



## FITTING MAIZE INTO SUSTAINABLE CROPPING SYSTEMS ON ACID SOILS OF THE TROPICS

W.J. HORST

University of Hannover,  
Hannover, Germany

### Abstract

One of the key elements of sustainable cropping systems is the integration of crops and/or crop cultivars with high tolerance of soil acidity and which make most efficient use of the nutrients supplied by soil and fertilizer. This paper is based mainly on on-going work within an EU-funded project combining basic research on plant adaptation mechanisms by plant physiologists, and field experimentation on acid soils in Brazil, Cameroon, Colombia and Guadeloupe by breeders, soil scientists and agronomists. The results suggest that large genetic variability exists in adaptation of plants to acid soils. A range of morphological and physiological plant characteristics contribute to tolerance of acid soils, elucidation of which has contributed to the development of rapid techniques for screening for tolerance. Incorporation of acid-soil-tolerant species and cultivars into cropping systems contributes to improved nutrient efficiency overall, and thus reduces fertilizer needs. This may help to minimize maintenance applications of fertiliser through various pathways: (i) deeper root growth resulting in more-efficient uptake of nutrients from the sub-soil and less leaching, (ii) more biomass production resulting in less seepage and less leaching, with more intensive nutrient cycling, maintenance of higher soil organic-matter content, and, consequently, less erosion owing to better soil protection by vegetation and mulch.

### 1. INTRODUCTION

Agricultural systems may be described as sustainable if the management of the resources successfully meets human needs while maintaining or enhancing the quality of the environment and conserving natural resources. Among the major threats to sustainable soil productivity related to soil acidity are: (i)  $H^+$ , Al and Mn toxicities (ii) low availability (P, Mo) and supply of nutrients (N, Ca, Mg), (iii) high nutrient (base) losses. One of the key elements of sustainable cropping systems is the use of crops with high tolerance of soil acidity that make most efficient use of nutrients supplied by soil and fertiliser. Adaptation to soil acidity is defined as the ability of a genotype to provide a yield above the average population under conditions of sub-optimal soil pH.

The main objectives of the EU-INCO Programme ERBIC 18CT 960063, on which this presentation is mainly based, are, to advance breeding strategies and breed maize cultivars with improved adaptation to acid soils high in Al and low in P; to develop screening procedures for Al resistance and P efficiency in maize, based on an improved, in-depth knowledge of underlying physiological and molecular mechanisms; to improve the quantitative understanding of the comparative contributions of genetic and agronomic approaches to sustainable maize production on acid soils.

### 2. CHIEF CONSTRAINTS

#### 2.1. Aluminium toxicity

Large variability in maize grain yield was found among genotypes, on a non-corrected acid soil as well as on a non-acid soil in Guadeloupe (Fig. 1) and in Cameroon (Fig. 2). Whereas the yields on the strongly Al-toxic and the non-acid soils were positively correlated in Cameroon, there was no relationship in Guadeloupe where the acid soil had less Al but more Mn. At both locations, one of the phenotypic characteristics that best correlated with adaptation to soil acidity was seminal root length (Fig. 3). Also, in Colombia, on a strongly acid, Al-toxic soil, root-length distribution down the soil profile revealed differences according to correction of soil acidity by liming and differences between adapted and non-adapted maize cultivars (Fig. 4).

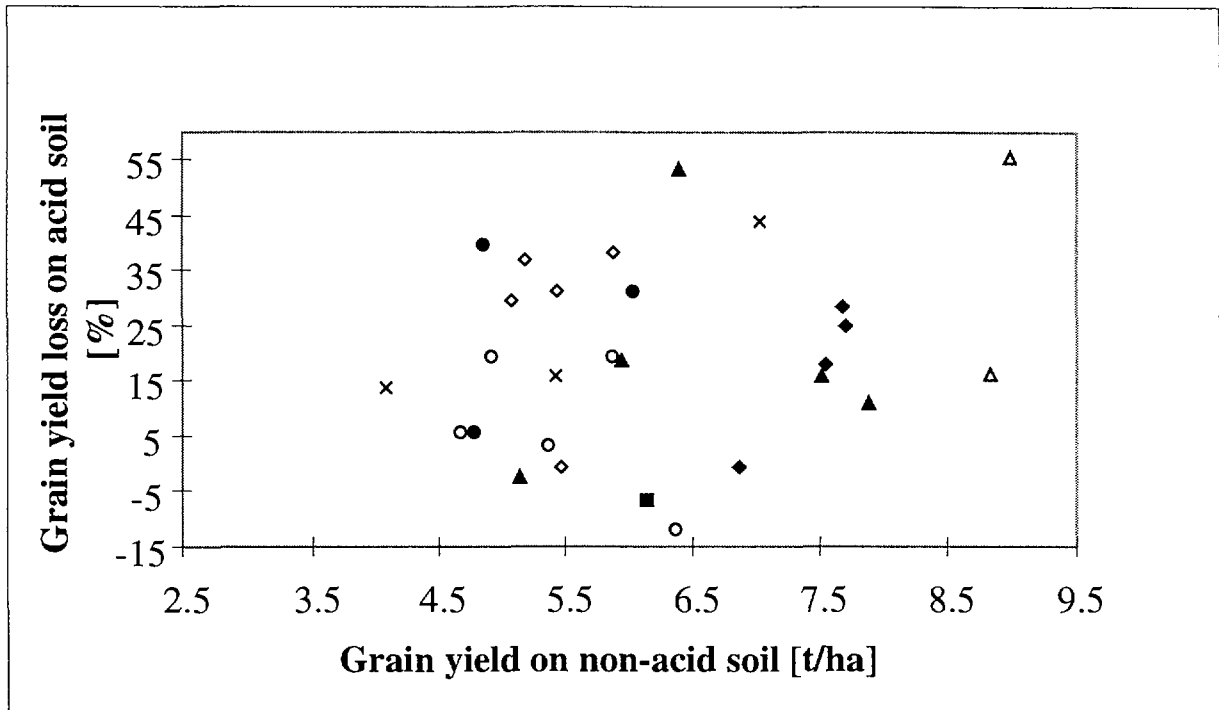


FIG. 1. Relationship between grain yield on non-acid soil (potential yield) and yield reduction of twenty-eight tropical maize genotypes grown on acid soil (C. Welcker, INRA-Guadeloupe, URPV).

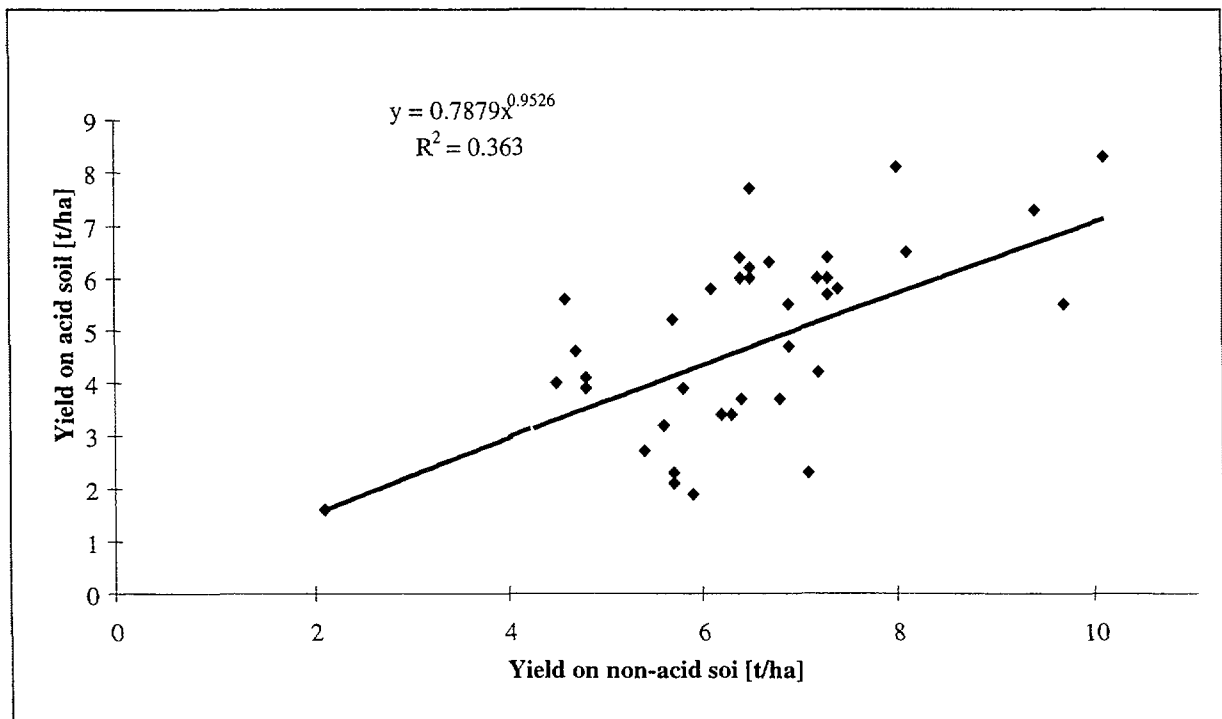


FIG. 2. Comparison of yield of maize cultivars grown on acid and non-acid soils (Ch. Thé, IRAD, Cameroon).

Inhibition of root growth typically indicates Al toxicity. The inhibition of root elongation by Al can be measured within minutes [1]; it is primarily due to accumulation in, and injury to, the distal part of the transition zone (1–2 mm from the apex) [2, 3]. Application of Al to this zone specifically and rapidly inhibits cell elongation in the elongation zone, although Al applied to this zone does not inhibit root elongation. Aluminium resistance appears to be related to the capacity to restrict Al uptake into this sensitive zone.

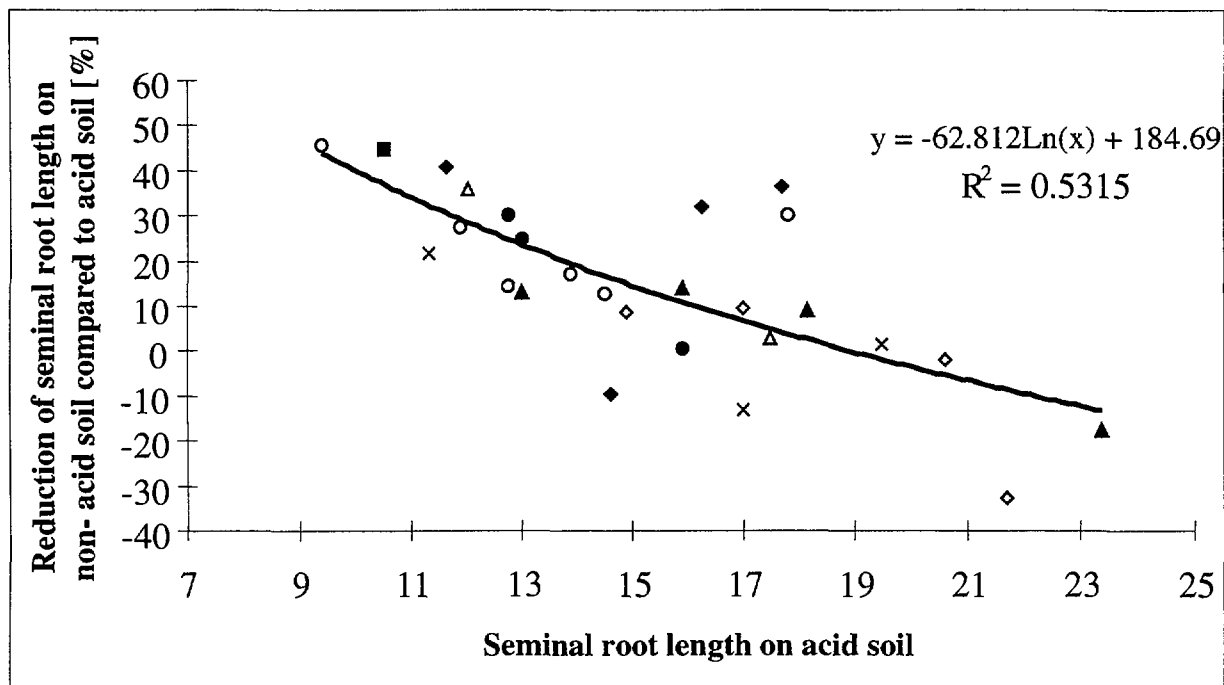


FIG. 3. Relationship between seminal root length of maize cultivars measured on acid soil and reduction of seminal root length on non-acid soil compared to acid soil (C. Welcker, INRA-Guadeloupe, URPV).

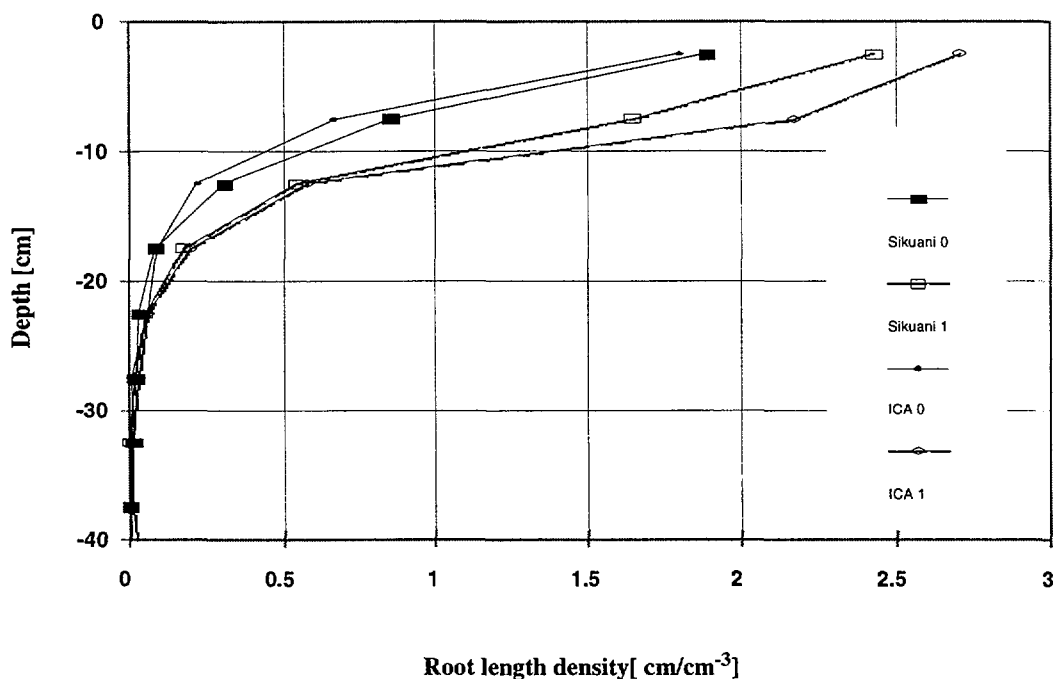


FIG. 4. Effect of maize cultivar and liming/P application on root distribution in the field experiment at CORPOICA, Colombia (J.-L. Chopard, CIRAD, France, L.A. Rojas and D. Roveda, CORPOICA, Colombia).

Based on this knowledge, a hematoxylin staining method for Al in root apices has been developed to screen rapidly for Al resistance. A rough pre-selection of genotypes appears to be possible, as has been shown for wheat [4].

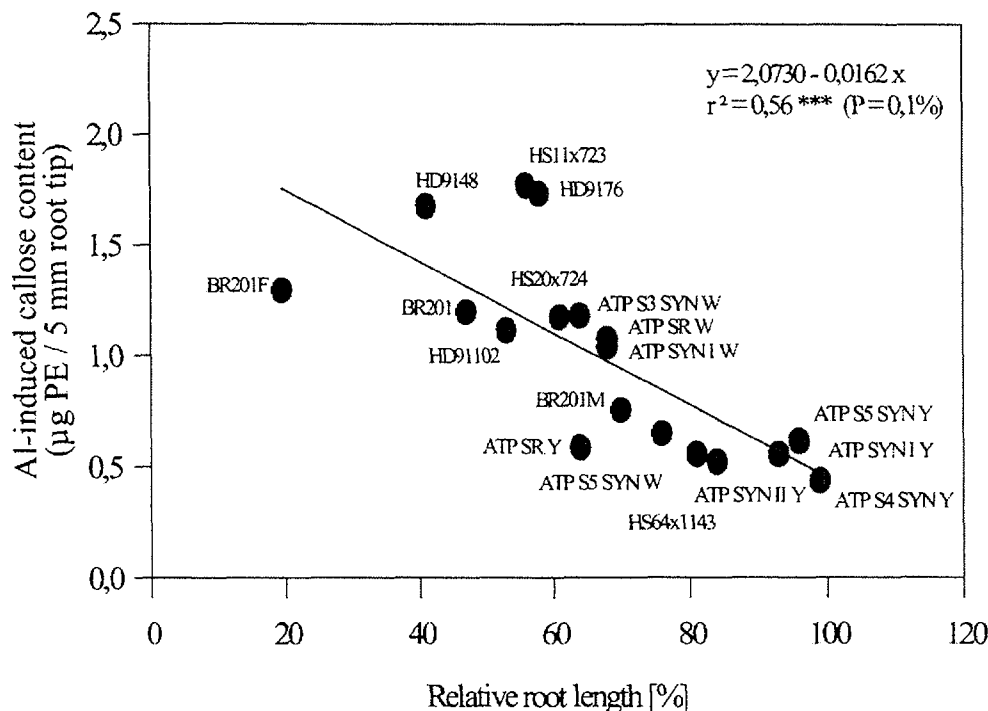


FIG. 5. Correlation between Al-induced callose contents and relative root length (RRL, +Al = 100%) of maize cultivars (RRL from CIRAD, Montpellier, France).

Induction of callose formation is a sensitive indicator of injury from Al [5], useful for comparing root apical zones [2] and maize cultivars differing in resistance (Fig. 5, [6]). This technique has been further developed into a non-destructive assay for screening for adaptation to acid soil on a single-plant basis within the CIMMYT maize-breeding programme at Cali, Colombia.

Screening maize seedlings for Al resistance with uniform exposure of the root system to Al, which does not occur under field conditions – in most cases the surface soil is less Al-toxic than the sub-soil – assumes absence of the Al-avoidance mechanism described for *Mucuna pruriens* [7]. This has been confirmed using a split-root approach (Fig. 6). Inhibition of root elongation was comparable when Al was supplied to half or the entire root system, and was independent of the P supply, with Al-sensitive and -resistant cultivars.

Evidence suggests that resistance to Al in maize is due to its exclusion from uptake into the root apex by sequestration with exuded citrate [8]. Our results show that toxicity can be modulated by the Al-binding characteristics of the pectic matrix of the root apoplast [9], suggesting an additional factor in the expression of resistance. The ameliorating effects of B [10] and Si [11], which are known to interfere primarily with cell-wall constituents, point in the same direction.

Reductions of crop yields on acid soils are due not only to direct toxic effects of Al, but also to indirect effects such as induced deficiencies of Mg and Ca. Decrease in the rhizobium/legume N<sub>2</sub>-fixing symbiosis is possible as are lower use-efficiencies of water and P through less exploitation of the soil profile and possibly also through reduced water conductivity of the roots [12].

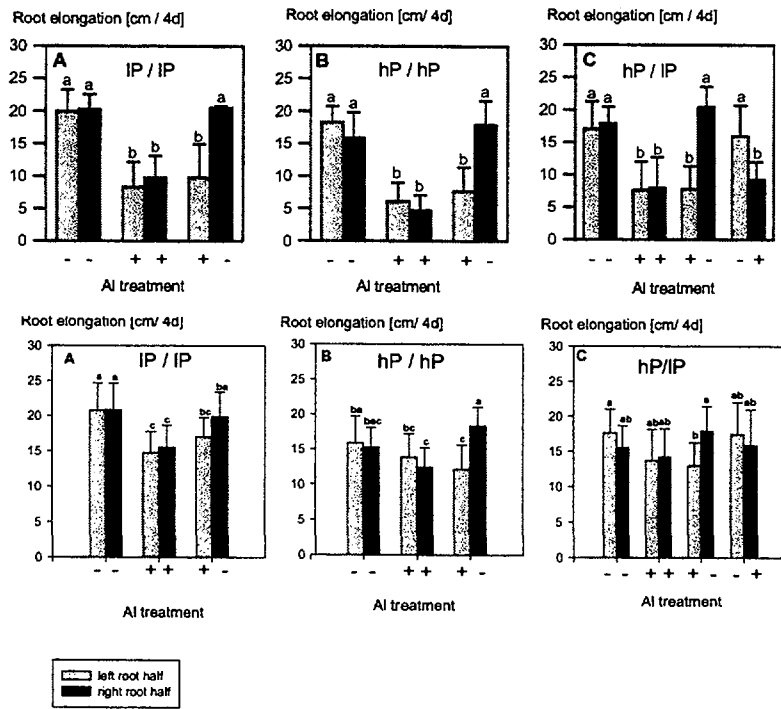


FIG. 6. Effect of Al and P supply on root elongation of maize cv. Lixis (upper) and BR201 (lower) in a split-root system.

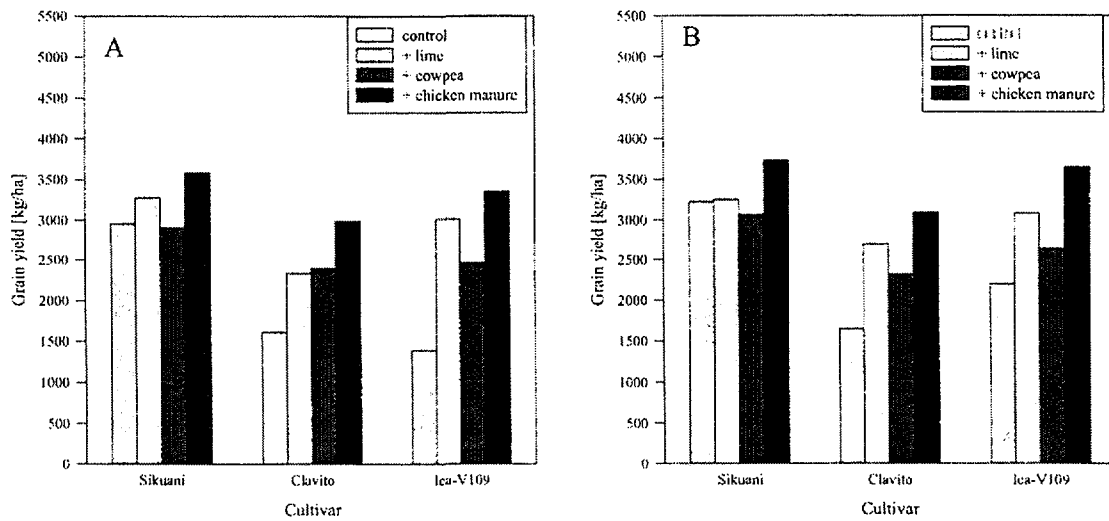


FIG. 7. Grain yields of three maize cultivars as affected by lime, cowpea green manure, or chicken manure; means of three seasons, A 25 kg P/ha, B 50 kg P/ha (L.A. Rojas et al., CORPOICA, Colombia).

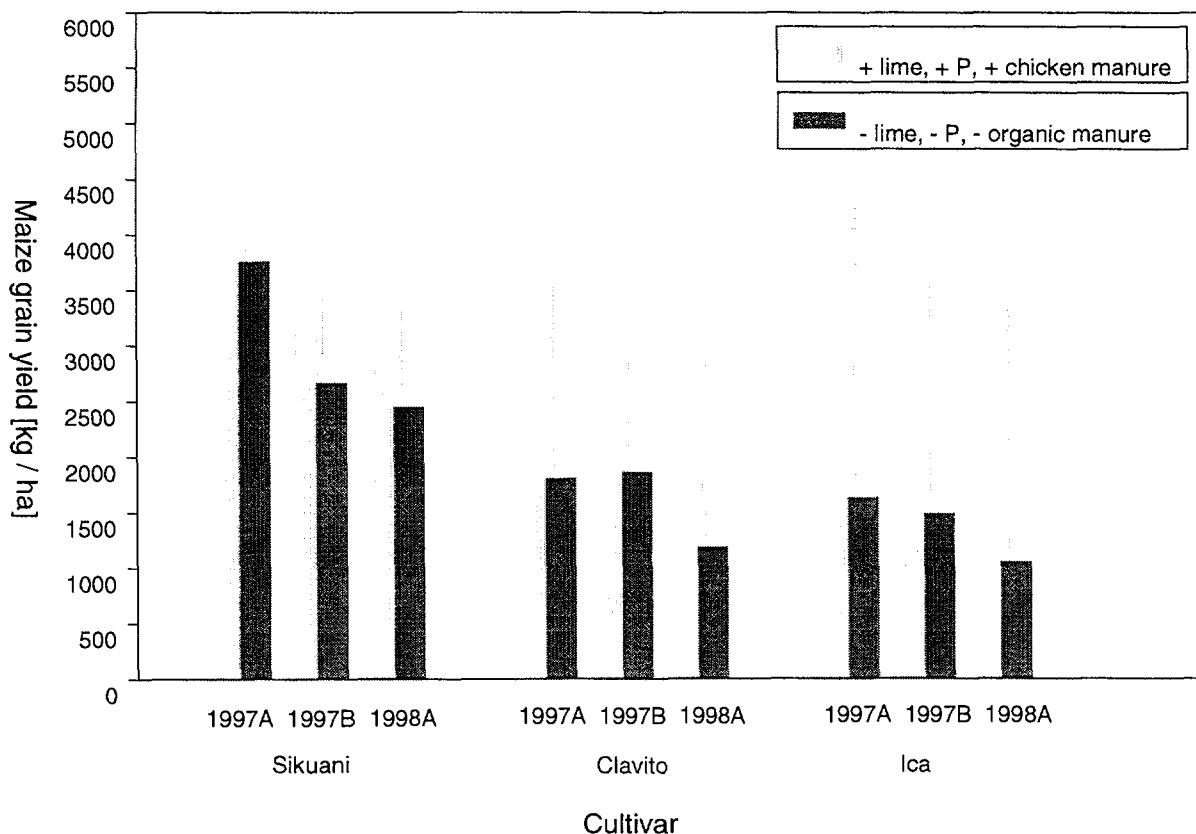


FIG. 8. Yields of three maize cultivars on an acid soil (Villavicencio) without and with correction of soil acidity.

The viability of the genetic approach to solving the problem of acid-soil infertility has been challenged repeatedly. Therefore, complex field experiments are being conducted by CORPOICA, Colombia, and IRAD, Cameroon, within the INCO programme, in order to establish the comparative contributions of genetic and agronomic approaches to sustainable maize production on acid soils. The superiority of maize cv. Sikuani, developed by CIMMYT for adaptation to acid soils of the Colombian Llanos, was clearly expressed when acidity was not corrected, independently of P supply (Fig. 7). Local, and, especially, improved non-adapted, cultivars strongly responded to lime and organic-matter application. Cowpea green manure was less efficient than chicken waste as a source of organic matter. After three seasons of cropping, yields of all cultivars declined independently of amendments, suggesting that maize monoculture is not sustainable at this location (Fig. 8). However, after only three seasons, preliminary conclusions may be premature. In Cameroon, on a highly Al-toxic acid soil, yields were low without amendments; however, acid-soil-tolerant cv. ATP-SR-Y clearly out-yielded non-adapted cv. Tuxpeno Sequia (Fig. 9). *Cassia* green manure was as effective in combating soil acidity as chicken manure. However, lime application was necessary to achieve optimum yields.

Data from Brazil suggest that optimum yields on acid soils can be achieved only with lime rates exceeding the need for Al detoxification [13]. This has been explained in terms of the important contribution of soil organic matter to the cation exchange capacity of these low-activity clay soils and its pH dependency [14]. However, maintenance of a higher soil pH requires not only continued applications of lime but also leads to accelerated decomposition of organic matter, resulting in increased CO<sub>2</sub> emissions and commensurate needs for inputs of C [15]. Too few quantitative data are available to reliably establish C balances of soils for different target pH values.

## 2.2. Phosphorus deficiency

On many acid soils, P deficiency is the second most important factor limiting maize yields, not only because of inherently low content, but especially because of non-availability to plants due to high P-fixation capacity. The use of P-efficient germplasm is not a long-term alternative to fertiliser application as it leads to mining of soil P and, ultimately, to destruction of soil fertility [16]. Although the process is likely to be slow since P uptake in traditional agriculture is usually low due to meagre yields [17, 18], agricultural productivity cannot be sustained without application of P to replace nutrients removed in the harvested product and by livestock.

Combined with strategic inputs, P-efficient germplasm will contribute to agricultural sustainability by: (i) reducing the need to adjust the soil-P status to higher levels to achieve similar productivity, a strategy that is also more demanding regarding maintenance levels of P; and (ii) increasing the efficiency of use of the applied P, which is a non-renewable resource [19]. Moreover, P-efficient crops would bring economic rates of applied P within the reach of small-holder farmers who might otherwise not use fertilisers.

Substantial genetic variation in P efficiency exists in maize, as was established in field experiments by EMBRAPA/CNPMS, Sete Lagoas, Brazil (Fig. 10). Generally, the factors that contribute to P efficiency are well established [20, 21], and can be divided into two components: (i) the efficiency of acquisition from the soil, and (ii) the efficiency of utilisation to produce yield. Phosphorus-uptake efficiency depends on traits such as root density and architecture, root-hair length and mycorrhizal infection that increases the interception of available P (which is largely immobile in soil), and root-induced changes of the rhizosphere through exudates that contribute to the mobilisation of less-available P sources. Phosphorus-utilisation efficiency depends on partitioning of P among plant parts, remobilization of P from vegetative to reproductive plant organs, and yield structure.

Whereas the principles are clearly established and plant species have been shown to adopt various strategies for P efficiency, the relative importance of these morphological/physiological traits is far from understood. Moreover, their compatibility with other plant traits required for high-yield capacity, such as N efficiency, drought resistance, disease and pest resistance, and competitiveness against weeds and companion crops in intercrops, has not been considered. For example, Lynch [22] demonstrated that higher P-uptake efficiency in *Phaseolus vulgaris* was associated with a more horizontally spread root architecture and higher density in the top-soil where available-P concentration is higher. However, such architectural adaptation of plants to low P supply reduces their capacity to acquire sub-soil water and N, reducing drought resistance and N-uptake efficiency while enhancing competitiveness for top-soil resources with crops grown in association.

Similar trades-off may result from increased P-utilisation efficiency through a higher P-harvest index (grain-P:stover-P ratio) producing more grain per unit of P taken up. A consequence of such an adaptation may be crop residues of low-P content that have less value as livestock fodder (important in small-holder farming systems) or as substrate for soil micro-organisms (important in the maintenance of soil fertility). On the other hand, a lower crop-residue decomposition rate may increase its value as mulch. While these considerations suggest the rather simple approach of increasing P-utilisation efficiency by selecting for low-P concentration in the grain, nutritive value of the grain would be decreased and seedling establishment in low-P soils may be adversely affected [23].

As indicated above, P efficiency is a multifaceted trait that is influenced a range of environmental factors. On one hand, this complicates the derivation of general conclusions from field screening, whereas, on the other hand, it makes field screening for this complex adaptation obligatory.

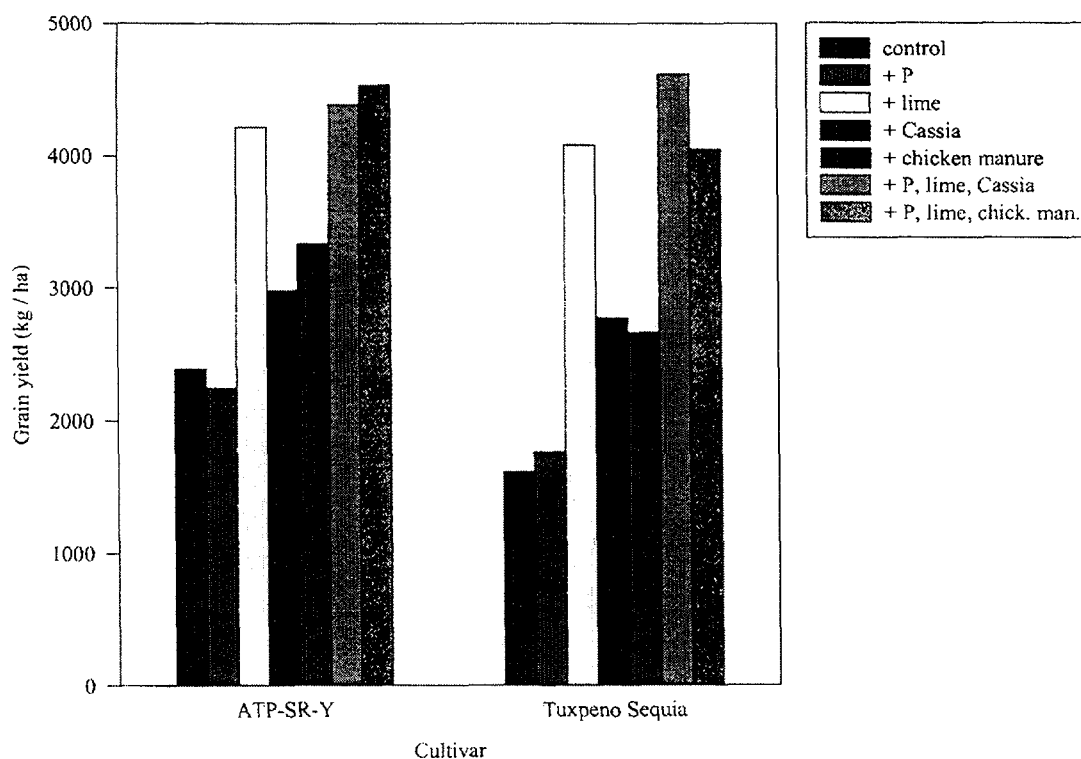


FIG. 9. Grain yields of two maize cultivars as affected by lime, Cassia green manure, and chicken manure (Ch. Thé, IRAD, Cameroon).

Although screening for P efficiency in the seedling stage using small pots filled with soil low in available P certainly reveals genetic variation in P uptake, agreement with field performance is often unsatisfactory [24]. A highly significant positive correlation between seed-P content and P uptake (Fig. 11) reveals the need for circumspection in interpreting P-uptake data. The quantification of P uptake and mobilisation, against a high background of seed P, may be achieved using isotope techniques [25, 26]. Pre-selection for P efficiency on the basis of physiological, morphological and molecular traits, therefore, is a prerequisite for more-efficient breeding for P efficiency.

Plant characteristics considered of primary importance for P efficiency are: (i) fine roots and high root density [27], (ii) long root hairs [28], (iii) P mobilization through root exudates [29], (iv) susceptibility to infection by mycorrhizal fungi especially in acid soils where root growth is inhibited [15], (v) reduced sensitivity to P deficiency in formation of yield components (flower initiation and grain set) [30], and (vi) less sensitivity in terms of leaf area and photosynthesis at early growth stages (also important for flower initiation and grain set) [31, 32]. Germplasm with desirable agronomic characteristics needs to be evaluated for these components; phenotypic markers for such traits need to be identified, and convenient screening techniques developed.

Although molecular markers have recently been used to support selection for P efficiency, their use for screening maize at this stage would be premature. Present investigations focus on acid phosphatases that are expressed under P deficiency [33]. However, the role of phosphatases in P acquisition is still uncertain [34]. In cropping systems in which P recycling from crop residues is significant, root-surface acid phosphatase cannot be excluded. Better understanding of the key plant characteristics for P efficiency and the role of P-efficient germplasm in sustainable crop production is necessary before costly molecular approaches can be used effectively. There is little doubt that morphological root characteristics are most important in determining the efficiency of uptake of nutrients of low mobility, such as P. Among those characteristics, root-hair length, which strongly and specifically responds to low P supply [35] is especially attractive because its contribution to P acquisition might be particularly energy-/C-efficient.



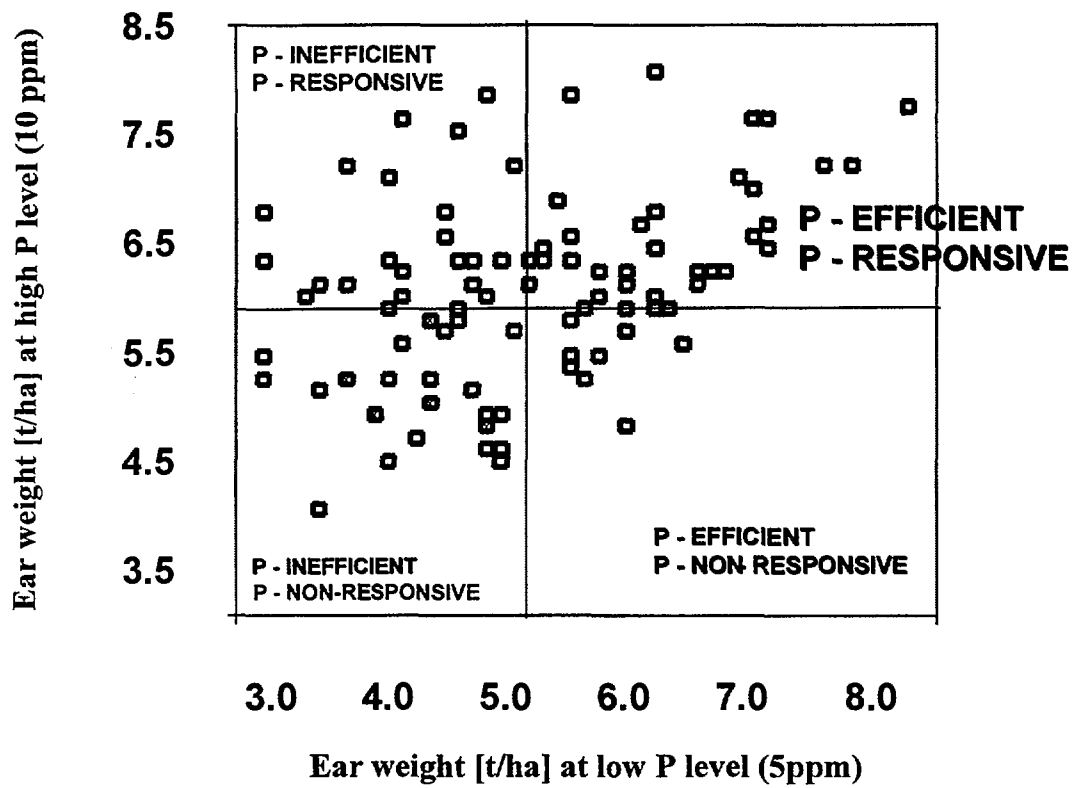


FIG. 10. Grain yields of one hundred maize hybrids at two levels of P (EMBRAPA/CNPMS, Sete Lagoas, Brazil).

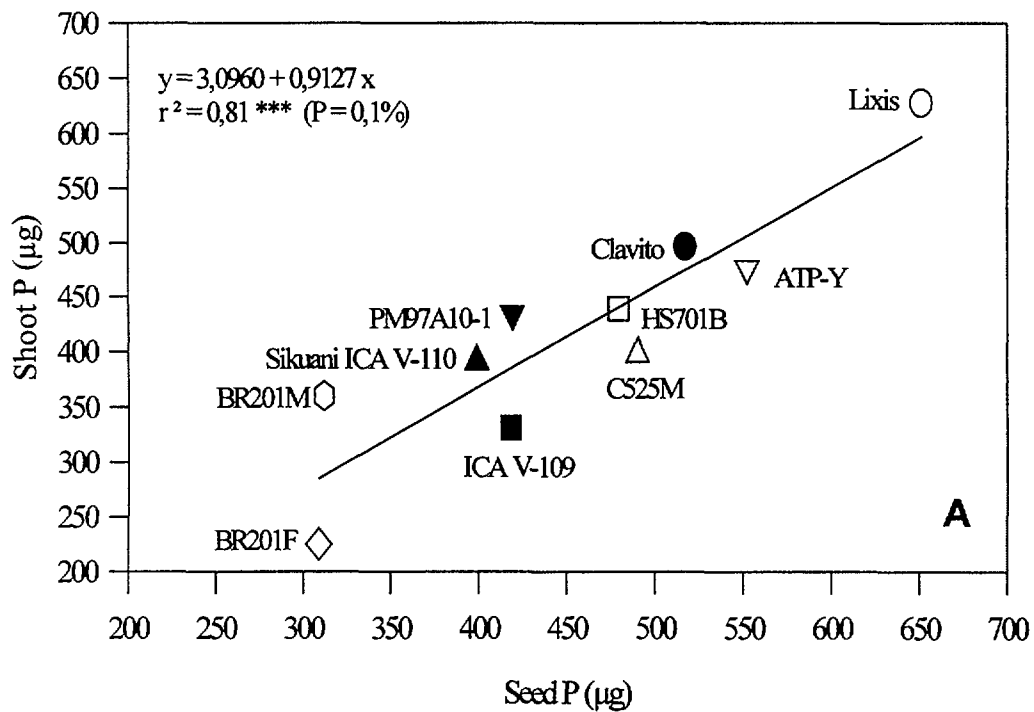


FIG. 11. Relationship between shoot-P uptake and seed-P content for ten maize cultivars grown in a P-deficient soil.

Some plant species, such as *Lupinus albus* [36] and *Cajanus cajan* [37], have evolved the capacity to mobilize sparingly soluble soil P by excretion of organic acids. We have indications that, in maize, genetic variation for excretion of protons (Fig. 12) and for mobilization of soil P through root exudates (Fig. 13) exists. There is preliminary evidence that incorporation of such species/cultivars into mixed cropping systems or rotations may improve the P nutrition of less-P-efficient components [34, 38], increasing the overall P efficiency of that cropping system. This may be due to the P-inefficient component having access to mobilised fractions of P made available by the P-efficient component, or improved physical and biological soil characteristics leading to increased infection by mycorrhiza (Fig. 14).

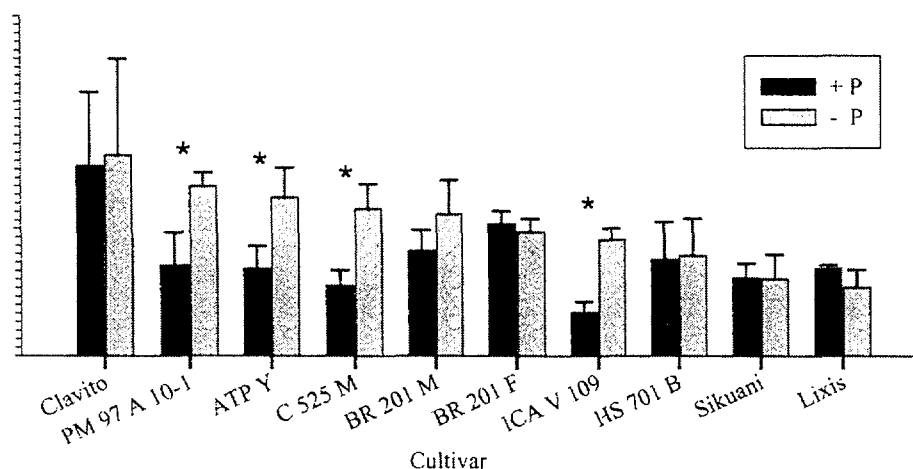


FIG. 12. Net proton excretion of maize cultivars as affected by P supply during preculture for 10 days in nutrient solution.

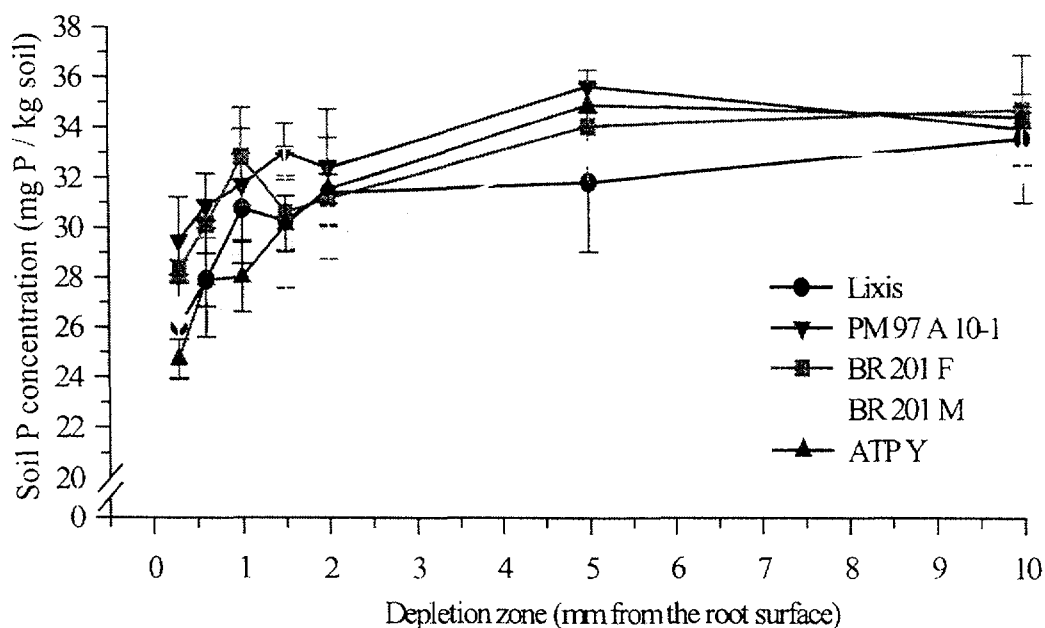


FIG. 13. Concentration of  $\text{NaHCO}_3$ -extractable inorganic soil P at the soil/root interface of maize cultivars grown.

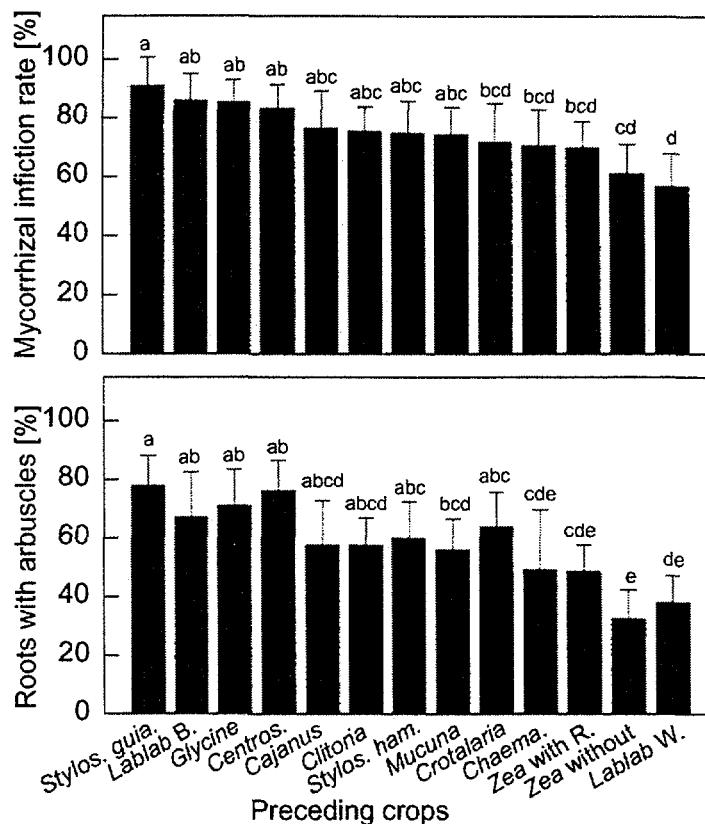


FIG. 14. Influence of preceding crops on mycorrhizal infection and roots with arbuscles in maize.

### 3. CONCLUSIONS

In conclusion, large genetic variability exists in the adaptation of plants to acid soil. There is a range of morphological and physiological characteristics that contribute to acid-soil tolerance. There is a need to better characterise these properties at the molecular level and to systematically select for them. Incorporation of acidity-tolerant species and cultivars will contribute improved nutrient efficiency to the cropping system as a whole, and thus reduce fertiliser needs.

The application of nuclear techniques may facilitate and enhance scientific progress especially in the following areas:

- Quantification of morphological root characteristics and rooting patterns,
- Water-use efficiency as affected by soil acidity and plant adaptation,
- Establishment of C and N budgets of cropping systems as affected by soil pH and crop management,
- Quantification of the P-mobilisation capacity of crops and cropping systems,
- Molecular characterisation of plant-adaptation mechanisms.

### ACKNOWLEDGEMENT

The financial support of part of the presented work by EU within the INCO Project ERBIC 18CT 960063 is gratefully acknowledged.

## REFERENCES

- [1] Llungany, M., et al., Monitoring of aluminium-induced inhibition of root elongation in four maize cultivars differing in tolerance to aluminium and proton toxicity, *Z. Pflanzenernähr. Bodenk.* **157** (1995) 447–451.
- [2] Sivaguru, M., Horst, W.J., The transition zone is the most aluminium-sensitive apical root zone of *Zea mays* L., *Plant Physiol.* **116** (1998) 155–163.
- [3] Sivaguru, S., et al., Impacts of aluminium on cytoskeleton and morphological organization of the maize root apex, *Plant Physiol.* **119** (1999) 1073–1082.
- [4] Polle, E., et al., Visual detection of aluminum tolerance levels in wheat by hematoxylin staining of seedling roots, *Crop Sci.* **18** (1978) 823–827.
- [5] Wissemeier, A.H., et al., Aluminium induced callose synthesis in roots of soybean (*Glycine max* L.), *J. Plant Physiol.* **129** (1987) 487–492.
- [6] Horst, W.J., et al., Induction of callose formation is a sensitive marker for genotypic aluminium sensitivity in maize, *Plant Soil* **192** (1997) 23–30.
- [7] Hairiah, K., et al., Tolerance and avoidance of Al toxicity by *Mucuna pruriens* var. Utilis at different levels of P supply, *Plant Soil* **171** (1995) 77–81.
- [8] Pellet, D.M., et al., Organic acid excretion as an aluminium-tolerance mechanism in maize (*Zea mays* L.), *Planta* **196** (1995) 788–795.
- [9] Horst, W.J., et al., Does aluminium affect root growth of maize through interaction with the cell wall-plasma membrane-cytoskeleton continuum? *Plant Soil* (in press).
- [10] Lenoble, M.E., et al., Prevention of aluminium toxicity with supplemental boron. I. Maintenance of root elongation and cellular structure, *Plant Cell Environ.* **19** (1996) 1132–1142.
- [11] Corrales, I., et al., Influence of silicon pretreatment on aluminium toxicity in maize roots, *Plant Soil* **190** (1997) 203–209.
- [12] Blamey, F.J.C., et al., In vitro evidence of aluminium effects on solution movement through root cell walls, *J. Plant Nutr.* **16** (1993) 555–562.
- [13] Raij, B. van, Quaggio, J.A., “Methods used for diagnosis and correction of soil acidity in Brazil: an overview”, *Plant-Soil Interactions at Low pH* (Moniz, A.C., et al., Eds.), Bras. Soil Sci. Soc., Campinas, SP, Brazil (1997) 205–214.
- [14] Goedert, W.J., et al., “Nutrient use efficiency in Brazilian acid soils: Nutrient management and plant efficiency”, *Plant-Soil Interactions at Low pH* (Moniz, A.C., et al., Eds.), Bras. Soil Sci. Soc., Campinas, SP, Brazil (1997) 97–104.
- [15] Siqueira, J.O., Moreira, F.M.S., “Microbial populations and activities in highly-weathered acidic soils: highlights of the Brazilian research”, *Plant-Soil Interactions at Low pH*, (Moniz, A.C., et al., Eds.), Bras. Soil Sci. Soc., Campinas, SP, Brazil (1997) 139–156.
- [16] Sanchez, P.A., et al., “Soil fertility replenishment in Africa: An investment in natural resource capital”, *Replenishing Soil Fertility in Africa* (Buresh, R.J., et al., Eds.), Soil Sci. Soc. Am., Madison (1997) 574 pp.
- [17] Buerkert, A., Hiernaux, P., Nutrients in the West African Sudano-Sahelian zone: losses, transfers and the role of external inputs, *Z. Pflanzenernähr. Bodenk.* **161** (1998) 365–383.
- [18] Lynch, J.P., The role of nutrient-efficient crops in modern agriculture, *J. Crop Prod.* **1** (1998) 241–264.
- [19] Helyar, K.R., Efficiency of nutrient utilization and sustaining soil fertility with particular reference to phosphorus, *Field Crops Res.* **56** (1998) 187–195.
- [20] Baligar, V.C., Duncan, R.R., *Crops as Enhancers of Nutrient Use*, Academic Press, Inc. San Diego (1990).
- [21] Sattelmacher, B., et al., Factors that contribute to genetic variation for nutrient efficiency of crop plants, *Z. Pflanzenernähr. Bodenk.* **157** (1994) 215–224.
- [22] Lynch, J.P., “Root architecture and phosphorus acquisition efficiency in common bean”, *Radical Biology: Advances and perspectives on the function of plant roots* (Flores, H.E., et al., Eds.), *Current Topics Plant Physiol.: Ann. Am. Soc. Plant Phys.*, **Series 18** (1997) 81–91.

- [23] Dinkelaker, B., Genotypische Unterschiede in der Phosphateffizienz von Kichererbse (*Cicer arietinum* L.), PhD Thesis, Univ. Hohenheim, Stuttgart (1990).
- [24] Fox, R.H., Selection for phosphorus efficiency in corn, *Comm. Soil Sci. Plant Anal.* **9** (1978) 13–37.
- [25] Fardeau, J.C., et al., The role of isotopic techniques on the evaluation of the agronomic effectiveness of P fertilisers, *Fert. Res.* **45** (1996) 101–109.
- [26] Zapata, F., Axmann, H., <sup>32</sup>P isotopic techniques for evaluating the agronomic effectiveness of rock phosphate materials, *Fert. Res.* **41** (1995) 189–195.
- [27] Horst, W.J., Genotypic differences in phosphorus efficiency of wheat, *Plant Soil* **155/156** (1993) 293–296.
- [28] Caradus, J.R., Genetic differences in the length of root hairs in white clover and their effect on phosphorus uptake”, *Proc. 9th Int. Plant Nutr. Coll. (SCAIFE, A., Ed.), Warwick* (1982), Commonwealth Agricultural Bureau, Slough (1982) 84–88.
- [29] Hoffland, E., et al., Solubilization of rock phosphate by rape. II. Local root exudation of organic acids as a response to P starvation, *Plant Soil* **113** (1989) 161–165.
- [30] Horst, W.J., et al., Differences between wheat cultivars in acquisition and utilisation of phosphorus, *Z. Pflanzenernähr. Bodenk.* **159** (1996) 155–161.
- [31] Barry, D.A.J., Miller, M.H., Phosphorus nutritional requirement of maize seedlings for maximum yield, *Agron. J.* **81** (1989) 95–99.
- [32] Cross, H.Z., Selecting for rapid leaf expansion in early-maturing maize, *Crop Sci.* **30** (1990) 1029–1032.
- [33] Trull, M.C., Deikman, J., “*Arabidopsis thaliana*: a model system for examining plant response to phosphorus starvation”, *Radical Biology: Advances and perspectives on the function of plant roots*, (Flores, H.E., et al., Eds.), *Current Topics in Plant Physiology*, *Ann. Am. Soc. Plant Phys.*, **Series 18** (1998) 5966.
- [34] Kamh, M., Mobilization of soil and fertiliser phosphate by cover crops, *Plant Soil* **211** (1998) 19–27.
- [35] Bates, T.R., Lynch, J.P., Stimulation of root hair elongation in *Arabidopsis thaliana* by low phosphorus availability, *Plant Cell Environ.* **19** (1996) 529–538.
- [36] Gardner, W.K., et al., The acquisition of phosphorus by *Lupinus albus* L. III. The probable mechanism by which phosphorus movement in the soil/root interface is enhanced, *Plant Soil* **70** (1983) 107–124.
- [37] Ae, N., et al., Phosphorus uptake of pigeon pea and its role in cropping systems of the Indian subcontinent, *Science* **248** (1990) 477–480.
- [38] Horst, W.J., Waschkes, C., Phosphatversorgung von Sommerweizen (*Triticum aestivum* L.) in Mischkultur mit Weißer Lupine (*Lupinus albus* L.), *Z. Pflanzenernähr. Bodenk.* **150** (1987) 1–8.