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1. Objectives

The objective of the project conducted by CIRAD was:
- The screening of maize germplasm for root growth resistance to Al.
- The characterisation of acid soils to determine the first limiting factor for maize growth.
- The development of a simulation model that allows to assess the relative importance of the factors determining seedlings growth on acid soils (soils parameters, soil solution, plant parameters) and finally to predict the performance of a seedling in a specific soil.
- The effects of soil management studying on root growth and distribution in the field.

2. Activities

2.1. Screening

Cultivars from experiment sites of Colombia, Cameroon, Guadeloupe and Brazil were compared with Al-sensitive and Al-tolerant check cultivars from Brazil C525M and HS701B first tested in a previous STD3 programme. The screening method is the one set up in a previous STD3 programme. Defined Al tolerance indexes were root growth, relative root growth and Al content of root expressed per unit of root surface. Relative root length, root length and root Al content per surface unit are normed from 0 to 100 with respective reference cultivar values from screening test in nutrient solution with or without Al 15µM.

2.2. Soil analyses

They related mainly to the sites of Ebolowa to Cameroon, Libertad to Colombia, Petit Bourg to Guadeloupe. They consisted of analyses of soil characterisation, analyses of samples of field experiment, analyses more specific for the development of an exchange model between the soil and the plant. Tropical acid soils are characterised by their colloids content with pH dependent variable charges (organic matter, hydroxides) and their kaolin clays with fixed charges. Plant/soil interactions require the knowledge of the respective values of both variable and fix soil charges, the intrinsic association constants between these charges and cations in solution (specially Al and Ca), the kinetic equation for Al release. We also evaluated the effect of biological activity and nitrogen mineralization on soil solution and exchange complex behaviour.

Dissolution kinetics was carried out at pH 3.5, 4.0 and 4.5 in soil column washed with $CaCl_2$ 200µM until a stationary state of Al solubility was reached (between 30 to 50 hours). Kinetics is characterised by a peak whose intensity is pH dependent. The rate of peak appearance and the amounts of dissolved Al are also pH dependent. Stationary state is reached 30 hours later at pH 4.5. These results lead us to consider a kinetic equation for the most Al soluble forms and incorporate this equation in the model with adjusted parameters <u>for every soil</u>.

Evaluation of the soil variable charges was carried out by measurement of zero salt effect point, pH0. CEC measurement was carried out with the Gilmann method modified by

ORSTOM. This method analyses adsorbed ions on a Ca-form soil at different pH. Fix CEC (CECf) is equal to:

$$CECf = [Al^{3+}] + [Ca^{2+}] - [Cl^{-}]$$

We evaluated the measurement errors of CECv by assessment of used H^+ quantities for the dissolution of Al hydroxides and H^+ quantities placed on exchangeable form, these quantities being initially evaluated as potential determining ions. Finally, the model calibration will be produced by using total CEC at pH 7 (ammonium acetate method) supposing that all potential determining ions are dissociated, fix CEC, and adjusting model parameters for measured variable CEC at the cobaltihexamine chloride pH. Ca/Al ratio from 30 to 0.1 was used to carry out Al-Ca exchange isotherms. Concentrations levels was the same one that cultivated acid soil solutions, so initial Al and Ca concentrations was contained between 10 and 200 µM. Measurement was carried out between pH 4.0 and pH 4.5.

Effect of soil organic compounds mineralization was carried out incubating soil with 2/3 maximum moist capacity for 90 days. pH analysis of 1/1 extracts show that ammonium making process before nitrification leads to a low pH increasing during the firsts 21 days of experiments, followed by a pH decrease as far as pH 4.0. Soluble Al and N-NO3 increased when pH decreased. Calcium, magnesium and ammonium concentrations increased in solution so.

2.3. Simulation model

The dynamic model describes the evolution of a culture substrate composed of a solution, a Donnan free space and a solid phase of soil, which are likely to exchange mineral elements. According to Nernst equation, concentrations in the diffuse layer phase are such that:

$$\forall i \in [1, n] \qquad \bar{a}_i = a_i \exp\left(-\frac{z_i F \psi}{RT}\right) \qquad [1]$$

Where z_i is the valence of ion i considered among the n ions in solution, a_i and $\bar{a}_i$ are its activity in the free solution and in the Donnan free space, F is the Faraday constant, R the perfect gas constant, T the absolute temperature and ψ the electrostatic potential of the Donnan free space. The law of mass action is applied to the local activities $\bar{a}_i$ assuming that the divalent ions are associated with two binding sites close to the exchange complex, i.e.:

$$\forall i \in [1, k] \qquad \overline{R_{z_i} X} = K_i \, \bar{a}_i \, \frac{\bar{R}}{z_i} \qquad [2]$$

Where $\overline{R_{z_i} X}$ is the concentration of cation X bound to the binding sites, K_i is the affinity constant of this cation for the binding sites, $\bar{R}$ is the concentration of non-associated binding sites, and k the number of cations in solution. The hypothesis has been extended here to the case of Al^{3+}, this trivalent ion being assumed to be associated with three neighbouring binding sites. The solid phase of aluminium hydroxide dissolves or precipitates in accordance with a kinetic law of a general nature:

$$\left(\frac{dC}{dt}\right)_{Al(OH)_3} = L_{Al(OH)_3}\left(\mu - \mu_e\right) \qquad [3]$$

Where $\left(\frac{dC}{dt}\right)_{Al(OH)_3}$ is the specific flux (mol L^{-1} s^{-1}), $L_{Al(OH)_3}$ the kinetic constant of the reaction (mol L^{-1} s^{-1}), and μ and μ_e the instantaneous and equilibrium chemical potentials of the reaction.

By analogy, the Donnan free space of the soil is assumed to release or bind ions according to a kinetic law that can be written as:

$$\left(\frac{dC_i}{dt}\right)_{soil} = L_{soil}(\psi - \psi_e) \qquad [5]$$

with
$$\psi - \psi_e = \frac{RT}{z_i F}\ln\left(\frac{\bar{a}_i}{\bar{a}_{i,e}}\right) \qquad [6]$$

Where L_{soil} is the kinetic constant of the exchange reaction (mol L^{-1} s^{-1}) assumed to be identical for all the ions, ψ and ψ_e are the instantaneous and equilibrium potentials, $\bar{a}_i$ the activity of species i in the Donnan free space and $\bar{a}_{i,e}$ its value if the Donnan free space was in equilibrium with the free solution.

The culture device is represented in figure 1. It consisted in producing a root mat which put in contact with a fine plate of soil (3mm) through a polyamide net of mesh 0.2µm. A filter paper tape placed under the plate of soil made it possible to feed the plant starting from a nutritive solution of known composition. The preparation of sowing and the analyses of soil and plant were described beforehand (Calba et al. 1999). The root mat (thickness 3mm) developed between the canvas and the net. Samples of Colombia and Cameroon were placed in cavities of diameter 5cm and 3mm thickness of the device then humidified and laid out on tanks containing of the nutritive solutions with K^+ 500µM and NH_4^+ 750µM. The two parts of the device were put in contact. After 14 days of culture, the roots and the soil were separate

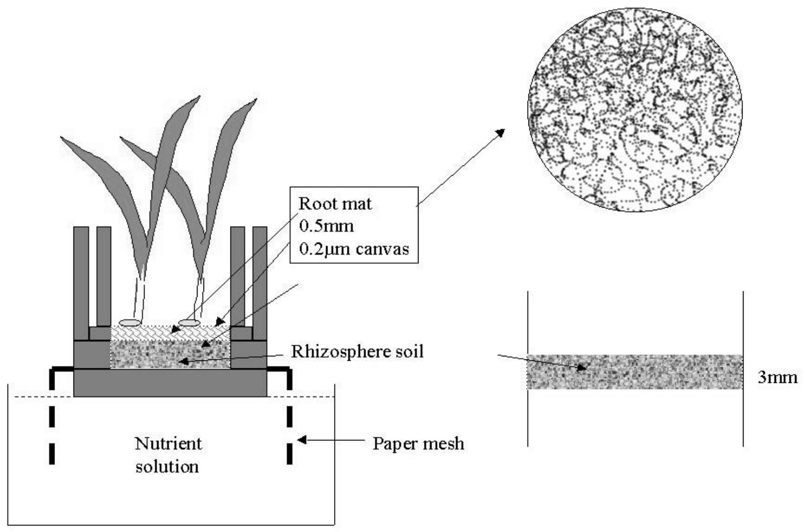


Fig. 1: Culture device

2.4. Soil management effects on root growth

Activities can be split in three parts:

Methodology studies. A technology and a model have been recently proposed, allowing to estimate root length density from root counts (grid method) on soil profiles (Chopart and Siband 1999). A model was validated in African conditions. A first preliminary test has been

conducted in local Colombian conditions. During the INCO project software “RACINE” has been developed in Windows configuration. It was used to manage field root data and describe root length density distribution in the profile from root counts, using the published model (Chopart and Siband 1999).
Transfer of technology. An important part of contacts between CIRAD and CORPOICA was focalised about formation and transfer of technology about root studies at field conditions with “grid method”. During a first trip in Colombia, it has been transferred the root counts method and software RACINE. During a second one it has been transferred the “cube method” in order to describe root length density from root counts on soil profiles, and associated methods (root length measurements). CORPOICA’s INCO partners went two times at Montpellier (1998 and 1999) and during these stays we analysed root results together.
Agronomic studies. Thanks to transfer of technology and methodology studies, it was possible to conduct, during two years, a study about soil management effect (Organic Matter and Lime) on maize root growth and distribution in an acid soil at field conditions.

3. Results achieved

3.1. Screening

We considered three classes of cultivars defined by their performances in the field in response to the correction of the soil acidity, high Al-tolerant (HT), Al-tolerant (T), Al-sensitive (S). We considered that the intermediate varieties were classified like sensitive. The classification of the varieties tested according to an index consisted of the average of the normed values relative length of the roots and Al content expressed by unit of root surface ($\mu g.cm^{2-1}$). Values are normed with reference cultivars HS701B (Al=100, RRL=0) and C525M (Al=0, RRL=100). It appears that the index used discriminate well the cultivars HT (except HD9148) which are in the class index>70%, all sensitive cultivars Al are classified with one index<30%. Our results show that the only determination of the relative root growth is not sufficient to separate correctly from the sensitive or tolerant varieties. On the other hand the use of an Al index to associate with RRL makes it possible to distinguish without ambiguity the sensitive and very tolerant cultivars. We found previously (Calba et al. 1997) that varieties sensitive to Al adsorbed more Al per unit of root length than the Al-tolerant varieties. The use of the two indices Al and root growth (RL) make it possible to separate all the very Al-tolerant cultivars RL>50%, compared to the cultivars most sensitive. This last method makes it possible to be freed from the realisation of a control test without Al, but it is less precise to separate the Al-sensitive and Al-tolerant cultivars. On the other hand, the method used request a great rigour in control of the pH. We showed (Calba et al. 1999) that the pH optimum of Al adsorption was located between pH 4.3 and pH 4.4. It is necessary to standardise the results obtained using two Al-sensitive and Al-tolerant references in order to minimise the effect of the operating conditions on the results. This poses the problem of the choice of the references. In our work, if Al-tolerant reference were quite selected, the Al-sensitive reference was not most sensitive. Nevertheless, it appears that the method of screening authorises the comparison of series of cultivars for a set of reference given. However, the intermediate varieties of resistance remain difficult to classify.

3.2. Soil analysis

Samples from Cameroon, horizons 0-30cm, are characterized by high clay content (more than 50%), pH (water) ranged from 4.6 (0-10cm block1) to 5.2 (20-30cm block2), high content of exchangeable Al (1.6 to 2.5 meq%) and CEC close to 4 meq%. Per cent saturation of

exchangeable alkaline cations is low in the horizons below 10 cm depth and this soil is very likely phosphorus deficient.
The soil from Colombia is more sandy (>60% sand) with CEC less than 2 meq% and pH (water) ranged from 4.9 to 5.4. Exchangeable Al is less than 1meq% and this soil is phosphorus deficient. The lack of information on the experimental device did not allow a statistical analysis of treatment effects, but we observed a spatial heterogeneousness within the check samples.
The soil of Guadeloupe, deforested at the end of the years 1960 was put in fodder culture in the years 1970 (stylosanthes) and had an episodic occupation always by fodder in the years 1980 or was lied in fallow. It was limed in the years 1990 for plantation of Mahogany in particular in the piece known as limed. The results of available P obtained on the soil, respectively 13.7ppm ± 4.8 and 16.1 ±4.9 for the not limed and limed parts show that this soil is phosphorus deficient.

It appears that the effect of lime on the pH is limited on the soils of Cameroon and Colombia, it is more significant in the case of the soil of Guadeloupe. So exchangeable Al decreases in a significant way only in the case of the soil of Guadeloupe. In all the case, the effect of lime is observed on exchangeable Al (reduction) and Ca and exchangeable Mg (increase). It appears that the fertilisation P remains insufficient in the soils of Guadeloupe and which is very heterogeneous in the soils of Colombia and Cameroon. The effect of the organic matter on the parameters related to the Al toxicity (pH, exchangeable Al, Ca and Mg) is a function of the added organic matter. Cowpea increases exchangeable Al slightly and decreases the pH, whereas chicken manure alone or associated with lime decreases exchangeable Al and increases exchangeable Ca significantly. The effect on the pH is a function of the value buffer of the soil.

It appears also that the lime treatments and organic matter + lime act effectively on the parameters simulated using the model, pH, Al, Ca and exchangeable Mg. The manure containing animal excrements are effective, on the other hand the vegetable residues can have an action limited on these parameters even a negative effect, acidification by nitrification. A question arises on the homogeneity of the plots with respect to their exchangeable Ca content, it would be necessary to analyse the distribution of this element before the installation of the experimental tests taking into account the Ca importance in the response of the cultivars to aluminium toxicity.

Measurement of surface charges distribution, Al dissolution kinetics, evolution of soil solution composition and exchange complex with pH and ionic strength, should allow us now to calibrate the ionic exchange model of soil. The effect of biological activity on soil solution composition and the importance of N evolution on plants mineral nutrition and rhizospheric ions fluxes require to clarify the dynamic of the whole soil/plant system in order to validate the model.

3.3. Simulation model

The numerical data obtained by the analytical methods for the acid soil characterisation, soluble and exchangeable elements, were used to calibrate the model. These methods, titration, exchange, incubation allow to obtain different ratio Al/Ca in solution, various Al levels adsorbed on the exchange complex, and this in a very wide range of pH. For each set of results obtained with the various analytical methods, the concentration of the elements in solution was entered the model rhizodyn and the intrinsic exchange constants were defined by

adjustment of the values of the adsorbed elements fitted by the model compared to the measured experimental values: (i) Al, Ca, Cl, pH for the methods of Gilman and isotherms of Al/Ca exchange, (ii) Al, Ca, Mg, K, NH_4, NO_3, SO_4, Cl, pH for incubations.
The fit of exchange constant was carried out on the soils of Columbia and Cameroon by using an exchanging system with 2 or 3 sites. The exchanger with 2 sites, one with variable charge, the other with permanent charge, allows simulating the experimental results obtained with Al and Ca on the soil of Columbia. The respective affinity of the ions K, Al, Ca for the exchange sites is a function of the nature of the soil, the pH, the organic matter content, even partial pressure of CO_2. Our results showed that the Ca simulation under regard the exchangeable Ca values for the low soluble Ca concentrations. This effect is particularly significant within the framework of the measurements carried out using the culture device where the plant can reduce in a significant way the activity of the ions in solution (including Ca) in the immediate vicinity of the root.

Tab 1: Cation exchange capacity (CEC), relative volume of Donnan free space (v_{Donnan}) and affinity constants (K_i) of the cation X for the binding sites of the associative Donnan model used for the soils.

Parameters	Variable charge At pH 7.0		Permanent charge			
	Columbia	Cameroon	Columbia		Cameroon	
	Site 1	Site 1	Site 2	Site 3	Site 2	Site 3
CEC mol kg^{-1}	0.055	0.067	0.0092	0.003	0.029	0.003
V_{Donnan} m^3 m^{-3}	0.02	0.02	0.02	0.02	0.02	0.02
K_H	$2\ 10^6$	$2\ 10^6$	0	0	0	0
K_{Mg}	10	25	12	500	75	200
K_{Ca}	20	50	25	1000	150	1000
K_{Al}	12000	12000	1500	0	1500	0

We used a third site of exchange with permanent charge having a great affinity for Ca, which makes it possible to refine the adjusted Ca values. The followed principle was to define the constant values for H and Al then for Ca and Mg, the monovalent ions not intervening in the exchange under the selected experimental conditions. The values of the parameters of adjustment for the soils are given in table 1. The values of the parameters of adjustment for the maize roots are those measured and published previously (Calba and al. 1999), CEC 0.138 mol kg^{-1} of cell walls, vDonnan 0.45 m^3 m^3, K_{H^+} 4000, K_{Na^+} 1, K_{K^+} 1, $K_{Mg^{2+}}$ 70, $K_{Ca^{2+}}$ 160, $K_{AlOH^{2+}}$ 70, $K_{Al^{3+}}$ 700.

The culture device allowed analysing the composition of the water extract of the soil and the state of the exchange complex as well as the state of the root. It appears that when the rhizosphere becomes more acid the soil releases at the same time Al by dissolution and Ca by exchange. Al is adsorbed on the exchange complex whereas Ca leaves the exchanger. The concentration of Al and Ca increase in the soil solution, like in the root. It clearly appears as the pH decreases in the rhizosphere that the root system and the soil enter in competition for Al, which comes from the dissolution of materials under the acidifying effect of the plant. This process must be analysed in comparison with the importance granted in soil science with exchangeable Al. The results obtained show that the Al dynamics in the rhizosphere is conditioned by the functioning of an Al solubilization-exchange system without one being able to know the relative importance of a phenomenon compared to another. One observes however whom the variations of Al measured on the soil of Cameroon are well less significant than for the soil of Colombia to a given pH. With pH 4.4 the Al concentration of solution is six times higher in the soil of Colombia whereas the exchange capacity and the exchangeable Al content are lower than in the soil of Cameroon. It also appears that the concentrations of Al in soil solution of Colombia and Cameroon remains low until pH 4.45 then increase quickly below this pH, whereas the Al content in the root believes in a quasi linear way. In parallel, the Ca concentrations in solution in these soils remain stationary between pH 4.25 and 4.45.

Using the data obtained with the device of culture validated the model. The initial state of the solution of the soil, i.e. the concentrations of the elements in solution while being limited to Al, Ca, Mg, NH_4, NO_3, provides the input parameters of the exchange model, this one calculates the contents of fixed elements on the soil and the root at each step of time. The simulation of the functioning of the plant was carried out by introducing in parameter the remove of the ions by the plant throughout culture.

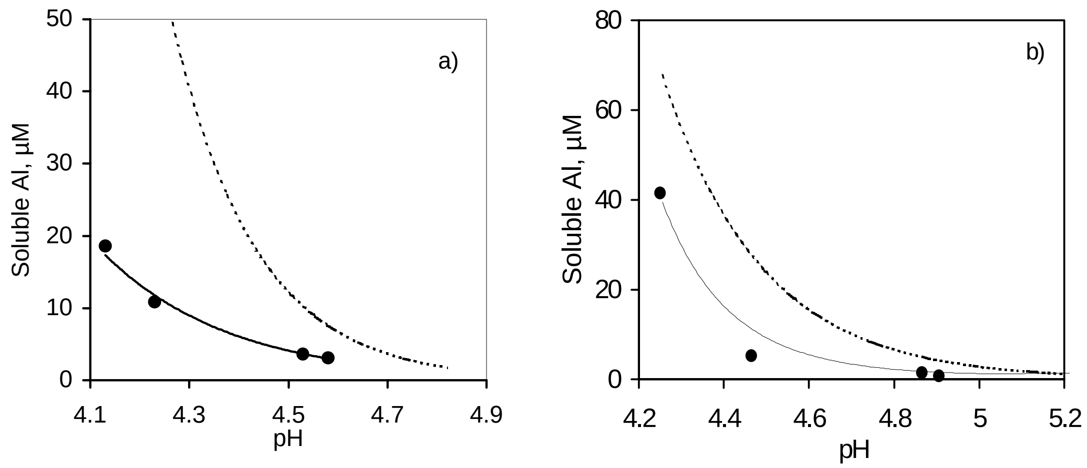
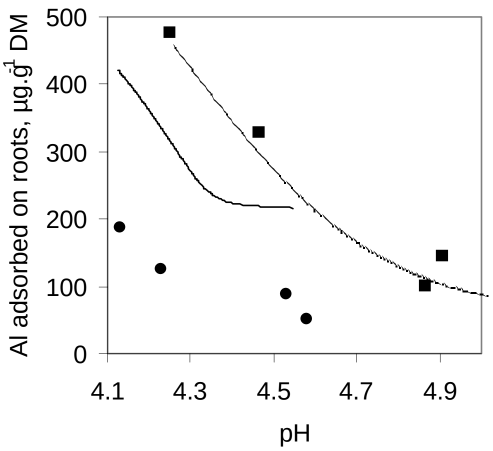


Fig. 2: Soluble Al as a function of pH in Cameroon (a) and Columbia (b) soils. Fitted Al with equilibrium (dotted line), data obtained with the device of culture (circle), and simulation of plant functioning (full line).

The remove of Ca and Mg were adjusted while taking as bases the variation of their contents on the exchange complex of the soils. The remove of Al is defined by the quantity of Al in the roots at the end of the culture. The monovalent ions were used to adjust the pH. The validation was acquired when the state of the system resulting from the model after 14 days a simulated time was identical at the final state (ions in solution and elements adsorbed) measured in experiments for the whole of the elements considered.
The measurements carried out after incubation of the soils allow defining the state of the soil/water system in the absence of the plant and with thermodynamic equilibrium for different pH. These data were introduced into the exchange model in order to adjust the Al solubility constant of the mineral phase likely to control the concentration of this element in solution. This approach has as a principle, which the pedogenic processes allow, compounds which define the lowest activity of Al_3^+ in solution to control in fine the solubility of Al. It is thus possible to compare the evolution of the system in the experimental device under culture of maize, simulated using the model, and a state of soil/solution equilibrium obtained in the absence of the plant (Fig. 2).
The values of the Al solubility products adjusted in the experiment without plant are respectively, log kso = 8.04 and 8.5 for the Cameroon and Columbia soils. For this last soil the adjusted Al solubility product corresponds to Al hydroxides less better crystallised than

Gibbsite, log kso = 8.04-8.11 or log kso=7.55 but better crystallised than amorphous Al, log kso = 9.66. It appears that the Al concentrations in soil solution of Cameroon after culture are lower than the concentrations with thermodynamic equilibrium without plant (Fig. 2a) even with pH close to 4.1. Moreover, the model shows that in the experiment with plant the soil solution is under saturated compared to the gibbsite after 24 hours of equilibrium in a soil/water ratio (1:1.5). The simulation was carried out using a rate constant of Al dissolution 2.0 10^{-9} mol kg^{-1} s^{-1}, corresponding to a duration of return to equilibrium of the system after disturbance of several hours (Calba and al. 1999).

The results obtained with the soil of Columbia show that the Al concentration in solution after culture is lower than that of the experiment without plant (Fig. 2b). This last concentration is obtained after 24 hours of equilibrium in a soil/water ratio (1:1.5) for a solubility constant of $Al(OH)_3$ close to 8.0. The soil solution could be in equilibrium with the gibbsite. It is observed however that the differences between Al in solution under culture and Al in solution with equilibrium are lower than in the case of the soil of Cameroon. The adjusted rate constant of Al dissolution for this soil is equal to 2.7 10^{-8} M kg-1 s-1 corresponding to a return to equilibrium of the system after disturbance, close to 1 hour, faster than for the soil of Cameroon. We showed (Calba et al. 1999) that the Al adsorption by the root passes by a maximum to pH 4.4.



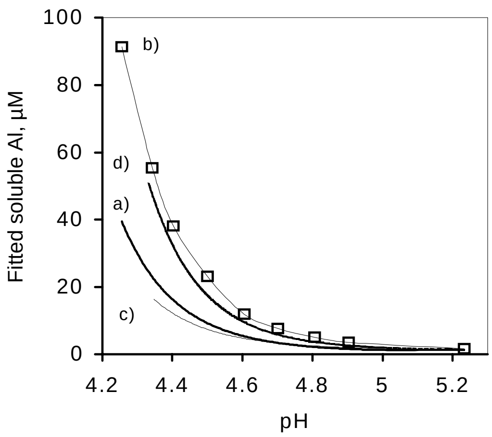


Fig. 3: Al adsorbed on roots in hydroponics (a) and soils (b) as a function of pH. Measured data, Cameroon (circle), Columbia (square). Simulation, Cameroon (thick line), Columbia (fine line).

Fig. 4 : Simulation of soluble Al as a function of pH in the soil of Columbia. Measured data with the device of culture, kH=2 10^{-6}, 100% cation removed (a), kH=2 10^{-5} (b), 10% cation removed (c). Measured data at equilibrium after incubation of the soil (d).

The fit of adsorbed Al on the root as a function of pH is compared with the experimental data obtained with the device of culture (Fig 3). It appears that the quantity of Al in the roots increases when the pH decreases. Moreover, the fitted data are higher than the experimental data for the soil of Cameroon. These results show that the process of detoxification by the protons observed in hydroponics below pH 4.4 is not observed on the roots of maize cultivated on the soils tested because of the continuous Al solubilization and the concomitant Al concentration increase in the soil solution.

The conditions of the model adjustment defined for the roots in hydroponics do not apply on the soil of Cameroon. The analysed soil samples have a thickness of 3 mm and it is possible that the low rate of Al dissolution defines conditions of local Al concentration near the root different from those obtained after extraction of the solution from the soil by a 24 hours contact with water in a ratio 1:1.5.
The model allows simulating particular situations of the functioning of the plant or the influence of the parameter values of fit. The analysis of the soil of Colombia (Fig. 4) shows on the one hand the influence of a modification of the dissociation constant of the protons (k_H), from $2\ 10^{-6}$ to $2\ 10^{-5}$, corresponding to an increase in the dissociation of the acid functions carried by the sites with variable charges, and on the other hand a reduction (90%) in the remove of the cations corresponding to a slower acidification of the medium or to a longer distance from the root. It appears that the principal factor controlling Al in solution is the rate of acidification of the medium or the distance to the root.

3.4. Soil management effects on root growth

Methodology studies

The volume of accessible soil to root system uptake constitutes the base for quantifying nutrient and water uptake. These determinations are based on root length density (RLD) estimations but RLD is not easy to quantify in the field. The study of root intersections on soil profiles offers the opportunity to quantify root distribution (Bohm 1976). Van Noordwijk (1987) formulated mathematical relationship between impact densities on cubes faces and the degree of root anisotropy, and between impact densities, root anisotropy and root length. An improved model, inferred from Van Noordwijk's one has been proposed (Chopart and Siband, 1999). It has been tested in the eastern plains of Colombia for a calibration study. Model proposed for maize in Africa has been tested with Colombian data set with, unfortunately, a low variability of data distribution. However, calculated results from local counts and African model to describe RLD from root counts are included in published relationship between root lengths measured and calculated. Therefore model coefficients found out in Africa seem to be able to be used in local Colombian conditions. The software "RACINE", has been developed and tested by CIRAD. It is now free available in French or English languages and is now used in Colombia and Ivory Coast, France (CIRAD Montpellier and Reunion Island).

Agronomic field studies (with CORPOICA INCO partners).

In studied Colombian acid soil, root front (30 cm) and root length density are very low (Tab. 2). In usual conditions, root system of maize is able to grow deeper than 1 meter and have a total root length more than 5 km m^{-2}. Observations on soil profiles don't show obvious physical barrier, and then the problem seems to have another cause.
Studied soil management treatments have low effect on root front but a positive effect on root length. There is a specific effect of manure, and particularly chicken manure on total root length and RLD of both cultivars, particularly after anthesis (manure decomposing or

aluminium increasing in soil during cycle?). Soil management treatments have also a positive effect on volume of soil available for root nutrient uptake. These results give a better knowledge of organic matter effect on plant growth and production in the studied acid soil and cultivars differences. Then they could help for advises in acid soil management practices and for crop modelling taking in account the hidden face of the plant.

Tab. 2: Effects of soil management treatments on two cultivars of maize root system: roots front (cm) and total root length ($m\ m^{-2}$ of cropped field) in an acid soil of Colombia (Villavicencio, eastern plains). Measurement between anthesis and beginning of grain maturation (70–95 DAE), four replications each year. OM: (chicken manure or green manure) 5t ha^{-1}; lime 1.5t ha^{-1}.

		Var. Sikuani V110 (tolerant)				Var. ICA V 109 (sensitive)			
Year		**Control**	**NPK**	**NPK+ OM**	**NPK +OM+Lime**	**Control**	**NPK**	**NPK +OM**	**NPK +OM+Lime**
Root front	98	29			30	25			31
	99		31	29			33	29	
Root length	98	1600			2440	1430			2920
	99		1150	1740			1310	1525	

Problem encountered
None

Technology implementation plan
A root study software “RACINE” has been developed. It is freed available for scientists of INCO project.

4. Conclusion and perspectives

The work realised within the framework of this program shows that the use of a mechanistic model describing the dynamics of the ions, mainly Al, H and Ca in the rhizosphere of maize cultivated on acid soils, is possible but requires to take into account permanent and variable exchange sites as well as the kinetics of solubilization of materials containing Al. The plant by its removal decreases the concentration of the ions in solution, in particular Al that can be in under saturation compared to Al hydroxides more soluble than the gibbsite or even compared to the gibbsite. The model allowed describing the functioning of the rhizosphere and the dynamics of the ions between the soil and the root. It shows that the adsorption of Al on the root is limited by a kinetic factor relative to the rate of Al dissolution. This rate is a global parameter, which associate the dissolution and the transport of Al of mineral surface with solution, as well as the influence of parameter such the pH and the activity of Al in solution on the rate of dissolution of Al compounds. Moreover, it is shown that the equilibrium of Al in solution can himself refer with various type of Al material more or less soluble, this not being able to explain however rates of adsorption of Al measured on the roots, our assumption being that the concentration of Al in vicinity of root is a function of rate of dissolution and of transfer of Al and that it can be lower with that measure in the experiment. Our work shows that the concept connecting Al toxicity in the acid soils to the only determination of exchangeable Al or the activity of Al in solution merits to be re-examined with the taking into account of kinetic parameters. The use of a model appears necessary to understand and evaluate the behaviour of the plants when the pH near the root lie

between 4.5 and 5.0, this according to the soil characteristic. On these levels of pH and in our experiments, the Al concentration in solution is of some micromoles, which makes difficult the speciation of the ions as well as measurements of interactions with other components in solution. However, other search remains necessary to measure the influence of the transport of the elements towards the root on dynamics of Al and Ca. Lastly, the importance of ligands such organic acids appears in comparison with the low concentrations of Al measured in solution with pH>4.5.
The comparison of the results obtained on the soils of Cameroon and Columbia shows that these two soils have a dynamics of Al very different related to their difference in content of amorphous Al and their CEC. The slower rate of Al solubilization in the case of the soil of Cameroon authorises rhizospheric pH lower than in the case of the soil of Colombia. For this last soil, the rate of acidification of the rhizosphere by maize seems a significant factor of the soil toxicity, throughout the culture; the Al concentration in solution is equal to that defined by the solubility of the gibbsite. In the case of the Cameroon and the Thailand soils the Al concentration near the root is lower than that defined by the product of solubility of the gibbsite. Others compounds of the Al silicates could then define the Al concentration in solution.

Methodology studies (software, models) conducted inside this project allowed to show that it is possible to describe root length density (RLD) distribution from root counts in the profile (grid method) and to infer availability of root system for nutrient and water uptake. Soil management practices (manure, lime) increase RLD in upper level of studied acid soil, but it is not possible to improve the low deep root front (30 cm). So, studied agronomic practices, but not clearly available water increase volume of soil available for nutrient uptake.

Methods developed inside INCO I project are planned to be used during INCO II project "Maize for sustainable cropping systems on tropical acid soils". Agronomic results are planned to be confirmed in Colombian and tested in Cameroon.

5. Publications and paper

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