contiene versiones revisadas de los trabajos presentados en el Simposio ID-10 del XV Congreso Mundial de la Ciencia del Suelo, celebrado en Acapulco en 1994. Este simposio fue organizado por el Dr. Ch. Hera del Organismo Internacional de Energía Atómica (OIEA) y por el Dr. J.J.Peña Cabriales del Centro de Investigaciones y de Estudios Avanzados del I.P.N. Unidad Irapuato y fue dedicado al 30^{avo} aniversario de la División Conjunta FAO/OIEA para técnicas nucleares en la agricultura y la alimentación.

El objetivo del simposio fue revisar los avances recientes en el uso de técnicas isotópicas en los diferentes aspectos de la fertilidad del suelo, nutrición vegetal, producción de cultivos y eficiencia del uso del agua, en prácticas agrícolas sustentables y en el estudio de problemas ambientales asociados con la agricultura. Además, facilitar que los científicos de América Latina y de otras regiones del mundo presenten sus experiencias más recientes en la aplicación de isotópos y técnicas de radiación en estudios sobre relaciones suelo-planta.

La edición de este número estuvo a cargo del Dr. J.J. Peña-Cabriales. La Comisión Editora de Terra se complace en que los artículos aquí contenidos hayan sido útiles como material de consulta para el Curso Internacional del Capacitación OIEA/FAO "El Uso de las Técnicas Nucleares en los Estudios de las Relaciones Suelo-Planta", celebrado en el CINVESTAV, con la participación de un selecto número de especialistas en el uso de las técnicas nucleares en investigación científica sobre agricultura, alimentación y medio ambiente.

A. Aguilar Santelises.
Editor

CARBON POOLS AND FLUXES IN BRAZILIAN NATURAL AND AGRICULTURAL SYSTEMS AND THE IMPLICATIONS FOR THE GLOBAL CO_2 BALANCE

Reservas y Flujo de Carbono en Sistemas Naturales y Agrícolas del Brasil y las Implicaciones para el Balance Global de CO_2

C. C. Cerri[1], M. Bernoux[1], and Graeme J. Blair[2]

[1]Department of Soil Chemistry, Center of Nuclear Energy in Agriculture, University of São Paulo, CP 96, 13400-970 Piracicaba (SP), Brazil.

[2]Department of Agronomy and Soil Science, University of New England, Armidale, N. S. W. 2351, Australia

Palabras clave: **Materia orgánica del suelo (MOS), CO_2 atmosférico, Caña de azúcar, Bosque tropical.**

Index words: **Soil organic matter (SOM),Atmospheric CO_2, Sugar cane, Rainforest.**

RESUMEN

Se ha estimado que la deforestación global contribuye con 6.5% del incremento anual en el CO_2 atmosférico. Avances recientes en el uso de ^{13}C han permitido identificar las fuentes de C en la materia orgánica del suelo (MOS) cuando la selva es convertida a pastizales tropicales o cañaverales (caña de azúcar). Se estima que la quema de la selva húmeda del Brasil contribuye con 27.9 t C/ha a la atmósfera y que la transferencia total de C a la atmósfera proveniente de la quema de 9.77 x10^6 ha de selva "clareada" representa 0.24% del total del CO_2 proveniente de deforestación en el mundo entero.

El desmonte de la selva amazónica para convertirlo en pastizales resultó en una disminución en MOS en los 20 cm superficiales de 90.0 a 68.8 t C/ha después de dos años del establecimiento de los pastizales, pero las entradas en MOS provenientes del pastizal durante un período de ocho años hicieron volver la MOS a 96 t C/ha, de las cuales 45.8 t/ha fueron derivadas del pasto. El balance neto de C durante el período de ocho años fue de 72.8 t C/ha mientras que el retorno de C de la MOS proveniente del pastizal fue aproximado al C proveniente de la selva.

La introducción del cultivo de caña de azúcar redujo el C del suelo de 72.0 t C/ha a 38.5 t C/ha en un período de 50 años a un nivel de equilibrio de 0.8% C. Tal disminución en 14.4 x10^6 ha de tierras de cultivo representa el 0.25% del incremento anual de CO_2 atmosférico global.

Se concluye que la conversión de la selva Brasileña a tierras agrícolas ha tenido un efecto pequeño en el nivel global de CO_2 y que el reto mayor que enfrenta la agricultura en Brasil es el desarrollo de sistemas de pastizal y de cultivo que sean económicos y biológicamente sustentables a través de la integración de la fertilización balanceada, manejo de los residuos de cosecha, y el uso de abonos verdes con sistemas de cultivo que conserven la MOS.

La pérdida en la calidad del recurso suelo representa un problema tan importante como la creciente concentración de CO_2 atmosférico y el posible calentamiento global.

SUMMARY

Global deforestation has been estimated to contribute 6.5% of the annual increase in atmospheric CO_2. Recent developments in the use of ^{13}C has enabled identification of the source of C in soil organic matter (SOM) when forest is converted to tropical grass pasture or sugar cane. It is estimated that burning of Brazilian rainforest contributes 27.9 t C/ha to the atmosphere and that the total C transfer to the atmosphere from burning the 9.77x10^6 ha of cleared forest represents 0.24% of the total CO_2 contributed by deforestation throughout the world.

Clearing of Amazonian rainforest for pasture resulted in a decline in SOM in the top 20 cm from 90.0 to 68.8t C/ha after 2 years of pastures but inputs of SOM from the pasture over an 8 year period returned SOM to 96t C/ha, 45.8 t/ha of which was derived from the pasture. The net C over the 8 year period was -72-8t C/ha with C return from the grazed pasture approximating the C return in the forest.

Introduction of sugar cane cropping reduced soil C from 72.O t C/ha to 38.5 t C/ha over a 50 year period to an equilibrium level of 0.8% C. Such a decline over 14.4 x 10^6 ha of cropped land represents 0.25% of the annual increase in global atmospheric CO_2.

It is concluded that conversion of Brazilian forest to agricultural land has had a minor effect on the global CO_2 level and that the greatest challenge facing Brazilian agriculture is to develop pasture and cropping systems that are economically and biologically sustainable through the integration of balanced fertilization, crop residue management and the use of green manures with SOM conserving cultivation systems.

The declining quality of the soil resource presents a problem as great or greater than increasing atmospheric concentration of CO_2 and possible global warming.

INTRODUCTION

Increasing attention to global warming, and environmental conditions in general, has focused attention on the atmospheric gasses than can potentially alter the global heat balance. Of particular attention has been CO_2. It has been estimated (Stevenson, 1986) that total additions of CO_2 form burning of fossil fuel amounts to approximately 23.0 x 10^9t/yr (6x10^9t C/yr) and that global deforestation can contribute 1.5-2 x 10^9t C/yr of this total. This estimate of the deforestation contribution is generally derived from a simple estimate of the loss of standing biomass and does not take into account the fluxes of carbon (C) in SOM and subsequent revegetation, and agricultural practices.

Until a recently SOM research has concentrated on knowledge of its structure (2), the understanding of its genesis (Stevenson, 1983), and on the evaluation of its importance to the soil-plant relations and pedogenetic processes. Recent developments in the use of ^{13}C stable isotopes (Cerri *et al.*, 1985) have enable a partitioning of the resident SOM into that contributed by C_3 and C_4 plants. This has been particularly important when forests (C_3 plants) have been converted to tropical pasture grasses or sugar cane (C_4 plants) which has occurred in large areas of Brazil.

To determine the net effect of forest clearing to pastures and sugar cane on C Pool sizes, the contributions of C fluxes from such development to global CO_2 emissions and the possible consequences for global climate change. In order to understand and predict the role of SOM in the global change it is necessary to quantify its accumulation and decomposition rates on different time scales.

The use of C and N stable isotopes in SOM research.

^{13}C and ^{15}N are the two most common isotopes used to study chemical and/or physical fractions of SOM because C and N are the most significant indicators of SOM state and they represent about 50% of the weight of SOM. The techniques uses the fact that abundance of these isotopes varies according to isotopic discrimination in SOM compounds during biological (Blair *et al.*, 1985) and/or physical (Farquhar *et al.*, 1982) processes. Carbon 13 abundance ($\delta^{13}C$) in plants is related to the photosynthetic type: C_3, C_4 or CAM pathway. The $\delta^{13}C$ value of a C_3 plant like most forest trees, wheat and legumes is-12 ‰ and that of C_4 plant like tropical grasses and corn is-26‰. This $\delta^{13}C$ value can be used (Blair *et al.*, 1985; Balesdent *et al.*, 1987) as an indicator of the origin of the carbon pool. When the original photosynthetic pathway of organic inputs is artificially (agriculture) or naturally (vegetation change due to climate modification) changing the $\delta^{13}C$ value this can provide information on the turnover of the original SOM.

When C_4 vegetation replaces the original C_3 vegetation after deforestation the soil C pool (Cs) can be divided into organic C remaining from the previous forest vegetation (Cdf) and C derived from the crop (Cdc). The Cdf component consists of two main fractions: one easily mineralized or biodegradable (Cdfb) and the other which is stable considering a time scale of less than a century. This hypothesis of a stable, i.e. non-biodegradable phase has been previously proposed (Balesdent *et al.*, Jenkinson and Rayner, 1977; Van Veen and Paul, 1981). These three pools are calculated using the following equations:

$$Cs = Cdf + Cdc \quad \text{(I)}$$

$$Cs.\delta^{13}Cs = Cdf.\delta^{13}Cdf + Cdc.\delta^{13}Cdc \quad \text{(II)}$$

$$Cdf(t) = Cdfs + Cdfb(t{=}O) \,.\, \exp(-k_f \cdot t) \quad \text{(III)}$$

where k_f is the decay constant for SOM derived from forest.

For a time t the total amount of output is Cdf (t=0) - Cdf (t) and of input is Cdc (t).

C fluxes when forest is converted to permanent grass pasture.

The Amazon Basin covers an area of 7 050 000 km^2 (Sioli, 1984) and occupies large portion of the national territories of Surinam, Venezuela, Colombia, Peru, Bolivia, Equador, Guyana, French Guyana, and Brazil. In Brazil the evergreen forests (tropical rainforest) cover 2.8 x 10^6 km^2, with the total forest area totaling 3.85 x 10^6 km^2 including semi-humid and deciduous forest of transition (Huguet, 1990).

Moraes (1991) estimates the area as 4 345 956 km^2 according to the considerations of Volkoff (1984) and estimates that there is nearly 41 x 10^6 t C stored in the top 1 m of the soil under these forests.

Areas which have been deforested have been converted to several forms of agriculture, including several forms of cropping, and the establishment of pastures. In a first part of this paper we estimate the flux of C resulting from cutting and burning of forested areas and the development of cultivated pastures. A brief outline of the parameters used to calculate these fluxes is present below:

Forest Biomass: Estimates published of the above ground biomass for the Brazilian Amazon forest range from 256t/ha (Klinge and Rodrigues, 1974) to 353 t/ha (Klinge *et al.*, 1975) near Manaus, and in other places values range from 248 t/ha at Tucurui (Cardenas *et al.*, 1982) to 300 t/ha (Uhl *et al.*, 1988) in Paragominas (Pará state). A mean value of 290 t/ha has been used. This value, assuming the traditional 0.45 value for C content, corresponds to 130.5 t C/ha.

Timber harvesting: Huguet (1990) reported that 4250 m^3 of rough timber was removed from a 100 ha study unit in 1986. Assuming a 0.62 mean wood density value (Brown and Lugo, 1982) and a carbon content of 0.50 for wood (Fearnside, 1985), the amount of C removed is equivalent to approximately 13.2 t C/ha.

Areas deforested and pasture developed: Estimates of area of pasture (S) in the Brazilian Amazon range from 70 000 km^2 (Serrão and Toledo, 1992), 100 000 km^2 (Hecht, 1985) to 120 000 km^2 (Koehelhepp, 1984). A mean value 97 700 km^2 has been used.

C production from burning: Combustion efficiency (Ce) has been estimated near Manaus to vary from 20.0% (Teixeira, 1987) to 27.6% (Fearnside *et al.*, 1993). Therefore a Ce average of 23.8% has been used. C flux to the atmosphere due to burning of forest for pasture formation has been obtained by the following calculation: $(C_{Biomass} - C_{timber}) \times Ce \times S$,

Pasture productivity : Estimates of pasture productivity in the Amazon are scarce. An annual above ground dry matter production estimate of 10 t/ha has been used (Teixeira, 1987) which has a carrying capacity of 1.5 beasts/ha and is found in much of the area.

Change in soil C: $\delta^{13}C$ data from a chronosequence of samples of pastures developed over an 8 year period has been used to estimate the C present in the 0-20 cm soil layer which originated from the forest vegetation and from C_4 grasses in the pasture (Choné *et al.*, 1990; Andreux *et al.*, 1990). Equations (II) and (III) have been used to estimate the biodegradable and stable C remaining from the forest vegetation. A total of 90 t/ha of C was found in SOM in the top 20 cm of the forest soil at Manaus at the time of clearing. Of this total 55% was estimated to be present in the biodegradable (Cdfb) fraction at clearing and this reduced to zero after 4 years (Figure la). Total C in the top 20 cm of soil from the forest declined to 69t/ha in years 2 and 3 as a result of mineralization of SOM.

The contribution of C of pasture origin (Cp) in the 0-20 cm layer (Figure la) was 7.2t C/ha (5%) after 1 year, 14.0t/ha (20%) after 2 years, and 45.8t/ha (40%) after 8 years. In this unfertilized well managed *Brachiaria humidicola* ecosystem (Choné *et al.*, 1990; Andreux and Cerri, 1989) stocked at 1.5 beast/ha it was shown that after eight years of pasture, the organic C content of the surface soil had exceeded its initial value.

Based on the above measurements, calculations and assumptions a C balance for the 8 years pasture system has been obtained (Table 1). This shows a loss of 50.7t C/ha in the year of burning and pasture establishment and a total loss of 23.9t C/ha over the next 7 years

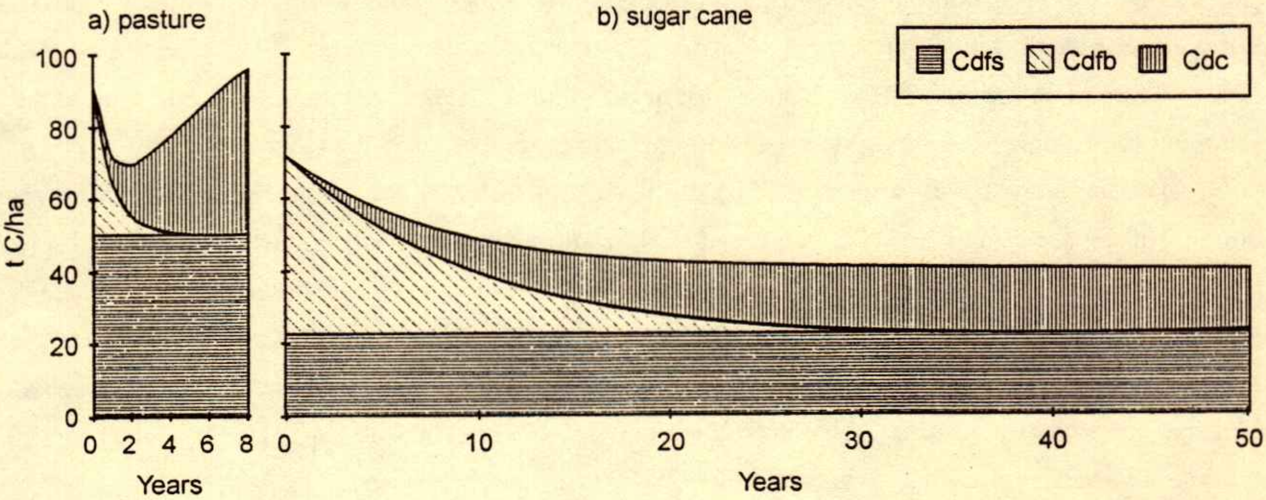


Figure 1. Carbon Derived from forest, separated into stable (Cdfs) and biodegradable (Cdfb) fractions an C from pasture or crop (Cdc). a) Pastures from Manaus in Amazon State over 8 years, b) Sugar cane from Sao Paulo State over 50 years.

(3.4 t C/ha/yr) which has a loss via continued decay of unburnt forest residue and mineralization of biodegradable forest (Cdfb) and a gain from unutilized pasture biomass. The reason why the C flux is not more negative can be obtain from a comparison of the C budget in forest and grazed pasture system. To do this a number of estimates and assumption must be made. In the estimate of the C budget presented here the following have been used:

Table 1. Estimated C pool sizes and transfer (t/ha) where a tropical rainforest at Manaus, Brazil was logged, burnt and converted to pasture.

	C pool size	C transfer		
		year 1	years 2-8	Net over 8 years
	----------------------------------t/ha	--------------------------------------		
Biomass	130.5			
Removed in timber	13.2			
Forest burning		-27.9	0	-27.9
Decay of unburnt biomass		-11.0	-77.0	-88.0
Soil C (0.20 cm)	90.0			
Soil C from forest cultivation		-26.2	-13.5	-39.7
Soil C pasture phase		+7.2	+38.6	+45.8
Pasture growth		+9.0	+63.0	+72.0
Annual burn		0	-35.0	-35.0
Total		-48.9	-23.9	-72.8

Forest litter production: Luizão (1989) measured litter production in a forest from Manaus over 3 year period ranging from 7.5 to 8.25t dry matter (DM)/ha/yr.

Pasture litter production : A production of the above ground biomass of 10 t/ha has been used (Teixeira, 1987). The pasture was stocked with cattle at 1.5 beast/ha which consumed 4.1 tDM/ha/yr. This leaves residual herbage return to the litter pool of 5.9 tDM/ha. Assuming an average digestibility of 60%, 40% of the intake would be returned in dung (1.6 t/ha).

It has been assumed that root turnover was the same in both systems. Based on the above the forest system has a return of C of approximately 3.6t C/ha (8tDM/ha x 45% C) whilst in the grazed pasture 3.3t C/ha (2.6 in litter and 0.7 in dung) is returned.

The above calculation is supported by the soil C data which shows that following clearing of the forest there is an initial decline in soil C but that this is restored to a level higher than the initial value after 8 years of unfertilizer grazed pasture because of the productivity of the pasture and the degree of recycling of C within the grazed system. The long term sustainability of this system will depend not on the availability of C but on the supply of nutrients, particularly N, P, and S to the pasture. With transference of these nutrients to concentrated areas such as dung, stock camps and yards and offtake in product and this transformation into less available soil forms it is inevitable that nutrients lost in this way will have to be replaced. The form (legume, fertilizer) in which there are returned will have a significant bearing on the economic and biological sustainability of the system. This, together with the population and economic pressures will determine whether these cleared areas will remain under pasture, be abandoned or converted to crop production.

C fluxes when cropping is introduced.

Brazil currently has an annual population growth rate of 1.8% and rising standard of living and at present the country is substantially reliant on alcohol, produced from sugar cane, to provide fuel for cars. This means that increasing areas of land will need to be converted to crop production and/or productivity increased in existing cropping areas. Such a change will place additional pressures on soil resources and have important effects on the C balance of the agriculture ecosystem. In this section of the paper the C fluxes in a sugar cane cropping system are considered.

Cerri *et al.*(1991) has investigated the changes in soil C in an Oxisol soil which hand grown sugar cane exclusively for 12 and 50 years. The contribution of forest (stable and biodegradable) and crop C to soil C in the 0-20 cm layer is presented in Figure lb.

The soil C pool of 72.0 t C/ha in São Paulo (SP) state compares with 90.0t C/ha in the Amazonia which most likely reflects the lower growth rate of the forest in SP which has a lower mean temperature and a longer dry season. Cropping, with frequent cultivation, which exposes organic matter to greater mineralization resulted in not only a decline in C derived from the forest but a low input of C from the sugar cane crop such that total soil C levels declined from 72.0 to 38.5t/ha over a 50 year period. This has important implications for the total C flux.

Calculation of Cdfs for the sugar cane system indicates that this represents only 29% of Cs whereas it represented 55% in the pasture at Manaus. Whilst this can be interpreted as the presence of a more biologically active soil C Pool at SP it could also represent a deficiency in the method of calculation of Cdfs which assumes an asymptotic exponential function. Earlier studies of soil C (Jenkinson and Rayner, 1977) suggests that SOM consists of a series of pools with varying tumover rates. Even though some pools turnover slowly they still contribute C to the microbial biomass and are therefore not stable. A recent study by Lefroy *et al.* (1994) has shown significant declines during cropping in both labile C and in the more stabilized soil C fraction not oxidized by $KMnO_4$.

Global and national consequences of altered C fluxes from Brazilian agriculture.

In the C balance shown in Table 1 the burning of the Brazilian forest contributes an immediate 27.9t C/ha to the atmosphere. Based on a total cleared area of the Amazonian forest of 9.77×10^6ha a total of 0.273×10^9t C has been added to the atmosphere by buming. This represents only 0.24% of the $115 \pm 35 \times 10^9$t C which has been estimated (Houghton and Skole, 1990) to have been released to the atmosphere throughout the world through changes in land use, mainly deforestation, between 1850 and 1985. In relation to the total amount of atmospheric C (353 ppmv, *i.e.* 748.4×10^9t C (Lal and Chakraborty, 1993) the contribution from Amazon forest buming represents less than 0.04%. Assuming that all the C in the unburnt forest biomass has subsequently been released when the pastures have been burnt the contributions are 1.0% and 0.15% respectively.

The estimate of C flux when Brazilian forest is cleared and converted to pasture made here has been over an 8 year time scale. At the end of the 8 years all of the unburnt forest has been lost such that from 8 years around the system returns to an equilibrium. An important component of the C flux calculation presented has been the inclusion of the changes in the SOM pool and the partitioning of C return that from the forest and that from the pasture which has been made possible through the use of the $\delta^{13}C$ technique. Developing sustainable technologies to maintain productive pastures is a challenge facing Brazilian agriculture.

The decline in the soil C pool in the 0-20 cm soil layer measured in the 50 years sugar cane cropping system represents an average decline of 0.67t C/ha/yr and a loss of 47% of C. The impact of this decline in soil C an global CO_2 flux has been estimated. Assuming that the magnitude of the decline in soil C has been the same in the 4.4 10^6 ha of sugar cane and $10x10^6$ ha of soybean cultivated annually in Brazil the C decline represents a loss of 482.4 $x10^6$ t C over 50 years or $9.65x10^6$t C/year. With global CO_2 increasing at 1.8 ppmv/yr ($3.8x10^9$ t C/yr) the input from the decline in soil C as a result or cultivation of crop land in Brazil represents 0.25% of this increase. The rate of decline in soil C is asympotic and reaches a new equilibrium of approximately 0.8% in cropped areas. Of importance is to know what proportion of this C is labile and able to turnover at a rate sufficient to maintain an active soil biomass. The combined use of the $\delta^{13}C$ and $KMnO_4$ fractionation techniques (Lefroy *et al.*, 1994) offer the possibility of estimating the labile and non-labile pools in such systems and the impact of agriculture practices such as fertilization, crop residue return and green manuring on the sustainability of the system. The sustainability index developed by Lefroy and Blair (Lefroy *et al.*, 1994) will be helpful in this regard.

Although the contribution of forest clearing and decline in soil C with cropping represents a small portion of the total increase in atmospheric CO_2 concentration, it is never-the-less a contribution. Economic pressures and the present lack of an economically sustainable technology to maintain pasture production in land cleared from Amazon forest is likely to reduce the rate of forest clearing. On the other hand increasing population and an increasing standard of living is likely to result in an increase in the cropping area in Brazil. For this to be sustainable, balanced fertilization and/or green manure and crop residue management systems and cultivation practices which conserves SOM, will have to be developed to maintain soil fertility and SOM at acceptable levels. Such systems will be CO_2 neutral with C fixation in product and residue equaling C loss by respiration and decay.

Continued refinement of techniques to monitor soil C pools will be required in order to be able to determine the effect of different production systems on short and long term sustainability. The challenge of maintaining the quality of the soil resource in world agriculture is as great as or greater than the problem of increasing atmospheric concentration of CO_2 and the possibility of global warming.

LITERATURE CITED

ANDREUX, F.G. AND C. C. CERRI. 1989. Current trends in the research on soil changes due to deforestation, burning and cultivation in the Brazilian tropics. Toxicol, and Environ, Chem, 20-21:275-283,

ANDREUX, F.G, C.C. CERRI, B. DE P. EDUARDO AND T. CHONÉ. 1990, Humus contents and transformations in native and cultivated soils. The Sci. of the total Environ., 90:249-265.

BALESDENT, J., A. MARIOTI AND B. GUILLET. 1987. Natural ^{13}C abundance as a tracer for studies soil organic matter dynamics. Soil Biol. Biochem. 19(1): 25-30.

BLAIR, N., A. LEU, E. MUÑOZ, J. OLSEN, E. KWONG AND D. DES MARAIS. 1985, Carbon isotopic fractionation in heterotrophic microbial metabolism. Appl. . Microbiol., 996. 1001.

BROWN, S. AND A. E. LUGO. 1982. The storage and production of organic matter in the tropical forests and their role in the global carbon cycle. Biotropica 14(3):161-187.

CARDENAS, J. D. R., F. L. KALN AND J. L. GUILLAUMET. 1982, Estimativa da fitomassa do reservatório da UHE da Tucuruí. 32 pp. *In*: Projeto Tucurui, Relatorio semestral (Jan.-Jun.), Vol. 2; Limnologia, macrófitas, fitomasse degradação de fitomassa doenças endêmicas, solos. INPA. Manaus.

CERRI, C.C., B. DE P. EDUARDO AND M.C. PICCOLO.1991. Use of stable isotopes in soil organic matter studies. Proc, IAEA-SM-313/48. Vienna 1-5 Oct. 1990. Austria, 247-259.

CERRI, C.C., C. FELLER, R.L. VICTÓRIA AND A. PLENECASSAGNE. 1985. Application du traçage isotopique naturel en ^{13}C à l'étude de la dynamique de la matière organique dans les sols. C.R. Acad, Sci. Paris, 300, II (9): 423-426.

CHONE, T., F. ANDREUX, J. C. CORRÊA B. VOLKOFF AND C.C. CERRI. 1990. Changes in organic matter in an Oxisol from the central Amazonian forest eight years as pasture, determined by ^{13}C isotopic composition. *In*: J, Berthelin and J. Bauds (eds). Proc. 8th Int. Symp. on Environmental Biogeochemistry (ISEB), Nancy, France, Sept. 1987. Marcel Dekker Inc., New-York,

FARQUHAR, G.D., M.H. O'LEARY AND J.A. BERRY. 1982. On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. Aust. J. Plant Physiol. 10:205-226.

FEARNSIDE, P.M. 1985. Summary of progress in quantifying the potential contribution of Amazonian deforestation to the global carbon problem. pp. 75-82. *In*: Proc. Workshop on Biogeochemistry of Tropical Rain Forests: Problems for research. University of São Paulo-CENA. Piracicaba. Brazil.

FEARNSIDE, P.M., N. LEAL FILHO AND P.M. FERNANDES. 1993. Rainforest burning and the global carbon budget: Biomass, combustion efficiency and charcoal formation in the Brazilian Amazon, J. of Geophys. Res, (in press).

HECHT, S. 1985. Environment, development and politics: Capital accumulation and fhe livestock sector in eastern Amazonia. World Development. 13:663-684.

HOUGHTON, R.A. AND D. L. SKOLE. 1990. Changes in the global carbon cycle between 1700 to 1985. The Earth Transformed by Human Action. B.L. Turner. (ed.) Cambridge University Press.

HUGUET, L. 1990. Regards sur l'Amazonie brésilienne actuelle. Re, For, Fr. XLII, 3: 301-315.

JENKINSON, D.S. AND J.H. RAYNER. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Sci. 123 : 298-305.

KLINGE, H., W.A. RODRIGUES, E. BRUNIG AND E.J. FITTKAU. 1975. Biomass and structure in a control Amazon rain forest. pp. 115- 122. *In*: Tropical ecology systems: Trends in terrestrial and aquatic research. F.B, Golley & E. Medina (eds.) Springer-Verlag. New-York.

KLINGE, H. AND W.A. RODRIGUES. 1974. Phytomass estimation in a Central Amazon rain forest. H. E. Young (ed). IUFRO Biomass Studies. University Press. Maine. USA. 339-350.

KOEHELHEPP, G. 1984. Development planning and practices of economic exploitation in Amazonia. Recent trends in spatial organization of tropical frontier region in Brazil (1966-1981) pp. 649-674. *In*: H. Sioli (ed.). The Amazon, Limnology and landscape of a mighty tropical river and its basin. Dr. W. Junk Publishers. Netherlands

LAL, M. AND B. CHAKRABORTY. 1993. Evidence for global warming: Antropogenic factors., pp. 19-36. In: M. Lal. (ed.) Global warming: Concern for Tomorrow Tata McGraw-Hill Publish. Comp. Ltd.

LEFROY, R.D.B. G., J. BLAIR AND W.M. STRONG. 1994.Changes in soil organic matter as measured by organic carbon fractions and ^{13}C natural isotope abundance, Proc. XII Int, Plant Nutrition Colloquium. Perth. Australia.

SIOLI, H. 1984. The Amazon, Limnology and landscape of a mighty tropical river and its basin H. Sioli (ed.) Dr. W. Junk Publishers. Netherlands, 763 pp.

STEVENSON, F.J. 1986. Cycles of Soil Carbon, Nitrogen, Phosphorus, Sulfur, Micronutrients, John Wiley & Sons Inc. Toronto. 380 pp.

STEVENSORE, F.J. 1982. Humus Chemistry. Genesis, Composition, Reactions. John Wiley & Sons Inc. Toronto. 443 pp.

TEIXEIRA, L.B. 1987, Dinámica de ecossistema de pastagem cultivada em área de floresta na Amazónia central. University of Amazonas. Manaus. Brazil. 100 pp. (Thesis dissertation)

UHL, C. AND R. BUSCHBACHER, E. A. S. 1988. Abandomned pastures in eastern Amazoni. I. Patterns of plant succession. J. of Ecology. 76:663-681.

VAN, VEEN J.A. AND E.A. PAUL. 1981. Organic carbon dynamics in grassland soils. I. Background information and computer simulation. Can J. Soil Sci. 61: 185-201.

VOIKOFF, B. 1984. Organisation régionale de 1a couverture pedólogique du Brésil. Chronologie des différenciation. Pédologie. Paris. 21(4); 225-236,

FAO/IAEA COORDINATED RESEARCH PROGRAMME TO ENHANCE BIOLOGICAL NITROGEN FIXATION OF COMMON BEAN IN LATIN AMERICA

Programa de Investigación Coordinada FAO/OIEA para Incrementar la Fijación Biológica de Nitrógeno de Frijol Común en América Latina

Gudni Hardarson[1], Juan Jose Peña-Cabriales[2] and Anita Herndl-Silmbrod[1]

[1]Soil Science Unit, FAO/IAEA Programme, Agency's Laboratory, A-2444- Seibersdorf, Austria
[2]CINVESTAV, Irapuato, Mexico.

Palabras clave: **Fijación biológica de nitrógeno (FBN), Isótopo de nitrógeno (^{15}N), Nitrógeno atmosférico (N_2), *Phaseolus vulgaris, Rhizobium.***

Index words: **Atmospheric nitrogen (N_2), Biological nitrogen fixation (BNF), Isotope nitrogen (^{15}N), *Phaseolus vulgaris, Rhizobium.***

RESUMEN

Por más de dos décadas, la Organización de las Naciones Unidas para la Agricultura y la Alimentación (FAO) y el Organismo Internacional de Energía Atómica (OIEA) a través de su División Conjunta en Viena y el Laboratorio de Agricultura en Seibersdorf, han coordinado programas internacionales en países en desarrollo sobre fijación biológica de nitrógeno. El objetivo principal de estos programas ha sido desarrollar y optimizar el método de la dilución isotópica ^{15}N para cuantificar la fijación de nitrógeno en cultivos de leguminosas y mejorar la fijación de nitrógeno en varios sistemas de cultivo.

Como parte de los programas coordinados de investigación, se diseñan experimentos para efectuarse simultáneamente en varios países, en los cuales se obtienen resultados bajo un amplio rango de condiciones ambientales. Además, una de las características más importantes de los programas FAO/OIEA es transferir esta tecnología durante los talleres y reuniones de investigación.

Durante el período de 1986-1991 se condujo un programa en América Latina con el objetivo de identificar cultivares de frijol común (*Phaseolus vulgaris* L.) con alto potencial de fijaci{on de nitrógeno. Intervinieron instituciones científicas de Brasil, Chile, Colombia, Estados Unidos, Guatemala, México y Perú. En este escrito se presentan algunos resultados obtenidos de este programa.

SUMMARY

The Food and Agriculture Organization of the United Nations and the International Atomic Energy Agency have through their Joint Division in Vienna and the Agriculture Laboratory, Seibersdorf, for more than two decades coordinated international programmes on biological nitrogen fixation in developing countries. The main objectives of these programmes have been to develop and optimize the ^{15}N isotope dilution method to quantify N_2 fixation in leguminous crops and to enhance nitrogen fixation in various cropping systems.

Experiments, conducted as part of coordinated research programmes, are performed in a number of countries simultaneously and, therefore, they give results under a wide range of environmental conditions. A major feature of FAO/IAEA programmes is the transfer of technology which occurs during research coordination meetings and workshops.

During 1986-1991 such a programme was conducted in Latin America with the objective of identifying cultivars of common bean (*Phaseolus vulgaris* L.) with enhanced biological nitrogen fixation. Scientific institutions from Brazil, Chile, Colombia, Guatemala, Mexico, Peru and the United States were involved. Some results from this programme are presented.

INTRODUCTION

The Joint FAO/IAEA Division in Vienna and the FAO/IAEA Agriculture Laboratory, Seibersdorf, Austria, have conducted many Coordinated Research Programmes (CRP) on various aspects of isotope tracer technology in crop and livestock production over its 30 year history. Each CRP aims to identify and resolve problems affecting agricultural production in developing countries. Scientists from 10-15 institutes participate in each programme either as funded research contractors from developing countries or as cost-free agreement holders from developed countries or International Institutes. Research Co-ordination Meetings are held to monitor the progress of research, share ideas and responsibilities, plan future work and finally report on results and recommend future work. These meetings help focus and clarify objectives for the researchers themselves as well as for the FAO/IAEA programme. Projects that are funded through a CRP receive an annual lump sum contract. Usually the amount awarded to each contractor is relatively small (US$ 5000/year) but this is usually enough to conduct some important and often difficult research. Each CRP lasts about 5 years. The results and conclusions are usually published by the FAO/IAEA and/or the individual participants.

Several of the international FAO/IAEA programmes have been conducted on biological nitrogen fixation (BNF) (Table 1). The first BNF programmes focused on grain legumes and the development of ^{15}N methodology to measure BNF. These were followed by others in which BNF

Table 1. Coordinated Research Programmes on biological nitrogen fixation which have been conducted by the Soil Fertility, Irrigation and Crop Production Section of the Joint FAO/IAEA Division.

Short title of programme	Duration	Number of participating countries
a) Fertilization of grain legumes,	1972 - 1977	14
b) Grain legumes[1],	1979 - 1983	19
c) Multiple cropping,	1980 - 1985	9
d) Pasture[2]	1983 - 1988	19
e) Azolla[1],	1984 - 1989	13
f) Common bean in Latin America,	1986 - 1991	7
g) Grain legumes in Asia[3],	1987 - (1994)	10
h) Tree legumes,	1989 - (1995)	15
i) Microbial ecology,	1992 - (1997)	12

[1]Funded by the Swedish International Development Authority.

[2]Funded by the Government of Italy.

[3]Funded by the United Nations Development Programme.

Table 2. Total amount of common bean (dry bean) produced in Latin American countries, as well as average yield and cultivated area in 1991 (FAO, 1992).

Country	production (x 1000 MT)	Yield (kg/ha)	Area(x 1000 ha)
Argentina	220	1128	195
Belize	2	686	4
Bolivia	12	1233	10
Brazil	2751	500	5508
Chile	119	1343	88
Colombia	108	808	134
Costa Rica	33	477	69
Cuba	26	351	74
Dominican Rp	33	1124	29
Ecuador	50	909	55
El Salvador	67	869	77
Grenada		833	
Guatemala	110	846	130
Haiti	55	655	84
Honduras	110	711	155
Jamaica		1000	
Mexico	1448	710	1584
Nicaragua	56	611	91
Panama	5	375	12
Paraguay	45	874	52
Peru	47	912	52
Puerto Rico		5660	
Uruguay	3	617	5
Venezuela	59	621	95
Total	5359		8960
Average		598	
World	17525	666	26316

in forage, pasture legumes, *Azolla* and tree legumes was quantified. The most recent programmes have emphasized the enhancement of nitrogen fixation in such plants as common bean through genetic improvements.

The common bean is among the most important food crops in Latin America; some 5.3 million tons of dry bean being produced in 1991 (FAO, 1992) (Table 2). Brazil (51%) and Mexico (27%) grow the most common bean whilst Argentina, Chile, Colombia, Guatemala and Honduras each produce between 2 and 4% of the total production in Latin America. It is likely that considerable amounts of bean are not included in these official statistics as they are often consumed locally. Bean production and cultivated area have increased over the last two decades (Table 3) although yield/ha has continued to be very low (600 kg/ha). For comparison the soybean production in Latin America has increased 15 times in the same period with yield increasing from 1278 to 1820 kg/ha.

The FAO/IAEA programme on "The Enhancement of Biological Nitrogen Fixation of Common Bean in Latin America" was conducted during the years 1986- 1991 (Bliss and Hardarson, 1993). Its objectives were to investigate the N_2 fixation potential of various cultivars and breeding lines of common bean and to identify lines which could be used as parents in breeding programmes to enhance N_2 fixation in this species. As some of the bean cultivars used in these field experiments showed very low percentage and amount of N_2 fixed, a greenhouse experiment was conducted at the FAO/IAEA Laboratory to study the effect of temperature on these factors. The objective was to find out whether high temperature had a detrimental effect on nitrogen fixation in common bean compared with other leguminous species.

Table 3. Total amount of common bean (dry bean) produced in Latin American countries, as well as average yield and cultivated area during the years of 1969 to 1991 (FAO, 1980; 1992).

	1969-71	1979-81	1989	1990	1991
Production (1000 MT)	3876	4064	3831	4589	5360
Yield (kg/ha)	604	551	491	567	598
Area (1000 ha)	6419	7385	7797	8096	8959

Some of the results of the above programme are presented in this paper with examples mainly from the studies in Mexico and Austria.

MATERIALS AND METHODS

Field experiments were performed in Austria, Brazil, Chile, Colombia, Guatemala, Mexico and Peru as part of the above CRP. Each experiment included approximately 20 bean genotypes in single rows with six replicates. They were compared using the ^{15}N isotope dilution method (Fried and Middelboe, 1977; McAuliffe *et al.*, 1958). 10 kg N/ha of approximately 10% ^{15}N atom excess ammonium sulphate was applied to the experimental area at the time of planting. Only cultivars of similar growth periods were included in each experiment. The evaluations of nitrogen fixation were made when the cultivars having the shortest growth cycle reached physiological maturity. At that growth stage all entries were harvested. Plant samples were weighed, chopped, sub-sampled and dried at 70 ^0C. The dried samples were finely ground and total N determinations were made by the Kjeldahl method (Eastin, 1978), and the N isotope ratio analyses by mass spectrometry (Fiedler and Proksch, 1975) at the FAO/IAEA Laboratory, Seibersdorf. The experiment conducted at Seibersdorf, Austria included twenty-nine bean lines and non-nodulating soybean as the reference crop (Table 4) and the one in Irapuato, Mexico had twenty bean lines and sorghum as reference crop (Table 5).

The ^{15}N isotope dilution method used in this study involves the growth of N_2 fixing and non-fixing reference plants in soil labelled with ^{15}N enriched inorganic fertilizers. It is based on differential dilution in the plants of ^{15}N tracer by soil and fixed nitrogen (Fried and Middelboe, 1977; McAuliffe *et al.*, 1958). A N_2 fixing plant will have a lower ^{15}N enrichment compared with the non-fixing reference plant due to assimilation of unlabelled N_2 from the air. Without N_2 fixation both will have the same enrichment. This methodology provides an integrated measurement of the amount of fixed N_2 accumulated by a crop over the growing season. Calculation of %N derived from the atmosphere (%Ndfa) was made by the following equation:

$$\%Ndfa = \left(1 - \frac{\%Ndff_F}{\%\ NdffN_{NF}}\right) \times 100 \qquad (1)$$

where $\%Ndff_F$ and $\%Ndff_{NF}$ are %N derived from fertilizer or tracer by fixing and non fixing plants, respectively.

Table 4. Common bean cultivars tested in Austria.

No.	Cultivar	No.	Cultivar
1	Riz 30	16	Riz 34
2	Dor 41	17	Riz 10
3	Riz 29	18	Wte 3
4	Riz 22	19	Riz 32
5	A 237	20	Bat 76
6	Bat 332	21	Bat 477
7	Riz 68	22	Bat 22
8	Rojo 70	23	Riz 44
9	Riz 53	24	Tostada
10	Catu	25	Nmutikili
11	Bat 1645	26	Rubona
12	Puebla 152	27	Ikinimba
13	Riz 13	28	Borlotto
14	Riz 27	29	Extender
15	Riz 36	Reference	Non-nod soybean

*1-23 from CIAT, Colombia; 24-27 from Rwanda; 28-29 from Austria.

Table 5. Cammon bean cultivars tested in Mexico

No.	Cultivars	No.	Cultivars
6	Sataya 425	16	Ojabra 400
7	Bayocel	17	Cacahuate Ags 19-3-2
8	Flor de Mayo RMC	18	Porillo Sintético
9	Apaseo 67	19	Bay Rio Grande
10	Negro Queretaro Criollo	20	Wisconsin 21-58
11	Criollo Huejutla	21	WBR 22-3
12	Mantequilla de Calpán	22	Diacol Colima
13	Bayo Madero	23	Puebla 152
14	Bayo Zacatecas	24	II-320-MRP-2-13-131
15	Bayo Los Llanos	25	Compuesto Chimaltenango 2
		Reference	Sorghum

A greenhouse experiment was performed to study the effect of temperature on nodulation and nitrogen fixation of common bean (cv. BAT 332), faba bean (cv. Wieselburger) and soybean (cv. 129). This experiment was conducted between February and May 1990 at the FAO/IAEA Agriculture Laboratory, Austria. Pots filled with 3.5 kg Typic Eutrocrepts soil:sand mixture (1:1) were incubated in water tanks adjusted to 16, 22, 28 and 34^{0}C soil temperature after an initial two week incubation at 25^{0}C. The ^{15}N isotope dilution method was used to quantify biological nitrogen fixation. At the time of germination 10 mg N/kg soil as ammonium sulphate of 10% ^{15}N atom excess was applied to all pots. A non-nodulating soybean (cv. 129) was used as a non fixing reference crop. All plants were harvested 10 weeks after planting. The plant samples were analyzed as described above.

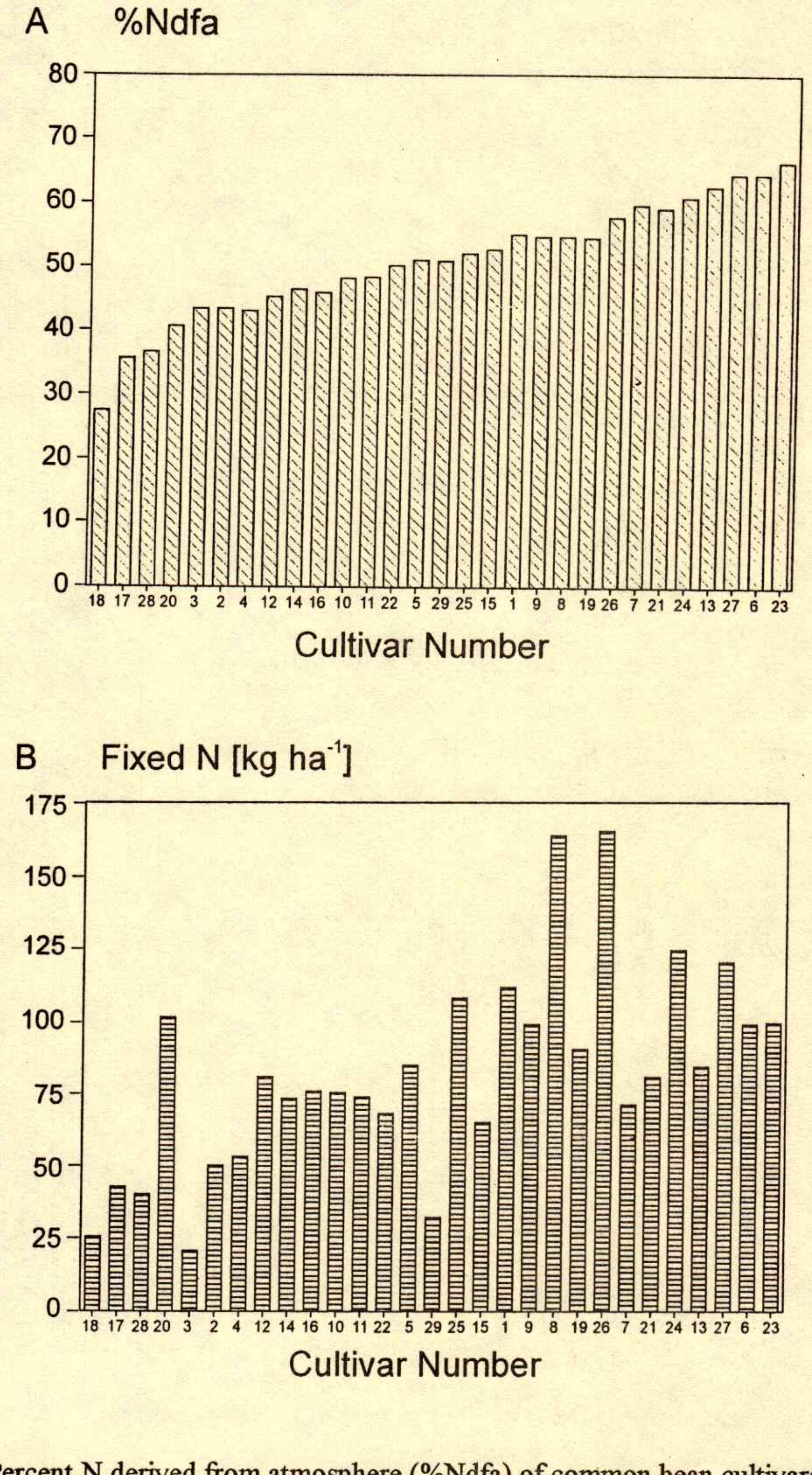
RESULTS AND DISCUSSION

The twenty-nine lines grown at Seibersdorf, Austria were very variable in %Ndfa which ranged from 27 to 67%; total N_2 fixed ranged from 25 to 165 kg N/ha. There was no strong correlation between %Ndfa and amount of N_2 fixed although in general the lines with high % Ndfa fixed more amount of N_2. The most effective cultivars in fixing nitrogen were Riz 44 and BAT 322 at approximately 65% Ndfa (Fig 1A), while Rubona and Rojo 70 fixed about 165 kg N/ha (Fig IB). Three lines that fixed large amounts of total N_2 were from Rwanda (Nos. 26, 24 and 27).

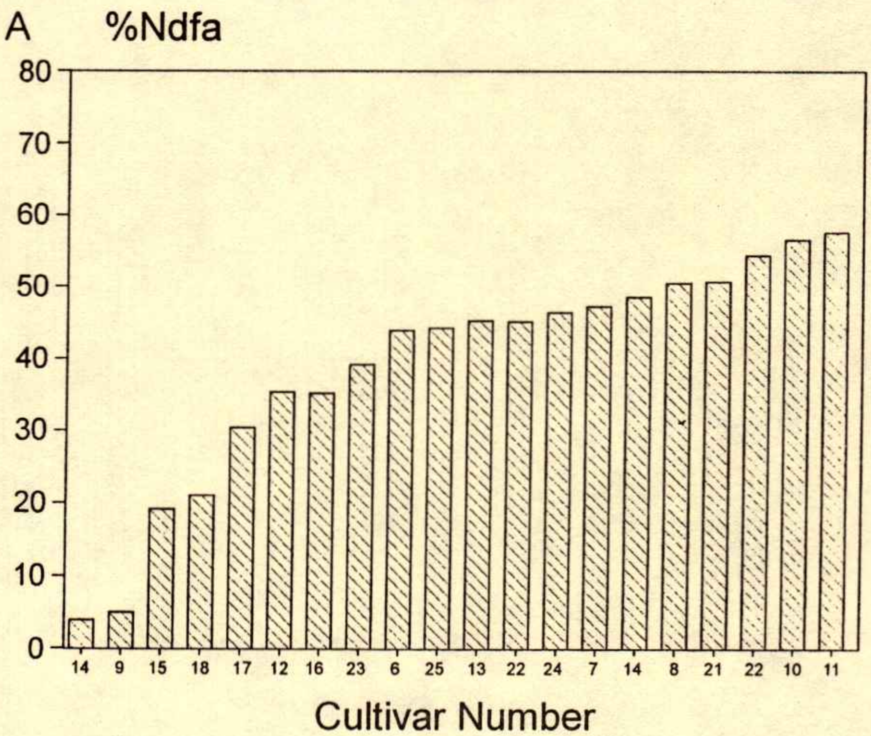
At Irapuato in Mexico %Ndfa and amount of N_2 fixed were very variable in the twenty bean lines tested which was similar to the results in Austria. The range of %Ndfa was from 5 to 58%, the best lines being Criollo Huejutla, Negro Queretaro Crillo and Wisconsin 21-58 (Fig 2A). The range for amount of N_2 fixed was from 7 to 108 kg/ha, with the best line being Wisconsin 21-58 (Fig. 2B).

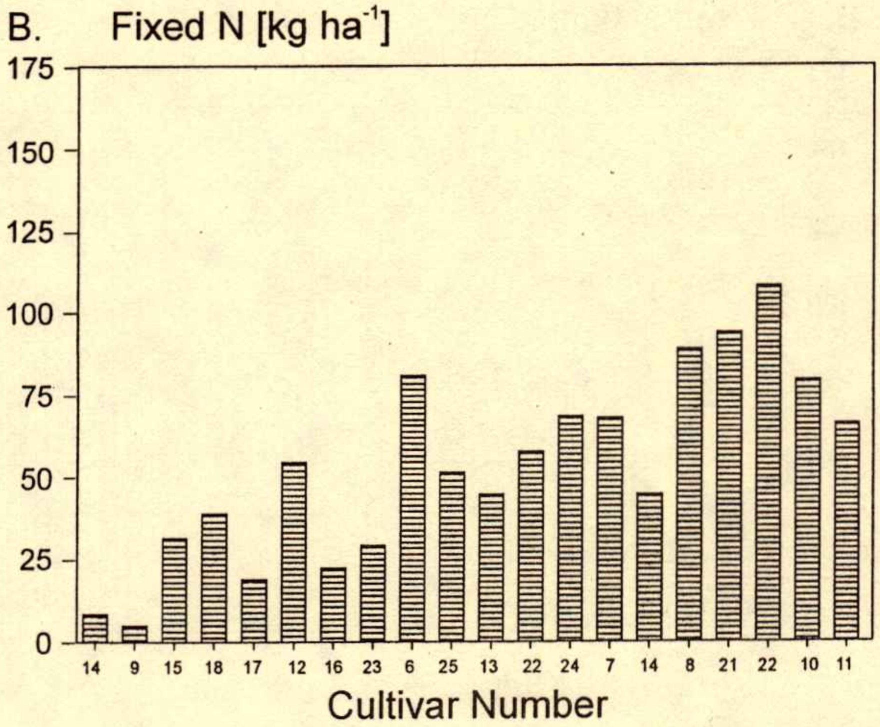
Analysis of 46 field experiments conducted over the last 15 years in Mexico showed that indigenous bacteria were abundant and that inoculation response was only observed in 11% of the experiments (Castellanos and Peña-Cabriales, unpublished data). Enhanced nitrogen fixation in common bean is therefore more likely to be obtained by working on the macro-symbiont as done in the present study.

Similar results to the ones from Austria and Mexico were obtained by other participants in the FAO/IAEA programme and a summary of the results is presented in Table 6 (Hardarson *et al.*, 1993). A wide range in nitrogen fixation was observed in common bean (5-70 %Ndfa) between and within experiments, with average values of 35 %Ndfa. The high values, which were greater than had been reported previously for common bean, were observed only when environmental factors were favorable.



Figures 1 (A) Percent N derived from atmosphere (%Ndfa) of common bean cultivars tested under field conditions in Austria and (B) the amount of N_2 fixed by the same cultivars. The cultivars are listed in Table 4.





Figures 2 (A) Percent N derived from atmosphere (%Ndfa) of common bean cultivars tested under field conditions in Irapuato, Mexico and (B) the amount of N_2 fixed by the same cultivaras. The cultivars are listed in Table 5.

Table 6. Percentage and amount of N derived from atmosphere of cultivars having the lowest and highest nitrogen fixation rates in the various countries (Hardarson *et al.*, 1993).

Country	% Ndfa		Amount of N_2 fixed	
	Min	Max	Min	Max
Austria[1]	27	67	25	165
Brazil, Goiania[2]	12	25	2	12
Brazil, Piracicaba[3]	19	52	12	53
Chile[4]	27	60	25	115
Colombia[5]	32	47	20	36
Guatemala[6]	22	73	12	125
Mexico, Colima[7]	0	50	0	70
Mexico, Irapuato[8]	5	58	7	108
Peru[9]	24	59	19	59

Data of: [1]Hardarson; [2]Henson and Pereira; [3]Tsai; [4]Longeri; [5]Kipe-Nolt; [6]Sanabria; [7]Cigales-Rivero; [8]Peña-Cabriales; [9]Manrique.

The greenhouse experiment investigated the effect of environmental conditions i.e. temperature on nitrogen fixation and growth of three leguminous species (Fig. 3 and 4). Faba bean was particularly sensitive to high temperature compared with common bean and soybean; yield, nodulation and nitrogen fixation all being relatively low at 34 ^{0}C. Soybean was, on the other hand, relatively sensitive to low temperature (16 ^{0}C) in terms of nodulation and N_2 fixation. Unexpectedly, common bean, which had been found to be sensitive to extreme environmental conditions, was relatively productive at both low and high temperature. However, a later study showed that there was considerable difference between common bean cultivars in their tolerance to high temperatures (unpublished data).

This study showed that common bean lines exist which can support high biological nitrogen fixation. After selection these can be used either directly as cultivars for production or in breeding programmes to enhance nitrogen fixation in other cultivars. The use of the better fixing cultivars of common bean by farmers in Latin America would increase N_2 fixation in common bean by at least 10 - 20%, which is equivalent to about 10 - 20 kg N/ha. They would have to apply 30 - 60 kg N/ha as fertilizer to provide the same amount of N to the crop. Therefore this increase is of economic importance for the farmers on that continent. Although environmental conditions, i.e.

high temperature and dry conditions, appeared to influence nitrogen fixation by common bean we were not able to confirm this under controlled conditions in the greenhouse. There is obviously much research to be done on the common bean/*Rhizobium* symbiosis before the most effective combinations can be identified to increase bean production in the LA region.

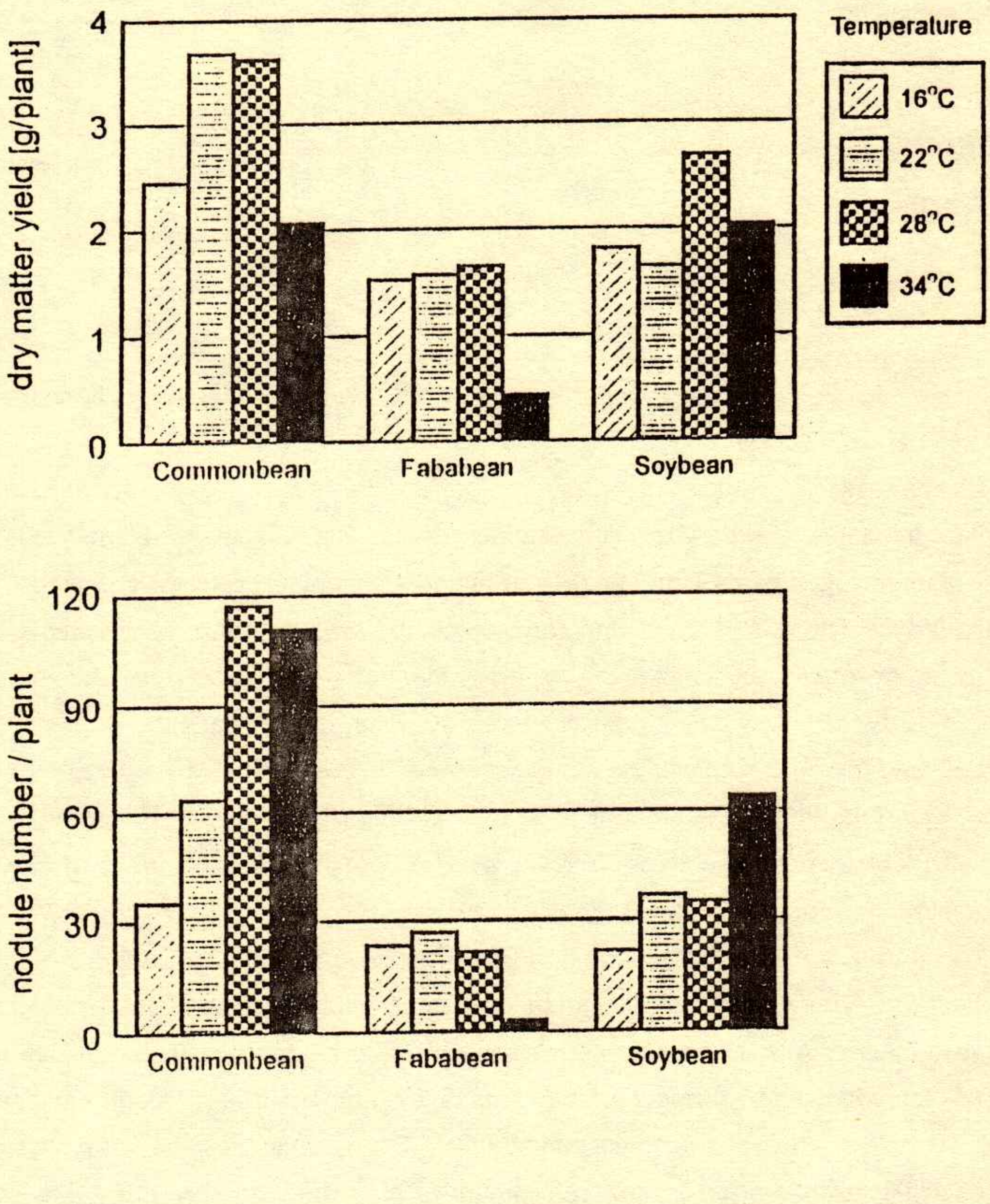


Figure 3. Dry matter yield (g/plant) and number of nodules/plant of common bean, fababean and soybean when grown at various temperatures.

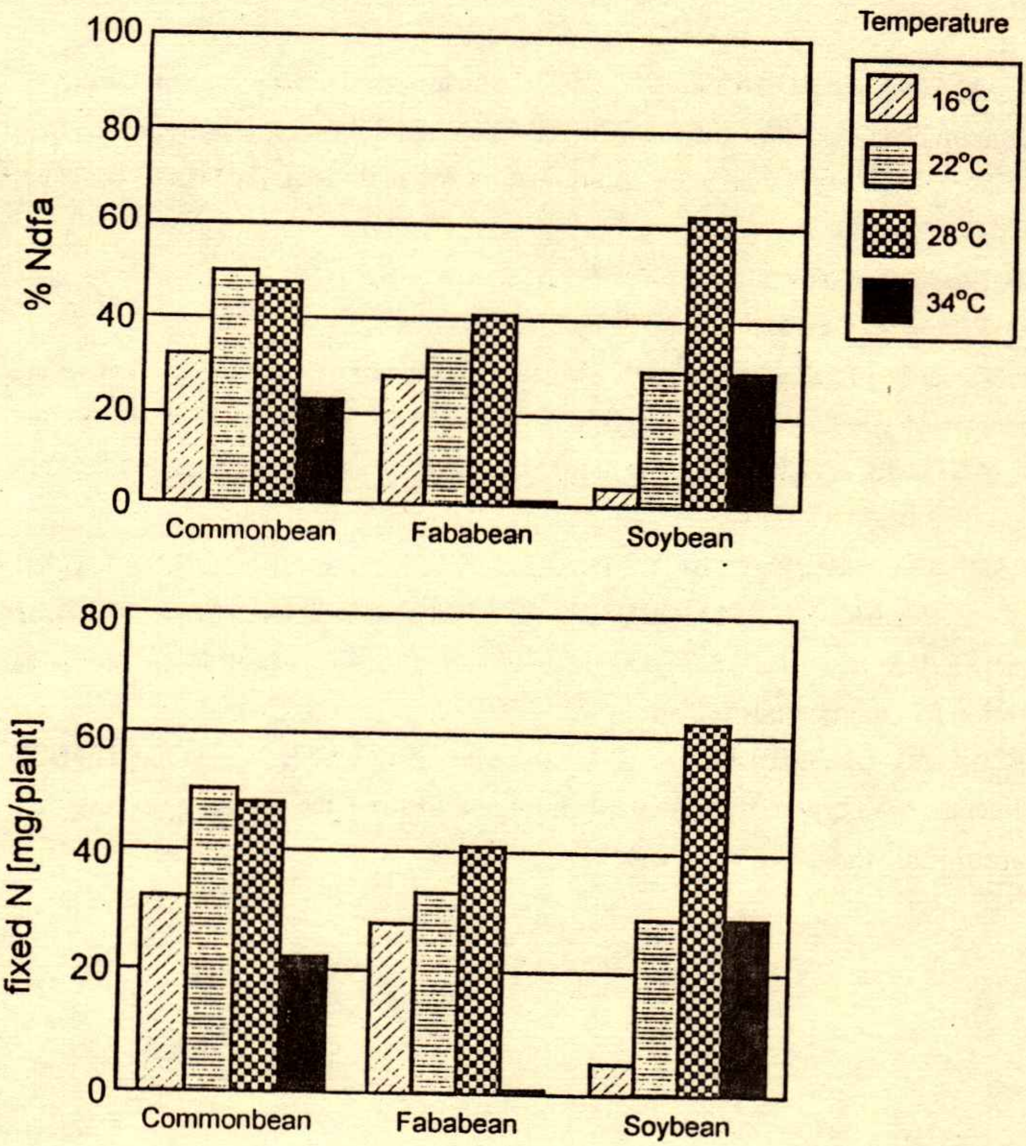


Figure 4. Percent N derived from atmosphere (%Ndfa) and amount of N_2 fixed (mg/plant) of common bean, fababean and soybean when grown at various temperatures.

REFERENCES

BLISS F., A AND HARDARSON, G. 1993. Enhancement of biological nitrogen fixation of common bean in Latin America. Kluwer Academic Publisher, Dordrecht, 160p.

EASTIN E., F. 1978. Total nitrogen determination for plant material. Anal. Biochem. 85, 591-594.

FAO 1980. Production Yearbook for 1979. FAO, Rome. 309p.

FAO 1992. Production Yearbook for 1991 , FAO. Rome. 265p.

FIEDLER R. and PROKSCH G. 1975. The determination of ^{15}N by emission and mass spectrometry in biochemical analysis: A review. Anal. Chim. Acta. 78: 1-62.

FRIED M. AND MIDDELBOE V. 1977. Measurement of amount of nitrogen fixed by a legume crop. Plant Soil 47: 713-715.

HARDARSON G., A. BLISS F., M R. CIGALES-RIVERO, A. HENSON R., J A. KIPE-NOLT, L. LONGERI, A. MANRIQUE, J.J. PEÑA-CABRIALES, J. PEREIRA P., A. SANABRIA C., AND S. TSAI M. 1993. Genotypic variation in biological nitrogen fixation by common bean. Plant Soil 152: 59-70.

McAULIFFE C., S. CHAMBLEE D., H. URIBE-ARANGO AND W. WOODHOUSE W. 1958. Influence of inorganic nitrogen on nitrogen fixation by legumes as revealed by N-15. Agron. J 50: 334-337.

GENOTYPIC VARIATION IN N_2 FIXATION BETWEEN AND WITHIN TREE SPECIES ESTIMATED BY THE ^{15}N ISOTOPE DILUTION TECHNIQUE.

Variación Genotípica en Fijación de N_2 entre Especies de Arboles, Estimada por la Técnica de Dilución Isotópica de ^{15}N

N. Sanginga, S.K.A.Danso, F. Zapata and G.D. Bowen

International Institute of Tropical Agriculture, PMB 5320 Oyo Road Ibadan, Nigeria, International Atolnic Energy Agency, Soils section, Joint FAO/IAEA Division, 5 Wagramerstrasse, A-1400, P.0.Box 100 Vienna, Austria. "Division of Soils, CSIRO, Glen Osmand 5064-, Australia.

Palabras clave: **Arboles fijadores de nitrógeno, Agroforestería, ^{15}N.**

Index words: **Nitrogen fixing trees, Agroforestery, ^{15}N.**

RESUMEN

Los arboles fijadores de nitrógeno (NFTs) son usados en sistemas agro-forestales en hileras para mantener o restaurar la fertilidad del suelo y producir madera, leña combustible y forraje para animales. Sin embargo, pocos estudios se han desarrollado sobre la nodulación y fijación biológica de N_2 por las simbiosis NFT/Rhizobium o Frankia, claves en el desarrollo exitoso de estos árboles en suelos deficientes en N.

Para maximizar la contribución de esta fuente natural y barata de N en sistemas agro-forestales, se han conducido durante 10 años experimentos de investigación tanto en macetas como en campo que involucran el método de la dilución isotópica de ^{15}N.

Estos estudios han mostrado grandes diferencias entre las especies de árboles y entre materiales genéticos de diverso origen dentro de las especies en su fijación de N_2. Algunas especies de árboles tales como *Leucaena leucocephala* y *Gliricidia sepium* pueden fijar 200-300 kg N ha^{-1} mientras que otras e.g. *Faidherbia albidia* pueden fijar cuando mucho una décima parte. *Senna siamea* y *S. spectabilis* con frecuencia usados en sistema de hileras

de árboles, no nodulan y su crecimiento vigoroso es debido a una alta eficiencia en el uso de N y un sistema radical efectivo. Nuestros estudios en maceta, han demostrado diferencias de 2-3 veces en fijación de N_2 entre fuentes genéticas/genotipo de *F. albidia*, *L. leucocephala*, *G. sepium* y diferencias de 3-5 veces entre "origenes" de *Casuarina equisetifolia* y de *C. cunninghamiara*. Estas diferencias fueron también verificadas en el campo paara *G. sepium* y *L. leucocephala*. Sin embargo, la selección para una fijación de N_2 alta no puede ser la única consideración en agro-forestería; por ejemplo, es necesario seleccionar también a la tolerancia a condiciones de estrés. Nuestros resultados demuestran claramente que el enfoque consistente en la selección del origen del árbol hospedero en base a su comportamiento simbiótico con un *Rhizobium* efectivo es más promisorio en el caso de especies arboreas caracterizada por una amplia variabilidad genética. La selección de genotipos superiores debe aumentar satisfactoriamente el rendimiento de estos árboles y su contribución de N en sistemas agro-forestales. La selección de "origenes" superiores debe obviamente acoplarse con la optimización de métodos de propagación vegetativa, permitiendo la producción de un abasto suficiente y continuo de material vegetal.

SUMMARY

Nitrogen fixing trees (NFTs) are used in agroforestry systems such as alley cropping to restore or maintain soil fertility and produced timber, fuelwood and forage for animals. Few studies, however, have been conducted on nodulation and biological N_2 fixation by various NFTs/*Rhizobium* or *Frankia* symbioses, key factors in the successful growth of NFTs in N deficient soils. To maximize the contribution of this natural and inexpensive source of N in agroforestry systems, research experiments have been carried out over ten years in pot and field conditions using the ^{15}N isotope dilution methods. These studies have shown large differences between tree species and between provenances within species in their N_2 flxation. Some tree species such as *Leucaena leucocephala* and *Gliricidia sepium* can fix 200 - 300 kg N ha^{-1} while others e.g. *Faidherbia albidia* may fix only one tenth as much. *Senna siamea* and S. *spectabilis* often used in alley cropping systehls, do not nodulate and their vigorous growth is due to a highly N use effiency and effective rooting system. Our pot studies, have shown 2 - 3 fold differences in N_2 fixation between provenances/genotypes of *F. albidia*, *L. leucocephala*, *G. sepium* and 3-5 fold differences between provenances of *Casuarina equisetifolia* and of *C. cunninghamiana*. These differences were also substantiated in the field for *G. sepium* and *L. leucocephala*. However, selection for high N_2 fixation can not be the only consideration in agroforesty; for example, it is necessary to

select for tolerance of stress conditions as well. Our results clearly demonstrate that the approach consisting of selecting the host provenance for its symbiotic performance with an effective *Rhizobium* is most promising in the case of species characterized by an extensive genetic variability such as NFTs. Selecting superior provenances should substantially increase yield of these trees and their N contribution in agroforestry systems. The selection of superior provenances should obviously be coupled with the improvement of methods of vegetative propagation, allowing the production of a large and continuous supply of planting stock.

INTRODUCTION

In recent years the potential of leguminous and actinorhizal trees has aroused considerable interest, and many international agencies have recommended their increased use, for example as fuelwood, paper pulp, hardwood, crop shade and in agroforestry systems. These trees may also be important for revitalization of impoverished tropical soils.

The symbiotic fixation of atmospheric N_2 by *Rhizobium* or *frankia* in root nodules and the enhancement of phosphorus (P) uptake by vesicular arbuscular (VA) mycorrhizae are the key factor in the successful growth of these trees or shrubs in a wide variety of N and P deficient soils common in tropical climates. A vigorous NFTs at a particular location is frequently a manifestation of an especially effective match between the tree genotype, its symbiotic partner(s) and its environment. In fact, such a tree could be heavily dependent on its microsymbioses for its nutrition.

With the exception of some species (e. g. *L. leucocephala*), our knowledge of NFTs is still very limited. Up to now, only a few studies have dealt with tree N_2-fixing systems that could be harnessed for a variety of purposes in forestry and agroforestry. Very little is known about the root nodule bacteria for tree legumes and actinorhizal plants in either their free-living or symbiotic states. We have only very few reliable data on actual N_2-fixation in the field. The role of nutrition and fertilization in improving N_2 fixation and yield is not well understood.

Whilst little work has bceil done, the principles and methods of study learned from work with other hosts grain and pasture legumes may apply, there are many special problems to be considered in studying symbiosis with tree legumes or actinorhizal plants. The most conspicuous obstacles being the high genetic variability of most tree species, the large variation in N_2-fixing that occur throughout the life of trees in function of age and season and the microsymbiont. Relatively few NFT species are self-pollinated (Halliday, 1984). Unlike annual food crop which are self-pollinated, genetic heterogeneity of most NFT species is problematic at virtually every stage in conventional crop improvement strategies. Heterogeneity complicates germplasm exploration, selection and multiplication, and is confounded by the often lenghty generation times of even the fast NFTs species.

Amont the *Rhizobium* strains capable of infecting and nodulating a particular MPTs there might be also great variation in their effectiveness in N_2 fixation. There might be a considerable *Rhizobium* strain X host NFTs variation and thus an opportunity to select and propagate superior combinations.

The microbial partners in the NFT/*Rhizobium* or *Frankia* symbioses have received much attention (Diem *et al.*, 1983; Dreyfus and Dommergues, 1981; Reddell *et al.*, 1986; Sanginga *et al.*,1989a), with considerable less research on the existing variability within and between NFT species as an approach for deriving greater benefits from N_2 fixation. Attempts to select superior NFTs demonstrated that some leguminous trees such as *L. leucocephala* or *F. albida*, used in agroforestry, have generally been assumed to be active in N_2 fixation, with few studies on the genetic variation in N_2 fixation within and between provenances or isolines of these tree species.

Sniezko (1987) reported that different provenances and accessions of *F. albida* exhibit considerable variation in growth, and attributed this to differences in nodulation patterns. Atta-Krah (1987) found variability in initial growth and leaf coloration of uninoculated. accessions of *G. sepium* and related this to differences in the initiation of nodulation. However, these authors used indirect criteria such as nodule scoring or above ground biomass as evidence for N_2 fixation, rather than the direct estimation to detect real variations in N_2 fixation potential between provenances. Recently, Sanginga *et al.*, (1990c), using the ^{15}N isotope dilution method, found differences in N_2 fixation between two isolines of *L. leucocephala* and indicated that large genetic diversity could exist withih species, and suggested that this should be exploited to improve N_2 fixation.

A major comprehensive programme could include the development of easy methods for identifying potential high NFTs, selection of highly effective symbiotic micro-organisms for a wide range of tree species, examination of soil and enviromnental constraints to N_2 fixation, the effects of management practices on N_2 fixation, and the selection of highly fixing genotypes or provenances within tree species.

MATERIALS AND METHODS

Variation in nodulation and N_2 fixation by leguminous trees e.g. *G. sepium*, *L. leucocephala* and *F. albidia* with *Rhizobium* spp symbiosis and by actinorhizal plant species e.g. . *equisetifolia* and *C. cunninghmiana* with *Frankia* symbiosis was examined in pot and field experiments at the International Institute of Tropical Agriculture (IITA), Ibada, Nigeria, (Transition forest-savanna) at Yangambi, Zaire (Humid forest) and at Domboshawa, Zimbabwe (Savanna, Miombo woodland) and at the International Atomic Energy Agency (IAEA), Seibersdort, Austria to back up research done in the field in the above sites in Sub-saharan Tropical Africa. The soils used in all these experiments were low in major nutrients especially N and available P. *Rhizobium* and *Frankia* strains used for the different tree species had previously proved effective on their respective hosts.

In all these experiments, different tree provenances within each species (minimum 10) were used. The N treatment for each provenance studies, comprised (i) ambient soil N plus 20 mg N kg^{-1} and inoculation with *Rhizobium* or *Frankia* spp, (ii) ambient soil N plus 20 mg N kg^{-1} soil, but with no inoculation, and (iii) ambient soil N in uninoculated plants with lOO mg N kg^{-1} soil. For the 2O mg N rate, 10 atom % ^{15}N was applied in solution to the inoculated and control plants and for the l00 mg N rate, the ^{15}N enrichment was 2 atom % ^{15}N excess.

The isotope dilution methodology (Fried and Middelboe, 1977) and the A value approach (Fried and Broeshart, 1975). The uninoculated NFTs treatments and non-NFT e.g. *Senna siamea*, *S. spectabilis* and *Eucaliptus* sp were used as reference to measure N_2 fixation.

RESULTS AND DISCUSSION

Measurement of N_2 fixation.

Because of the importance of trees in agroforestry there is a crucial need to assess the magnitude of N_2 fixed by different trees, directly in the field. Generally when used for grain and pasture legumes ^{15}N methods provide quantitative, integrated and the most reliable values of N_2-fixed. The long-term in a given tree raises problems that are associated with perennial plants e.g. long duration of growth and greater difficulty in obtaining reference crops that will match during the many different seasons. For young or small trees, and for pot experiments, ^{15}N procedures similar to those adopted in grain or pasture legumes would be expected to give equally satisfactory results. The greatest problems with N_2 fixation estimations using ^{15}N will occur in mature trees, due to their perennial nature and massive sizes, leading to logistic and sampling difficulties or differences in $^{15}N/^{14}N$ ratio of soil due to differences in nitrogen turnover processes that occur under the fixing and reference crops with time. The influence of these effects may differ depending on how the ^{15}N is applied. What is therefore urgently needed now is an examination of which of the existing ^{15}N procedures, e.g. isotope dilution, A value or the natural ^{15}N abundance and what method of ^{15}N application should be adopted under different situations. In this paper, we have considered for N_2 fixation measurements the two parameters defined by Dommergues (1987). The nitrogen fixing potential (NFP) of a species, i.e., the nitrogen fixed with all environmental constraints removed, including the possible inhibitory effect of soil nitrogen. However, almost without exception the field data reported are subject to some environmental constraints and the concept of NFP is a qualified one, and the actual nitrogen , fixed (ANF), which is the resultant of NFP, modified by enviromnental constraints.

Based on the above definitions, we have identified high and low NFT species. The former included such species as *L. leucocephala* and *G. sepium* for which records occur of 100 to 300 (sometimes 500) kg N fixed ha-' yr-' representing about 65% of their total N from atmospheric N_2, the latter include such species as *F. albidia* with which fixation has been reported as less than 20 kg N ha^{-1} yr ' i.e. 10 - 20% of its total N. Species such as *Casuarina* sp. are intermediate fixing between 60 and 120 kg N ha^{-1}. It is likely that when more species are studied there will be more of continuum. The major factors in hig NFP are a high potential growth and a high percentage of nitrogen derived from the atmosphere (% Ndfa). This last parameter generally appears to be less affected by environmental conditions than a total N fixed (Danso *et al.*, 1992). However, there is increasing evidence of large genotype/provenance differences withing legume NFT species in their N_2 fixation.

Genotipyc or provenance variation in N_2 fixation within NFTs.

Pot studies and few field studies, have shown large differences between cultivars and provenances within NFTs in their N_2 fixation. Pot studies, give indications of differences in N_2 fixing potential and have been useful for early selection of superior high N_2 fixer NFTs.

As indicated above, *L. leucacephala* derived an average about 65% of its total N from atmospheric N_2 compared to about 20% by *F. albida*. However, significant differences % Ndfa occur between provenances of isolines within species. Sanginga *et al.*, (1990b) showed that despite the generally poor N_2 fixation ascribed to *F. albida*, vast differences exist. One provenance supported the highest N_2 fixation and derived 8 mg N $plant^{-1}$ or 36% of its total N from fixation; another on the other hand, fixed only 6% of total N under identical conditions. This stresses the importance of selecting tree provenances with high capability for N_2 fixation. This was applicable to *L. leucacephala* as well.

Many alley cropping studies (e.g. at the International Institute of Tropical Agriculture in Ibadan, Nigeria) have used *L. leucacephala* K8 (Kang *et al.*, 1981; 1985). Sanginga *et al.*, (1989) reported that a well nodulated K8 derived 40% of its N from atmospheric N_2. Results obtained by Sanginga *et al.*, (1990b) showing a variation of % Ndfa from 37 to 74 indicate that great scope for screening genotypes for N_2 fixation improvement in *L. leucacephala*. The most promising provenances or isolines would then be used as a source of N in alley cropping system.

Ranking of *L. leucacephala* isolines or *F. albida* provenances for their % Ndfa capabilities was highly dependent on the growth stage over evaluation period. The % Ndfa of selected provenances (poor, intermediate, and good fixers) increased with time, with the average values being in most cases similar within species at 36 WAP. A practical implication of this is that there is a chance of reaching different conclusions on the N_2 fixation potential of species and provenances depending on the growth stage. Since trees are normally perennial, long duration studies should therefore be preferable if possible. This is a weakness in the existing pot studies. Except for cases where early N_2 fixation is essential to good establishment, differences in time for high N_2 fixation e.g. *L. leucacephala* K636 and K28 may be of little long term consequence in the field. It is now highly appropriate to extend such studies in the field.

Similar significant differences to *L. leucacephala* in the proportions and amounts of N_2 fixed in *G. sepium* were observed in the same growing conditions. *G. sepium* derived 45% of its total N from atmospheric N_2. However % Nfda ranged from 26 to 68% between the 25 provenances examined (Sanginga *et al.*, 1991). Such variations were confirmed in field conditions although values were lower than in pot experiments.

Significant differences in the proportions and amounts of N_2 fixed in two *Casuarina* species were observed in the same growing conditions (Sanginga *et al.*, 1990a). *C. equisetifolia* derived, on the average 63% from atmospheric N_2 fixation, compared to 43% by *C. cunninghamiana*. These values are also similar to those of *G. sepium* and *L. leucacephala* grown under fairly similar conditions. Thus *Casuarina* species could be considered, as efficient in fixing atmospheric N_2 as some of the commonly-grown leguminous trees. This N_2-fixation capacity offers a great advantage where agroforestry is the farming system of choice and where soil restoration or conservation is the major concern. Nitrogen fixation also varied substantially within provenances of each species with

% Ndfa ranging from 14 to 76% for the *C. cunninghamiana* provenances and from 25 to 75% within *C. equisetifolia*. The data also indicate that although on the average, *C. equisetifolia* was superior than *C. cunninghamiana* in N_2 fixation, N_2 fixed in a few of the *C. cunninghamiana* provenances was similar to the average N_2 fixed in *C. equisetifolia*. This supports the suggestion for the screening of genotypes, even for species suspected to poor N_2 fixers.

Our results have demonstrated that the genetic variability in N_2-fixing abilities of *Casuarina* is high, and that N_2 fixation by this species may be significantly improved in any given environmet by screening a large collection of different host genotypes for high symbiotic performance with inoculated *Frankia*. This promising approach has however been giveh little attention relative to the microbial symbiont. Selecting superior plant genotypes should substantially ircrease yield of these trees to be established in N-deficient soils.

Growth of these NFTs increased with either inoculation with *Frankia* or *Rhizobium* or N fertilizer addition, but marked differences developed between these N treatment with time. In general, growth of inoculated plants was more variable than that of plants dependent on soil fertilizer N. This variation in the growth of the inoculated plants was thus due to the large differences in the N_2-fixing abilities than to intrinsic growth differences. There is increasing evidence of large genotype/provenance differences with NFTs in their N_2 fixation. Such differences are being confirmed in field studies. This has great implications for N_2 fixation in agroforestry. Vegetative propagation, often relatively easy with tree species, could lead to rapid and significant farmer implementation. However selection for high N_2 fixation can not be the only consideration in mixed ecosystems; for example, it is necessary to select for tolerance of stress conditions as well.

Effect of microbial component on variation in N_2 fixation.

Genetic diversity of planting materials is just one of the features of NFTs. Studies have indicated large differences in the occurence of nodulation and in the nitrogen-fixing ability of different *Rhizobium / Frankia* strains on NFTs.

Nitrogen fixing trees and their rhizobia exhibit a degree of specificity; e.g.within the genus *Acacia* not all species will be nodulated by the one bacterial strain. It is therefore important to determine the degree of host specificity of the selected NFT species to help in predicting firstly the need to inoculate them at sowing, and secondly, to develop a strain which nodulate and fix nitrogen with a great nulnber of the useful species if possible (promiscuous strain). Conversely a promiscuous host, that is a NFT which may nodulate effectively in a soil in which the *Rhizobium* population may be small.

Taking into account some data reported in tropical Africa (Drefus and Dommergues, 1981; Sanginga *et al.*, 1989b), one can classify NFTs into three broad groups: group 1, which nodulates with fast-growing strains (e.g. *L. leucocephala, G. sepium, S. rostrata, Sesbania sp., Acacia farneciana, A. nilotica, A. raddiana* and *A. senegal*); group 2, which nodulates both with fast and slow-growing strains (e.g. *G. sepium* , *Acacia seyal*, *A. cyanophylla*, *paras holocericia*, *A. mearnsii T. vogelii* and *G. sepium*). The first group is *consiponia spp.*); group 3, which nodulates with slow-growing strains (e.g. *F. albidia*, *A. holocericia*, *A. mearnsii T. vogelii* and *G. sepium*). The first group is considered as specific and exhibits a symbiotic range narrower than that of the other two groups belonging probably to the "cowpea micsellanous" type which inhabit most of the tropical soils (Vincent, 1970) now called *Bradyrhizobium*. The strains of fast-growing rhizobia associated with group 1 NFTs are probably related to the "advanced degenerate forms" (Norris, 1956) represented by the fast-growing rhizobia.

The practical implication of the specificity of group 1 is that their establishment requires inoculation with the compatible fast-growing strains, which are generally less ubiuquitous than the typical *Bradyrhizobium*. This explain the spectacular response to inoculation of *L. leucocephala* with *Rhizobium* IRc 1045 or IRc 1050 (Sanginga *et al.*, 1985, 1986) in the field at **IITA** and Fashola in Nigeria. At both places inoculated plants produced more N and dry matter thah the controls. This effect was statiscally equivalent to the application of 150 kg ha^{-1} of urea. Further, the strains survived and competed well in the field, as was shown in observations made 10 years after their establishment (Sanginga unpublished data). Inoculation of field-grown *A. mearnsii* and *F. albidia* rarely results in a significant yield increase since most tropical soils harbor the competent rhizobia of the cowpea miscellany (Dommergues, 1987).

The proportions and amounts of N_2 fixed by NFTs is influenced by the effectiveness of *Rhizobium* strains. In a field study conducted in Southwestern Nigeria, Sanginga *et al.*, (1989) indicated that estimates with the ^{15}N dilution method gave nitrogen fixation of 134 kg ha^{-1} in six months when *L. leucocephala* was inoculated with *Rhizobium* strain IRc 1045 and 98 kg ha^{-1} when inoculated with *Rhizobium* strain IRc 1050. This nitrogen represented 34 - 39% of the plant nitrogen.

Another experiment included six strains of *Rhizobium* spp. and two methods of *G. sepium* inoculation i.e. seed or soil inoculation (Sanginga *et al.*, 1991). The plants were harvested 14, 35 and 53 weeks after planting. In the first harvest significant differences were found between the number of nodules and the percentage and amount of N_2 fixed. There was also a significant correlation between the number of nodules and the amount of N_2 fixed ($r = 0.92$; $P = 0.05$). In the final harvest no correlation was observed, although there were significant differences between the number of nodules and the percentage of N_2 derived from the atmosphere. The amount of N_2 fixed increased with time (from an average of 27% at the first harvest to 58% at the final harvest) and was influenced by the *Rhizobium* spp. strain and the method of inoculation. It ranged from 36% for *Rhizobium* spp. strain SP 14 to 71% for *Rhizobium* SP 44 at the last harvest. Values for the percentage of atmosphere derived N_2 obtained by soil inoculation were slightly higher than those obtained by seed inoculation.

Awonaike *et al.*, (1992) have also demonstrated that nitrogen fixation and general performance of a *G. sepium* genotype was either low or high depending on the rhizobial inoculum strain. However they showed that no one strain was superior over all the host genotypes and no one genotype over the strains in nitrogeh fixation in a study involving five plant genotypes and five bacterial strains.

CONCLUSION

To date the use of NFTs (legumes or on legumes) in forestry and agroforestry has been largely neglected. However, the success of introduction of species with a high N_2-fixing potential, for example *L. leucocephala* and *G. sepium*, is such that interest in NFTs is increasing. Large plant-to-plant variation and genotype variation in nodulation and growth have been recorded in NFTs. Further use of NFTs requires, as a first step, screening between and within species to determine which exhibit the highest N_2-fixing potential. As a second step, it appears necessary to improve our knowledge of the requirements of the selected trees with regard to their effective endophyte *Rhizobium* or *Frankia* in order to prepare appropriate inoculants. Nitrogen fixation can thus be maximized by judicious selection of these. Due to their big heterogeniety, tree species are prime candidates for vegetative propagation. Therefore, the integration of selection of high N fixing genotypes and the biotechnology of mass vegetative propagation could lead to large increases in N fixation in agroforestry systems.

REFERENCES

ATTA-KRAH, A.N. 1987. Variability in initial growth and leaf coloration in relation to initiation of nodulation in uninoculated accessions of *Gliricidia sepium* (JACQ) Stend. *Nitrogen Fixing Tree Research Report* 5: 39-41.

AWONAIKE, K.0., G. HARDARSON AND S. KUMARASINGHE S. 1992. Biological nitrogen fixation of *Gliricidia sepium/Rhizobium* symbiosis as influenced by plant genotype, bacterial strain and their interactions *Trop. Agric.* (Trinidad), 69: 381-386.

DANSO, S.K.A., G. HARDARSON AND ZAPATA. 1986. Assessment of dinitrogen fixation potential of forage legumes with ^{15}N technique. *In*: Haque, S. Jutzi and P. J. H. Neate, eds. Potential of Forage Legumes in Farming systems of Sub-saharan Africa. pp. 26-58. ILCA Ethiopia

DANSO, S.K.A., G.D. BOWEN AND N. SANGINGA. 1992. Biological nitrogen fixation in trees in agro-ecosystems. *Plant Soil* 141: 177-176.

DIEM, H.G., D. GAUTHIER AND Y.R. DOMMERGUES. 1983. Inoculation of *Casuarina* using a pure culture of *Frankia*. *Nitrogen Fixing Tree Research Report* 1: 18-19.

DOMMERGUES, Y.R. 1987. The role of biological nitrogen fixation in agroforestry. *In*: H.A. Steppler and P.K.R Nair eds. Agroforestry a Decade of Development. pp. 245-271 ICRAF Nairobi Kenya.

DREYFUS, B.L. AND Y.R. DOMMERGUES.1981. Nodulation of *Acacia* species by fast and slow growing tropical strains of *Rhizobium*. *Appl. environ. microbiol.*, 41(1): 97 - 99.

FRIED, M. AND H. BROESHART. 1975. An Independent measurement of the amount of nitrogen fixed by legume crops. *Plant Soil.* 43: 707-771.

FRIED, M. AND V. MIDDLEBOE. 1977. Measurement of amount of nitrogen fixed by a legume crop. *Plant Soil*. 47: 713-715.

GAUTHIER, D., H.B. DIEM AND Y.R. DOMMERGUES,. F. GANRY F. 1985. Assessment of N_2 fixation by *Casuarina equisetifolia* inoculated with *Frankia* ORSO21OOl using ^{15}N methods. *Soil Biol. Biochem* 17:375-379.

HALLIDAY, J. 1984. Integrated approach to nitrogen fixing tree germplasm development. *Pesq. agropec. brs.*, 19:91 - 117.

KANG B,T., L. SIPKENS, G.F. WILSON AND D. NANGJU. 1981. *Leucaena leucocephala*, (Lam.) de Wit prunings as nitrogen source for maize (*Zea mays* L.) *Fert. Res.*, 2: 279 -277.

NORRIS D, 0. 1956. Legumes and *Rhizobium* symbiosis. *Emp. J. of Exp. Agric.* , 21:247-270.

REDDELL, P., P.A. ROSBROOK, G.D. BOWELL AND D. GWAZE. 1986. Growth responses in *Casuarina cunningghamiana* plantings to inoculation with *Frankia. Plant Soil* 108:79-86.

SANGINGA, N., K. MULONGOY AND A. AYANABA. 1985. Effect of inoculation and mineral nutrients on nodulation and growth of *Leucaena leucocephala*. *In*: H. Ssali and S O Keya eds. Biological Nitrogen Fixation in Africa. pp 419-427. Nairobi MIRCEN, Nairobi Kenya.

SANGINGA, N., K. MULONGOY AND A. AYANABA. 1986. Inoculation of *Leucaena leucocephala* (Lam.) de Wit with *Rhizobium* and its nitrogen contribution to a subsequent maize crop. Biol. Agric. Hortic. 3: 34-347.

SANGINGA, N., S.K.A. DANSO AND G.D. BOWEN. 1989a. Nodulation and growth response of *Allocasuarina* and *Casuarina* species to phosphorous fertilization. *Plant Soil* 118: 125-132.

SANGINGA, N., K. MULONGOY AND A. AYANABA. 1989b. Effectivity of indigenous rhizobia for nodulation and early nitrogen fixation with *Leucaena leucocephala* grown in Nigerian soils. *Soil Biol. Biochem.* 21: 231-235.

SANGINGA, N., K. MULONGOY AND A. AYANABA. 1989c. Nitrogen fixation of field-inoculated *leucaena leucocephala* (Lam.) de Wit estimated by the ^{15}N and the difference methods. *Plant Soil* 117: 269-274.

SANGINGA, N., G.D. BOWEN AND S.K.A DANSO. 1990a. Genetic variability in symbiotic nitrogen fixation within and between provenances of two *Casuarina* species using the ^{15}N-labelling methods. *Soil Biol. Biochem.* 22: 539-547.

SANGINGA, N., G.D. BOWEN AND S.K.A DANSO. 1990b. Assessment of genetic variability for N_2 fixation between and within provenances of *Leucaena leucocephala* and *Acacia albida* estimated by ^{15}N labelling techniques. *Plant Soil* 127:169-178.

SANGINGA, N., F. ZAPATA, S.K.A. DANSO AND G.D. BOWEN. 1990c. Effect of successive cuttingon nodulation and nitrogen fixation of *leucaena leucocephala* using ^{15}N dilution and the difference methods. *In*: M L van Beusicheln ed. Plant Nutrition-Physiology and Applications. pp 667-674. Kluwer Academic Publishers, Dordrecht, The Netherlands.

SANGINGA, N., K. MANRIQUE AND G. HARDARSON. 1991b. Variation in nodulation and N_2 fixation by the *Gliricidia sepium/Rhizobium* spp. symbiosis in cacareous *Soil. Bioi. Fertil. Soil* 11: 273-278.

SNIEZKO, R.A. 1987. Range-wide provenance variation in nodulation of *Acacia albidia* seedlings. *Nitrogen Fixing Tree Research Reports* 5: 20-22.

VINCENT, J.M. 1970. A manual for the practical study of root Nodule Bacteria. IBP Handbook No 15, Blackwell Oxford. p. 164.

ZHANG, Z., M.F. LOPEZ, J.G. TORREY. 1984. A comparison of cultural characteristics and infectivity of *Frankia* isolates from root nodules of *Casuarina* species. *Plant Soil* 78: 79-90.

FERTILIZER NITROGEN USE AND EFFICIENCY IN DIFFERENT CROPPING SYSTEMS

Uso y Eficiencia de los Fertilizantes Nitrogenados en Diferentes Sistemas de Cultivo

0. Van Cleemput, and Ch. Hera

Faculty Agricultural and Applied Biological Sciences, University of Ghent, Ghent, Belgium and Soil Fertility, Irrigation and Crop Production Section, Joint FAO/IAEA Division, IAEA, Vienna, Austria respectively.

Palabras clave: **Balance de nitrógeno, Dilución isotópica, ^{15}N, Fertilizantes nitrogenados, Fuentes de nitrógeno.**

Index words: **Balance of nitrogen, Isotopic dilution method, Nitrogen fertilizer, ^{15}N Sources of nitrogen.**

RESUMEN

Tanto en países desarrollados como países en vías de desarrollo, razones económicas y de calidad ambiental motivan a los investigadores a estudiar los factores que influyen en la toma de fertilizantes nitrogenados y de proveer información sobre cómo aumentar la eficiencia en el uso de fertilizantes. El comportamiento de los fertilizantes y la metodología para determinar la eficiencia en el uso de fertilizantes son discutidos y varios ejemplos muestran que el uso de compuestos marcados permiten estudiar de una manera precisa el destino de los fertilizantes.

SUMMARY

In developing as well as in developed countries, economic and environmental-hygienic reasons force researchers to study the factors influencing the uptake of fertilizer N and to provide information on how to increase the fertilizer use efficiency. Fertilizer

behaviour and methods to assess fertilizer use efficiency are discussed and several examples show that the use of labelled compounds allow to accurately study the fate of fertilizers.

INTRODUCTION

The explosive growth of the world population during the present century puts a lot of stress to the amount of food supply and the amount of agricultural land. It is expected that by the year 2100 the population will stabilize at about 10.5 billion, of which 87% will live in developing countries (Sadik, 1988). Through famine, the fragile tropical and subtropical soil system may rapidly become depleted and infertile.

Although the use of fertilizers can importantly help, they are often beyond the means of farmers. In addition to this, the available soil water is often a limiting factor in productivity. In contrast to developing countries, many industrialized countries, for which availability of fertilizers and agrochemicals is a minor problem, are confronted with a problem of another kind. There is high concern about the non-efficient part of the fertilizer.

It has been shown that the efficiency of fertilizers is often lower than 50% (Keeney, 1982). In addition, the unrecovered part of the fertilizer might have an adverse impact on the environment such as groundwater NO^-_3 pollution, eutrophication, acid rain, and global warming (Ramanathan *et al.*, 1985). This means that while there is a continuous need for N use for sustainable agricultural production, important environmental and economic factors impose an as high as possible N-use efficiency. This is not an easy task because the N-cycle in soil-plant-water systems is of very complex nature. Indeed, its primary processes are independently and interactively regulated by soil chemical and physical properties, crop characteristics (N demand, root morphology and plant characteristics in general), climate (temperature, rainfall, cycles of drying/wetting, freezing/thawing, radiant energy), topography and anthropogenic activities (tillage, fertilization, management). It is quit clear that, therefore, sufficient attention should go to increasing the effectiveness of fertilizers. Proper management techniques, efficient use of water, proper mechanization, irrigation and use of agrochemicals are very helpful in attaining this goal.

Isotopes are an excellent tool to study some of the processes and factors influencing the efficiency of added fertilizers and to study the fate of the non-efficient part.

Nitrogen supply and methods to asses fertilizer use efficiency.

Sources of nitrogen.

The extend to which crop growth is limiled by insufficient presence of nutrients depends on the crop demand and the capacity of the soil to supply them. As far as nitrogen is concerned, three sources can be considered: the fertilizer (mineral or organic) source, the soil supply and the air as nitrogen source.

With ample supply of water and nutrients, 20 to 30 t of total dry matter ha^{-1} y^{-1} can be obtained (Greenwood *et al.*, 1977; Loomis and Gerakis, 1975). Warmer climates are more favourable because of longer growing periods and more efficient photosynthesis (Loomis and Gerakis, 1975). The dry matter of crops grown with ample supply of nutrients seldom contains less than 1.5% N, 0.3% P and 1.5% K (Greenwood *et al.*, 1980a; Greenwood *et al.*, 1980b; Greenwood *et al.*, 1980c). However, if maximum yields are to be achieved, crops must contain at least 300 kg ha^{-1} of N, 60 kg ha^{-1} of P and 300 kg ha^{-1} of k. These quantities can only be obtained through application of fertilizers, because the amount of nutrients provided by the soil itself is generally small.

The inherent capacity of soils to supply nutrients generally diminishes from temperate regions towards the equator (Engelstad and Russel, 1975). In hot climates, an important amount of plant nutrients have been leached out of the soil, leaving a matrix, often mainly of Al_2O_3 and Fe_2O_3, with little capacity to hold cations and high ability to absorb any applied phosphate. In addition, higher temperatures favour faster breakdown of organic matter, resulting in a smaller reserve of nitrogen. And it should be kept in mind that the long-term sustainability of soils and productivity of soils depends on organic matter, in particular organic N and C.

Next to soil and fertilizer N supply, biological nitrogen fixation (BNF) is to be considered as an extremely important N source (Zapata and Van Cleemput, 1986). Indeed, in a majority of countries, fertilizers cannot be obtained because of high costs, the low per capita income and limited credit facilities of most farmers, as well as because of lack of effective infrastructure for fertilizer production and distribution. It is unlikely that the amounts of fertilizer actually used in these countries will importantly increase in the coming years, on the contrary. In these areas N fixing crops such as legumes can play an increasingly important role. They bring in atmospberic N_2 and leave after harvest through their nodulated roots and harvest residues a valuable source of N for replenishment of soil organic N. In contrast to earlier findings (Clarke, 1984; Evans and Herridge, 1986; Russell, 1980), there is clear evidence that annual crop legumes contribute to the subsequent crop and the organic N in the soil (Herridge and Bergersen; 1988; Zapata, 1990).

Fertilizer behaviour and efficiency.

If water is not a limiting factor, application of fertilizers (especially N) normally significantly increases yield. However, the amount of fertilizer N to be added depends on a number of factors which influence positively as well as negatively the total amount of plant-available N (Fig. 1).

Fertilization should balance the N present in the root zone of the soil profile at sowing time plus the N coming from mineralization during the growing period on one side and the need of the plant for obtaining maximum yield on the other side. The amount of N which might escape out of the rooting zone should hereby also be taken into consideration. The importance of other factors on plant yield such as deposition, erosion, and fixation on clay minerals might be of minor importance, although not always negligible. Ammonia volatilization, denitrification and leaching should, however, be controlled.

It is thus clear that the effect of fertilization or the fertilizer efficiency is influenced by a large number of factors. Before going into these factors, the term fertilizer efflciency should be clearly defined.

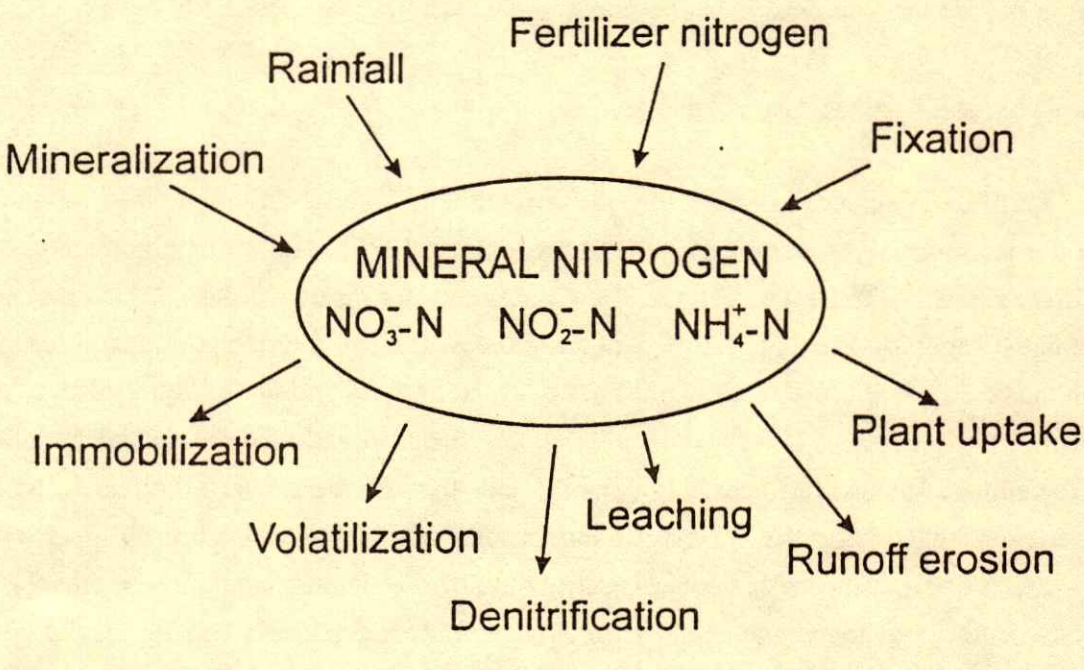


Fig. 1. Factors influencing positively and negatively the plant available mineral N (after Van Cleemput and Baert, 1980)

Efficiency of fertilizers or agrochemicals in general can be considered from various viewpoints (Bowen and Zapata, 1991; Dilz, 1988): (1) fertilizer use efficiency: the yield increase (grain or tubers or other plant parts) per unit of applied nutrient. According to Bock (1984), this is an agronomic approach also defined as yield efficiency; (2) nutrient uptake efficiency: the amount of a nutrient absorbed per unit applied nutrient. This is an ecophysiological approach; and (3) physiological nutrient use efficiency: the yield per gram of nutrient absorbed. This is a physiological parameter.

According to Greenwood (1981), the term efficiency can also be defined in other ways including the increase in the well-being of man or the increase in food production. Needless to say that for economic as well as for environmental-hygienic reasons, the uptake or efficiency of fertilizers should be as high as possible. In addition, quantification and location of the non-efficient part of the fertilizer is a necessity in order to be able to introduce the proper measures to protect our environment.

All processes influencing the combined action of providing enough available nutrients but keeping the environment clean are difficult to study without the use of isotopes. Indeed, nuclear techniques are unique (1) to determine the efficiency and residual effect of the applied ferlilizer, (2) to quantify the amount of biologically fixed N_2, (3) to study the fate of the non-efficient part of the fertilizer, and (4) to evaluate the amount and movement of water, in many cases the most important limiting factor.

Methods to asses fertilizer use efficiency.

Fertilizer N uptake can be determined by the non-isotopic difference method as well as by the isotopic direct method (Hauck and Bremner, 1976). The difference method uses the difference in N uptake between fertilized plants and non-fertilized plants. Also the slope of the linear regression relating the N content in the plants and the rates of applied fertilizer N can be used. With this method, different levels of fertilization (possibly also a zero fertilization) is necessary. The isotopic method determines directly the amount of N derived from the applied labelled fertilizer in the plant. It can also use the slope of the regression line between the labelled N uptake against the amount of applied labelled fertilizer N.

Several experiments have been carried out to evaluate and compare these two methods. Both have advantages and disadvantages, but they provide usually results which are closely correlated (Broadbent and Carlton, 1980; Harmsen and Moraghan, 1988; Olson, 1980; Roberts and Janzen, 1990; Westerman *et al.*, 1972).

When comparing both techniques a number of considerations should be taken in mind (Bowen and Zapata, 1991). Because the difference method compares data obtained from different levels of fertilization, the assumption is made that all fertilization levels have the same influence on the soil N. This is seldom true because of its influence on soil N turnover as well as on root development. The isotope method, on the other hand, assumes that no biological interchange occurs between the labelled and nonlabelled N. In its excellent review on 'priming' effect, Jenkinson et al. (1985) showed that also the isotopic technique is not without shortcomings. The isotopic technique usually provides results which have a lower variability and higher sensitivity, resulting in more accurate information in a shorter period of time (Fried, 1978a; Fried, 1978b).

An important point, however, is that for both methods adequate field experimentation techniques (lay-out sampling and sub-sampling and analysis) are absolutely necessary (Saffigna, 1988; Zapata and Baert, 1989).

It is clear that under conditions of low soil N, the indirect method can be preferred to obtain general fertilizer recommendations. In soils with a high amount of native N, the isotopic method is to be preferred. In addition, the isotopic method provides more accurate information on a shorter period of time.

Experimental lay-out for effiency studies.

Each experiment on fertilizer N efficiency calls for a certain number of treatments and repetitions, according to the basic principles of statistical analyses.

In the direct isotopic method, a clear distinction should be made between the isotopic plot and the yield plot. In the classical experimentation, the isotopic plots are usually scattered microplots covering the smallest possible area required to obtain a representative sample for a good estimate of the isotopic parameter. The isotopically labelled fertilizer is applied to these small plots. Microplot size may vary from about 1 m^2 (small grain cereals, pastures) to about 10 m^2 (widelyspaced row crops). Yield plots cover a relatively larger (10-15 m^2) area in order to obtain precise information on yield and other observations. With individually labelled microplots, the nonharvested border area might be quite high.

Another approach has been developed by Khanif et al. (1984). In their approach the labelled fertilizer is applied in one area of the field and subdivided in a number of subplots. A same number of subplots is also used outside the labelled place, to get information on yield. These subplots are scattered ad random in the field (Fig. 2). The yield and variability in the labelled and non-labelled subplots are then compared with the t-test and double-tailed F-test. This comparison allows to conclude if information obtained on the labelied plots can be extrapolated to the whole field. Because of less border effect, the same amount of labelled

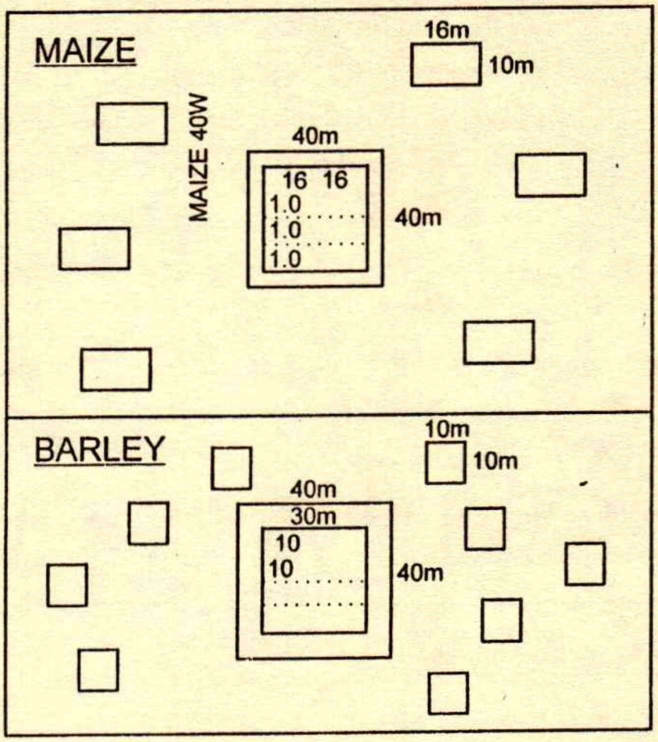


Fig 2. Experimental layout of ^{15}N field experiments.

material allows to fertilize a higher surface than with the approach whereby the labelled plots are scattered in the field.

RESULTS AND DISCUSSION

Despite research during several decades, a scientifically justified N fertilization is still difficult. The main reasons are the narrow limits for an optimum N fertilization and the complex N transformation processes (Hofman and Van Cleemput, 1992). For most arable crops only a limited deviation of the optimum is allowed and for environmental reasons, these limits are even more strict.

Worldwide seen, the use of fertilizers is approached in two different ways. In developed countries -as a result of overproduction for several crops - farmers' interest moved from maximizing production towards optimization with lower and more efficient use of production factors. On the other hand, in developing countries, the first aim is still a search for maximization of production and environmental concern is of second order.

During more than 25 years, fertilizer N efficiency studies have been conducted throughout the world (Bowen and Zapata, 1991; Dilz, 1988; Hera, 1992; Hofman and Van Cleemput, 1992). Factors such as fertilizer placement, timing, type of fertilizer, cultivation practices (irrigation, plant density, cropping sequence), identification of N efficient genotype, competition in mixed agricultural and natural ecosystems, etc. have been studied and progress has been made in selecting the best conditions for increasing the fertilizer efficiency.

The strength of the isotope in these studies is that information can be obtained without the abovementioned problems of interactions due to the effect of plant growth, nutrient uptake or other factors that may be a result of the fertilizer treatment. The Soil Fertility, Irrigation and Crop Production Section of the Joint FAO/IAEA Division, together with the Soil Science Unit at the IAEA Seibersdorf laboratory has played a key role in the implementation of research programmes by developing isotope techniques, providing analytical services and transferring this technology to the IAEA and to FAO member States (Hera, 1992). To illuslrate the potential of using labelled fertilizers, a number of results will be shown related to different experiments on N fertilization.

Nitrogen fertilizer studies with direct labelling.

In the direct isotopic method, the N fertilizer itself is labelled and applied. The effects of fertilizer management practices, doses, application times and many other variables can be studied simply. In all these studies, the central goal is to control fertilization with the aim to provide the plant with a certain amount of available N only when it is needed. However, one should realize that this control can be interrupted by climatic conditions, influencing crop growth and indirectly influencing fertilizer and nutrient uptake. As a consequence, part of the fertilizer can escape out of the plant/soil/animal system and arrive somewhere it is not wanted. These flows can be grouped into fluxes towards the groundwater (mainly nitrate), towards the atmosphere (NH_3, N_2O, NO, N_2) or towards vertical movement (erosion and runoff). Their importance needs to be taken into account when N fertilizer strategies are being developed (Bacon and Freney, 1989). As far as N is concerned, a high number of papers related to efficiency studies under a variety of conditions is available. Some of the main conclusions of these fertilizer studies are given in the next paragraphs and some are illustrated in the following tables.

It has been demonstrated that good timing and a proper method of fertilizer application can result in lower amounts of residual fertilizer N and consequently in lower leaching. High fertilization and/or manuring rates in light textured soils, on the other hand, are favourable for leaching and pollution of groundwater. However, plant cover and cropping conditions can be very helpful in reducing leaching (Grimme and Juo, 1985). Split application may further increase the fertilizer efficiency (De Datta *et al.*, 1990). This is illustrated in Table 1.

Table 1. Influence of split application on labelled fertilizer recovery and loss (after Satrusajang *et al.*, 1991)

Timing	Application	% N Recov. plant	% N Recovery soil (0-30 cm)	Unrecovered N-15 (% of applied N)
Basal	Incorporation	5.1	8.2	85
12 DT	Broadcast	20.6	26.0	53
5-7 DBPI	Broadcast	46.3	26.2	27
PI	Broadcast	34.4	16.4	49

DT: days after planting

DBPI: days before panicle initiation

PI: panicle initiation

According to Bijar-Singh *et al.* (1991) split application up to tree splits was effective in reducing leaching losses of N beyond the root zone of rice, but increasing the number of split doses of urea from 3 to 10 did not enhance the efficiency of the urea-N.

It should also be noticed that the ,availability of fertilizer N to crops is influenced by the type of tillage. A study in Northeastern Thailand on poorly-drained rice-growing soils with low sorption capacity, fertilized with labelled urea showed that a sizeable fraction of the fertilizer N remains in the floodwater following application.

The mode of fertilizer application is also very important. It has been found that band application gives more efficient fertilizer use than broadcasting (Malhi and Nyborg, 1991), and consequently less risk for loss. The importance of the rate of application and timing is illustrated in Table 2 and 3.

Shallow rooting crops, such as potatoes, need high levels of N in the soil profile for economic optimum yield, but leave substantial amounts of N in the profile susceptible for leaching, upon harvest (Table 4).

Runoff can also be an important mechanism of nutrient loss in areas with high probability for inundation following intense rainfall (Saoud *et al.*, 1992).

Table 2. **N utilization coefficient by sunflower as a fuction of NP application rate (Hera, 1979b)**

1972		1973	
Treatment	% Utilization coefficient	Treatmen	% Utilization coefficient
P40N0			
P40N40	29.3		38.2
P40N80	33.5		36.2
P40N120	29.7		38.4
P60N0			
P60N40	25.0		45.7
P60N80	30.6		42.3
P60N120	31.6		42.7

Table 3. Effect of timing and type of fertilizer on fertilizer **N** uptake by wheat (Hera, 1979b)

Time and Rate of N application (kg N ha^{-1})		Kernel			Straw			Total		
Autumn	Spring	I	II	III	I	II	III	I	II	III
$^{15}NH_4NO_3$										
60*	60	8.0	7.6	25.3	7.9	6.1	20.3	15.9	13.7	45.6
60	60*	10.4	9.8	32.7	9.0	7.0	23.3	19.4	16.8	56.0
total		18.4	17.4	29.0	16.9	13.1	21.8	35.3	35.3	50.8
$NH_4\ ^{15}NO_3$										
60*	60	10.2	9.6	32.0	10.6	8.3	27.7	20.8	17.9	59.7
60	60*	12.0	11.3	37.7	13.0	10.2	34.0	25.0	21.5	71.7
total		22.2	20.9	34.8	23.6	18.5	30.8	45.8	39.4	65.6

I : % **Ndff**

II : **N** absorbed from fertilizer (kg ha^{-1})

III: Utilization coefficient (%)

* : labelled with ^{15}N

Table 4. Balance at harvesting time and distribution of applied labelled $^{15}NH_4{}^{15}NO_3$ to potatoes (Saoud *et al.*, 1992)

	Fertilizer recovery			
	kg N ha^{-1}		% of applied N	
	1985	1986	1985	1986
Plant Soil	45.5	84.4	25.3	56.3
0-10	28.1	25.7	15.6	17.1
10-20	7.9	2.1	4.4	1.4
20-30	1.8	8.6	1.0	5.7
30-60	23.8	4.4	13.2	2.9
60-90	8.3	6.0	4.6	4.0
90-120	9.2	3.6	5.1	2.4
total	79.1	50.4	43.9	33.6
Total	124.6	134.8	69.2	89.9
Loss	55.4	15.2	30.8	10.1

The behaviour of urea is somewhat different. Upon application it hydrolyses into ammonium ions with an accompanying rise in pH. This can lead to important ammonia loss and lower efficiency. The use of urease inhibitors, however, can slow down the hydrolysis rate, lower the pH rise and ammonia loss, and consequently increase the urea efficiency and yield. According to Sakorn Phongpan and Byrnes (1990), however, not much difference was found between treatments with and without an urease inhibitor, nBTPT (Table 5). It was found by Buresh *et al.* (1990) that band placement of urea at 2 cm depth was more effective in reducing N loss than broadcasting urea with the urease inhibitor, phenyl phosphorodiamidate.

Table 5. Recovery of ^{15}N of urea and nBTM-amended urea in the floodwater-plant-soil system at 37 days after fertilization (51 kg N ha^{-1}) (Sakorn.Phongran and Byrnes, 1990)

Distribution	Urea	Urea + nBTPT
Floodwater	0.20	0.54
Plant	28.50	28.34
Soil (including roots)	21.14	21.60
Total recovery	49.83	50.47
^{15}N unaccounted for	50.17	49.33

Table 6. Balance of applied labelled fertilizer N to different types of crops in a temperate climate (Khanif *et al.*, 1983; Khanif *et al.*, 1984; Van Cleemput and Baert, 1984)

Plant species	Fertilizer N recover %			Non-accounted for N, %
	Plant	Soil	Total	
Barley 1984	57.1	32.5	89.6	10.4
Barley 1983	79.3	1 1.8	90. 1	9.9
Maize 1984	17.5	68. 1	85.7	14.4
Maize 1983	84.2	10.5	94.7	5.3
Winter wheat 1984				
lst application	52.6	20.8	73.4	26.6
2nd application	59.4	21.7	81.1	18.9
3rd application	66.8	19.7	86.5	13.5
Sugar beet 1982	64.0	25.0	89.0	11.0
Rye grass 1981	75.0	11.0	86.0	14.0

Table 7. Recovery (%) of applied labelled $(NH_4)_2SO_4$ to sesame and sunflower in Egypt (Atta and Van Cleemput, 1988)

Plant fraction	% Ndff	% Ndfs	% Recovery
Sunflower			
Seeds	47.5	52.5	14.4
Flower rests	34.3	65.7	2.1
Leaves	39.5	60.5	4.5
Stems	18.6	81.4	0.7
Roots	19.9	80. 1	0.6
Total			22.3
Sesame			
Seeds	33.3	66.7	5.0
Flower rests	31.8	68.3	2.0
Leaves	33.5	66.5	2.3
Stems	29.2	70.8	2.6
Roots	29.2	71.7	0.4
Total			12.3

Under field conditions, values of fertilizer N recovered by plants are usually around 50 to 60%, as illustrated in Table 6 (Feigenbaum and Hodas, 1980; Riga *et al.*, 1980; Van Cleemput *et al.*, 1981; Westerman and Kurtz, 1974; Zapata and Baert, 1989). But, low values can also be found, especially under severe (cold, wet, dry) climatic conditions, leading to low yield (Table 7).

Another advantage of the use of isotopes is that it allows to study the carry over of fertilizer to a subsequent crop. This is clearly illustrated in Table 8.

Table 8. Nitrogen utilization coefficient in wheat as a main crop and maize as a second crop (Hera, 1992)

Fertilization level (kg N ha^{-1})	% N utilization wheat	% N utilization maize (subsequent crop)	% utilization total
120	27.7	3.3	31.0
240	19.7	7.7	27.4

As a result of these types of fertilizer studies with information on the fate of fertilizer N, it has been found that in order to minimize transfer of N into the environment (water and/or atmosphere) the following management practices can help: (1) minimizing the period when the soil is left bare, (2) avoiding to apply fertilizers and organic manures long before the plants can use them, and (3) avoiding ploughing up of old grassland and clearance of old woodland (JenKinson, 1990).

Nitrogen fertizer studies with indirect labelling.

For those fertilizers which cannot be investigated by direct labelling, the isotopic dilution method in which a labelled common source is added as tracer to the soil has been providing useful information. A decline in the $^{15}N/^{14}N$ ratio of the treatment including the unlabelled source indicates N uptake from the source. This technique requires a 'standard' treatment omitting the test source. The studies with organic fertilizers such as guano, compost, animal slurry, green manures and crop residues, biological N fertilization and contribution of *Azolla* N to rice crop are among the best examples of this technique (Danso and Papastylianou, 1992; Fried and Broeshart, 1975; Kumarasinghe *et al.*, 1986; Zapata and Van Cleemput, 1986).

Table 9 illustrates the use of the indirect method to evaluate guano as organic fertilizer to barley. The evaluation of commercial urea of different sizes can also be evaluated indirectly as illustrated in Table 10. Out of this table it can be seen that a same amount of ammonia loss is noticed from 1 kg of powdered urea, 1.28 kg of prilled urea and 2 kg of 2.9 mm urea.

Table 9. Evaluation test of guano as source of N for barley by means of the isotopic indirect method (Bowen and Zapata, 1991)

Fertilizer treatment	Dry matter yield (g/pot)	N yield (mg N/pot)	% Ndf	A value (mg N/pot)
$(^{15}NH_4)_2SO_4$	7.28	135	29.4	242
$(^{15}NH_4)_2SO_4$ + commercial $(NH_4)_2SO_4$	7.62	187	17.8	463
$(^{15}NH_4)_2SO_4$ + guano (Peru)	8.15	247	11.3	785
$(^{15}NH_4)_2SO_4$ + commercial (Zaire)	7.99	224	13.5	644
LSD (0.05)	1.48	28	1.9	44

Table 10. Relative comparison of different sizes of urea towards NH_3 emission in different types of alkaline soil.

Soil type	Relative values		
	powder	prill	granule (2.9 mm)
Light clay (pH 8.0)	1	1.20	2.22
Clay (pH 7.2)	1	1.35	1.96
Clay (pH 9.4)	1	1.29	1.81
Mean	1	1.28	2.00

CONCLUSIONS

Experiments with labelled fertilizers, through the direct experimentation or through the indirect approach, form a strong tool to obtain precise quantitative information on the efficiency of fertilizers, residual effect, movement and transformation. Under these conditions correct information can be obtained on the amount taken up by the plant and on the fate of the non-used fertilizer. Although a lot of information has already been collected on several crops under a variety of conditions, still a number of questions need to be solved. Fertilizer uptake and nutrient carry-over in mixed systems, the residual effect of fertilizers, fertilizer efficiency in agroforestry, study of nutrient competition in mixed ecosystems, and study of N efticient genotypes are still important topics to be studied.

Besides information on efficiency, the use of isotopes can also provide information on the fate of the fertilizer part which has not been taken up as well as the contribution of gaseous nitrogen compounds.

LITERATURE CITED

ATTA, S.KH. AND O. VAN CLEEMPUT. 1988. Field study of the fate of labelled fertilizer ammonium-N applied to sesame and sunflower in a sandy soil. Plant Soil 107: 123-126.

BACON, P.E. AND J.R. FRENEY. 1989. Nitrogen loss from different tillage systems and the effect on cereal grain yield. Fert. Res. 20:59-66.

BIJAY-SINGH. C.S. YADVINDER-SINGH, KHIND AND O.P. MEELU. 1991. Leaching losses of urea-N applied to permeable soils under lowland rice. Fert. Res. 28:179-184.

BOCK B.R. 1984 Efficient use of nitrogen in cropping systems. In: Hauck R.D. (ed.) Nitrogenin crop production. Madison, Wisconsin, USA, 273-294.

BOWEN, G.D. AND F. ZAPATA. 1991. Efficiency in uptake and use of nitrogen by plants. In: IAEA (ed.) Stable isotopes in plant nutrition, soil fertility and environmental studies, IAEA Vienna, 349-362.

BROADBENT, F.E. AND AB. CARLTON. 1980. Methodology for field trials with nitrogen-15 depleted nitrogen. J. Environ. Qual. 9:236-242.

BURESH, R.J., P.L.G. VLEK AND K. HARMSEN. 1990. Fate of fertilizer nitrogen applied to wheat under simulated Mediterranean environmental conditions. Fert. Res. 23:25-36.

CHRISTIANSON, C.B. AND P.L.G. VLEK. 1991. Alleviating soil fertility constraints to food production on West Africa: efficiency of nitrogen fertilizers applied to food crops. Fert. Res. 29:21-33.

CLARKE, A.L. 1984. Crop rotations in dryland farming systems. In: Proc. Int. Congr. Dryland Farming Proc., Adelaide 1980, Sth Aust. Dept. Agric., Adelaide, 316-341.

DANSO, S.K.A AND I. PAPASTYLIANOU. 1992. Evaluation of the nitrogen contribution of legumes to subsequent cereals. J. Agric. Sci., 119: 13-18.

DE DATTA, S.K., R.J. BURESH, W.N. OBCEMEA AND E.G. CASTILLO. 1990. Nitrogen-15 balances and nitrogen fertilizer use efficiency in upland rice, Fert. Res. 26:179-187.

DILZ, K. 1988. Efficiency of uptake and utilization of fertilizer nitrogen by plants. In: Jenkinson, D.S. and Smith, K.A. (eds.) Nitrogen efficiency in agricultural soils, Elsevier Applied Science, London, 1-26.

ENGELSTAD AND O.P., D.A. RUSSELL. 1975. Fertilizers for use under tropical conditions. Adv.Agron. 27: 175-208.

EVANS, J. AND D.F. HERRIDGE. 1986. Nitrogen inputs and fertilization in crop legumes. In: Bacon, P.E., Evans, J., Storrier, R.R. and Taylor, A.C. (eds.) Nitrogen cycling in temperate Agricultural systems. Austr. Soc. Soil Sci., Wagga Wagga, 14-43.

FEIGENBAUM, S. AND A. HODAS A. 1980. Utilization of fertilizer nitrogen-15 by field-grown alfalfa. Soil Sci. Soc. Amer. J. 44:1006-1010.

FRIED, M. 1978. "Critique of field trials with isotopic labelled nitrogen fertilizer". In: Nielsen, D.R. and MacDonald, J.G. (eds.) Nitrogen in the environment, vol 1, New York Academic Press, 43 -62.

FRIED, M. 1978. "Direct quantitative assessment in the field of fertilizer management practices". Trans. 11 th Int. Congr. on Soil Science, Edmonton, Int. Soc. Soil Sci. 103-129.

FRIED, M. AND H. BROESHARD. 1975. An independent measurement of the amount of nitrogen fixed by a legume crop. Plant Soil 43:707-711.

GREENWOOD, D.J. 1981. Fertilizer use and food production: world scene. Fert. Res. 2:33-51.

GREENWOOD, D.J., T.J. CLEAVER, M.K. TURNER, J. HUNT, K.B. NIENDORF AND S.M.H. LOQUENS. 1980a. Comparisons of the effects of nitrogen fertilizer on the yield, nitrogen content and quality of 22 different vegetables and agricultural crops. J. Agric. Sci., Camb. 95:471-485.

GREENWOOD, D.J., T.J. CLEAVER, M.K. TURNER, J. HUNT, K.B. NIENDORF AND S.M.H. LOQUENS. 1980b. Comparisons of the effects of phosphate fertilizer on the yield, phosphate content and quality of 22 different vegetables and agricultural crops. J. Agric. Sci., Camb. 95:457-469.

GREENWOOD, D.J., T.J. CLEAVER, M.K. TURNER, J. HUNT, K.B. NIENDORF AND S.M.H. LOQUENS. 1980c. Comparisons of the effects of potassium fertilizer on the yield, potassium content and quality of 22 different vegetables and agricultural crops. J. Agric. Sci., Camb. 95:441-456.

GREENWOOD, D.J., T.J. CLEAVER, S.M.H. LOQUENS AND K.B. NIENDORF. 1977. Relationship between plant weight and growing period for vegetable crops in the U.K. Ann. Bot. 41:987-997.

GRIMME, H. AND A.S.R. JUO. 1985. Inorganic nitrogen losses through leaching and denitrification in soils of the humid tropics. In: Nitrogen management in farming systems in humid and subhumid tropics, IB (Haren, The Netherlands) and IITA (Ibadan, Nigeria), 57-71.

HARMSEN, K. AND J.T. MORAGHAN. 1988. A comparison of the isotope recovery and difference method for determining nitrogen fertilizer efficiency. Plant Soil 105: 55-67.

HAUCK, R.D. AND J.M. BREMNER. 1976. Use of tracers in soil and fertilizer nitrogen research. Adv. Agron. 28:219-266.

HERA, CH. 1979a. Some aspects of nitrogen fertilization using ^{15}N. In: I.A.E.A. (ed.) Isotopes and radiation in research on soil-plant relationships. IAEA-SM-235/36, Vienna, 107-123.

HERA, CH. 1979b. The contribution of isotopes and radiation techniques to the development of agricultural production in Romania. In: I.A.E.A (ed.) Isotopes and radiation in research on soil-plant relationships. IAEA-SM-235/53, Vienna, 149-162.

HERA, CH. 1992. Role of isotopes in fertilizer studies. Paper presented at the International Fertilizer Conference, Kuala Lumpur.

HERRIDGE, D.F. AND F.J. BERGERSEN. 1988. Symbiotic nitrogen fixation. In: Wilson J.R. (ed.) Advances in nitrogen cycling in Agricultural Ecosystems, C.A.B. Intenational, Wallingford, 46-65.

HOFMAN, G. AND O. VAN CLEEMPUT. 1992. Nitrogen cycling in agricultural systems. In: François et al. (eds.) Nitrogen cycling and leaching in cool and wet regions of Europe. COST 814, Proc. Workshop Gembloux, Belgium, 1-7.

JENKINSON, D.S. 1990. Leaks in the nitrogen cycle. In: Merckx, R., Vereecken, H., Vlassak K. (eds.) Fertilization and the environment Leuven University Prees, Leuven, Belgium, 35-49.

JENKINSON, D.S., R.H. FOX AND J.H. RYNER. 1985. Interactions between fertilizer nitrogen and soil nitrogen . the so-called 'priming' effect. J. Soil Sci. 36:4U-444.

KEENEY, D.R. 1982. Nitrogen management for maximum efficiency and minimum pollution. In: Stevenson FJ. (ed.) Nitrogen in Agricultural Soils. Amer. Soc. Agron., Madison, WI 605-649.

KHANIF, Y.M., O. VAN CIEEMPUT AND L. BAERT. 1984. Field study of the fate of labelled fertilizer nitrate applied to barley and maize in sandy soils. Fert. Res. 5:289-294.

KHANIF, Y.M., O. VAN CLEEMPUT AND BAERT, L 1983. Fate of field-applied labelled fertilizer nitrate on sandy soils. Plant Soil 74:473-476.

KUMARASINGHE, K.S., F. ZAPATA, G. KOVACS, D.L. ESKEW AND S.K.A. DANSO. 1986. Evaluation of the availability of Azolla-N and urea-N to rice using ^{15}N. Plant Soil, 293-299.

LOOMIS, R.S. AND P.A. GERAKIS. 1975. Productivity of agricultural ecosystems. In: Cooper J.P. (ed.) Photosynthesis and productivity in different environments, pp.145-172, Cambridge, Cambridge University Press.

MALHI, S.S. AND M. NYBORG. 1991. Recovery of ^{15}N-labelled urea: influence of zero tillage, and time and method of application. Fert. Res. 28:263-269.

OLSON, R.V. 1980. Fate of tagged nitrogen fertilizer applied to irrigated corn. Soil Sci. Soc.Amer. J. 44:514-517.

RAMANATHAN, V., R.J. CICERONE, H.B. SINGH AND KIEHL. 1985. Trace gas trends and their potential role in climate change. J. Geophys. Res. 90:5547-5566.

RIGA, A.V., V. FISHER AND H.J. VAN PRAAG. 1980. Fate of feriilizer nitrogen applied to winter wheat as $Na^{15}NO_3$ and $(^{15}NH_4)_2SO_4$ studied in microplots through four course rotation. I. Influence of fertilizer splitting on soil and fertilizer nitrogen. Soil Sci. 130:88-99.

ROBERTS AND T.L. H.H. JANZEN. 1990. Comparison of direct and indirect methods of measuring fertilizer N uptake in winter wheat. Can. J. Soil Sci. 70:119-124.

RUSSELL, J.S. 1980. Crop sequences, crop pasture rotations and soil fertility. In: Proc. Aust. Agron. Conf. Lawes, Qld Agric. Coll. Press, Lawes, 15-29.

SADIK, N. 1988. The state of world population 1988, United Nations Population Fund, New Yort 22p. SAFFIGNA, P. 1988. ^{15}N methodology in the field. In: Wilson, J.R. Advances in nitrogen cycling in agricultural ecosystems. C.A.B. International, Wallingford, 433-451.

SAKORN-PHONGPAN, B.H. BYRNES AND B.H. 1990. The effect of the urease inhibitor N-(n-butyl) thiophosphoric triamide on the efficiency of urea application in a flooded rice field trial in Thailand. Fert. Res. 25:145-151.

SAOUD, A.A., O. VAN CLEEMPUT AND G. HOFMAN. 1992. Uptake and balance of labelled fertilizer nitrogen by potatoes. Fert. Res. 31:351-353.

SATRUSAJANG, A., P. SNITWONGSE, R.J. BURESH AND D.K. FRIESEN. 1991. Nitrogen -15 and sulfur-35 balances for fertilizers applied to transplanted rainfed lowland rice. Fert. Res. 28:55-65.

VAN CLEEMPUT O. AND L. BAERT. 1984. The fate of labelled fertilizer nitrogen split-applied to winter wheat on a clay soil. Pedologie, 34:291 -300.

VAN CLEEMPUT, O., G. HOFMAN AND L. BAERT. 1981. Fertilizer nitrogen balance study on sandy loam with winter wheat. Fert. Res. 2:19-126.

VAN CLEEMPUT, O. AND L. BAERT. 1980. Recovery and balance of field applied nitrate. Pedologie 30:309-321. -

WESTERMAN, R.L., L.T. KURTZ AND R.D. HAUCT . 1972. Recovery of nitrogen-15 labelled fertilizers in field experiments. Soil Sci. Soc. Amer. Proc. 36:82-86.

WESTERMAN, R.L. AND L.T. KURTZ. 1974. Isotopic and non-isotopic estimation of fertilizer uptake by Sudan-grass in field experiments. Soil Sci. Soc. Amer. Proc. 38:107-109.

ZAPATA, F. 1990. Field experimentation in isotope-aided studies. In: Hardarson, G. (ed.) Use of nuclear techniques in studies of soil-plant relationships. Training course series No. 2, IAEA Vienna 35-40.

ZAPATA, F. AND L.BAERT.1989. Air nitrogen as fertilizer. In: Van Cleemput, O. (ed.) Soils for development. ITC-Ghent Publication series 1, 61 -84.

ZAPATA, F. AND O. VAN CLEEMPUT. 1986. Fertilizer nitrogen recovery and biological nitrogen fixation in fababean-sugar beet and spring wheat-fababean cropping sequences, 8:263-268.

DYNAMICS OF PHOSPHORUS IN SOILS AND PHOSPHATE FERTILIZER MANAGEMENT IN DIFFERENT CROPPING SYSTEMS THROUGH THE USE OF ISOTOPIC TECHNIQUES

Dinámica del Fósforo en Suelos y Manejo de Fertilizante Fosfatado en Diferentes Sistemas de Cultivo con el Uso de Técnicas Isotópicas

F. Zapata[1], E. Casanova[2], A.M. Salas[2] and I. Pino[3].

1) Soil Science Unit, FAO/IAEA Programme, IAEA Laboratories, A-2444 Seibersdorf, Austria; 2) Instituto de Edafología, Facultad de Agronomía, U.C.V., Maracay, Venezuela; 3) Comisión Chilena de Energía Nuclear, Santiago, Chile.

Palabras clave: **Andisol, Método de intercambio de radioisótopo ^{32}P, Roca fosfatada, Ultisol.**

Index words: **Andisol, ^{32}P radisotope exchange method, Phosphate rock, Ultisol.**

RESUMEN

En áreas tropicales y subtropicales con frecuencia los suelos son bajos en P disponible y por lo tanto se requiere de la adición de fertilizantes P para alcanzar el óptimo en el crecimiento de las plantas, en la producción de alimentos y fibras. Los estudios sobre el "status" de P disponible en el suelo son por lo tanto esenciales para predecir respuestas en rendimiento y para determinar el régimen de fertilización de P requerido. Existe todavía un error considerable asociado con los diferentes métodos químicos de extracción del P disponible. El método de intercambio del isótopo ^{32}P, aunque no destructivo, presenta la ventaja de proveer tres parámetros básicos para determinar la dinámica del P en el suelo, cantidad, intensidad y capacidad.

Debido a consideraciones económicas, el costo de aplicar fertilizantes P solubles en agua, importados o producidos localmente, es con frecuencia mayor que utilizar rocas fosfatadas autóctonas. La eficacia agronómica de rocas fosfatadas y su conveniencia para ser aplicados directamente requiere ser evaluada adecuadamente. El enfoque más apropiado para determinar la

disponibilidad de P en materiales de rocas fosfatadas para los cultivos es a través del uso de trazadores isotópicos.

Los suelos tropicales de Venezuela bajo estudio fueron clasificados de acuerdo a su capacidad de fijar P en altos, medios y bajos, dependiendo si los índices de adsorción de P isotópico r_1/R eran < 0.2 ; 0.2-0.6 y > 0.6, respectivamente. Una evaluación isotópica del P extractable por el método I de Bray en algunos suelos Venezolanos mostró que del 10 al 98 % del P disponible era extraído por éste método.

En suelos derivados de cenizas volcánicas en Chile, los parámetros isotópicos mostraron una capacidad de fijación de P de alta a muy alta, dependiendo de su grado de intemperización.

Resultados de evaluaciones agronómicas de materiales a base de rocas fosfatadas usando técnicas isotópicas mostraron aumentos en la producción de materia seca, toma de P, y valores L. Todos estos parámetros fueron directamente relacionados a la solubilidad de la fuente de P en un Ultisol de Venezuela. En un Andisol de Chile, 3.8 y 6.4, 1.2 y 1.3, y 0.7 y 0.8 kg P de rocas fosfatadas de Bahía Inglesa y Bayovar fueron equivalentes a 1 kg P de TSP durante el primero, segundo y tercer año respectivamente en una rotación trigo-avena-trigo.

SUMMARY

Soils in tropical and subtropical areas are often low in available P and therefore require inputs of P fertilizer for optimum plant growth and production of food and fiber. Studies on the "available" P status of the soil are essential to predict crop yield responses and to determine the required P fertilization regime. There is still considerable error associated with various chemical methods of extracting bioavailable P. The ^{32}P radioisotope exchange method while being non-destructive holds the advantage of providing three basic parameters to assess soil P dynamics, quantity, intensity and capacity.

Due to economic considerations, the cost of appying imported or locally produced water-soluble P fertilizers is often greater than utilizing indigenous phosphate rock. The agronomic effectiveness of phosphate rock and its suitability for direct application needs to be properly evaluated. The most appropriate approach for assessing the availability of P in phosphate rock materials for crops is through the use of isotopic tracers.

The tropical soils of Venezuela under study were classified as having high, medium and low P fixing capacities depending on wether the r_1/R isotopic P adsorption capacity indexes were <0.2; 0.2 - 0.6 and >0.6, respectively. An isotopic evaluation of the P extracted by Bray I method in some Venezuelan soils showed that 10 to 98% of the available P was extracted by that method.

In the volcanic ash derived soils in Chile the isotopic parameters showed a high to very high P fixing capacity depending on their degree of weathering.

Results from the agronomic evaluation of phosphate rock materials using isotopic techniques showed increases in dry matter production , P uptake and L values. All these parameters were directly related to the solubility of P source in an Ultisol from Venezuela. In an Andisol of Chile 3.8 and 6.4, 1.2 and 1.3, and 0.7 and 0.8 kg P from Bahia Inglesa and Bayovar phosphate rocks were equivalent to 1 kg P from TSP during the first, second and third year respectively in a wheat-oat-wheat rotation.

INTRODUCTION

Soils in tropical and subtropical areas are often low in available P and therefore require inputs of P fertilizer for optimum plant growth and production of food and fiber. Studies on the assessment of the "bioavailable" P status of the soil are essential to predict crop yield responses and to determine the required P fertilization regime to obtain maximum agronomic and economic benefits.

Much research has gone into determining the bioavailability of P in soils (Fixen and Grove, 1990). A large number of chemical extractants are used for assessing bio-available P in soils, e.g. Bray and Mehlich. However, there is still considerable error associated with various methods of extracting bio-available P especially when mineralizable organic P is present or soil has not reached equilibrium with addition of water-soluble P sources, and phosphate rock is present in soil, and also when comparisons are made across varying fertilizer sources, soil types, and environmental conditions. Common soil extractants do not necessarily remove the actual fraction of P in soil that is bioavailable; they are also destructive due to chemical reactions, and correlations have to be established for individual soil and environmental conditions. A better method of assessing bioavailability would be a non-destructive one which would simulate the ability of plant roots to absorb soil P. Methods that closely meet these criteria are resin-P (Saggar *et al.*, 1990), Fe-oxide filter paper (Menon *et al.*, 1989) and radioisotope exchange (Olsen and Khasawneh, 1980). Of these, radioisotope exchange method holds the advantage of mesuring 3 critical parameters in assessing soil P status, viz. Quantity, intensity, and capacity (Fardeau *et al.*, 1991). The resin and filter paper techniques only measure quantity.

Due to economic considerations, the cost of applying imported or locally produced watersoluble P fertilizers is often greater than utilizing indigenous phosphate rock. The agronomic effectiveness of phosphate rocks and their suitability for direct application needs to be properly evaluated (Khasawneh and Doll, 1978). The most appropriate approach for assessing the bioavailability of P in phosphate rock materials for crops is through the use of the isotope tracers, ^{32}P and ^{33}P (26). The Joint FAO/IAEA' Division for the Application of Nuclear Techniques in Food and Agriculture and the IAEA. Agriculture Laboratory are promoting research and development as well as transfer of this technology to developing Member States of FAO and IAEA through various mechanisms. This paper presents results from isotopic experiments carried out under FAO/IAEA Technical Co-operation projects in tropical and sutropical areas in Chile and Venezuela. Furthermore, future research strategies to be developed by an FAO/IAEA international networked research programme will be outlined.

MATERIALS AND METHODS

^{32}P isotopic method for the assessment of bioavailable soil P.

A laboratory method (Fardeau *et al.*, 1991; Sen Tran *et al.*, 1988) based on the isotopic exchange kinetics of phosphate ions performed in a suspension of soil in water in a steady state was followed. The characterization of bioavailable soil P status was made through the determination of three parameters: (i) factor intensity (I) , ie: the phosphate ion concentration in the soil solution , (ii) factor quantity (Q) , ie: amount of P isotopically exchangeable during the first minute (E_1) , and (iii) instantaneous capacity factor or the decrease with time of $^{32}PO_4$ ions in the soil suspension. This method was utilized to characterize the bioavailable P in soil in samples taken from the arable layer (0-20 cm) from 6 locations in Venezuela.

Isotopic evaluation of bioavailable soil P obtained using a chemical extraction method.

Common soil extractants do not necessarily proportionally remove the actual fraction of P in soil that is bioavailable (Fardeau *et al.*, 1988). In this experiment the ^{32}P isotope was utilized to assess the nature of the P extracted by a chemical method, Bray I, and to evaluate the proportion of exchangeable or available phosphate extracted. The procedure described in detail by Morel and Fardeau (1987) consists of a sequential determination of the isotopic exchange to characterize the specific activity in the soil solution (SAss) followed by the chemical extraction to determine the specific activity in the extract (SAext). This technique was utilized in 5 tropical soils from Venezuela. These soils are highly weathered, acid, with low fertility, generally with N, P, Ca , Mg and S nutrient deficiencies and in some cases toxic levels of exchangeable Al and Mn, resulting in serious constraints to crop growth.

Use of ^{32}P isotope techniques in phosphate adsorption/desorption kinetics studies.

Some tropical (Ultisols, Oxisols) and temperate (Andisols, Ultisols) soils show a variable phosphate adsorption capacity, thus requiring higher P fertilizer rates to obtain optimum yields. Therefore, it is essential to obtain data on the P sorption characteristics of these soils to explain differences in their response to P fertilizer application.

A series of laboratory experiments were carried out to establish phosphate adsorption curves in volcanic ash derived soils in Chile (Pino *et al.*, 1983; Pino *et al.*, 1986; Varderdeelen *et al.*, 1973). These soils classified mainly as Andisols and Ultisols cover about 60 % of the arable land of this country. They are very acid (pH 4.1-5.5), low in available P and depending on their degree of weathering, contain variable amounts of volcanic glass and allophone, which are major constituents affecting P sorption capacity (Soil Survey Staff, 1992).

In order to illustrate the utilization of ^{32}P a recent study will be reported here. The Langmuir equation was utilized to describe the kinetics of P adsorption through the determination of the parameters Q and I (De Grelle, 1993). Furthermore the following isotopic technique was utilized: a suspension of 10 g soil in 0.01 M CaCl solution with increasing P concentrations ranging from 100 to 2000 ppm was continuously shaken for 24 hours. After this equilibration time, samples were filtered and the phosphate ions in the solution were determined colorimetrically. Immediately thereafter, ^{32}P was added as 20 ml $KH_2{}^{32}PO_4$ with a SA of 0.2 μ Ci/ml. The suspension was shaken for 6 hours, samples were then filtered and both the remaining radioactivity and the concentration of phosphate ions in the filtrate were measured.

Isotope techniques for evaluating the agronomic effectiveness of P fertilizers, in particular phosphate rock.

The constraint of low P is normally removed by application of water-soluble P fertilizers. Another alternative P source is natural and modified phosphate rock products. However, this practice requires basic knowledge about the agronomic effectiveness of the P source to be utilized (Khasawneh and Doll, 1978). Several isotopic techniques using P-32 labelled materials have been proposed to quantitatively evaluate the bioavailability of P from phosphate fertilizers including phosphate rock (Fried, 1954; Fried, 1964; IAEA, 1976; Zapata, 1990).

Greenhouse and field isotopic-aided experiments were carried out in Venezuela and Chile to assess the best conditions for the utilization of locally available phosphate rock. The procedures followed have been described in detail elsewhere (IAEA, 1976; Pino and Casas, 1990; Zapata, 1990; Zapata and Axmann, 1991).

A series of greenhouse studies was carried out to assess the agronomic evaluation of two indigenous and modified phosphate rocks (Riecito and Monte Fresco) in tropical soils of Venezuela. Labile P (L values) was determined in an Ultisol (Valle La Pascua) according to the modified procedure of Probert (Fried, 1964).

Isotopic-aided field experiments were carried out in volcanic soils in various agricultural regions of Chile to assess the agronomic effectiveness of the local phosphate rock Bahia Inglesa, applied at two P rates over a three year crop rotation. Phosphatic rocks were added only once at the beginning of the crop rotation and the P-32 labelled superphosphate was applied at planting time. The A value technique was utilized to evaluate the immediate and residual value of the phosphate rock. Data of one crop rotation, wheat-oat-wheat, grown in an Andisol, (series Santa Barbara) will be presented here.

RESULTS AND DISCUSSION

^{32}P isotopic method for the assessment of bioavailable P in soil.

As inferred from the physico-chemical analysis of the soils (data not shown), there arc large differences in all parameters measured to assess bioavailable P in soil (Table 1).

The intensity factor or the concentration of P (C_P) in the soil solution is related to the reserves of P in the solid phase and to the adsorption capacity of the soil (Ratio r_1/R). Water-soluble P in all soils was less than 0.2 ppm which is considered as critical value of the intensity factor for most crops (Salcedo *et al.*, 1990; Smith and Sanchez, 1982). The highest value of C_P for

Table 1. Parameters measured to assess bioavailable P in tropical soils of Venezuela

Soils Series - Classification (Soil Taxonomy)		C_P mg P l^{-1}	r_1/R ratio	n	E_1 mg P kg^{-1}	E_1/C_P 1 Kg^{-1}
Taguanes	Tipic Paleustult	0.048	0.82	0.14	0.60	1.3
Valle de la Pascua	Tipic Paleustult	0.022	0.74	0.17	1.40	6.4
Portuguesa	Aeric Tropaquept	0.029	0.28	0.39	1.00	3.5
Pao	Aquic Paleustult	0.027	0.19	0.34	1.40	5.2
Paragua	Oxic Haplustalf	0.032	0.01	0.30	31.00	96.9
Guataparo	Tropeptic Haplustox	0.008	0.01	0.42	8.10	101.3

the Taguanes soil is likely to be associated with higher reserves of P in the solid phase. Valle la Pascua, Portuguesa, Pao and Guataparo soils showed deficient values. Therefore, it is important to assess the sorption capacities of these soils for replenishing the soil solution (Sen Tran *et al.*, 1988; Smith and Sanchez, 1982). Soils with r_1/R ratios higher than 0.6, such as Taguanes and Valle La Pascua, do not fix phosphate ions particularly and the applied P fertilizer remains relatively available. However, there are differences in the P reserves of these soils, as mentioned before. Soils with r_1/R ratios between 0.2 and 0.6 (Pao and Portuguesa) have medium P-sorption capacities so leaving some proportion of the P fertilizer applied available. Soils with a ratio lower than 0.2 (Paragua and Guataparo) have an extremely high P-sorption capacity and so show a limited response to P fertilizer application.

The kinetic value n is obtained from the decrease of radioactivity remaining in the solution versus time (Sen Tran *et al.*, 1988). Values of n close to zero (Taguanes, Valle La Pascua) denote soils with a good capacity to replenish the pool of labile P whereas values of n approaching 0.5 indicate soils with a high P-sorption capacity, in particular of the applied water soluble P fertilizer (Sen Tran *et al.*, 1988).

The quantity factor or the pool of labile P is expressed by the E_1 value. It is observed however, that the soils Paragua and Guataparo which have high P-sorption capacities showed the highest E_1 value. It has been reported that E_1 values can be overestimated in soils with high P-sorption capacity. To solve this problem, Fardeau and Jappe (1980) have proposed the determination of the pool of mobile ions M_1 through a double isotope dilution procedure. The ratio E_1/C_p is utilized as a capacity factor because it represents the apparent value of phosphate ions in the solid phase. It is a relatively stable value based on soil type. Most soils showed a low capacity factor, with the exception of the Taguanes and Guataparo in which the overestimation of E_1 has a strong influence on this parameter (Fardeau *et al.*, 1991).

Isotopic evaluation of biovailable soil P extracted by Bray I method.

The isotope ^{32}P in this experiment was be used to differentiate the bioavailable P from the extractable P on the assumption that the specific activity (SA) of P taken up by a crop is the same as the SA of P in the soil solution (SAss). Therefore, a comparison of the SA values in the soil solution and any chemical extractant can be made for evaluating the predictive capacity of the chemical method for bioavailable soil P (Morel and Fardeau, 1987).

Large differences in SAss and SAext were observed in four of the soils studied (Table 2) ; only in Pao soil were the values similar. In the last column of the Table 2 , the evaluation is

Table 2. Isotopic evaluation of bioavailable soil P extracted by the Bray I method on five acid soils from Venezuela.

Soils Series - Classification (Soil Taxonomy)		pH	SAss % µg P g^{-1}	SAext[1] % µg P g^{-1}	Available P in[2] Bray I extract (%)
Tigre	Tipic Paleustult	5.1	105.0	16.6	15.8
Taguanes	Tipic Paleustult	4.7	70.0	7.2	10.3
Tachira	Tipic Tropoudult	4.8	17.7	4.1	31.1
Portuguesa	Aeric Tropaquept	5.0	16.4	5.1	31.3
Pao	Aquic Paleustult	4.8	11.9	10.6	88.8

1 Specific activity (SA) in a soil solution or in an extract at 100 minutes incubation time.

$$SA = \frac{\frac{\text{Activity in solution or extract}}{\text{total activity added}} \times 100}{\text{p concentration } (\mu g\ P\ g\text{-}1)}$$

2 The percentage of the available P extracted by the Bray I method was obtained from the ratio of SAext and Sass.

presented as an index of available P in Bray I extract; 10 - 89 % of the P present in the Bray I extract was bioavailable i. e. corresponded to isotopically exchangeable P. Only in one soil was the value close to 100% (89% for Pao). Nevertheless, the values were extremely variable indicating that there is still considerable error associated with this chemical method in these soils. It is known that most chemical methods extract unavailable soil P and do not extract all the available soil P (Fardeau *et al.*, 1988; Morel and Fardeau, 1987). This makes the selection of an universal method of extraction very difficult.

Use of ^{32}P isotopic techniques in phosphate sorption kinetic studies in volcanic ash derived soils of Chile.

The soils under study are listed in increasing order of P sorption capacity (Table 3). Volcanic ash derived soils with relatively low degree of weathering (Lonquimay 1 and 2) also showed relatively low Qmax, while more developed Andisols (Santa Barbara and Victoria) are the soils with highest Qmax values. The other soils (Mirador, Merenco, Collipulli and Perquenco) showed intermediate values. Similar trends were observed for the **K** values (adsorption energy coefficient), which range from 0.0112 (young volcanic ash derived soil) to 0. 1903 (Santa Barbara Andisol) with the highest energy of P adsorption.

Table 3. Qmax and K values derived by the Langmuir equation for volcanic ash derived soils from Chile.

Soils	Classification	Qmax	K
Lonquimay 1	Vitrandepts	582.4	0.0112
Lonquimay 2	Vitrandepts	1045.7	0.0213
Mirador	Rhodoxeralf	3233.5	0.0208
Metrenco	Paleohumult	3248.2	0.0202
Collipulli	Paleohumult	3512.7	0.0179
Perquenco	Haploumbrept	3610.4	0.0386
Santa Barbara	Andisol	4834.3	0.1903
Victoria	Andisol	4882.7	0.0629

The Quantity/Intensity (Q/I) curves shown in Figure 1 relate the amount of P adsorbed and the concentration of P remaining in solution at increasing P concentrations ranging from 100 to 6000 ppm for the various soils under study. The highest leveles of P adsorbed correspond to the Qmax values at the 6000 ppm P concentration. It may also be observed in Figure 1 the differential P fixation capacity of the various soils. The curves located in the upper part correspond to soils with the highest P fixation (Santa Barbara and Victoria) , and those at the bottom to soils with the lowest P fixation (Lonquimay 1 and 2). The curves of the other soils occupy intermediate position.

Table 4. Percentage (%) radioactivity remaining in solution after 6 hours (r6h) in relation to the initial radioactivity (R), at various P concentration levels for volcanic ash derived soils from Chile.

Soils	100 ppm	200 ppm	500 ppm	1000 ppm	2000 ppm
Lonquimay 1	2.89	13.16	19.69	27.21	34.85
Lonquimay 2	0.79	2.43	8.89	14.43	20.67
Mirador	0.17	0.31	0.44	1.91	4.25
Metrenco	0.54	0.69	1.27	2.35	6.07
Collipulli	0.36	0.44	1.24	2.64	6.45
Perquenco	0.21	0.27	0.60	0.83	1.69
Santa Barbara	0.51	0.59	0.57	0.63	0.83
Victoria	0.28	0.37	0.39	0.36	0.55

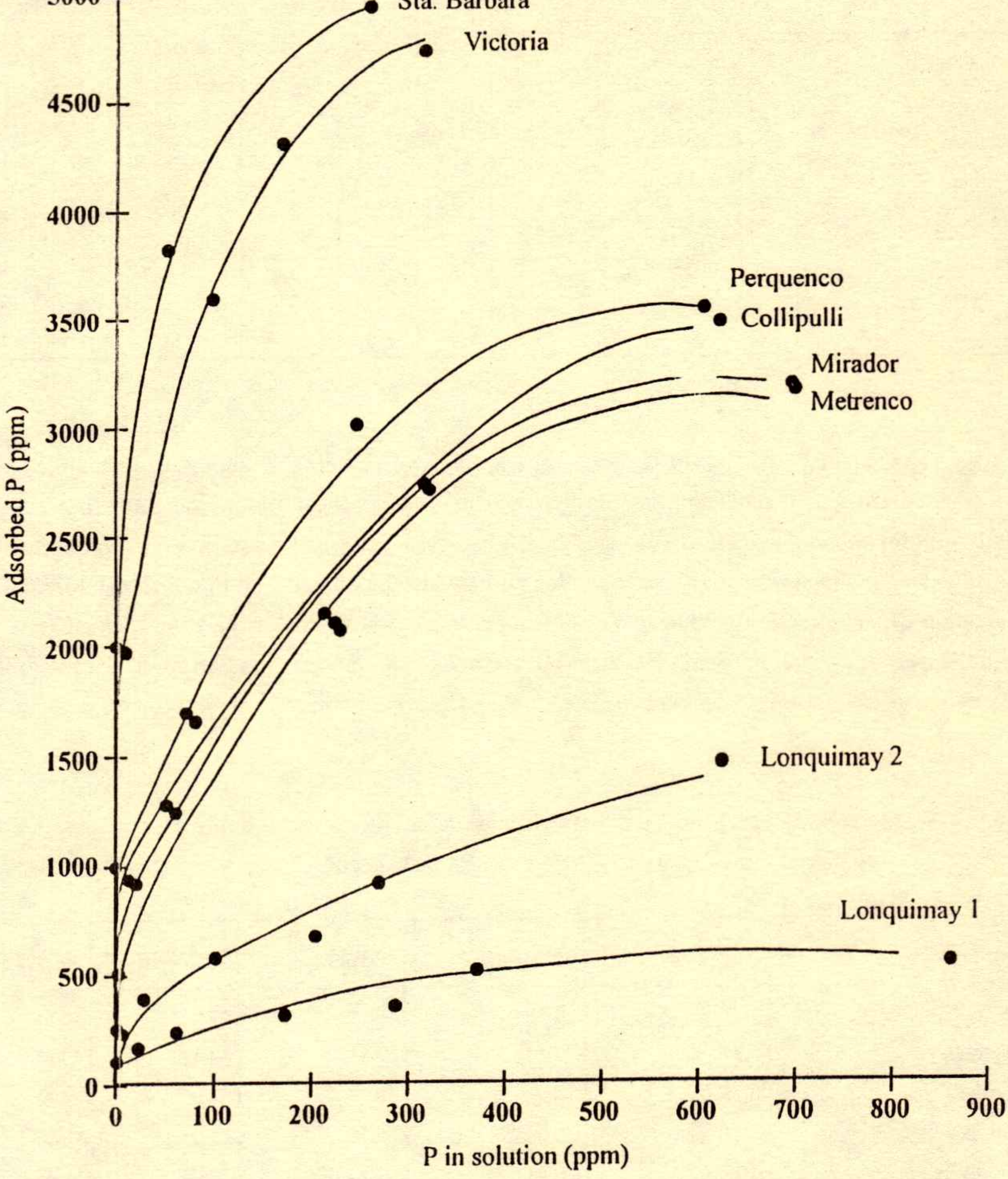


Fig. 1. Quantity/Intensity curves from volcanic ash derived soils in Chile

The percentage of the radioactivity remaining in solution after 6 hours (r6h) in relation to the initial radioactivity (R) is utilized as an index of the P sorption capacity of the volcanic soils under study at various P concentration levels ranging from 100 to 2000 ppm (Table 4). A P sorption capacity index (r_1/R) has been proposed by Fardeau as one typical parameter to characterize dynamics of available soil P (Fardeau *et al.*, 1991). The method utilized here is an adaptation for volcanic soils (De Grelle, 1993). It is observed that soils derived from volcanic ash (Lonquimay 1 and 2) showed the highest residual activity of phosphate ions in solution, in particular at 500 ppm (10-20 %) and a corresponding relatively high fixation capacity. On the other hand , the Andisols showed the lowest values almost irrespective of the P concentration added (less than 1 %). This indicates not only a higher P fixation capacity (Table 4) but also a stronger energy of P adsorption, becoming non-exchangeable. A non-isotopic routine characterization of volcanic soils was also made by the method of Blakemore et al. (data non shown here). The total adsorbed P ranged from about 3 % in the young volcanic ash derived soil (Lonquimay 1) to 94 % in the Santa Barbara Andisol. The results are in agreement with those previously shown. However, from previous experiments have shown that the critical P concentration depends upon a series of factors, ie: soil type, temperature, etc.(Pino *et al.*, 1983; Pino *et al.*, 1986; Vanderdeelen *et al.*, 1973). The use of ^{32}P allows rapid quantification of the parameters characterizing the dynamics of available P in soil. It also allows discrimination of the adsorbed P from the total P added. In this way, it is possible to get a better understanding of the soil characteristics affecting soil/phosphate behaviour and the soil P parameters controlling phosphorus availability to, and fertilizer requirements of, cultivated crops (Warren, 1990).

Agronomic evaluation of phosphate rock materials through the use of isotopic techniques.

Isotopic and conventional parameters were measured in three cuttings of *Agrostis communis* for evaluating the agronomic effectiveness of indigenous and modified phosphate rock (PR) materials. Values obtained in an Ultisol of Venezuela (La Pascua) are reported in Table 6. In general, for all cuttings the addition of any P source resulted in an increase in dry matter and total P uptake. Thus all P fertilized treatments showed higher dry matter production and total P uptake compared with the control. No major differences were observed between P fertilized treatments, except that the P uptake of TSP treatment decrease with time whereas those of PR treatments remained almost constant. Thus at the 1st cutting the P uptake of the PR treatments and Monte Fresco 40% partially acidulated phosphate rock (PAPR) was significantly higher than that of TSP and Riecito 40% PAPR. Similar results were seen for dry matter production.

L values for the Monte Fresco PR increased from 28 to 58 ppm P from the first to the third cutting while those of Riecito PR remained constant with time (67 to 70 ppm). Thus Monte Fresco PR showed a higher residual effect. The availability of P in the PAPR products tested decreased with time. This decrease was more pronounced with Riecito 40% PAPR (from 95 to 7O ppm P). The same effect was noted with the TSP treatment (from 123 to 78 ppm). The decrease of P availability (L values) from the P sources is related to a decrease in total P uptake. In all cuttings the magnitude of L values was directly related to the expected availabilities of the P fertilizer sources tested. The highest L values corresponded to the TSP treatment and the lowest to the PR treatments. The PAPR products showed immediate values.

The isotopic parameters used for the field evaluation of the agronomic effectiveness of phosphate rock materials over a 3 year crop rotation are shown in Table 6. The results of the first year with wheat as head crop of the rotation showed that the percentage of P in the crop derived from the phosphate rock was not higher than 22 % with Bahia Inglesa PR (RBI) at 350 kg P ha^{-1}. RBI was superior than Bayovar PR (RBY).

Table 5. Greenhouse evaluation of various phosphate rock materials in an Ultisol (Valle la Pascua) from Venezuela (data of 3 cuttings of *Agrostis communis*)

P Fertilizer	Dry matter yield (g/pot)			P uptake (ppm)			L value (ppm)		
Treatments	C-1	C-2	C-3*	C-1	C-2	C-3	C-1	C-2	C-3
Control	0.51b**	0.29b	0.07e	3.1e	1.7d	0.4c	7.7f	3.2e	3.3d
Monte Fresco PR	0.67a	0.79a	1.06a	11.9d	13.8bc	14.3a	27.9e	54.1d	57.9c
Riecito PR	0.75a	0.77a	1.01ab	19.2b	15.1b	13.8a	69.6d	66.4c	66.5b
Monte Fresco 40% PAPR	0.78a	0.75a	0.96b	19.9b	14.5b	14.3a	76.2c	70.1c	68.0b
Riecito 40% PAPR	0.70a	0.66a	0.88c	16.5c	12.3c	11.5b	95.0b	77.2b	69.6b
TSP	0.78a	0.68a	0.79d	23.9a	18.5a	11.1b	122.7a	123.0a	78.0a
CV (%)	7.7	9.4	6.0	7.0	9.0	10.1	2.6	6.5	4.7

* C-1, C-2, C-3 are cuttings 1, 2 and 3 .

** Values within the same column with the same letter are not significantly different, according to the DUNCAN multiple range test.

The best treatment was RBI at the lower rate of 175 kg P ha^{-1}. The TSP (standard fertilizer) was the best P source under these conditions because the wheat crop used was a high-yielding cultivar with high nutritional requirements. The magnitude of the A_R values expressed as equivalent units of TSP in Kg P ha^{-1} was low. As regard to the agronomic evaluation: 1 kg P as TSP was equivalent to 3.8 kg P as RBI and to 6.4 kg P as RBY.

During the second year with oats as the rotation crop , the percentage of P derived from the phosphate rock (% PdfR) increased to 45-47%. This effect was confirmed by the magnitude of the A_R values. Both phosphate rocks at the lower P rate 175 kg P ha^{-1} were superior to RBI at 350 Kg P ha^{-1}. Both phosphate rocks also showed a similar efficiency as the TSP during this

Table 6. Isotopic-aided field evaluation of the agronomic effectiveness of phosphate rock materials over a three year crop rotation in an Andisol from Chile.

1 st Year crop: Wheat, cultivar Laurel

P fertilizer[1)] Treaments	PdfR %	A_R value[2)] kg P ha^{-1}	Amount equivalent to 1 kg P as TSP	Relative[3)] efficiency ratio
T_1 RBI-175	19.73b	47b	3.8b	1.0b[4)]
T_2 RBI-350	21.59a	52a	6.7a	1.8a
T_3 RBY-175	12.54c	27c	6.4a	1.7a

2nd Year crop: Oat, cultivar Nehuen

P fertilizer[1)] Treaments	PdfR %	A_R value[2)] kg P ha^{-1}	Amount equivalent to 1 kg P as TSP	Relative[3)] efficiency ratio
T_1 RBI-175	44.8b	131c	1.3b	1.1b
T_2 RBI-350	45.8ab	137b	2.6a	2.2a
T_3 RBY-175	46.8a	143a	1.2b	1.0b

3rd Year crop: Wheat, cultivar Siko

P fertilizer[1)] Treaments	PdfR %	A_R value[2)] kg P ha^{-1}	Amount equivalent to 1 kg P as TSP	Relative[3)] efficiency ratio
T_1 RBI-175	58.0b	236b	0.7a	1.0a
T_2 RBI-350	69.0a	372a	0.9a	1.3a
T_3 RBY-175	56.6ac	219c	0.8a	1.1a

1) P Fertilizer treatments
T_1 RBI-175 denotes Bahia Inglesa phosphate rock applied at a rate of 175kg P ha^{-1}
T_2 RBI-350 ditto but at a rate of 350 kg P ha^{-1}
T_3 RBY-175 denotes Bayovar phosphate rock applied at a rate of 175kg P ha^{-1}

2) A_R value is the available amount of P from the phosphate rock expressed in equivalent units of triple superphosphate (P-32 labelled fertilizer used as a reference standard).

3) Relative efficiency ratio relates the amounts equivalent to 1 kg P as TSP of the different fertilizer P treatments tested.

4) Values within the same column with the same letter are not statistically different according to the DUNCAN multiple range test.

second year. Thus, 1 kg P as TSP was equivalent to 1.2 and 1.3 kg P as RBY and RBI, respectively.

During the third year with wheat as the rotation crop, it was observed that the residual effect of the P in the PR tested was very high. The % PdfR increased to 57-69%. The highest % PdfR and A_R values corresponded to the RBI applied at the higher rate of 350 kg P ha^{-1}

Both phosphate rocks were slightly superior to the TSP; thus 1 kg P as TSP was equivalent to 0.7 - 0.8 kg P as RBI and RBY respectively. These results clearly demonstrate the residual effect of the tested PR, thus indicating that long-term field experiments are needed for the agronomic evaluation of PR materials (Fried, 1954; Zapata and Axmann, 1991).

The relatively low agronomic efficiency of the PR materials during the first year suggests that this would be improved by soil management or treatments that enhance P supply from the beginning. For this purpose, new phosphate rock-based formulations are being developed (Chien,SH, personal communication).

The isotopic method was very effective in measuring the P supply with time under the experimental conditions. Factors affecting the agronomic effectiveness of PR materials such as inherent PR characteristics, crop rotation and environmental factors (soil/climate) can be easily studied with the isotopic method, which estimates the P in the plant derived from the phosphate rock (%PdfR). This isotopic parameter is yield-independent and very sensitive for evaluating the factors mentioned above (Zapata and Axmann, 1991).

Future prospects on the use of P-32 isotope techniques in agricultural phosphate research.

It has been demonstrated that P-32 isotopic techniques are extremely important tools in agricultural phosphate research. They provide more reliable and accurate information on various aspects of soil/phosphate behaviour. In order to take advantage of the potentiality of these techniques, a FAO/IAEA consultants meeting was convened in Vienna, Austria from 10- 12 May 1993 to review the present status and future trends of agricultural phosphate research with particular emphasis on the potential use of phosphate rock-based products, bioavailability of P in soils amended with these products and use of radioisotope techniques for the aforementioned studies.

The meeting recommended the creation of an international research network programme with the following objectives:

a) To assess bioavailable P: soil using isotopic exchange techniques and other chemical extraction techniques for comparison

b) To quantitatively evaluate P uptake from P fertilizers (water-soluble P fertilizers, indigenous and modified phosphate rock products) by crops under a variety of soil and climatic conditions. Research should also focus on ways and means to enhance the agronomic effectiveness of phosphate rock-based products.

c) To obtain agronomic and economic recommendations on the use of P fertilizers.

Based on these recommendations the Joint FAO/IAEA Division for Nuclear Applications in Food and Agriculture through the Soil Fertility, Irrigation and Crop Production Section with financial support of the French Government is launching a 5-year Co-ordinated Research Programme on "The Use of Nuclear and Related Techniques for Evaluating the Agronomic Effectiveness of Phosphate Fertilizers, in particular Phosphates Rocks" to address the topics above mentioned using isotopic techniques.

ACKNOWLEDGEMENTS

The isotopic data of the Venezuelan soils were obtained by Ms. A.M. Salas while on IAEA fellowship in the laboratory of J.C. Fardeau, at CEN, Cadarache, France. The field trials in Chile were carried out under a Co-operative Research Agreement, Chilean Nuclear Energy Commission (CCHEN) and National Institute for Agriculture and Livestock Investigations (INIA). The authors are grateful to Dr. J. C. Fardeau for the critical comments on the manuscript, Dr. J.I. Richards and Ms. M.A. Ablöscher for editing and typing the manuscript respectively.

LITERATURE CITED

DE GRELLE, V. 1993. Adsorption du phosphore dans une séquence d'altération de sols dérivés de pyroclastes au Chili. Mémoire présenté en vue de l'obtention du grade d'Ingénieur Agronome. Université Catholique de Louvain. Faculte des Sciences Agronomiques en collaboration avec le CCHEN.

FARDEAU, J.C. AND J. JAPPE. 1980. Choix de la fertilization phosphorique des sols tropicaux: emploi du phosphore 32. Agron. Trop. 35 :225-231.

FARDEAU, J.C., C. MOREL AND R. BONIFACE. 1988. Pourquoi choisir la méthode Olsen pour estimer le phosphore "assimilable" des sols? Agron. 8:577-584.

FARDEAU, J.C. C. MOREL AND R. BONIFACE. 1991. Cinétiques de transfert des ions Phosphatés du sol vers la solution du sol: paramètres caractéristiques. Agron. 1 1 787-797.

FIXEN, P.E. AND J.H. GROVE 1990. Testing soils for phosphorus. *In* Westerman R.L. (ed). Soil testing and plant analysis, 3rd ed SSSA, Madison, WI, 141-80.

FRIED, M. 1954. Quantitative evaluation of processed and natural phosphates. Agric. Food Chem. 2: 241-244.

FRIED, M. 1964. E, L, and A values. *In:* Trans. 8th Int. Cong. Soil Sci., Bucharest Vol.4:29-41.

IAEA 1976. Measurement of soil and fertilizer phosphorus availability to plants. *In:* IAEA (ed). Tracer Manual on Crops and Soils. Vienna, Austria, Tech. Rep. Series 171:129-138.

KHASAWNEH, F.E. AND E.C. DOLL 1978. The use of phosphate rock for direct aplication to soils. Adv. Agron.30:159-206.

MENON, R.G., L.L. HAMMOND AND H.A. SINGH 1989. Determination of plant-available phosphorus by the iron hydroxide-impregnated filter paper (Pi) soil test. Soil Sci.Soc. Am. J. 52:110-115.

MOREL, C. AND J.C. FARDEAU 1987. Le phosphore assimilable des sols intertropicaux: ses relations avec le phosphore extrait par deux methodes chimiques. Agron. Trop. 42:248-257.

OLSEN, S.R. AND F.E. KHASAWNEH 1980. Use and limitations of physico-chemical criteria for assessing the status of phosphorus in soils. In Khasawneh, F.E. et al (ed) The role of phosphorus in agriculture. ASA, CSSA, and SSSA. Madison, WI, 361-410.

PINO, I., M.C. URBINA,W. LUZIO AND L. CASAS 1983. Retención de fósforo en dos suelos derivados de cenizas volcánicas. Nucleotécnica 3:47-50.

PINO, I., L. CASAS AND M.C. URBINA 1986. Evaluación de la capacidad de retención de fósforo en suelos derivados de cenizas volcánicas. Nucleotécnica 4:43-47.

PINO, I. AND L. CASAS 1990. Phosphoric rock appraisal in volcanic ash soils of Chile *In*: Trans. 14th Int. Cong. Soil Sci. , Kyoto, Japan. Vol.IV, 122-125.

PINO, I., A. MONTENEGRO, M. BUNEDER AND N. RODRIGUEZ 1991. Evaluación Agronómica de la Fosforita de Bahía Inglesa mediante técnicas isotópicas. Congreso Internacional de Rocas Sedimentarias del Pacífico Sur. Santiago- La Serena, Chile.

PROBERT, M.E. 1972. The dependence of isotopically exchangeable phosphate (L value) on phosphate uptake. Plant Soil 36:141.

SAGGAR, S., M.J. HEDLEY AND R.E. WHITE 1990. A simplified resin membrane technique for extracting phosphorus from soils. Fert. Res. 24:173-180.

SALCEDO, I., F. BERTIE AND E. SAMPAIO 1990. Reactivity of phosphorus in Northern Brazilian soils assessed by isotopic dilution. Soil Sci. Soc. Am. J. 55:140-145.

SEN TRAN, R., J.C. FARDEAU AND M. GIROUX 1988. Effect of soil properties on plant available phosphorus determined by isotopic dilution phosphorus-32 method. Soil Sci. Soc. Am. J. 52: 1383-1390.

SMITH, T. AND P. SANCHEZ 1982. Phosphaterockdissolution and availabilityin Cerrado soils as affected by phosphorus sorption capacity.Soil Sci. Soc. Am. J. 46: 339-345.

SOIL SURVEY STAFF, 1992. Keys to Soil Taxonomy. 5th edition, SMSS. Technical Monograph No. 19. Blacksburg, Virginia. Pocahontas Press Inc. 556 pp.

VANDERDEELEN, J. , I. PINO AND L. BAERT. 1973. Kinetic of phosphate adsorption in a soil derived from volcanic ash. Turrialba 23(3):291-296.

WARREN, G.P. 1990. Understanding P availability in tropical soils by the use of sorption parameters for P-32. *In* Trans. l4th Int. Cong. Soil Sci. , Kyoto, Japan, Vol.IV, 104-109.

ZAPATA, F. 1990. Isotope techniques in soil fertility and plant nutrition studies. *In* Hardarson, G., (Ed) Use of Nuclear Techniques in Studies of Soil-Plant Relationships. Training Course Series No.2, IAEA, Vienna, 109-127.

ZAPATA, F. AND H. AXMANN 1991. Agronomic evaluation test of phosphate rock materials by means of radioisotope techniques. Pédologie XLI-3:291-301.

CHARACTERIZATION OF SOIL WATER STATUS USING NUCLEAR METHODOLOGY

Caracterización del Estado de Agua en el Suelo Empleando Metodologías Nucleares

P. L. Libardi and K. Reichardt

Department of Physics and Meteorology, ESALQ, University of São Paulo, C. P. 9, 13.418-970, Piracicaba, SP, Brazil.

Palabras claves: **Balance hídrico, Rayos gama, Sonda de neutrones, Tensiometros.**

Index words: **Gamma bean,Neutron probes, Tensiometers, Water balance.**

RESUMEN

La caracterización del "status" hídrico en eco-agrosistemas es de gran importancia para lograr un manejo sustentable de los mismos. Las tecnologías para monitorear el agua del suelo han mejorado considerablemente en las ultimas décadas. Entre estas tecnologías, las basadas en procesos nucleares juegan un papel importante, debido principalmente a la propiedad de penetrar en el material bajo estudio sin causar interferencia importante.

En ésta contribución, se discute el uso de sondas de neutrones y de rayos gamma para la determinación de la propiedad del suelo de retener y transmitir agua, y lograr establecer balances hídricos del suelo, y para la caracterización de las partículas del suelo y su arreglo como un medio poroso. Esto se hace principalmente analizando la investigación llevada a cabo en Latinoamérica.

INTRODUCTION

The characterization of soil water status in eco-agrosystems is of prime importance for their sustainable management. The technologies to monitor soil water have improved considerably in the last decades and, as a result, we have today methods and tools capable to characterize precisely and accurately soil physical parameters related to the water status in the soil. Among these technologies the ones based on nuclear processes play an important role, due mainly to the property of penetrating into matter with minor interference in the medium under study. The neutron moderation and the gamma-attenuation processes permit, today, efficient, non-destructive and time saving estimation of soil water contents and other properties. Neutron moisture gauges and laboratory gamma beams are now considered reliable instruments (Nielse and Cassel, 1984), used routinely for research and practical investigations in agriculture and related disciplines. As can be seen in a series of papers from IAEA (IAEA, 1974; 1979; 1983) research on soil-water-plant relations relies heavily on these methodologies.

It is the pourpose of this symposium paper to discuss the use of neutron probes and of gamma beams, for the assessment of soil water retention and transmission properties, for the establishment of soil water balances, and for the characterization of soil particles and their arrangement as a porous medium. This is done, mainly, citing research work carried out in Latin America.

Soil water retention and transmission properties.

Neutron probes in combination with tensiometers are extensively used to characterize soils, field plots and extensive areas through soil water retention curves $\varnothing_m = \varnothing_m(\theta)$ and hydraulic conductivity $K = K(\theta)$ functions. Buckingham-Darcy's equation for soil water flux density (q) in a rigid, non saturated porous material, can be written as

$$\vec{\mathbf{q}} = -\mathbf{K}(\theta)\left[\frac{\partial\Phi_m(\theta)}{\partial z} + \frac{\partial\Phi_z}{\partial z}\right]\hat{k} \qquad (1)$$

where Φ_m is the soil water pressure head (or matric soil water potential); θ the volumetric soil water content; Φ_z the gravitational pressure head (or gravitational soil water potential); z the vertical position coordinate; and k the unit vertical direction vector. Considering a medium in which $\Phi_m(\theta)$ is unique, the term $\partial\Phi_m(\theta)/\partial_z$ of equation (1) can be extended through the chain rule, to obtain

$$\vec{\mathbf{q}} = -\mathbf{K}(\theta)\left[\frac{d\Phi_m(\theta)}{d\theta}\frac{\partial\Phi_z}{\partial z} + \frac{\partial\Phi_z}{\partial z}\right]\hat{k} \qquad (2)$$

or

$$\vec{q} = -\left[D(\theta)\frac{\partial \Phi}{\partial z} + K(\theta)\frac{\partial \Phi z}{\partial z} \right] \hat{k} \tag{3}$$

where

$$D(\theta) = K(\theta)\frac{d\Phi m(\theta)}{d\theta} \tag{4}$$

D (θ) being the soil water diffusivity.

These three functions $\Phi_m(\theta)$, K(θ) and D(θ) are very important soil hydraulic properties, the first referring to retention and the two last to transmission of soil water.

There are few examples of field determination of $\Phi_m(\theta)$, using neutron probes and tensiometers. One of these studies Villagra *et al.* (1981) has shown that spatial variability plays an important role making it dificult to define useful representative average values.

For the case of K(θ), simple field methods Libardi *et al.* (1980) have been developed based only upon soil water content measurements obtained during the water redistribution process in a soil profile previously saturated, with the prevention of water evaporation at the soil surface. For this type of measurements, neutron probes are extremely suitable, due to the possibility of measuring θ at exactly the same points, over long periods of time.

In the case of soil water diffusivity, a new equation was developed Reichardt and Libardi, (1973) to estimate D(θ) based on the concept of similar media (Miller and Mieller, 1956) and using a simple "scaling" technique (Reichardt *et al.*, 1972). The experimental procedure of this method is very much facilitaded when using the gamma attenuation technique to obtain soil water profiles. This method led to the development of an equation to estimate K(θ), published one year later (Reichardt *et al.*, 1975).

Soil water balance studies.

Examples of water balance studies are numerous in the literature. Here some of these studies are pointed out, which allowed to estimate fertilizer leaching in the soil profile.

The knowledge of soil water dynamics during a crop cycle gives essential elements for the establishment and refinement of management practices which aim productivity maximization.

Water is a fundamental factor in crop growth, affecting mainly root development, absorption and transfer of nutrients to plants. Its dynamics is traditionaly studied through water balances, mainly based on information obtained in the atmosphere, leaving to a second priority soil information. Studies of water dynamics that emphasize soil water fluxes at the root zone are less frequent, in many cases incomplete due to the great complexity of the required experimental procedures. In one example in which fluxes below root zone are measured Reichardt *et al.* (1979a) the water balance of a corn crop growing on a medium textured latosol was studied. During the 97 days of the crop cycle, drainage below root zone reached about 50 % of all losses, indicating the importance of these fluxes in this type of soil, which may imply in significant fertilizer leaching.

The importance of nitrogen in agrosystems is well known, mainly in soils located in humid tropical regions, in which the mobility of N, its high mineralization rate and the high cost of fertilizres play a great role. Therefore, fertilizer use became limited, demanding a deeper knowledge of the processes and interactions that occur in the soil-water-plant system.

Studies related to N movement, availability, absorption and losses are many times limited by the difficulty of distinguishing applied N from native N. Today, the most precise methods to study the behaviour of applied N, use ^{15}N labeled fertilizers (Broadbent and Carlton, 1978; Hera, 1979).

To quantily N leaching losses below root zone it is necessary to know soil water flux densities and N concentration in soil solution. With this objective, the group of the Soil Physics Section at CENA, USP, developed several experiments in which leaching losses of N were quantified (Reichardt *et al.*, 1982). Results are summarized in Table 1.

Table 1. Leaching losses of N at the 120 cm depth, in soils of the region of Piracicaba, SP.

Authors	Soil	Crop	Period (Days)	Fertilizer rate (kg N/ha)	Total leaching N (kg N/ha)	Fertilizer leaching (kg N/ha)	Rainfall (mm)
[Libardi and Reichardt, 1978]	Alfisol	beans	120	120	6,7	-	661
[Moirelles et al. 1980]	Alfisol	beans	365	100	15,0	1,4	1382
[Araujo-Silva, 1982]	Alfisol	corn	150	100	32,4	11,0	620
[Reichardt et al. 1979b]	Oxisol	corn	130	80	9,2	0,4	717
[Urquiaga, 1982]	Alfisol	beans	86	42	-	0,8	403
Mean				88,4	15,8	3,4	757

Using average values which certainly present several limitations, it can be verified that for application rates of the order of 90 kgN/ha^{-1} , only 4.5 g of fertilizer N are lost by leaching, per hectare and per mm of rain. This indicates that such fertilizer rates showld not cause ground water contamination problems. In these studies, N leaching fluxes (q_N) were estimated from

$$q_N = q.C_N \qquad (5)$$

where C_N is the concentration of N in soil solution, considered only as NO^-_3, which is the most mobile N form in soils. Soil solution was extracted with ceramic porous cups (Reichardt *et al.*, 1977).

Recently, a study Libardi (1984) was developed in a sequence of four crops (beans, corn, beans, corn), concluding (i) the failure to measure some components of the nitrogen cycle might lead to erroneous conclusions due to the variability of the system; (ii) the leaching and gaseous fertilizer N losses were negligible; (iii) the measurement of ^{15}N concentration in only one convenient part or organ of the plant is sufficient to estimate fertilizer N in the whole plant; (iv) although applying 42 $kgN.ha^{-1}$ as ^{15}N enriched anunonium sulphate, at the end of the crop cycle, calculations recovered more than 100%, i.e. 77,26 ± 5,36 $kg.ha^{-1}$, what indicates the importance of spatial variability independently of analytical erros, even in small plots of 5x5 m.

This variability poses an enormous challenge to soil scientists in describing and predicting soil water phenomena occuring under field conditions. Although having been widely recognized since the beginning of this century, Viera *et al.* (1981); Warrick and Nielsen (1980), it continues to focus the attention of researchers, mainly due to the fact that in recent years soil properties and processes are being more intensively studied in the field. More recently the difficulties of measuring soil water fluxes, due to soil spatial variabiliy have been studied Reichardt *et al.* (1993) in connection with the use of Darcy-Buckingham's equation. Working with an oxisol at Piracicaba (SP) Brazil these authors (Reichardt *et al.*, 1993) established water balances at 25 (5x5 m^2) experimental plots, distributed along a 125 m linear transect. An analysis of the experimental shows the convenience of using neutron probes to estimate soil water contents θ, mainly because one can be sure that measurements made at different times are, in fact, performed at the same location and, as a consequence, it is possible to analise the contribution of soil spatial variability to the total variance of θ. One point, difficult to improve, still remains: seldomly θ measurements can be obtained with errors lower than 2% and such errors play an important role when estimating K values from K(θ) relations. Hydraulic conductivity values may vary some orders of magnitude for these small variations in θ. For sure, efforts have to be spent to improve θ measurements, mainly with neutron probes. It has been shown that in wet periods, 27 neutron probe access tubes would be needed to estimate a new θ mean, within 1% of acceptable error, at a probability level of 95%. In dry periods this number trippled, being 92 access tubes, which is much over the 25 used, and which is prohibitive. Therefore, the efforts to improve θ measurements with neutron probes should focus calibration aspects.

Soil particle distributions.

The use of gamma-ray attenuation to study soil particles and water started in the fifties, and a comprehensive revision has been presented (Ferraz and Mansel, 1979). Monoenergetic beams were replaced by double beams in order to measure simultaneously soil water contents and bulk densities. One shortcomming which still remains is the path length of the radiation beam within the sample, which is difficult to be measured in oddshaped samples, and which might introduce significant errors in the measurements. The most recent improvement in these aspects is the use of computed tomography (Crestana *et al.*, 1985). This new technology can be used on any shaped sample, and starts to be used in field diagnosis (Vaz *et al.*, 1989).

Another new development is the use of gamma attenuation to study soil particle distributions (Vaz *et al.*, 1992). The advantage of not interfering with the sedimentation process gives to this method a high credibility and permits a more generalized analysis of Stocke's law. It has been shown recently Martins de Oliviera *et al.* (1994) that moving the samples under sedimentation, measurement time is reduced about ten times, and that automation of the method becomes very practical, making it much more attractive for routine soil analysis.

CONCLUSION

Although nuclear methodologies need further refinement for many special uses, they have significantly contributed for the knowledge of the soil-plant-atmosphere system. The main reason for that is the possibility of negligible interference in the system under study.

LITERATURE CITED

ARAUJO SILVA, J.C. 1982.Movimento e perdas por lixiviacão de nitrogênio-CO('sNH_2)$_2$ em um Alfisol cultivado com milho (*Zea mays* L.). Piracicaba, ESALQ/USP, 71 p. (M.Sc. dissertation).

BROADBENT, F.E. AND A.B. CARLTON. 1978. Field trials with isotopically labelled nitrogen fertilizer. In: Nielsen, D.R. and MacDonald, J.G. (Eds.). Nitrogen in the environment. New York, Academic Press, 1: 1-41.

CRESTANA, S., S. MASCARENHAS AND R.S. POZZI-MUCCELLY. 1985. Static and dynamic three-dimensional studies of water in soil using computed tomography scanning. Soil Sci. Baltimore, 140, 326-332.

FERRAZ, E.S.B. AND R.S. MANSEL. 1979. Determining water content and bulk density of soil by gamma-ray attenuation methods. University of Florida, Gainsville, Bulletin 807 (Technical). 5l pp.

HERA, C. 1979. Some aspects of nitrogen fertilization using ^{15}N. In: IAEA. Isotopes and radiation in research on soil-plant relationship. Vienna. p. 107-123.

IAEA (1974). Isotope and radiation techniques in soil physics and irrigation studies. Procedings of a Symposium, Vienna, 1-50 October, 1973. 516 pp.

IAEA (1979). Isotope and radiation in research on soil-plant relationships. Procedings of a Symposium, Colombo, 11-15 December, 1978. 660 pp.

IAEA (1983). Isotope and radiation techniques in soil physics and irrigation studies.Procedings of a Symposium, Aix-en-Provence, 18-22 April, 1983. 596 pp.

LIBARDI, P.L. AND K. REICHARDT. 1978. Destino da ureia aplicada a um solo tropical. R. Bras. Ci. Solo. Campinas, 2: 40-44.

LIBARDI, P.L. 1984. Balanso de nitrogenio em culturas agrícolas e desvios encontrados na sua quantificacão. Piracicaba, ESALQ/USP, 113 p. (Associate Professor Thesis).

LIBARDI, P.L., K. REICHARDT., D.R. NIELSEN. AND J.W BIGGAR., 1980. Simple field methods for estimating soil hydraulic conductivity. S. Sci. Soc. Am. J., Madison, 44: 3-7.

MARTINS DE OLIVEIRA, J.C., C.M.P. VAZ AND K. REICHARDT. 1994. Improvement of soil mechanical analysis through gamma-ray attenuation. Submitted to S.S.S.A.J., Madison.

MEIRELLES, N.M.F., P.L. LIBARDI AND K. REICHARDT. 1980. Absorscão e lixiviacão de nitrogenio em cultura de feijão (*Phaseolus vulgaris* L.). R. Bras. Ci. Solo. Campinas, 4: 83-88.

MILLER, E.E. AND R.D. MILLER. 1956. Physical theory for capillary flow phenomena. Jour Appl. Phys. 27: 324-332.

NIELSEN, D.R. AND D.K., CASSEL. 1984. Soil water management. In: M.F. L'Annunziatta and J.C. Legg (ed.) Isotopes and Radiation in Agricultural Science. Vol. 1. Soil-Plant-Water Relationships.Academic Press, N.Y., 292 p.

REICHARDT, K.; P.L. LIBARDI AND S.S. URIQUIAGA C. 1982. The fate of fertilizer nitrogen in soil-plant systems with emphasis on the tropics. International Symposium on"Agrochemicals: Fate in Food and the Environment Using Isotope Techniques". IAEA-SM.263/36.

REICHARDT, K., D.R. NIELSEN AND J.W. BIGGAR. 1972. Scaling of horizontal infiltration into homogeneous soils. Soil Sci. Soc. Am. Proc. 36: 241.

REICHARDT, K., O.O.S. BACCHI, M.M. VILLAGRA, A.L. TURATTI AND Z. PEDROSA. 1993. Hydraulic variability in space and time in a dark red latosol of the tropics. Geoderma, Amsterdam, 5: 832-838.

REICHARDT, K., P.L. LIBARDI, N.M.F MEIRELLES, F.F. FERREYRA H., ZAGATTO, E.A.G., E. MATSUI. 1977. Extracão e análise de nitratos em solucão do solo. R. Bras. Ci. Solo. Campinas, 1: 130-132.

REICHARDT, K., P.L. LIBARDI, R.L. VICTORIA AND G.P. VIEGAS. 1979. Dinmica do nitrogênio num solo cultivado com milho. R. Bras. Ci. Solo. Campinas, 3: 17-20.

REICHARDT, K. AND P.L. LIBARDI. 1973. A new equation for the estimation of soil-water diffusivity. In: Isotope and Radiation Techniques in Soil Physics and Irrigation Studies. IAEA - Vienna p.45-51.

REICHARDT, K., P.L. LIBARDI. AND D.R. NIELSEN. 1975. Unsaturated hydraulic conductivity by a scaling technique. Soil Science, Baltimore, 120(3) : 165-168.

REICHARDT, K., P.L. LIBARDI.., L.C.U. SAUNDERS. AND A. CADIMA. 1979. Dinamica da água em solo cultivado com milho. R. bras. Ci. Solo, Campinas, 3: 1-5.

URQUIAGA, C. , S.S. 1982. Dinãmica do nitrogênio no sistema solo-planta na cultura de feijão (*Phaseolus vulgaris* L.) cultivar carioca. Piracicaba, ESALQ/USP, 154 p. (Ph. D. thesis).

VAZ, C.M.P., S. CRESTANA, S. MASCARENHAS, P.E. CRUVINEL, K. REICHARDT AND R. STOLF. 1989. Using a computed tomography miniscanner for studying tillage induced soil compaction. Soil Technology, Cremlingen, 2, 313-321.

VAZ, C.M.P., J.C.M. OLIVEIRA, K. REICHARDT, S. CRESTANA, P.E. CRUVINEL AND O.O.S. BACCHI. 1992. Soil mechanical analysis through gamma-ray attenuation. Soil Technology, Cremlingen, 5, 319-325.

VIEIRA, S.R., D.R. NIELSEN AND J.W. BIGGAR. 1981. Spatial variability of field-measured infiltration rate. Soil Sci. Soc. Am. J. , Madison, 45: 1040-1046.

VILLAGRA, M.M., O.M, MATSUMOTO, O.O.S. BACCHI, S.O. MORAES, P.L. LIBARDI AND K. REICHARDT. 1988. Tensiometria e variabilidade espacial em terra roxa estruturada. R. bras. Ci. Solo, Campinas, 12: 205-210.

WARRICK, A.W. AND D.R. NIELSEN. 1980. Spatial variability of soil physical properties in the field. In: D.Hillel (Ed.), Applications of Soil Physics. Academic Press, N.Y. 385pp.

FIELD MEASUREMENT OF WATER AND NITROGEN LOSSES UNDER IRRIGATED MAIZE BY THE COMBINED USE OF NEUTRON MOISTURE METER, TENSIOMETERS AND ^{15}N LABELLED FERTILIZER

Medición en Campo de las Pérdidas de Agua y Nitrógeno en Maíz Irrigado por el Uso Combinado de Sonda de Neutrones, Tensiómetros y Fertilizante Marcado con ^{15}N

L. Kengni, G. Vachaud , J. L. Thony, R. Laty[1], B. Garino[2] and S. Recous[3].

[1]Laboratoire d'étude des Transferts en Hydrologie et Environment (INPG, UJF, CNRS URA 1512), BP 53 X, F- 38041 Grenoble

[2]Lycée Agricole, F-38260 La Cóte Saint-André

[3]INRA, Station d'Agronomie, BP 101,F-01000 LAON Cedex

Palabras clave: **Absorción, Balance hídrico, Consumo de Agua, Drenaje, Lixiviación, Maíz, Mineralización, Nitrogeno-15, Sonda de neutrones, Tensiómetros.**

Index words: **Corn, N-15, Drainage, Leaching, Mineralization, Neutron moisture, Tensiometers, Uptake, Water balance.**

RESUMEN

Se estableció un experimento multidiciplinario y a largo plazo en el sitio de "La Cote-Saint-Andre", cerca a Grenoble (Francia). El objetivo principal fue determinar un esquema de aplicación óptima de fertilizante en un sistema de agricultura intensiva con el doble propósito de mantener la calidad del ambiente y mantener un nivel sustentable en la producción del cultivo. Este estudio está explícitamente relacionado al cultivo de maíz irrigado, principal cultivo en el área. Los diferentes conceptos en el balance hídrico (consumo, drenaje, almacenamiento en suelo) y del ciclo de nitrógeno (mineralización, toma por el cultivo, lixiviación) fueron obtenidos a través de un monitoreo intensivo en la capa superficial del suelo (0.8 m, correspondiente a la zona radical del cultivo) con el uso combinado de una sonda de neutrones, tensiómetros y medidores de la succión del suelo.

Para determinar el uso específico del fertilizante, una sub-parcela fue fertilizada con 260 kg N/ha de $^{15}NH^{+}_{4}$ - $^{15}NO_{3}$ (exceso isotópico promedio, 1. 2788 átomos % de ^{15}N). Haciendo uso combinado de la extracción de la solución del suelo, y mediciones del contenido de agua del suelo semanalmente, fue posible obtener la dinámica y el balance de agua y fertilizante en la capa de suelo correspondiente a la zona de la raíz, a lo largo del ciclo de cultivo.

Los resultados han mostrado que, en términos de balance hídrico, la irrigación es muy eficiente, ya que las pérdidas en drenaje (y nitrógeno) en el cultivo son insignificantes durante el ciclo del cultivo.

La situación es totalmente diferente durante el período entre cultivos (Octubre-Abril), cuando el suelo es mantenido desnudo y la evaporación es muy reducida. Bajo estas condiciones, el drenaje corresponde a cerca del 90 % del total de entradas por precipitación, y la lixiviación de nitratos a cerca de 155 kg-N/ha, de los cuales 28 % se originaron a partir de fertilizantes. Finalmente, el método de estimar el balance de N ha sido revalidado satisfactoriamente a través de una comparación entre toma de N medida por un análisis directo en la planta completa y el valor estimado por las variaciones temporales de N en el suelo. Los dos valores de toma de N fueron 300 vs. 288 kg - N/ha respectivamente, 65 % de los cuales se originaron en fertilizantes nitrogenados.

SUMMARY

An intensive multiyear and multidisciplinay experiment has been set up at the site of La Cóte Saint-Andre, close to Grenoble (France). The major objective was to determine an optimal fertilizer application scheme in an intensive agricultural system with the dual goal of maintaining the quality of the environment while maintaining a sustainable level of crop production. This study is explicitly related to the cultivation of irrigated maize, a major crop production in the area. The different terms of the water balance (consumption, drainage, soil storage) and of the nitrogen cycle (mineralization, plant uptake, leaching) have been obtained from an intensive monitoring in the upper layer of the soil (0.8 m, corresponding to the root zone of the crop) with the combined use of a neutron moisture meter, tensiometers and soil suction cups. To determine the specific fertilizer use, one subplot was fertilized with 260 kg-N/ha of $^{15}NH^{+}_{4}$ - $^{15}NO^{-}_{3}$ (mean isotopic excess, 1.2788 atom % of ^{15}N). With the combined use of soil solution extraction and soil water measurement, it has been possible to obtain on a weekly basis the dynamics and the mass balance of water and fertilizer in the root zone layer during the whole crop cycle.

The results have shown that, in terms of the water balance, irrigation is extremely efficient, since drainage (and nitrogen) losses under the culture are negligible during the crop cycle. The situation is totally different during the intercrop period (October - April), when the soil is maintained bare and evaporation is very small. Now, drainage corresponds to about 90 % of total inputs from precipitation, and the nitrate leaching to about 155 kg-N/ha of which 28 % originated from the fertilizer. Finally the method of estimation of N balance has been successfully validated by a comparison between N uptake determined by direct analysis on the entire plant and the value estimated from the temporal variations of N in the soil. The two values of uptake were 300 versus 288 kg-N/ha respectively, 65 % originating from the fertilizer-N.

INTRODUCTION

Non-point source agricultural pollution of ground water has become a real threat to the environment over the last 30 years. Although subject to controversy, the relation between nitrate pollution and agricultural practices remains uncontested (Sébilotte, 1987). In Europe, studies have shown that only 50 to 70 % of the fertilizer is generally used by crops, the rest being volatilized, denitrified or leached (Guiraud, 1984). Leaching of nitrate is responsible for the ground water pollution. There is a need to determine optimal fertilization rate in such a way that the amount of N remaining in the soil after harvest, and potentially leachable during winter, will be minimized, without negative economic implications concerning the level of crop production.

^{15}N labelling is probably the only tool able to allow an evaluation of the major phenomena relative to the N cycle (Guiraud, 1984). Indeed, the selective labelling of the fertilizer N permits one to distinguish between the nitrogen derived from the soil, or that from the fertilizer. During the last decade, many studies have been conducted using this methodology; but up to now, the ^{15}N enrichment has only been determined on drainage water from lysimeters (Guiraud, 1984; Walters y Malzer, 1990), or on plants (Bigeriego *et al.*, 1979; Feigenbaum y Hadas, 1980; Francis *et al.*, 1993; Hahne *et al.*, 1990; Recous, 1988; Recous *et al.*, 1992; Varvel y Todd, 1992) or from soil samples (Bigeriego *et al.*, 1979; Broadbent *et al.*, 1980; Francis *et al.*, 1993; Norman *et al.*, 1990; Recous *et al.*, 1992). Weaknesses are the lack of representatitivity of lysimeters studies, and the lack of reproducibility in time, at the same location, for destructive sampling techiques. We have tried here to take advantage of a nondestructive and accurate measurement technique based on the simultaneous estimation of soil water balance, with the combined use of soil moisture neutron gauge and tensiometers and determination of the water flux with the use of Darcy's law, and of temporal changes in the isotopic ^{15}N dilution in the soil solution extracted from soil solution suction cups. Our aims were i) to determine the proportion of the fertilizer N that leaves the system through the drainage water during and after the growing season; ii) to assess the amount of fertilizer N taken up by crops.

Our contribution to the development of such a strategy has been done within the framework of a research programme initiated by the Commission of European Communities (DGXII-STEP) over a multiyear experiment during the period 1991-1994. The results which will be presented in this paper are related to the first year only, from April 1991 to February 1992. More detailed information has recently been reported (Kengni, 1993a; Kengni *et al.*, 1993b).

MATERIALS AND METHODS

The study was conducted on the Experimental Farm of La Cóte Saint-André, located 40 km northwest of Grenoble, France. The site is a typical glacial terrace, with approximately 1 m thick soil resting on a layer 10-20 m thick of gravels and pebbles of high permeability. The upper layer (0-30 cm), is a loamy sand, rich in organic matter (2 to 3 %). An important point is the increase, in % and size, of gravels and stones with increasing depth. As a result, the root zone is practically no deeper than 0.80 m, and augering is scarcely possible past 1 m.

The treatments.

In order to determine the amount of leaching (both water and nitrate) for conventional farmers' practices and to obtain information on the response of the crop to fertilization, different levels of treatment were applied. Two of them were instrumented for intensive measurements (Kengni *et al.*, 1993b): conventional fertilization rate in the region, 260 kg-N/ha of ammonium-nitrate, applied at sowing (April 22); or no fertilization. In the fertilized treatment, the four ^{15}N replicate microplots were 2 x 2.4 m. The $^{15}NH^{+}_{4}$ -$^{15}NO^{-}_{3}$ fertilizer was applied using a hand sprayer, with successive crossed applications. The microplots were sampled at harvest (October 8). The dry matter content of the aerial parts (cut immediately above the soil) was determined. Soil samples from the 0-10 and 10-30 cm layers were obtained by mixing nine separate cores taken from each microplot. Six cores

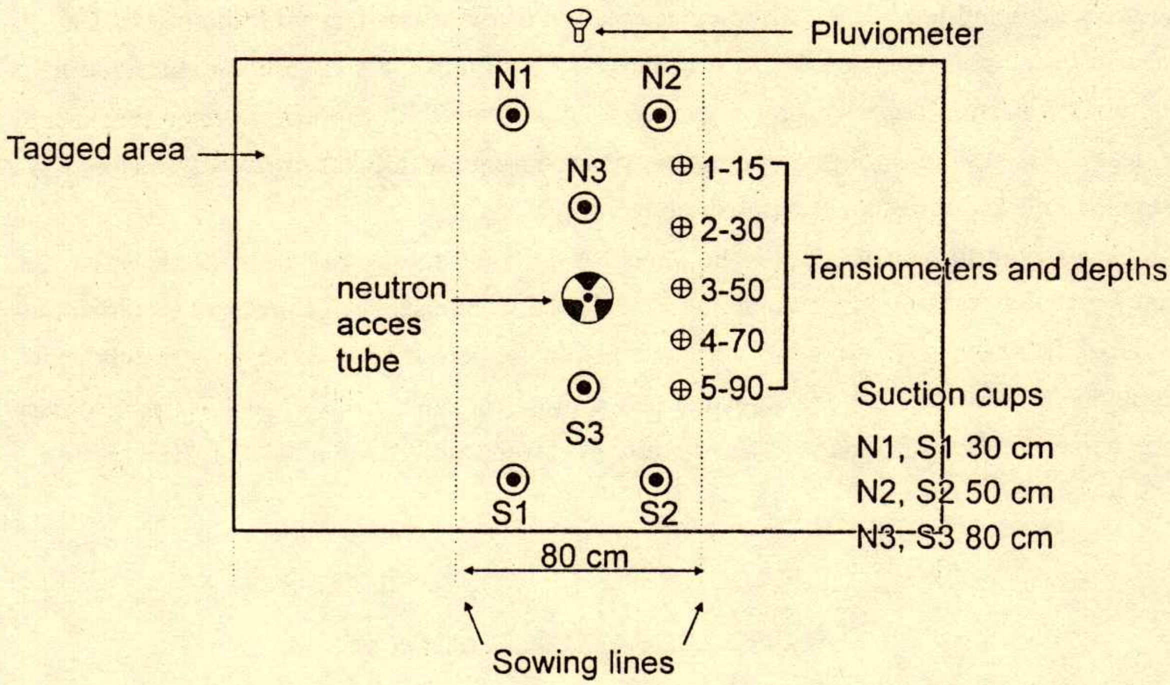


Figure 1: Experimental scheme, detail of the monitoring N-15 labelled site

were taken from the 30-60 and the 60-90 cm layers. The above ground parts and roots (0-30 cm layer) were analyzed for dry matter, total N and ^{15}N. Soil inorganic N and organic C and ^{15}N were determined according to (Recous *et al.*, 1992). One of these microplots was fully instrumented, as described later, in order to obtain continuous measurements with the conventional methods.

Measurements.

Measurements involved the following equipment (Fig. 1) :

- one neutron access tube to allow soil water monitoring every 10 cm down to 90 cm,
- five mercury tensiometers installed vertically at 15, 30, 50, 70, 90 cm,
- six suction probes at 30, 50 and 80 cm depth, replicated in two series (northern and southern), in order to account for the variability of N-nitrate concentration and the ^{15}N enrichment in the soil solution, even at a short distance,
- one rainfall recorder, at the level of the canopy.

Measurements of soil moisture and soil solution were taken weekly from June to October, and then every two weeks until mid-February. Tensiometer readings were recorded daily from June to harvest, and then every week until the onset of frost. Rainfall/irrigation and micrometeorological data were obtained every 30 min with the use of a data acquisition system connected by modem to the laboratory.

The soil solution extracted from ceramic porous cups was immediately sterilized in-situ with the use of a 0.4 μm Millipore filter (MILLEX SLHV 025LS) and then deep-frozen. The samples were first analyzed by liquid chromatography, to obtain the nitrate concentration, then reduced by dehydration, and the isotope ratio determined by mass spectroscopy at the "Service Central d'Analyses-CNRS", Solaize-France. The unit of measure used here is the ^{15}N per cent enrichment compared to the standard :

$$E\,\% = \frac{^{15}N}{^{14}N + {}^{15}N} \times 100 - 0.3663 \qquad [1]$$

where 0.3663 is the reference standard in the air (Mariotti, 1982).

Agronomic measurements were made every two weeks on samples of the entire plant in order to assess total dry matter and total nitrogen uptake. Yield and grain analyses were also performed with the same objectives.

Determination of water balance.

The water balance was calculated from the mass conservation equation :

$$\Delta S = R - D - AET \qquad [2]$$

where ΔS is the change in water storage in the root zone, R the rainfall and irrigation amount, D the drainage at the depth z_r below the root zone, and AET the actual evapotranspiration during a given period of time Δt. Runoff was neglected, as this was practically nil on this particular field site. In this equation, rainfall or irrigation were measured with standard raingages, the change in water storage was obtained by the difference of water storage in the root zone (from 0 to 0.8 m) as measured by the neutron probe between two consecutive dates. The remaining unknown terms are then D and AET. For most of this work, the drainage component D was calculated from Datcy's Iaw :

$$D = q \cdot \Delta t = - K(\theta) - \mathrm{grad}H \cdot \Delta t \qquad [3]$$

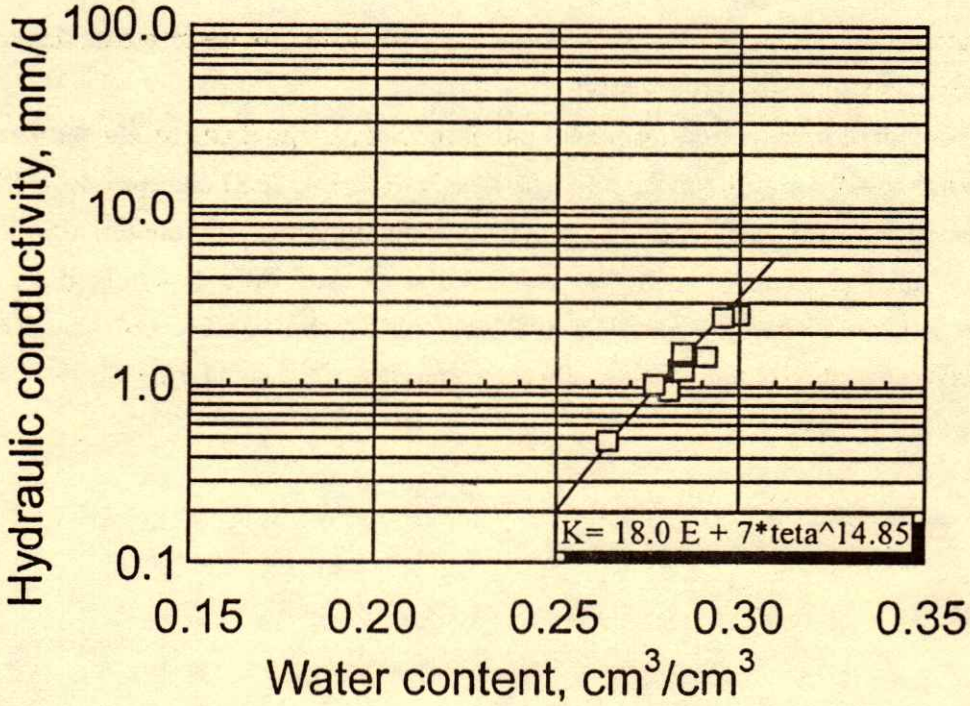


Figure 2: Relation between the hydraulic conductivity and the water content obtained in- situ

where q is the mean volumetric flux density (mm/day) during Δt, $K(\theta)$ is the hydraulic conductivity (mm/day) corresponding to the water content θ at z_r , and gradH is the hydraulic head gradient at this same depth. This method request that $K(\theta)$ be known. This relationship was determined through the use of the **"zero flux plane"** method described in detail by (Vachaud *et al.*, 1978). A typical result is given in Fig.2, the curve was fitted with a power law as was suggested by previous results (Vachaud *et al.*, 1991).

In order to increase the accuracy of estimation of drainage, because of the high sensitivity of K with θ, computations were done on a daily basis from June to September, following a method detailed in Kengni *et al.* (1993b).

Nitrogen movement and balance.

It was proved by different tests (Kengni, 1993a) that nitrogen was, in this experiment, essentially in the form of nitrate. The amount of N-nitrate in a soil layer was then calculated from the formula :

$$N = \frac{[NO^-_3] \times \theta_{\Delta z} \times \Delta z}{4.42} \qquad [4]$$

where $[NO^-_3]$ is the nitrate content inthe soil solution, $\theta_{\Delta z}$ then mean water content of the layer Δz and N the nitrogen amount expressed in quantity per area unit, and 4.42 is the molar ratio between NO^-_3 and N. It was assumed that the nitrate content of the soil solution extracted at 30 cm was representative for the 0-30 cm layer, and that at 50 cm for the 30-60 cm layer, and that at 80 cm for the 60-90 cm layer. From measurements of these depths, their summation gives the total amount of N-nitrate in the soil profile. Finally, the amount of nitrogen leaching below the root zone was obtained from the relation :

$$L_N = D \cdot C_{0.8} \qquad [5]$$

where **D** is the water drainage calculated previously at 0.8 m and $C_{0.8}$ the nitrate content at that depth. Obviously, this equation does not consider the effect of dispersion. It has been shown (Bigeriego *et al.*, 1979) that the dispersive term of the full transport equation represents at a maximum only 6 % of the value of the convective term. Finally in Eqs 4 and 5, the partitioning between N derived from fertilizer and total N, was done with the use of the per cent enrichement obtained for every soil layer :

$$N_E = \frac{N_T \times E}{E_0} \qquad [6]$$

where $\mathbf{N_E}$ is the mineral N from the fertilizer, N_T the total mineral N in the layer, **E** the ^{15}N enrichment in the same layer and E_0 the ^{15}N enrichment of the fertilizer. Then, the amount derived from the soil mineralization, $\mathbf{N_S}$, is obtained through the difference $\mathbf{N_S = N_T - N_E}$. In the same way,

$$L_E = \frac{L_N \times E}{E_0} \qquad [7]$$

L_E is the amount of fertilizer leached.

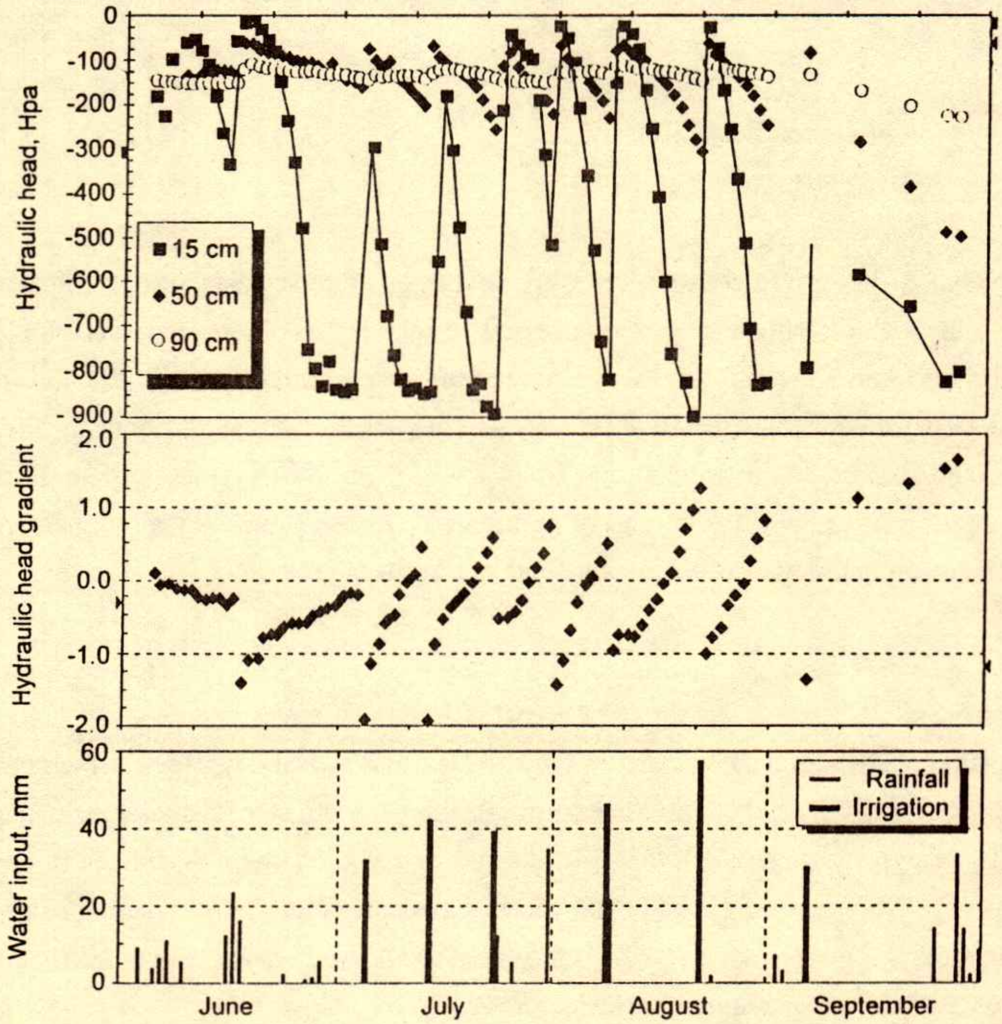


Figure 3: Daily tensiometers (at 15, 50 and 90 cm) and hydraulic head gradient (at 80 cm) responses

RESULTS AND DISCUSSION

Water balance.

The water input during the period of reference (April 1991 - February 1992) is reported in Table I.

This period is divided in three parts : from sowing (April 22) to the 6-leaf stage (June 22), and from then to harvest (October 4), and finally the intercrop season until February 12. Irrigation was applied with a sprinkler gun at an interval of approximately 10 days and occured only from mid June to September. The total amount of water input during the crop cycle was 563 mm, 238 mm of which was by irrigation in 6 applications.

A characteristic of this soil is a very quick response to water input, due to its sandy and rocky nature, as illustrated in Fig. 3 for three depths. Very clearly, the tensiometer at 90 cm responds to a water application on the same day. It is because of this dynamic behavior that it becomes necessary to establish the water balance with the use of Darcy's law on a daily basis, as discussed previously.

Cumulative drainage is reported on Fig. 4. It occured essentially either before emergence of the plant, or at the end of the cycle when physiological activity had stopped, or after harvest. During the active crop cycle, it is important to note that drainage losses are negligible. This is a good proof of the efficiency of irrigation. During the intercrop period, water losses are important however and amount to approximately 90 % of the rain. In terms of evapotranspiration, cumulative values amount to 490 mm with a distribution during the period of reference given on Fig.4. Results are summarized in Table 1 .

Table 1. Water (mm) and nitrogen (kg-N/ha) balances under the maize crop

	R/Irr	**ΔS**	**Dr**	**AET**	**Dn**	**Np**
Phase I	141.1	21.6	44.2	75.3	2.3 (0)	
Phase II	422.1	-18.4	25.3	415.2	4.3 (0.2)	**288 (169)**
PhaseIII	320.7	18.8	273.1	29.0	154.5 (43.5)	-
Total	**883.9**	**22.0**	**342.6**	**519.5**	**161.1 (43.7)**	-

[Phase I: from April 22 to June 19; Phase II: from June 19 to October 4; Phase III: from October 4 to February 12; R/Irr: rainfall, irrigation; ΔS: variation of the water storage; Dr: drainage at 80 cm; AET: actual evapotranspiration; Dn and Np respectively nitrogen leaching at 80 cm and plant N uptake (in parantheses, nitrogen from the fertilizer)]

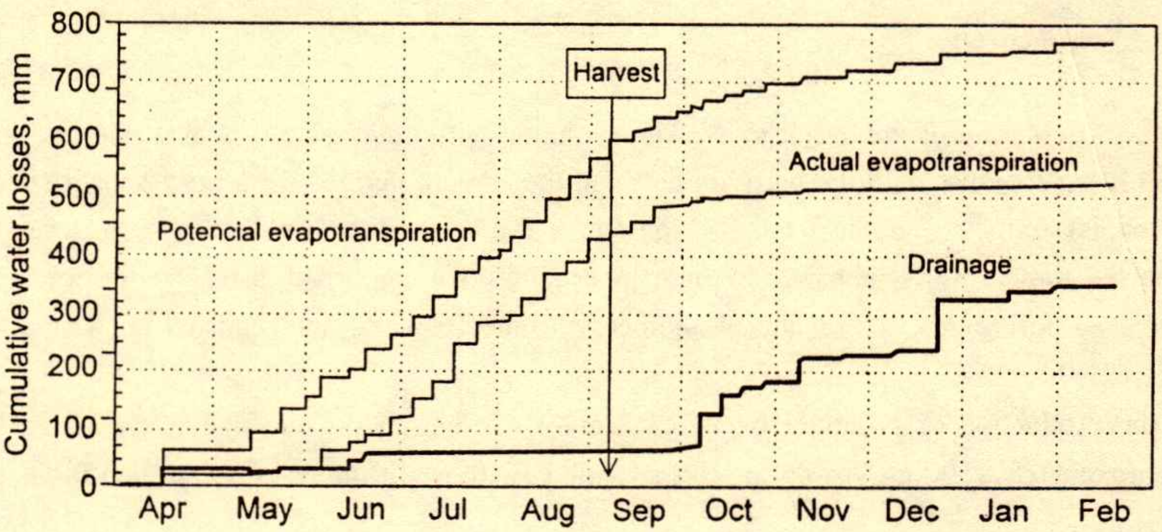


Figure 4: Cumulative drainage and evapotranspiration from April 16 to February 12

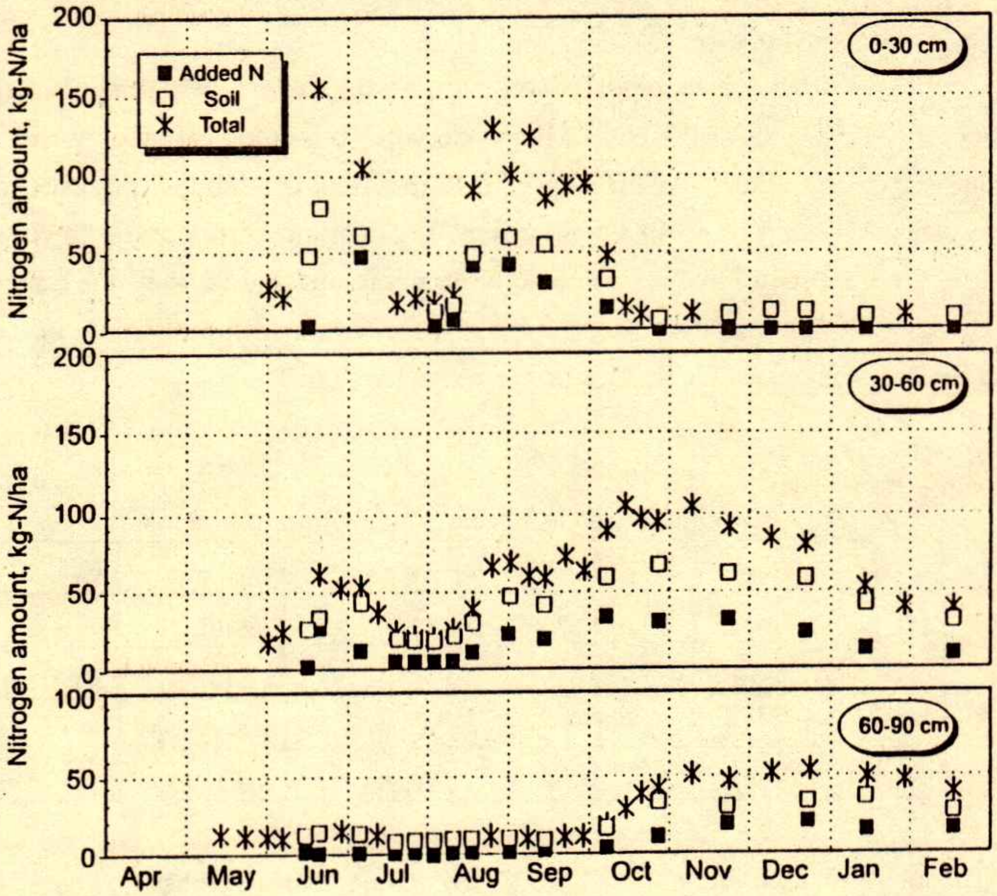


Figure 5: Evolution with time of N derived from the fertilizer, from the soil and the total N available per soil layer (Soil: mineralization; Added N: fertilizer input)

Fertilizer recovery.

Evolution of the fertilizer *-N.* The evolution with time of total N available in every soil layer, together with the partition between the amount derived from the fertilizer (filled symbols) and that derived from the soil (open symbols), is shown in Fig.5. In order to analyze these results, one has to take in account two important pieces of information obtained during this experiment on another instrumented sites, and reported in (Kengui *et al*., 1993) :

- the production of N-nitrate by mineralization of the soil organic matter amounted to approximately 150 kg-N/ha during this specific year (a result obtained on the non-fertilized sites).

Table 2. Evolution with time of the cumulative dry matter and nitrogen uptake by the maize crop [Source: Lycée Agricole]

	Dry matter (tons/ha)			Nitrogen uptake (kg/ha)		
Date	**leaves + stems**	**ear**	**total**	**leaves + stems**	**ear**	**total**
05- June	0.0		0.0	1.9		1.9
12-June	0.1		0.1	3.3		3.3
19-June	0.2		0.2	9.8		9.8
26-June	0.7		0.7	29.0		29.0
03-July	1.8		1.8	65.4		65.4
17-July	8.5		8.5	221.4		221.4
30-July	10.7		10.7	200.6		200.6
15-August	14.5	0.3	14.7	218.8	3.7	222.5
28-August	14.3	6.4	20.7	182.6	67.1	249.7
05-September	12.2	11.6	23.7	145.4	145.3	290.7
16-September	12.2	11.6	23.7	144.7	145.2	289.8
25-September	9.5	12.9	22.4	110.1	182.9	293.0

The plant nitrogen uptake on the fertilized sites (resulting from plant analysis done on a two weeks interval (Table 2) represented a maximum of 12 kg-N/day during the first two weeks of July.

Fig. 6 shows clearly that due to interactions between nitrogen transformations and plant uptake, the peak of total nitrogen available in the root zone was followed by a very fast decrease, such that at the end of the period of maximum plant uptake (mid July) the soil was almost totally depleted. In terms of the evolution of fertilizer (filled symbols), two characteristics points merit analysis :

i) for an input of 260 kg-N/ha, and a plant uptake of about 220 kg-N/ha from sowing to mid July (Table 2), the total amount of N fertilizer remaining in the soil in mid-July is almost nil. The deficit in the mass balance, at least 40 kg-N/ha, can only be explained by conversion of the fertilizer from mineral to organic form, and by gazeous losses.

ii) during a second mineralizing flush, between mid August and mid September, there is an increase of about 50 kg-N/ha of nitrogen fertilizer in the soil. This can be attributed to the mineralization of the previously-immobilized N fertilizer. This could also have been arising from decay of plant roots.

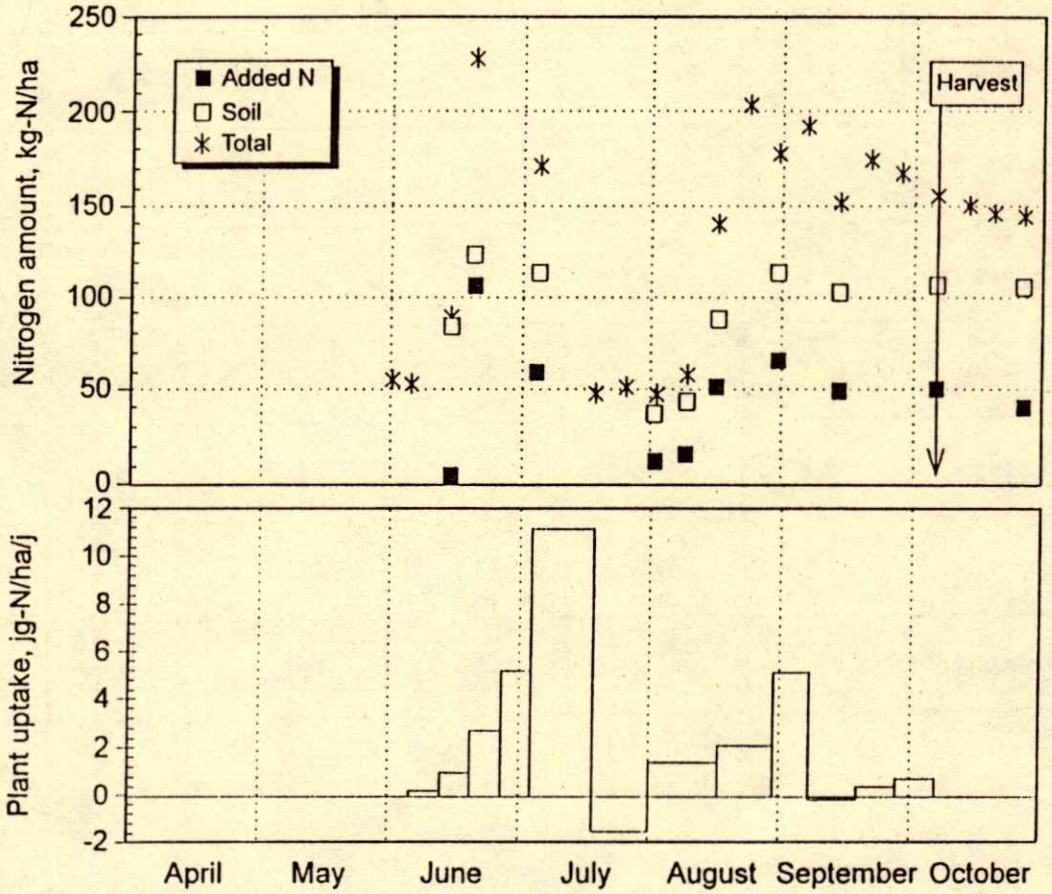


Figure 6: Relation between the total nitrogen amount available in the root zone [0-90 cm] as a function of its origin and the plant uptake (Sources: Lycée Agricole, AGPM, 1991)

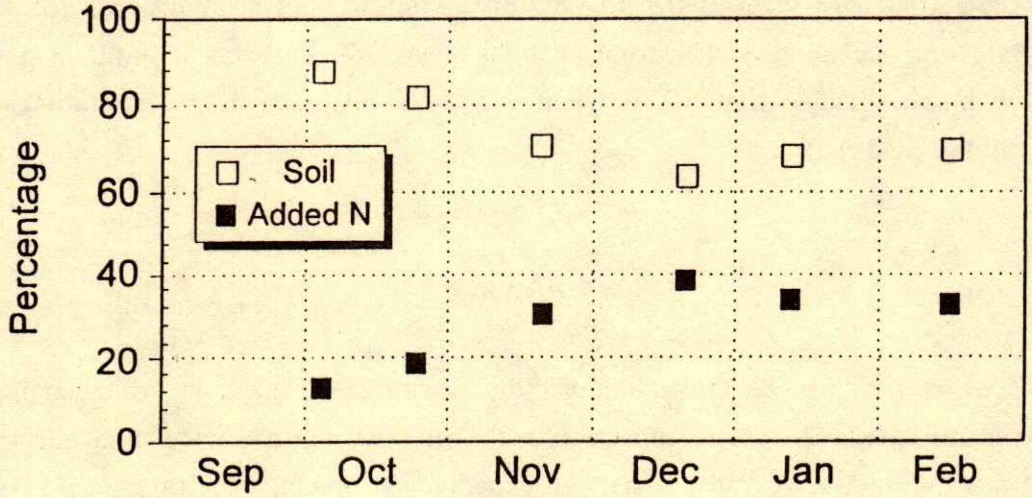


Figure 7. Partition between nitrogen from the fertilizer and nitrogen from the soil in the leached water during winter (Soil: mineralization; Added N: fertilizer input)

Nitrogen and fertilizer leaching. With the continuous monitoring of the isotopic ratio in the soil solution concentration at 80 cm, and the use of Darcy's law, it has been possible to estimate the amount of nitrogen from the fertilizer that is leached. During the crop cycle, leaching was almost nil, in logical agreement with the fact that drainage of water is negligible.

At harvest, the mineral N residue was 156 kg-N/ha of which 32 % is from the fertilizer N. Most of it was found in the layer 0-60 cm (see Fig.5). During the intercrop period, climatic conditions were favourable for nitrate leaching which amount to a total of 155 kg-N/ha as illustrated in Table 1 , with the partition between nitrate originated from the soil and from the fertilizer. It is therefore important to note the increasing proportion of the fertilizer contributing to the leaching after the harvest (Fig.7). Some 28 % of the leaching during the entire intercrop period originated from the fertilizer. This represented 17 % of the total input, which is proof that the traditional fertilization scheme is excessive.

Recovery of the fertilizer-N by plant. Finally, the fertilizer uptake was calculated as the amount of fertilizer N in the soil profile at sowing (260 kg-N/ha), and less the fertilizer nitrate remaining at harvest (50 kg-N/ha), and less the amount leached during the crop cycle (0), less any denitrification or immobilization. Because of the climatic conditions, denitrification was assumed to be negligible. The fertilizer-N immobilized into soil organic compounds amounted to 41 kg-N/ha at the end of the growing season. This value was obtained from nitrogen analysis (mineral and organic, including ^{15}N) on soil samples taken on this site just after harvest. Thus the estimate of the fertilizer plant uptake was 169 kg-N/ha i.e. 65 % of that applied. The total N uptake was 288 kg-N/ha, a result in good agreement with that obtained directly from plant analysis on plant samples taken on that site after harvest (300 kg-N/ha).

CONCLUSIONS

This experiment has demonstrated that the tensiometer - neutron probe method, coupled with utilisation of ceramic cups is suitable for assessing the water and nitrogen balance by field monitoring. Clearly, under the experimental conditions, irrigation was not responsible for pollution by nitrate leaching during the crop cycle. Conversely, it is clear that a misunderestimation of the potential mineralization of the soil, which in fact was not taken into account by farmers when choosing the N application rate, resulted in excessive N-nitrate residue in the root zone at harvest. This was responsible for important leaching during winter rains.

The use of ceramic porous cup samples for ^{15}N determination was satisfactory because :

- i) methodologically, the approach is convenient for characterizing the simultaneous evolution of the nitrogen from fertilizer, or from the soil in field conditions. Thus, sampling can be repeated during the growing season, without altering the water and (consequently) nitrate dynamics. Plant and soil sampling at regular intervals can do this.
- ii) the results are consistent. Hypotheses concerning the non participation of the fertilizer to leaching during the crop cycle were verified. However the total recovery in the plant is only 65 %. The residue at harvest, 50 kg-N/ha, i.e. 20 % of the input, remains essentially in the top layers of the soil. This confirms that the rate of application was excessive. Leaching occured during the intercrop period, so that by February, two-thirds of the 23 kg-N/ha fertilizer residue remaining in the soil had passed below 60 cm. Fertilizer N is about 28 % of the total N leached.

ACKNOWLEGMENTS

The authors wish to thank the farmer's association in collaboration with the Lycée Agricole for encouraging the study and furnishing data as soon as required, the Laboratoire d'Ecologie Microbienne Lyon 1 for providing nitrogen transformation data on soil samples, and the Service Central d'Analyse, CNRS Solaize for taking care of nitrates and ^{15}N analysis. They are also grateful to M. Richard H. Cuenca, Oregon State University, USA and Peter Ross, CSIRO, Australia, for heplful comments and advices.

Funds for this work were provided by the European Communitee through the STEP-DGXII program, by the Conseil Général de l'Isère and by the Chambre Régionale d'Agriculture Rhóne Alpes. A scholarship was kindly offered to the senior author by the Cameroon government and the Centre International des Etudiants et Stagiaires.

LITERATURE CITED

BIGERIEGO, M., R.D HAUCK AND R.A. OLSON. 1979. Uptake, translocation ant utilization of ^{15}N depleted fertilizer in irrigated corn. Soil Sci. Soc. Am. J. 43:528-533.

BROADBENT, F.E., R.S. RAUSCHKOLB, K.A. LEWIS AND G.Y. CHANG 1980. Spatial variability of nitrogen-15 and total nitrogen in some virgin and cultivated soils. Soil Sci. Soc. Am. J. 44:524-527.

FEIGENBAUM, S. AND A. HADAS. 1980. Utilization of fertilizer nitrogen-nitrogen-15 by field grown alfalfa. Soil Sci. Soc. Am. J. 44:1006-1010.

FRANCIS, D.D., J.W. DORAN AND R.D. LOHRY. 1993. Immobilization and uptake of nitrogen applied to corn as starter fertilizer. Soil Sci. Soc. Am. J. 57:1023-1026.

GUIRAUD, G. 1984. Contribution du marquage isotopique à l'évaluation des transferts d'azote entre les compartiments organiques et mineraux dans les systemes sol-plante.Univ. P. et M. Curie. These Doct. d'Etat-Es Sciences Naturelles.

HAHNE, H. C. H., W. KROONTJE AND J.A. LUTZ. 1977. Nitrate fertilization. I: Nitrate accumulation and losses under continuous corn cropping. Soil Sci. Soc. Am. J. 41:562-567.

KENGNI, L. 1993a. Measure *in-situ* des pertes d'eau et d'azote sous culture de mais irriguée : application à la plaine de la Bievre (Isere). Univ. Joseph Fourier Grenoble I, Grenoble.These Doct.

KENGNI, L., G. VACHAUD, J.L. THONY, R. LATY, R. VISCOGLIOSI AND CASABIANCA. 1993b. Field measurements of water and nitrogen losses under irrigated maize. (*Submitted for publication*)

MARIOTTI, A. 1982. Apport de la géochimie isotopique à la connaissance du cycle de l'azote. Univ. P. et M. Curie, These de doct.

NORMAN, R. J., J.T. GILMOUR AND B.R. WEILS. 1990. Mineralization of nitrogen from nitrogen-15 labelled crop residues and utilization by rice. Soil Sci. Soc. Am. J. 54:1351-1356.

OLSON, R.V. 1980. Fate of tagged nitrogen fertilizer applied to irrigated corn. Soil Sci. Soc. Am. J. 44: 514-517.

RECOUS, S. 1988. Dynamique de l'azote en sol cuitive: organisation microbienne des formes ammoniacale et nitrique, consequences sur l'utilisation de I'azote des engrais par une culture de ble. Univ CIaude Bernard - Lyon 1. These Doct.

RECOUS, S., J.M. MACHET AND B. MARY. 1992. The partitioning of fertilizer-N between soil and crop: comparison of ammonium and nitrate applications. Plant and soil 144:101-111.

SEBILOTTE, M. 1987. L´excès des nitrates dans les eaux: un problème à résoudre, une lutte engagée. Perspectives Agricoles, n° 115, pp 12-17.

VACHAUD, G., M. VAUCLIN AND R. LATY. 1991. Caractérisation hydrodynamique in-situ de quelques sols soudano-sahélien à l'aide d'un progranune assiste par ordinateur International Conf. on "Soil Water Balance in the Sudano-Sahélian Zone", Niamey, Niger IAHS Publi. 166 : 175-185

VACHAUD, G., C. DANCETTE, M. SONKO AND J.L. THONY. 1978. Méthodes de caractérisation hydrodynamique in-situ d'un sol non saturé. Application à deux types de sol du Senegal en vue de Ia determination des termes du bilan hydrique. Ann. Agronomiques, 29: 1-36

VARVEL, G. E. AND A.P. TODD. I992. Nitrogen fertilizer recovery by soybean in monoculture and rotation systems. Agron. J. 84: 215-218.

WALTERS, D. T., G.L. MALZER. 1990. Nitrogen management and nitrification effects on nitrogen-15 urea: I. yield and fertilizer use efficiency. Soil Sci. Soc. Am. J. 54:115-122.

CROP PRODUCTION IN DELETERIOUS SOILS WITH SPECIAL EMPHASIS ON ACID SOILS

Producción de Cultivos en Suelos Deletereos con Enfasis en Suelos Acidos

S. Urquiaga, and R. M. Boddey.

EMBRAPA, Centro Nacional de Pesquisa de Agrobiologia, Itaguai, 23851-970, Rio de Janeiro, Brazil.

Palabras clave: **Aluminio, Cal, Fósforo, Materia orgánica, Metales pesados, Nitrógeno -15, Suelos ácidos, Yeso,**

Index words: **Acid soils, Aluminum, Heavy metals, Gypsum, Lime, ^{15}N, Organic matter, Phosphorus.**

RESUMEN

Algunas propiedades del suelo pueden causar pérdidas importantes en la producción de cultivos. Debido a la magnitud de las áreas afectadas, los factores detrimentales más importantes son: acidez del suelo (asociada principalmente con toxicidad de aluminio), salinidad y contaminación por metales pesados. Esta última es de creciente importancia conforme el hombre aumenta su impacto en el medio ambiente.

Con referencia a los suelos ácidos del trópico, especialmente aquellos con problemas de aluminio (Oxisoles, Ultisoles y algunos Andosoles), prácticas de manejo eficiente (encalado y/o adiciones de yeso) se han desarrollado de tal manera que hoy la toxidez por aluminio no es ya un problema insoluble. Desafortunadamente, éstas técnicas están siendo ampliamente aplicadas solo en los Estados Unidos de Norteamérica, Brasil y Sudamérica, y muy infrecuentemente en el resto del mundo.

El control de la alta acidez en el subsuelo promueve un enraizamiento más profundo de los cultivos permitiendo así que las plantas recuperen más de los nutrientes lixiviados hacia abajo de la capa arable. Cierta evidencia se ha obtenido al respecto a través de experimentos con ^{15}N. Escasa atención se ha dado al efecto de la materia orgánica en el control de la acidez del suelo y no hay dudas sobre los efectos positivos de los abonos verdes en la disminución de la actividad de Al y otros elementos tóxicos en suelos ácidos. En

estos estudios las técnicas isotópicas serían de gran ayuda para entender estos procesos. En el caso de la contaminación por metales pesados, aunque hay situaciones donde la contaminación ha causado disminuciones en la producción de cultivos debido a efectos tóxicos directos, el fenómeno es más serio en términos de los efectos en la salud humana y el medio ambiente.

Los procesos microbianos en el suelo parecen ser más susceptibles a la intoxicación por metales pesados. Aquí existen ejemplos de efectos sobre nitrificación, fijación de N_2 por microorganismos de vida libre, y la sobrevivencia de cepas efectivas de *Rhizobium*.

Esta observación puede permitir la identificación de parámetros microbianos que indiquen contaminación del suelo por metales pesados. Por otro lado, el fitomejoramiento representa un buen prospecto para atenuar estos problemas. Las técnicas nucleares, las cuales hasta ahora, han sido poco explotadas, pueden ser muy útiles en la investigación de los efectos nocivos de los fenómenos mencionados.

SUMMARY

Some soil properties can cause significant losses in crop production. Because of the extent of the areas affected, the most important detrimental factors are: soil acidity (associated principally with aluminium toxicity), salinity, and heavy metal pollution. This last is of increasing importance as man increases his impact on the environment. With reference to acid soils of the tropics, especially those with aluminium problems (Oxisols, Ultisols and some Andisols), efficient management practices (liming and/or gypsum addition) have been developed such that today Al toxicity is no longer an insoluble problem. Unfortunately, these techniques are only being widely applied in the USA, Brazil and South Africa, and very infrequently in the rest of the World. The control of strong acidity in the sub-soil can be of tremendous benefit in terms of increasing the fertility of highly weathered soils of the tropics specially those subject to dry periods during the cropping season. The control of acidity of the subsoil promotes deeper rooting of crops enabling plants to recover more of the nutrients leached down from the ploughed layer. Some evidence for this has been obtained from experiments with ^{15}N. Little attention has been given to the effect of organic matter on the control of soil acidity and there are doubts concerning the positive effects of green manures on the decrease in Al activity and other toxic elements in acid soils. In these studies isotope techniques would be of great help in understanding these processes. In the case of heavy metal pollution, while there are situations where contamination has caused decreases in crop production due to direct toxic effects, the phenomenon is more serious in terms of

the effects on human health and the environment. The microbial processes in the soil seem more sensitive to intoxication by heavy metals. Here there are examples of effects on nitrification, N_2 fixation by freeliving microorganisms, and the survival of effective *Rhizobium*. This observation may allow the identification of microbial parameters which indicate pollution of the soil by heavy metals. On the other hand plant breeding offers good prospects to alleviate these problems. Nuclear techniques, which until now have been little exploited, could be most useful in investigating the detrimental effects of the phenomena mentioned above.

INTRODUCTION

The soil and its interaction with climate, are considered as one of the principal factors which influence crop production. Independent of the effect of climate the productive capacity of a soil will depend on, among other factors, the availability and the balance of nutrients, the degree of acidity of the soil which affects the solubility of elements (Al and Mn) toxic to plants, the degree of contamination by heavy metals and soil salinity. In these last three situations, where plants can suffer toxic effects of certain elements, crop production can be seriously reduced. These constitute soils deleterious for crop production.

It should be pointed out that in many cases the problems mentioned above, especially soil acidification and salinization, has been aggravated in many areas of the world by poor management practices. This together with erosion has contributed to the reduction of crop production potential of immense areas which in many situations are difficult to recuperate. It is estimated that between 6 and 11 million hectares of cultivated land deteriorate each year, an area greater than those incorporated into agriculture (Ceres, 1978; Greenland, 1981)).

Many studies are being conducted to reduce the expansion of areas of "problem soils" and recover existing ones. For this the use of corrective soil management practices, together with the selection of tolerant species/varieties is yielding good results.

In this paper the problems associated the management of highly acidic soils of the tropics and soils polluted with heavy metals are discussed, giving emphasis on techniques which are being applied to attenuate the limitations for crop growth. Problems of the management of soils affected by salinity are the subject of another symposium at this congress and not addressed here.

Deleterious soils for crop production.

Among the worst deleterious soils are those which are strongly acidic, and within this group because of the large areas involved, are the acid soils of the tropics. Of the 1,600 to 2,200 million hectares of potentially cultivatible land in the tropics of Africa, Asia and Latin America (Buringh y Van Heemst, 1977), almost 140 million ha are planted with rice and approximately 700 million ha are occupied by other crops. The remainder (800 to 1400 million ha) are yet to be utilized in agriculture (Greenland, 1981), and more than 50% of them (Oxisols, Ultisols and some Inceptisols) are acid with high levels of soluble aluminium and poor in nutrients (Sanchez, 1976; Van Wanbeke, 1976). It is these soils which must support the food crops for the future of humanity (Greenland, 1981; Sanchez y Buol, 1975).

One problem, which in recent years is receiving more attention, is the contamination of the environment with heavy metals. In the case of agriculture, soils which present this problem do not permit the normal growth of crops, principally because the contaminants are toxic to microorganisms useful to them (McGrath *et al*., 1988). In fact, nearly all the soils contaminated with heavy metals are result of recent human activity, often due to the intensification of agriculture, and the increase in the use of fertilizers and pesticides, and the spreading of organic residues from urban sewage which are important sources of heavy metals (McGrath *et al*., 1988; Turner, 1994).

Acid deleterious soils for agriculture

Acid soils with aluminium toxicity problems.

Acid soils have a wide global distribution and constitute a large proportion of many soil types. However, acid soils with problems of aluminium toxicity and low nutrient availability only occur in a part of these areas, which in the tropics occupy approximately 1500 million ha (Oxisols, Ultisols and some Inceptisols) , and in the temperate regions (Ultisols) approximately 600 million ha (Sanchez y Logan, 1992).

Within certain limits, the low pH values recorded in these soils are not *per se* a great restriction to crop growth. The greatest problem occurs when the pH of the soil diminishes below 5.5 or 6.0. The exchangeable aluminium and the Al^{3+} activity in the soil solution may attain levels toxic to plant growth (and/or soil microorganisms), and hence diminish crop productivity (Abruña *et al*., 1975; Kamprath, 1972; Keyser and Munns, 1979). A level of 60% aluminium saturation of the action exchange complex (effective CEC) of the soil, is considered as a minimum reference value in the identification of acid soils with aluminium toxicity problems (Kamprath, 1970; Sanchez y Logan, 1992). The restriction of strong soil acidity and aluminium toxicity has been largely resolved by management of the soil (eg. liming , application of gypsum) and by plant breeding programmes which have managed to select, or generate varieties, or genotypes capable of tolerating high levels of aluminium saturation.

Control of soil acidity (aluminium toxicity) by liming and the growth of crops.

It is difficult to identify the level of acidity (pH or aluminium toxicity) where this becomes prejudicial to plant development. It is considered that a pH between 6.0 and 6.5 is ideal for plant growth as these are optimum conditions for the physico-chemical and microbiological activity which favor the balanced availability of nutrients in the soil and their absortion by plants.

Normally liming of the soil is the most variable economic means of correcting the problems derived from acidity. However, there is not as yet an adequate definition of which parameter should be followed (pH, or soil aluminium saturation) in recommending the level of lime addition which permits adequate plant growth (Kamprath, 1984; Quaggio *et al.*, 1985; Raij, 1991). From the point of view of the control of aluminium toxicity, the degree of aluminium saturation of the soil would seem to be the most convenient reference and it is this parameter which is most applied in highly weathered soils of the humid tropics (Kamprath, 1984). Using this parameter, the modest levels of lime recommended, do not raise the soil pH to neutrality, which results in a practice which is less expensive and more in line with the economies of poorer tropical nations, where the cost of lime is often high. It is important to realize that in highly weathered soils, a large change in pH can cause a disequilibrium in the nutrient availability (decrease the availability of some micronutrients), or in the soil microbial population, prejudicing plant development, as was observed by Kamprath (1984).

The response of crops to liming does not only depend on the degree of neutralization of exchangeable aluminium, or in the rise of pH, but also on the interaction with other soil parameters (eg. availability and balance of nutrients). For this reason it is not unusual to see positive responses of some crops (maize, potato, triticale, soybean, cotton, groundnuts) when soil pH is increased above 5.6 (Caires y Rosolen, 1991; Fox *et al.*, 1985; Quaggio *et al.*, 1985; Raij *et al.*, 1983). In the case of crops like groundnut, the response to high rates of applied lime may be associated with its higher demand for calcium. Apart from this, the response of crops to liming to pH close to 6.0 may be associated with the control of high levels of manganese, which are frequently encountered in highly weathered soils (Sanchez, 1976). On the other hand, in acid soils with pH less than 5.5 but with no aluminium toxicity problem, which occupy 25% of the tropics (1100 million ha), failures to correct soil acidity by liming can limit the growth of crops sensitive to low pH such as cotton, alfalfa (Sanchez y Logan, 1992), and legumes dependent on biological nitrogen fixation such as *Phaseolus* beans (Franco y Munns, 1982). Another common justification for liming such soils is that without this it would be necessary to add higher amounts of fertilizers to attain the same yield. An example of this is shown for potato and maize where these crops responded significantly to the application of 2 Mg ha^{-1} of lime (Fig. 1). Even though the potato variety (cv. Mariva) is renowned for its high tolerance to aluminium (Villagarcía, 1973) it responded well to liming. In this experiment, liming may have improved by the availability of phosphorus in the soil as was indicated by the large response of the crops applications of up to 70 kg P ha^{-1}.

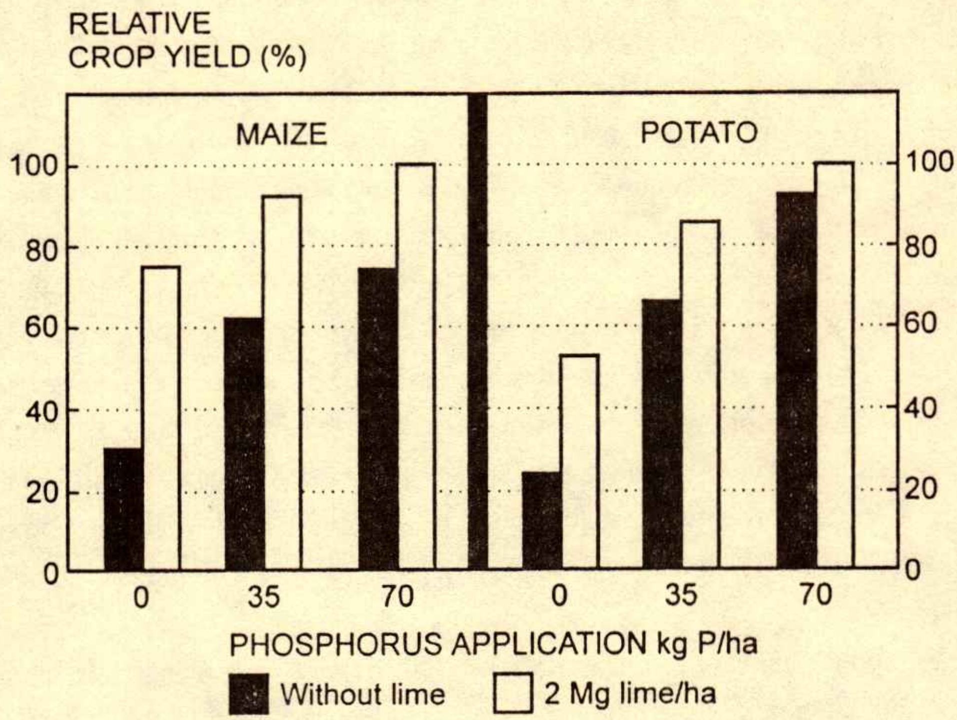


Fig. 1. Response of grain yield of maize (hybrid PM 265) and tuber yield of potato (cv. Mariva) to application of lime (2 Mg ha^{-1}) and superphosphate grown in an Inceptisol of ph 5.7 (maize), and an Alfisol of ph 5.5 (potato), with low available P (4-6 ug P g $soil^{-1}$ - olsen). Unpublished data of Villagarcia and Urquiaga.

In acid soils showing high aluminium saturation, apart from the problem of aliminium toxicity, there is a low availability of phosphorus. The fixation of phosphorus in soil occurs in practically all soils, independent of pH, but in highly acidic soils there is the additional negative effect of the active presence of exchageable aluminium and usually sesquioxides of iron and aluminium (Coleman *et al.*, 1960) which decrease the availability of P in the soil and the efficiency of phosphorus fertilization (Goedert, 1983; Sanchez, 1976).

According to Coleman *et al.*, (1960), 1 c mole kg^{-1} of exchangeable Al^{3+} can fix approximately 70 ppm P, such that P fertilization becomes a way of neutralizing Al^{3+}, which Sanchez (1976) called "liming with phosphorus"; clearly an uneconomic means of controlling soil aluminium toxicity. In the soils of the humid tropics and edaphic savannas (eg the Cerrado of Brazil) which are very phosphorus deficient, it has only been possible to obtain high crop yields when P levels have been corrected with the generous application of superphosphate (Lobato, 1980). As an more economic alternative the application of rock phosphate has been proposed, taking advantage of the acidity of the soil to dissolve this source of P, of low solubility compared with superphosphates. In Brazil, in the Oxisols of the Cerrado, the rock phosphates of Araxa, Catalão and Patos did not give the hoped-for results (Goedert y Lobato, 1980; Yost *et al.*, 1982). Urquiaga *et al.*, (1982) using ^{32}P, also observed a low fertilizer use efficiency of the Araxa rock phosphate. This rock phosphate (13% P) had an efficiency equivalent to a soluble phosphate with only 1.75% P.

According to Leon *et al.*, (1986), the efficiency of rock phosphates depends basically on the nature of the phosphate, those of sedimentary origin (eg. Bayovar rock phosphate from Peru) being the most efficient. The data presented in Fig. 2, illustrate the importance of liming and the application of rock phosphate for the production of potato and maize in an highly acid Ultisol low in available P. The Bayovar phosphate had an efficiency comparable to single superphosphate although in the unlimed treatments the rock phosphate was more efficient. These results show the importance of acid soil conditions in the solubilization and fertilizer use efficiency of this rock phosphate.

In areas of the tropics dedicated to traditional shifting cultivation, the use of low input technology for food production is a good option in consideration of the socio-economic problems which frequently limit the large additions of lime and fertilizers for crop production (Sanchez and Benites, 1987). In low input systems the use of high-solubility rock phosphate would be a great help in view of the high cost of superphosphates. The use of rock phosphates for crops which tolerate soil acidity favors their efficiency as the plants grow in conditions which favours the dissolution of these phosphates. Several studies indicate the possibility of the direct use of rock phosphates of high solubility in acid soils low in P (Bationo *et al.*, 1990; Gichuru y Sanchez, 1988; Reeve and Sumner, 1972). Another

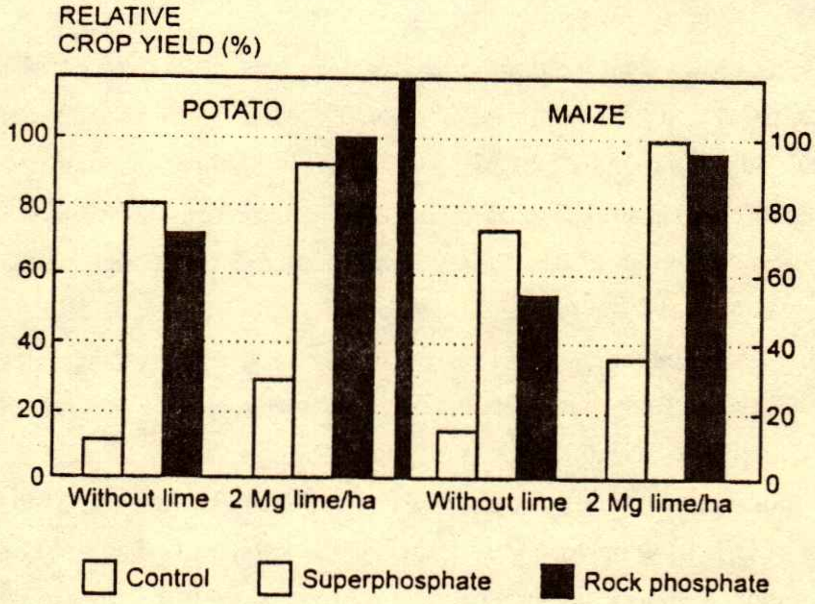


Fig. 2. Effect of lime and the addition of 70 kg P ha^{-1} of two sources of phosphorus (single superphosphate with 8.7% P, and natural Bayovar rock phosphate with 8.7% P) on the yield of potato tubers (cv. Marina) and maize grain (hybrid PM 265), on an Oxisol (ph 4.8) low in avalable P (3 ug P g $soil^{-1}$ - Olsen) in the locality of San Ramón, Junin, Peru.
Unpublished data of Villagarcia and Urquiaga.

possibility is the application in split doses of soluble phosphates. Using ^{32}P Bastidas *et al.* (1988) showed promising results with potato.

The control of acidity of the sub-soil and its influence on crop growth.

The correction of acidity in only the ploughed layer of the soil in many cases has been shown to be insufficient for good crop growth, especially in regions of the humid or semiarid tropics where during dry periods in the rainy season, the plough layer does not supply sufficient water for crop growth. This is a consequence of the poor growth of roots in the sub-soil due to its acidity and aluminium toxicity.

The inhibition of root growth caused by aluminium toxicity in the sub-soil is common in tropical Oxisols and Ultisols and in Ultisols of temperate regions (Adams y Moore, 1983; Goedert, 1983; Sanchez, 1977; Sumner *et al.*, 1986). In the case of the acidic soils of the Brazilian savannas (Cerrados), the limitation to root growth in the sub-soil created a great problem for agricultural production in this region. Despite the high clay content of most of these soils they behave as very sandy soils because of the strong aggregation of the clay particles, and in consequence, the retention of water is very low. More than 90% of the available water in the soils is stored at tension less than 0.1 MPa (Salati *et al.*, 1980), from which is can be deduced that the only way that plants will obtain more water is by the development of a deeper rooting system, whereby they exploit a greater volume of soil. The problem becomes critical when during season there are occasional periods of drought (15 to 70 days) know in Brazil as "Veranicos" . Wolf (1975) showed that in the Brazilian Cerrado maize starts to wilt after 6 days without rain. Some authors (Haynes, 1984; Wolf, 1975) have considered that sustainable economic crop production is not possible, especially in the poorer soils of the humid tropics, without soil management practices which favor the development of the plant rooting system.

Studies on the effects of deeper incorporation of lime in these soils have shown significant increase in crop production, which was associated with the reduction of aliminium saturation of the sub-soil and a greater availability of calcium (Bouton *et al.*, 1986; Goedert *et al.*, 1982; Gonzalez-Erico *et al.*, 1979; Sumner *et al.*, 1986). Gonzalez-Erico *et al.*, (1979) found that maize grown in a medium textured Oxisol of the Brazilian Cerrado produced 1300 kg more of grain where lime was incorporated to 0 to 30 cm than when liming was only in the surface layer (0-15 cm). This was explained by the improved exploitation by the roots of water stored in the subsoil.

As the correction of acidity of the sub-soil by deeper incorporation of lime is difficult and not economically viable, research workers have studies the means by which this can be achieved (Brown *et al.*, 1956; Farina and Channon, 1988; Pavan and Bingham, 1982; Pavan *et al.*, 1982; Quaggio *et al.*, 1985; Raij *et al.*, 1977; Reeve and Sumner, 1970; Ritchey *et al.*, 1980; Shainberg *et al.*, 1989; Sumner *et al.*, 1986).

These studies started more than 30 years ago when it was observed that the residual acidity of nitrogen fertilizers stimulated the movement of bases within the soil profile improving the root growth of crops in Latosols with strongly acid sub-soil (Pearson *et al.*, 1962; Weir, 1974). Other authors also observed that the type of management of the plough layer, including the application of lime and fertilizers, and the time under cropping, favored the movement of calcium to the sub-soil (Gonzalez-Erico *et al.*, 1979; Reeve y Sumner, 1972; Ritchey *et al.*, 1980). The best results were achieved with high rates of gypsum applied in the plough layer. Gonzalez-Erico *et al.* (1979) and Ritchey *et al.* (1980) found that the greater effect of single superphosphate versus triple superphosphate on maize yield was associated with a significant decrease in the saturation of Al^{3+} in the sub-soil which permitted better development of the maize roots. This could only be explained by the significant proportion of gypsum in the single superphosphate. The data of Ritchey *et al.* (1980) showed that where single superphosphate was applied, maize roots reached down to 120 cm, while in the treatment with triple superphosphate the roots did not exceed a depth of 45 cm, below which the aluminium saturation was greater than 60%. Apart from it is apparent that there is a positive interaction of liming and gypsum application in the correction of acidity of the sub-soil. Liming diminishes the adsorption of sulphate by the soil in the plough layer favouring the vertical movement of calcium and magnesium down the profile, increasing the efficiency of the gypsum (Couto *et al.*, 1979).

Although gypsum can cause large decreases in the saturation of aluminium in the sub-soil, the pH tends to remain stable, and when changes are observed this is generally of the order of only 0.2 to 0.3 pH units. The explanation for this comes from the reaction between gypsum and the soil, in which Ca^{++} replaces H^+ and Al^{3+} (which hydrolyses to produce H^+), and SO_4^{--} which replace OH^- in ion exchange reaction. Consequently the resulting pH depends on the extent of the two reactions in each case (Sainberg *et al.*, 1989). This explains the apparent contradictory results concerning soil pH changes when gypsum is applied. In soils with high Al^{3+} saturation the liberation of H^+ by the hydrolysis of Al^{3+} can exceed the liberation of OH^-, resulting in a lowering of pH (Pavon *et al.*, 1982) and the opposite can occur in highly weathered soils with lower levels of exchangeable aluminium (Farina and Channon, 1988; Ritchey *et al.*, 1980).

On the other hand there is a close relationship between exchangeable Al^{3+} (or Al saturation) with the level of Al in the soil solution (Sanchez, 1976). In many cases root growth is not well correlated with pH and Al saturation, but more with the activity of Al^{3+} in the soil solution (Adams and Lund, 1966). For the same concentration of aluminium in the soil solution an increase in the concentration of Ca^{++} decreases the chemical activity of the Al^{3+}. Studies performed with soybean (Pavon y Bingham, 1982) and coffee (Bruce *et al.*, 1988) in solution culture have reinforced this hypothesis.

There are many reports in the literature concerning the response of crops to gypsum application (or phospho-gypsum, a by product of the phosphoric acid industry) in soil (see review of Shainberg *et al.*, 1989), but apart from the hydric factor little attention has been given to other variables which could also have a strong influence on the positive responses of crops to its application. Gypsum is an important source of calcium and sulphur for crops and calcium especially is found in low levels in highly weathered sub-soils (Ritchey *et al.*, 1980). In the case of groundnut, known for its high susceptibility to calcium deficiency derived from the necessity of the pods to absorb significant quantities of calcium directly from the soil (Walter *et al.*, 1979); gypsum has been shown to be the best fertilizer (Mehlich and Tewari, 1974). Regarding sulphur it should be noted that in soils under intensive agriculture there is a tendency for the natural reserves of this element to decrease due to continuous decomposition (oxidation, erosion etc) of soil organic matter, the principal source of this nutrient. The problem is becoming more serious because, owing to high fertilizer transport costs there is a transition towards the utilization of fertilizers of high nutrient content and low in sulphur, such as urea, anhydrous ammonia, triple superphosphate and potassium chloride. In consequence today there are large areas where significant crop growth responses to sulphur application are observed. In these areas the greater part of any response to gypsum is likely to be due to its sulphur content (Mehlich and Tewari, 1974; Vitti *et al.*, 1986).

Another aspect of the advantages of deeper rooting systems is the greater exploitation of nutrients from the sub-soil if the aluminium toxicity of this layer is corrected. Amongst these nutrients, the most important is NO_3^- . Several authors have reported that nitrogen fertilizer use efficiency for various crops is in the region of 50%, the remainder being left in the soil or lost by leaching, denitrification and/or ammonia volatilization (Reichart *et al.*, 1992; Urquiaga *et al.*, 1991). The residual N is normally the largest fraction of the N not absorbed by the crop and usually subsequent crops do not succeed in recovering much of this. A part of this residual N may be in the sub-soil and not recovered by the crop owing to poor root growth in this zone. In Japan, Saigusa *et al.* (1991) studying two Andisols with high Al^{3+} saturation in the (non-allophanic) subsoil and another with an allophanic sub-soil with low Al^{3+}, observed that the low recovery (4.7%) of applied ^{15}N labelled ammonium sulphate was associated with poor root growth in the sub-soil. In the case of the soil with no aliminium problem the N fertilizer recovery was much greater (30.5%). It was only possible to improve fertilizer use efficiency (to approximately 50%) when the fertilizer was added later when the roots in the surface layer were already well development and the plants had a greater demand for N. The authors recommended that for soils with high Al^{3+} saturation in the subsoils which limits root growth, the N fertilizer should be fractionated or slow release forms should be used. In Brazil Quaggio *et al.* (1991) and Souza and Ritchey (1986) observed that the application of high doses of lime or gypsum favored the absorption of NO_3^- by maize, and this was associated with a greater recovery of NO_3^- from the sub-soil. Quaggio *et al.* (1991), found that in the absence of lime the roots of maize only penetrated the 0 to 20 cm layer, but when 6 Mg ha^{-1} of lime were added roots reached 50 cm and at the highest lime application (12 Mg ha^{-1}) they reached 100 cm. On the other hand, according to Raij *et al.* (1988) the preferential absorption of nitrate and sulphate by the plants increased the anion:cation ratio which contributed to the reduction of acidity by the efflux of OH^- and HCO_3^-. More studies on this subject are required, preferably using ^{15}N for greater precision, with the aim of increasing the efficiency of the recovery of N fertilizer and other nutrients by crops.

Soil organic matter and the activity of aluminium in soil.

Generally, under favorable climatic conditions and free soil drainage, the organic matter content of soil is synonymous with its fertility. In acid soils, with high Al^{3+} saturation, organic matter generally attenuates the toxic effects of this element. Organic matter can act as a source of nutrients, increase the cation exchange capacity (CEC) of soil and its water retention, block phosphorus fixation sites and reduces the activity of aliminium (Adams y Moore, 1983; Greenland, 1986; Sanchez, 1976). Aluminium in soil can be complexed by organic colloids to non-exchangeable forms or the those with lower activity, such that aluminium toxicity is reduced (Bell y Edwards, 1986). It is important to mention that under shifting cultivation with minimal inputs where, for economic reason, lime and fertilizer are rarely used, the rapid loss or degradation of soil organic matter can result in a considerable detrimental effects for sustainable agriculture. This is possibly one of the reasons why traditional peasant farmers of the humid tropics resort to deforestation. In Amazonia alone, 500,000 families of settler clear approximately 1.5 million ha $year^{-1}$ of either primary or secondary forest for their subsistance.

Unfortunately little has been done to adequately understand the great importance of the management of organic matter in acid soils. It is possible that the positive effects of green manures on crop growth is less associated with the provision of plant nutrients and more with their effect as a physical conditioner of the soil and the complexing action of the organic colloids derived from the plant residues which inactivate toxic elements such as aluminium.

More studies should be realized to better understand the role of organic matter in the physico-chemical processes of soils, with the aim of improving its management. In these studies isotopic tracers would be of great value.

Varietal tolerance to aluminium.

Liming is the technique generally used to control soil acidity and increase plant growth. However, in many parts of the world this technique cannot often be used, either because of high cost, or because of the difficulty to incorporate lime into the soil, especially in sub-soils having high aluminium saturation (Farina and Channon, 1988; Reeve and Sumner, 1972). Because of this, the use of acid-tolerant crops or varieties offers great perspectives especially as an important contribution to minimum input systems for the humid tropics (Sanchez and Benites, 1987).

The differences between growth and/or production of different crops in acid soils depends principally on their respective tolerance to low pH and active Al^{3+} and Mn^{++} of the soil and their requirement for phosphorus, calcium and magnesium, or a combination of these factors (Howeler, 1991; Sanchez, 1976). In the case of cassava, pineapple and the forage legume, *Stylosanthes guianensis*, which are highly dependent on VA-mycorrhizae and also highly tolerant to acid soil conditions, it is not yet clear if this tolerance is influenced by the mycorrhizal infection (Howeler, 1991). There are also crops such as cotton which, although also highly dependent on mycorrhizae, do not show tolerance to high soil acidity. Other crops which are very tolerant and grow and yield well in acid soils, where sensitive crops such as maize and soybean die out, are coffee, rubber and tea.

As the greatest limitation to crop growth in highly acid soils is related to aluminium toxicity and low phosphorus activity, plant breeding programs have principally addressed these two problems which, incidently, are closely related and difficult to separate. Great advances have been made in this area and highly tolerant genotypes have been produced for rice (Howeler and Cadavid, 1976), sorghum (Malavolta *et al.*, 1981; Pita *et al.*, 1979; Salinas and Sanchez, 1977), maize (Salinas and Sanchez, 1977), wheat and barley (Foy *et al.*, 1965) and common beans (Malavolta *et al.*, 1981; Salinas and Sanchez, 1977) amongst others.

On the other hand it should be pointed out that most genotypes or varieties with high tolerance to aluminium and low soil phosphorus availability are not high yielding and still await finalization of the breeding programs before liberation for commercial planting. Varieties with proven tolerance and good yields which have recently been released are: Alondra 4545 (wheat), Cross XXXIV (barley), G-PIR (sorghum) and ICA-Catumare (cassava) (Howeler, 1991). In Brazil the National Centre for Maize and Sorghum Research (CNPMS) of EMBRAPA, has recently released acid tolerant high-yielding maize and sorghum varieties and the double hybrid of maize, BR 201, is already planted in almost 1.5 million ha (Bahia-Filho *et al.*, 1993; Magnavaca and Bahia-Filho, 1993).

Soils contaminated with heavy metals

Although it is not easy to find information concerning the direct toxic effects of heavy metals on the growth of plants in contaminated soils, this subject is of growing importance, principally from the point of view of human healt and environmental considerations (Tiller, 1989; Turner, 1994). The contamination of soil and the environment with heavy metals has been common over the last 150 years, ever since the industrial revolution led man to user ever increasing quantities of metals in daily life. In consequence industrial waste and sewage effluents are important sources of contamination (Giller and McGrath, 1988; Tiller, 1989). To dispose of these wastes the cheapest and most common alternative has been to deposit them on the soil, in river or in the sea. Organic residues from cities or cattle or pig slurry have been widely applied to agricultural soils as a source of nutrients and to improve the physical and chemical properties of the soil. Continuos application of these materials for long periods has led to soils becoming contaminated with high levels of heavy metals (McGrath *et al.*, 1988). Generally the areas closest to urban districts or industry have been most affected.

In agricultural practice usually the principal sources of contamination are fertilizers and pesticides. In the case of fertilizers, the greatest concern has been with regard to cadmiun (Cd) due to the intensive use of phosphate fertilizers which are important sources of cadmiun (Tiller, 1989), and this element is relatively easily transferred to plants (Schroeder and Balassa, 1963). Tiller (1989) suggested that the direct application of rock phosphates in the field is more likely to distribute cadmiun in the environment than the application of sewage residues from cities. This subject should be examined with great care as actually, because of the low cost, there is a trend to use more rock phosphates in low input agriculture systems in the humid tropics (Sanchez and Benites, 1987). On the other hand it should be remembered that some heavy metals (Cu, Zn) essential for plants are very often at levels where the plants are deficient, especially in highly weathered soils (Ultisoils and Oxisoils) of the tropics. Possibly the better performance of the rock phosphate Bayovar over that of triple superphosphate with various crops in infertile soils of the Andes in Peru (Villagarcía-pers. comm.) is associated with the additions of "heavy metals" to the soil.

Another important source of contamination of agricultural soils with heavy metals are agro-chemicals, starting with the well known Bordeaux sprays, which are based on copper and have been used as fungicides in many parts of the World. In some regions of Costa Rica, where for centuries copper-containing products have been used to disinfect bananas for exportation, today banana plants show symptoms of copper toxicity (extreme zinc deficiency) (Cervantes-pers. comm.). Other insecticides and fungicides based on salts of zinc, copper, lead arsenates and organo-metallic compounds are still widely used (Tiller, 1989).

Crops grown in areas contaminated with high levels of heavy metals generally do not present visible symptoms of toxicity and in many cases no good correlations are found between the quantity and frequency of application of contaminated sludge additions and the concentrations of these elements in the plants. Several authors (Chaney and Giordano, 1977; Dowdy *et al.*, 1978) observed no change in the levels of zinc and copper in common beans, or cadmium in forage crops, grown in soils which had been subject to many years of sludge addition. Hinesly *et al.* (1979) observed that 4 years after the last sludge addition, the concentration of cadmium and zinc in maize grain diminished to close to background levels, while leaves still maintained high concentrations. The question arises whether plants can show such high discrimination of a heavy metal (cadmium in this case) between the different tissues.

The availability of heavy metals in soil depends on the clay content, the levels of organic matter, pH, and the interaction of these variables (Tiller, 1989) and little is known about what fraction of the metal is available (Turner, 1994). However, soil is an important medium which can fix or decrease the activity of heavy metals, as has been shown in many experiments where their extraction by plants decreased significantly as time passed (Tiller, 1989).

It appears that soil microorganisms are much more sensitive to high levels of heavy metals than plants, and legumes, which rely on biological nitrogen fixation, can suffer large decreases in production unless the crops are fertilized with nitrogen (Giller *et al.*, 1989; McGrath *et al.*, 1988). In a soil which until 25 years ago had received more than 30 years of applications of heavy metals, it was observed that the low yield of white clover was associated with N deficiency because of the lack of nitrogen fixation by the *Rhizobium leguminosarum* biovar *trifolii* (McGrath *et al.*, 1988). In contaminated soil only ineffective strains of the *Rhizobium* survived, and when the clover was inoculated at seeding with effective strains N_2 fixation was significant. However, when efficient strains were exposed to the soil 2 months before seeding, again N_2 fixation was zero, indicating that the toxicity of the metals affected the survival of the bacteria in the soil but not within the nodules (Giller *et al.*, 1989). It was also observed that R. *meliloti* was less sensitive than *Rhizobium leguminosarum* biovar *trifolii* and R. *loti* (Giller *et al.*, 1992). In this highly contaminated soil other microbial parameters such as the size of the microbial biomass, hydrogenase activity, nitrification, N_2 fixation by free-living bacteria and cyanobacteria were reduced, while the mineralization of organic carbon and nitrogen were only slightly affected (Brookes and McGrath, 1984; Brookes *et al.*, 1986). These results open up the possibility of finding microbiological parameters which could be used to indicate levels of heavy metal pollution in soils.

Final considerations and perspectives for future research.

The production capacity of immense areas actually, or potentially, used for agriculture in the World is reduced either by high soil acidity or by high levels of salinity. In very acidic soils the greatest problem is aluminium toxicity, which actually can be controlled by liming and application of gypsum. The application of gypsum which permits the greater movement of bases into the sub-soil, facilitates root development in deeper layers in the soil, which allows the plants to better exploit the nutrients and water stored in the sub-soil. These techniques have only received much attention in the USA, Brazil and South Africa, but should spread to other regions, especially in those countries fighting for self-sufficiency in food crops.

Attention should be given to the effect of gypsum movement of magnesium and potassium within the soil profile with regard to the possibility of increased losses. Also little attention has been given to the influence of organic matter on decreasing the activity of Al^{3+}, but it is known that in many highly weathered soils the organic matter accounts for more than 80% of the CEC of the soil. On the other hand the increased rooting depth caused by gypsum addition opens up the possibility to increase the recovery by the plants of nutrients prone to leaching applied to the plough layer. Isotopic tracer techniques, along with the use of neutron probes for soil moisture estimation, offer a great help in understanding these phenomena.

In recent years great interest has been shown in the possible losses in crop productivity on soils contaminated with heavy metals. Although this contamination rarely causes direct losses in crop yields, in many cases there are significant accumulations of metals in plant tissues which may cause risks to human or animal health. The information available indicates that the microbial population of the soil is more sensitive to heavy metal toxicity than higher plants and this can be expressed as reduced nitrification and N_2-fixing activity as well as inhibition of the survival of effective *Rhizobium*, drastically reducing legume yields in N deficient soils.

ACKNOWLEDGMENTS

The authors would like to thank Sra. Dorimar dos Santos Felix for organizing the bibliography of this paper and Dr. Paulo Eira for critical reading of the text.

REFERENCES

ABRUÑA, F. , R.W. PEARSON AND R. PEREZ-ESCOBAR. 1975. Lime responses of corn and beans grown on tropical ultisols and oxisols of Puerto Rico. p. 261-281. *In:* E. Bornemisza and A. Alvarado (ed.) Soil management in tropical America. North Carolina State University, Raleigh.

ADAMS, F. AND B.L. MOORE. 1983. Chemical factors affecting root growth in subsoil horizonts of coastal plain soils. Soil Sci. Soc. Am. J. 47:99-102.

ADAMS, F. AND Z.F. LUND. 1966. Effect of chemical activity of soil solution aluminium on cotton root penetration of acid subsoils. Soil Sci. 101:193-198.

BAHIA-FILHO, A.F.C., R. MAGNAVACA AND R.E. SCHAFFERT. 1993. Identification, utilization and economic impact of maize germplasm tolerant to low levels of phosphorus and toxic levels of exchangeable aluminium in the soil in Brazil. Proc. 3rd Int. Symp. Plant Soil Interactions low pH. 12-16 Sept, Brisbane, Australia. (in press)

BASTIDAS, O.G., S. URQUIAGA AND A.L. ALVAREZ. 1988. Influência da epoca de aplicação e ^{32}P-superfosfato triplo na eficiência da fertilização fosfatada e na productividade de batata. Pesq. Agropec. Bras. 23:963-970.

BATIONO, A. , S.H. CHIEN , J. HENAO , C.B. CHRISTIANSON AND A.U. MOKWUNYE. 1990. Agronomic evaluation of two unacidulated and partially acidulated phosphate rocks indigenous to Niger. Soil Sci. Soc. Am. J. 54:1772-1777.

BELL, L.C. AND D.G. EDWARDS. 1986. The role of aluminium in acid soil infertility. p. 201-223. *In*: Soil Management under Humid Conditions in Asia. Latham M. Ibsram, Khon Kaen.

BOUTON, J.H., M.E. SUMNER, J.E. HAMMEL AND H. SHANANDEH. 1986. Yield of an alfalfa germplasm selected for acid soil tolerance when grown in soils with modified subsoils. Crop Sci. 26:334-336.

BROOKES, P.C. AND S.P. MCGRATH. 1984. Effects of metal toxicity on the size of the soil microbial biomass. J. Soil Sci. 35:341-346.

BROOKES, P. C., S. P. MCGRATH AND C. HEIJNEN. 1986. Metal residues in soils previously treated with sewage-sludge and their effects on growth and nitrogen fixation by blue-green algae. Soil Biol. Biochem. 18:345-353.

BROWN, B. A., R. I. MUNSELL, R. F. HOLT AND A.V. KING. 1956. Soil reactions at various depths as influenced by time since application and amounts of limestone. Soil Sci. Soc. Am. Proc. 20:518-522.

BRUCE, R. C., L.A. WARRELL, D.C. EDWARDS AND L.C. BELL. 1988. Effects of aluminium and calcium in the soil solution on root elongation of *Glicine max* cv. Forest. Aust. J. Agric. Res. 38:319-338.

BURINGH, P. AND H.D.J. VAN HEEMST. 1977. An estimation of World food production based on labour oriented agriculture. Centre for World Food Market Research. Wageningen, The Netherlands.

CAIRES, E.F. AND C.A. ROSOLEN. 1991. Root growth of peanut cultivars and soil acidity. p. 239-243. *In*: R. J. Wright *et al*. (ed.) Plant-soil interactions at low pH. Kluwer Acad. Publ., Dordrecht, Netherlands.

CERES. 1978. How much good land is left? Ceres. 11:13-16.

CHANEY, R.L. AND P.M. GIORDANO. 1977. Microelements as related to plant deficiencies and toxicities. p. 235-279. *In*: Soils for management of organic wastes and waste waters. Am. Soc. Agron. Madison, WI, USA.

COLEMAN, N.T., J.T. THORUP AND W.A. JACKSON. 1960. Phosphate sorption reactions that involve exchangeable aluminium. Soil Sci. 90:1-7.

COUTO, W., D.J. LATHWELL AND D.R. BOUDIN. 1979. Sulphate sorption by two oxisols and an alfisol of the tropics. Soil Sci. 127:108-116.

DOWDY, R. H., LARSON, J.M. TITRUD AND J.J. LATTERELL. 1978. Growth and metal uptake of snap beans grown on sewage sludge-amended soil: a four-year field study. J. Environ. Qual. 7:252-257.

FARINAI M.P.W. AND P. CHANNON. 1988. Acid-subsoil amelioration. II. Gypsum effects on growth and subsoil chemical properties. Soil Sci. Soc. Am. J. 52:175-180.

FOX, R.L., S.R. YOST, N.A. SAIDY AND B.T. KANG. 1985. Nutritional complexities associated with pH variables in humic tropical soils. Soil Sci. Soc. Am. J. 49:1475-1480.

FOY, C.D., W.H. ARMIGER, L.W. BRIGGLE AND D.A. REID. 1965. Aluminium tolerance of wheat and barley varieties in acid soils. Agron. J. 57:413-417.

FRANCO, A.A. AND D. N. MUNNS. 1982. Acidity and aluminium restraints on nodulation, nitrogen fixation, and growth of *Phaseolus vulgaris* in solution culture. Soil Sci. Soc. Am. Proc. 46:296-301.

GICHURU, M.P. AND P.A. SANCHEZ. 1988. Phosphate rock fertilization in tilled and non-till low-input systems in the humid tropics. Agron. J. 80:943-947.

GILLER, K.E. AND S.P. MCGRATH. 1988. Pollution by toxic metals on agricultural soils. Scientific correspondence. Nature 335:676.

GILLER, K.E., S.P. MCGRATH AND P.R. HIRSCH. 1989. Absence of nitrogen fixation in clover grown on soil subject to longterm contamination with heavy metals in due to survival of only ineffective *Rhizobium*. Soil Biol. Biochem. 2l:841-848.

GILLER, K.E., R. NUSSBAUM, A.M. CHAUDRI AND S.P. MCGRATH. 1992. *Rhizobium meliloti* is less sensitive to heavy-metal contamination in soil than *R. leguminosarum* bv. *Trifolii* or *R. loti*. Soil Biol. Biochem. 25:273-278.

GOEDERT, W.J. 1983. Management of the cerrado soils of Brazil: a review. Soil Sci. 34:405-428.

GOEDERT, W.J. AND E. LOBATO. 1980. Eficiência agronômica de fosfatos em solo de cerrado. Pesq. Agropec. Bras. 15:311-318.

GOEDERT, W.J. E. LOBATO AND M. RESENDE. 1982. Management of tropical soils and world food prospects. Proc. l2th Int.Congr. Soil Sci., New Delhi.

GONZALEZ-ERICO, E., E. J. KAMPRATH, G. C. NADERMAN AND W. V. SOARES. 1979. Effect of lime incorporation on the growth of corn on a oxisol of Central Brazil. Soil Sci. Soc. Am. J. 43:1155-1158.

GREENLAND, D.J. 1981. Soil management and soil degradation. Soil Sci. 32:301-322.

GREENLAND, D.J. 1986. Effects or organic matter on the properties of some red soils. p. 262-273. *In*: Proc. Int. Symp. on Red Soils. Science Press, Beijing, China; Elsevier, Amsterdam.

HAYNES, R.J. 1984. Lime and Phosphate in the soil-plant system. Adv. Agron. 37:249-315.

HINESLY, T.D., E.L. ZIEGLER AND G.L. BARRETT. 1979. Residual effects of irrigation of corn with digested sewage sludge. J. Environ. Qual. 8:35-38.

HOWELER, R.H. 1991. Identifying plants adaptable to low pH conditions. p. 885-904. *In* R.J. Wright *et al.* (ed.) Plant-soil interactions at low pH. Kluwer Acad. Publ., Dordrecht, Netherlands.

HOWELER, R.H. AND L.F. CADAVID. 1976. Screening of rice cultivars for tolerance to Al-toxicity in nutrient solutions as compared with a field screening method. Agron. J. 68:551-555.

KAMPRATH, E.J. 1970. Exchangeable aluminium as a criterion for liming leached mineral soils. Soil Sci. Soc. Am. Proc. 34:252-254.

KAMPRATH, E.J. 1971. Potential detrimental effects from liming highly weathered soils to neutrality. Proc. Soil Crop. Sci. Soc. Fla. 31:200-203.

KAMPRATH, E.J. 1972. Soil acidity and liming. p. 136-149. *In* Soils of the humid tropics. National Academic of Sciences, Washington.

KAMPRATH, E.J. 1984. Crop response to lime on soils in the tropics. p. 349-368. *In* F. Adams (ed.) Soil acidity and liming. 2.ed. Am. Soc. Agron, Madison, Wisconsin. (Agronomy, 12).

KEYSER, H.H. AND D.N. MUNNS. 1979. Tolerance of rhizobia to acidity, aluminium and phosphate. Soil Sci. Soc. Am. J. 43:519-523.

LEON, L.A., W.E. FENSTER AND L.L. HAMMOND. 1986. Agronomic potential of eleven phosphate rocks from Brazil, Colombia, Peru, and Venezuela. Soil Sci. Soc. Am. J. 50:798-802.

LOBATO, E. 1980. Adubação fosfatada em solos sob vegetação de cerrado. EMBRAPA/Centro de Pesquisa Agropecuaria dos Cerrados. Planaltina-DF, Brazil.

MAGNAVACA, R. AND A.F.C. BAHIA-FILHO. 1993. Success in maize acid soil tolerance. Proc. Workshop Adapting Plants to Soil Stress. 2-5 August. INSORMIL, Lincoln, NE, USA.

MALAVOLTA, E., F.D. NOGUEIRA, I.P. OLIVEIRA, L. NAKAYAMA AND I. EIMORI. 1981. Aluminium tolerance in sorghum and beans Methods and results. J. Plant Nutr. 3:687-694.

MCGRATH, S.P., P.C. BROOKES AND K.E. GILLER. 1988. Effects of potentially toxic metals in soil derived from past applications of sewage sludge on nitrogen fixation by *Trifolium repens* L. Soil Biol. Biochem. 20:415-424.

MEHLIH, A. AND G.P.TEWARI. 1974. The roles of gypsum (calcium sulphate) in agriculture. U.S. Gypsum Co., Chicago, Illinois.

PAVAN, M.A. AND F.T. BINGHAM. 1982. Toxicity of aluminium to coffee seedlings grown in nutrient solution. Soil Sci. Soc. Am. J. 46:983-997.

PAVAN, M.A. AND F.T. BINGHAM, P. F. PRATT. 1982. Toxicity of Al to coffe in ultisols and oxisols amended with $CaCO_3$, $MgCO_3$ and $CaSO_4.2H_2O$. Soil Sci. Soc. Am. J. 46:1201-1207.

PEARSON, R. W., F. ABRUNA AND J. VINCENT-CHANDLER. 1962. Effect of lime and nitrogen applications on downward movement of calcium and magnesium in two humid tropical soils of Puerto Rico. Soil Sci. 93:77-82.

PINO, I., S. URQUIAGA AND L. CASAS. 1988. Evaluación agronómica de roca fosfórica con técnicas isotópicas. Simiente 58:11.

PITTA, G.V.E., R.E. SHAEFFER, R. A. BORGONOVI, C. A. VASCONCELLOS, A.F. BAHIA FILHO AND A. C. OLIVEIRA. 1979. Evaluation of sorghum lines to high soil acidity conditions. II. *In:* Proc. 12th Brazilian Corn and Sorghum Research Conference, Goiánia, Goiáis, Brazil.

QUAGGIO, J.A., B. RAIJ AND E. MALAVOLTA. 1985. Alternative use of the SMP-buffer solution to determine lime requirement of soils. Commun. Soil Sci. Plant Anal. 16:245-260.

QUAGGIO, J.A., N.J. RAMOS, O.C. BATAGLIA, B. VAN RAIJ AND M. SAKI. Liming for crop succession of potato, triticale and corn using limestones with different magnesium contents. Bragantia 4:391-406.

QUIAGGIO, J.A., V. J. RAMOS, P. R. FURLANI AND M. L. C. CARELLI. 1991. Liming and molybdenum effects on nitrogen uptake and grain yield of corn. p. 327-332. *In* R. J. Wrigth *et al.* (ed.) Plant-soil interactions at low pH. Kluwer Acad. Publi., Dordrecht, Netherlands.

RAIJ, B. V., A.P. CAMARGO, M.A.A. MASCARENHAS, R. HIROCE, C.T. FEITOSA, C. NERY AND C.R.P. LAUN. 1977. Effect of levels of liming on soybean production. R. Bras. Ci. Solo 1:28-31.

RAIJ, B. V., A.P. CAMARGO, H. CANTARELLA AND N.M. DA SILVA. 1983. Exchangeable aluminium and base saturation as criteria for lime requirement. Bragantia 42:149-156.

RAIJ, B. V. H. CANTARELLA AND P.R. FURLANI. 1988. Influence on soil reaction of amonium and nitrate uptake by sorghum plants, in presence or absence of gypsum. R. Bras. Ci. Solo 12:131-136.

RAIJ, B. V., 1991. Fertility of acid soils. p. 159-167. *In* R.J. Wright *et al*. (ed) Plant-soil interactions at low pH. Kluwer Acad. Publ., Dordrecht, Netherlands.

REEVE, N.G. AND M.E. SUMNER. 1970. Lime requirements of Natal oxisols based on exchangeable aluminium. Soil Sci. Soc. Am. Proc. 34:395-398.

REEVE, N.G. AND M.E. SUNNER. 1972. Amelioration of subsoil acidity in Natal oxisols by leaching of surface-applied amendments. Agrochemophysica. 4:1-6.

REICHARDT, K., P.L. LIBARDI AND S. URQUIAGA. 1992. The fate of fertilizer nitrogen in soil-plant system with emphasis on the tropics. p. 277-290. *In* Int. Symp. on Agrochemical: Fate in food and the environment using isotope technique. IAEA, Vienna.

RITCHEY, K.D., D.M.G. SOUZA, E. LOBATO AND O. CORREA. 1980. Calcium leaching to increase rooting depth in a Brazilian savannah oxisols. Agron. J. 72:40-44.

SAIGUSA, M., N. MATSUYAMA, T. HONNA AND T. ABE. 1991. Chemistry and fertility, of arid andisols with special reference to subsoil acidity. p- 73-80. *In:* R.J. Wright *et al.*(ed.) Plant-soil interactions at low pH. Kluwer Academic, Netherlands.

SALATI, E., K. REICHARDT AND S. URQUIAGA. 1980. Efeitos da adição de vermiculita na retenção e armazenamento de água por latossolos. R. Bras. Ci. solo 4:125-131.

SALINAS, J.G. AND P.A. SANCHEZ. 1977. Tolerance to Al-toxicity and low available P. p. 115-137. *In:* Agronomic-Economic Research in the Tropics. Annual Report for 1976-1977. North Carolina State University, Raleigh, North Carolina, USA.

SANCHEZ, P.A. 1976. Properties and management of soils in the tropics. John & Wiley, New York.

SANCHEZ, P.A. 1977. Advances in the management of oxisols and ultisols in tropical South America. p. 535-566. *In:* Proceedings International Seminar on Soil Environment and Fertility Management in Intensive Agriculture, Society of the Science of Soil and Manure. Tokyo, Japan.

SANCHEZ, P.A. AND J.R. BENITES. 1987. Low input cropping for acid soils of the humid tropics. Science 238:1521-1527.

SANCHEZ, P.A. AND S.W. BUOL. 1975. Soils of the tropics and the World food crisis. Science 188:598-603.

SANCHEZ, P.A. AND T.J. LOGAN. 1992. Myths and science about the chemistry and fertility of soils in the tropics. p. 35- 46. *In*: R. Lal and P.A. Sanchez (ed.) Myths and science of soils of the tropics. Am. Soc. Agron. Madison, USA. (SSSA Special Publication, 29).

SCHROEDER, H.A. AND J.J. BALASSA. 1963. Cadmium: uptake by vegetables from superphosphate in soil. Science 140:819-820.

SHAINBERG, I., M.E. SUMNER, W.P. MILLER, M.P.W. FARINA, M.A. PAVAN AND M.V. FEY. 1989. Use of gypsum on soils: a review. p. 1-11. *In*: B.A. Stewart (ed.) Advances in Soil Science. v-9. Springer-Verlag, New York.

SOUZA, D.M.G. AND K.D. RITCHEY. 1986. Uso do gesso no solo de cerrado. p. 119-144. *In:* I Seminário sobre o uso de fosfogesso na agricultura. EMBRAPA, Brasília, Brazil.

SUMNER, M.E., H. SHABANDEH, J. BOUTON AND J. HAMMEL. 1986. Amelioration of an acid soil profile through deep liming and surface application of gypsum. Soil Sci. Soc. Am. J. 50:1254-1258.

TILLER, K.G. 1989. Heavy metals in soil and their environmental significance. p.113-142. *In:* B.A. Stewart (ed.) Adv. Soil Sci. v- 9. Springer-Verlag New York.

TURNER, A.P. 1994. The responses of plants to heavy metals. *In:* S.M. Ross (ed.) Toxic metals in soil/plant systems. Wiley & Sons. In Press.

TURNER, A. P. 1994. The responses of plants to heavy metals. *In*: S.M. Ross (ed.) Toxic metals in soil/plant systems. Wiley & Sons. In press.

URQUIAGA, S., B. ALVES AND R.M. BODDEY. 1991 Dinâmica do N no solo. p. 181-243. *In:* Anais so Simpósio Brasileiro sobre Nitrêgenio em Plantas. Universidade Federal Rural do Rio de Janeiro, Itaguai, Brazil.

URQUIAGA, S., K. REICHARDT AND P.L. LIBARDI. 1982. Efeito do fosfato de Araxa e Superfosfato simples em algumas propriedades fisico-químicas e do fósforo residual disponível em um solo oxic Paleudalf. Pesq. Agropec. Bras. 17:195-202.

VAN WANBEKE, A. 1976. Formation, distribution and consequences of acid soils in agricultural development. p. 15-24. *In*: M.J. Wright (ed.) Plant adaptation to mineral stress in problem soils. Cornell Univ. Agric. Exp. Stn., Ithaca, New York.

VILLAGARCIA, S. 1973. Aluminium tolerance in the Irish potato and the influence of substrate aluminium on growth and mineral nutrition of potatoes. North Carolina State University, Raleigh. Ph. D. Thesis.

VITTI, G.C., M.E. FERREIRA AND E. MALAVOLTA. 1986. Respostas de culturas anuais e perenes. p. 17-43. *In:* I Seminário sobre o uso de fosfogesso na agricultura. EMBRAPA, Brasília, Brazil.

WALTER, M.E., R.A. FLOWERS, R.J. HENNING, T.C. KRESLING AND B.G. MULLINIX. 1979. Response of early bunch peanuts to calcium and potassium fertilization. Peanut Sci. 6:119-123.

WEIR, C.C. 1974. Effect of lime and nitrogen application on citrus yields and on the downward movement of calcium and magnesium in soils. Trop. Agric. 51:231-234.

WOLF, J.M. 1975. Soil-water relations in oxisoils of Puerto Rico and Brazil. p. 145-154. *In:* E. Bornemisa and A. Alvarado (ed) Soil management in tropical America. North Carolina State University, Raleigh, NC.

YOST, R.S., G.C. NADERMAN, E.J. KAMPRATH AND E. LOBATO. 1982. Availability of rock phosphate as a measured by an acid tolerant pasture grass and extractable phosphorus. Agron. J. 74:462-468.

CARTAS AL EDITOR

El Sistema Internacional de Unidades

Jorge Alvarado López

Introducción

Una de las características que debe tener el lenguaje científico es el ser universal, esto es con el propósito de que entre los científicos de todo el mundo se hable el mismo "idioma". Así como existen reglas para manejar los nombres científicos de organismos vivos, los nombres de compuestos químicos, los números, los símbolos químicos, etcétera, también existen normas para el manejo de unidades y cantidades de medidas (Sistema Internacional de Unidades).

La redacción de esta nota tiene el propósito de llamar la atención de todos los miembros de nuestra comunidad científica hacia un punto que se ha descuidado mucho: la escritura y manejo de unidades. Aquí sólo se resaltarán algunos aspectos de este problema.

Aun cuando el Sistema Internacional de Unidades (SI) tiene muchos años de haber sido adoptado por los científicos como su medio de expresar unidades, en algunos miembros de nuestra comunidad (Sociedad Mexicana de la Ciencia del Suelo) todavía existe desconocimiento de las reglas de dicho sistema. Conocer el SI es importante no sólo para escribir artículos, también lo es para entender los artículos de otros.

Sistema Internacional de Unidades

El Sistema Internacional de Unidades fue aprobado como tal en 1960, por la Conferencia Internacional de Pesas y Medidas (autoridad internacional en unidades). Anteriormente ya se habían hecho algunos intentos por regular o establecer un sistema internacional de unidades.

El SI está formado por tres tipos de unidades (básicas, suplementarias y derivadas) y un conjunto de prefijos

Las unidades básicas son siete y expresan cantidades independientes, éstas son: el metro, el kilogramo, el segundo, el kelvin, la mol y la candela (Cuadro 1).

Las unidades derivadas se expresan en términos algebraicos de unidades básicas. Algunas unidades derivadas tienen nombres y símbolos especiales (newton-N-), y se usan para expresar otras unidades derivadas (Cuadro 2).

Las unidades suplementarias aún no se clasifican como básicas ni como derivadas, son sólo dos: el radián y el esterradián (Cuadro 1).

Cuadro 1. Unidades básicas suplementarias del Sistema Internacional de Unidades (American Society of Agronomy *et al.*, 1988; Thien y Oster, 1981).

Unidades	Cantidad	Nombre	Símbolo
Básicas	Longitud	metro	m
	Masa	kilogramo	kg
	Tiempo	segundo	s
	Corriente eléctrica	amperio	A
	Temp. termodinámica	kelvin	K
	Cantidad de sustancia	mol	mol
	Intensidad luminosa	candela	cd
Suplementarias	Angulo plano	radián	rad
	Angulo sólido	esterradián	sr

Cuadro 2. Unidades derivadas con nombres y símbolos especiales del Sistema Internacional de Unidades (Thien y Oster, 1981)

Cantidad	Nombre unidad	Símbolo unidad	Fórmula y definición
Frecuencia	hertz	hz	(ciclo)/s = s^{-1}
Energía, trabajo, cantidad de calor	joule	J	Nm = m^2 kg s^{-2}
Fuerza	newton	N	m kg s^{-2}
Presión, tensión	pascal	Pa	N/m^2 = m^{-1} kg s^{-2}
Potencia, flujo radiante	watt	W	J/s = m^2 kg s^{-3}
Cantidad de electricidad, carga eléctrica	culombio	C	sA
Potencial eléctrico, diferencia de potencial, fuerza electromotriz	voltio	V	W/A = m^2 kg s^{-2} A^{-2}
Capacitancia	faradio	F	C/V = m^{-2} kg^{-1} s^4 A^2
Resistencia eléctrica	ohmio	Ω	V/A = m^2 kg s^{-3} A^{-2}
Conductancia	siemens	S	A/V = m^{-2} kg^{-1} s^3 A^2
Flujo magnético	weber	Wb	Vs = m^2 kg s^{-2} A^{-1}
Densidad de flujo magnético	tesla	T	Wb/m^2 = kg s^{-2} A^{-1}
Inductancia	henrio	H	Wb/A = m^2 kg s^{-2} A^{-2}
Flujo luminoso	lumen	lm	cd sr
Iluminancia	lux	lx	lm/m^2 = m^{-2} cd sr
Actividad (radio-nucleótido)	becquerel	Bq	s^{-1}
Dosis absorbida	gray	Gy	J/kg = m^2 s^{-2}
Equivalente de dosis	sievert	Sv	J/kg = m^2 s^{-2}

Cuadro 3. Prefijos del Sistema Internacional de Unidades (American Society of Agronomy *et al.*, 1988; Thien y Oster, 1981).

Orden de magnitud		Prefijo	Símbolo
10^{18}	1 000 000 000 000 000 000	exa	E
10^{15}	1 000 000 000 000 000	peta	P
10^{12}	1 000 000 000 000	tera	T
10^{9}	1 000 000 000	giga	G
10^{6}	1 000 000	mega	M
10^{3}	1 000	kilo	k
10^{2}	100	hecto*	h*
10^{1}	10	deca**	d*
10^{-1}	0.1	centi*	c*
10^{-3}	0.001	mili	m
10^{-6}	0.000 001	micro	μ
10^{-9}	0.000 000 001	nano	n
10^{-12}	0.000 000 000 001	pico	p
10^{-15}	0.000 000 000 000 001	femto	τ
10^{-18}	0.000 000 000 000 000 001	alto	a

* Evitar su uso cuando sea posible.

** No debe usarse.

Los prefijos y sus símbolos sirven para expresar diferentes magnitudes de unidades SI (Cuadro 3).

Reglas para el uso de SI

1. Las unidades SI deben escribirse por su nombre completo o por su símbolo correcto: metro o m; kilogramo o kg.
2. Los nombres de unidades se escriben con minúscula, excepto Celsius. También los prefijos que indican potencia de 10^3 o menos y todos los símbolos (excepto aquellos derivados de nombres propios):
   joule (J), newton (N), megagramo (Mg), etc.
3. Los símbolos deben separarse de los valores numéricos:
   40m (incorrecto), 40 m (correcto).
4. Los símbolos no tienen plural; los nombres de unidades siguen las reglas gramaticales.
   Los nombres lux, hertz y siemens no tienen plural.
5. El producto de dos unidades puede indicarse por un punto o por un espacio. Ejemplo:
   N.m o N m.

6. La división de una unidad o una combinación de unidades por otra puede expresarse con una diagonal o con un supraíndice negativo: J/S o $J\ S^{-1}$.
   Sólo se permite una diagonal, es incorrecto usar dos o más: en lugar de $W/m^2/Sr$, mejor usar: $W\ m^{-2}\ Sr^{-1}$ o W/m Sr.
7. No deben usarse prefijos compuestos: $\mu\mu$ F (incorrecto), debe reemplazarse por pF.
8. Sólo debe usarse un prefijo al formar un múltiplo decimal. Generalmente, el prefijo se une al numerador, excepto cuando se usa la unidad básica kg.
9. Para separar decimales se usa el punto, no la coma, por ejemplo: 1.7 no 1,7.
10. Para separar números con más de cuatro dígitos se usa un espacio, no coma. Por ejemplo: 56 420, no 56,420.
    En cuadros se separan los números con cuatro dígitos: por ejemplo 1 000, en texto no.
11. Los símbolos no llevan punto.

Uso de unidades que no pertenecen al SI

En algunas revistas se acepta el uso de unidades que no pertenecen al SI, particularmente en las áreas agronómicas y de suelos. Los siguientes son algunos casos:

a) Se utiliza hectárea (1 ha = 10 000 m^2) para medir una área o superficie.
b) Se emplea litro (L) para medir volumen, aunque se prefiere m^3.
c) Se acepta el uso de cm para expresar medidas como son: altura de planta, ancho de surco, profundidad de suelo.
d) La densidad del suelo puede expresarse como $g\ cm^{-3}$, pero se prefiere Mg o $t\ m^{-3}$.
e) Se acepta el uso de minuto, hora, día, semana, año; sin embargo, se prefiere el segundo como unidad de tiempo.
f) Se acepta el uso de $t\ ha^{-1}$ para expresar rendimiento de cultivos.

Problemas comunes del uso de las unidades en los artículos enviados a la revista Terra.

a) Uso incorrecto de símbolos.
   Un problema que se presenta con frecuencia en los artículos es el emplear símbolos incorrectos de unidades, los siguientes son algunos ejemplos:

Unidad	Símbolo incorrecto	Símbolo correcto
Litro	l o lt	L
Mililitro	ml	mL
Tonelada	Ton o T	t
Kilogramo	Kg	kg
Hora	hr	h
Gramo	gr	g
Hectárea	Ha	ha
Segundo	seg	s
Kelvin	°K	K

b) Empleo de meq/100 g para expresar capacidad de intercambio catiónico.
   De acuerdo con el SI, debe emplearse $cmol_c/kg$.
c) Uso de mmho/cm a 25 °C para medir la conductividad eléctrica. El SI recomienda utilizar $S\ m^{-1}$ (siemens por metro); 1 mmho/cm = 1 mS/m.
d) Uso de partes por millón (ppm). Este término es ambigüo, por esta razón se recomienda utilizar unidades SI o bien aceptadas por el SI. Por ejemplo, en función del tipo de datos, puede usarse $\mu L\ L^{-1}$, $mg\ L^{-1}$ o $mg\ kg^{-1}$.
e) Uso de por ciento. En casos en que quiere expresarse la composición de una mezcla, es incorrecto hacerlo en función del porcentaje; ésta debe expresarse con base en unidades del SI. Tal es el caso de la concentración de nutrimentos en la planta.
f) Utilización de normalidad. La normalidad, unidad de concentración basada en el concepto de equivalente químico, no debe utilizarse para expresar concentración. En su lugar debe usarse el concepto de molaridad ($mol\ L^{-1}$).
g) Empleo de mμ o angstrom para expresar longitud de onda. Debe utilizarse nanómetro (nm). Por ejemplo, la longitud de onda óptima para determinar fósforo con vanadomolibdato es 470 nm, no 470 mμ ni 470 Å.

BIBLIOGRAFIA

American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. 1988. Publications Handbook and Style Manual. Madison, Wisconsin, USA.

Campbell, G. S. and J. van Shilfgaarde. 1991. Use of SI units in soil physics. J. Agron. Edu. 10:73-74.

Carballo Q., A. 1990. Guía para el uso del Sistema Internacional de Unidades. Colegio de Postgraduados, Montecillo, México.

Downs, R. J. 1988. Rules for using the International System of Units. HortScience 25:811-812.

Hesse, P. R. 1984. S. I. Units and nomenclature in soil science. FAO Soil Bulletin 28. Food and Agriculture Organization-Organization of the United Nations, Rome, Italy.

Salisbury, F. B. y C. W. Ross. 1994. Fisiología vegetal. (Apéndice A: Sistema Internacional de Unidades: uso de las unidades SI en fisiología vegetal). Traducción de V. González V. Grupo Editorial Iberoamérica, México.

Savage, M. J. 1979. Use of the International System of Units in the plant sciences. HortScience 14:492-495.

Thien, S.J. and J.D. Oster. 1981. The International System and its particular application to soil chemistry. J. Agron. Edu. 10:62-69.

Vorst, J. J., L. E. Schweitzer, and V. L. Cechtenberg. 1981. International System of Units (SI): Application to crop science. J. Agron. Edu. 10:70-72.

COMENTARIOS Y CARTAS AL EDITOR