Shoot and root growth of two tropical grasses, *Brachiaria ruziziensis* and *B. dictyoneura*, as influenced by aluminium toxicity and phosphorus deficiency in a sandy loam Oxisol of the eastern plains of Colombia

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Abstract

Phosphorus (P) deficiency and aluminium (Al) toxicity are widespread in Oxisols of the tropical savannas of eastern Colombia. A field experiment was conducted to determine the effect of Al toxicity and P deficiency on plant growth and nutrient uptake of two *Brachiaria* species. To examine the influence of nutrient supply and lime on root and shoot growth, two levels of fertiliser application (low and high) were superimposed on the control, lime and gypsum treatments. Results from this field study showed that growth limitations of *B. ruziziensis* and *B. dictyoneura* (syn. *B. humidicola*) did not result from either P deficiency or Al toxicity. *B. ruziziensis,* despite lower root length, produced under the experimental conditions more shoot dry matter than *B. dictyoneura* with similar or greater P and Ca concentrations. Therefore, efficiency of Ca and/or P uptake per unit root length was greater in *B. ruziziensis* than in *B. dictyoneura*. This ability of *B. ruziziensis* may contribute to its rapid establishment during the first year of pasture growth. Further studies are warranted to verify the apparent growth responses of these grasses to application of Ca on these soils.

Introduction

Productivity of tropical forage species in acid soils is often limited by a number of factors including low pH, toxicities of aluminium (Al) and manganese (Mn) and deficiencies of phosphorus (P), calcium (Ca) and magnesium (Mg) (Rao *et al*. 1993; Rao 2001). In Oxisols of the savannas of eastern Colombia (Llanos Orientales), P deficiency is a significant growth-limiting factor (Sieverding and Howeler 1985; Rao *et al.* 1992, 1996a). On these soils, P deficiency in plants is caused by low soil P content and/or high phosphate fixation, as well as by Al toxicity that inhibits root elongation (Salinas *et al.* 1985; Foy 1988; Polle and Konzak 1990). Deficiencies of N and P (Dodd *et al.* 1990), and Ca (Rao *et al.* 1995) are growth-limiting factors in Carimagua Oxisols. Toxicity of Al and deficiency of Ca could restrict root growth in the subsoil (Ritchey *et al*. 1989).

In the Llanos, pasture-based livestock production is the most profitable form of land use (Sanchez and Tergas 1979), and grasses of the genus *Brachiaria* are particularly important (Pizarro *et al.* 1996). However, the various commercial *Brachiaria* species differ in their suitability (Miles *et al*. 2004). For example, *B. dictyoneura* (taxonomically classified as *B. humidicola*, Renvoize *et al.* 1996) is recommended for the infertile soils of Carimagua (Miles and Lapointe 1992), while *B. ruziziensis* is regarded as suited for relatively more fertile clay loam Oxisols (Lapointe and Miles 1992). According to Humphreys (1981), *B. ruziziensis* also demands high N fertilisation. Salinas (1982) considered the higher demands of *B. ruziziensis* for mineral nutrients contributed to its lower level of Al tolerance, compared with *B. humidicola, B. brizantha* and *B. decumbens*.

In previous pot experiments at CIAT, shoot growth of *B. dictyoneura* on an Oxisol from the Colombian savanna increased significantly with increasing P levels (Rao *et al.* 1992; 1996a), suggesting that P limits plant growth in pot trials with these soils. There is limited information from pot experiments (Rao *et al*. 1996a; 1996b) and from field experiments (Rao 1998) on root growth. Leaching of Ca, and the decrease in Al

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saturation and activity in the soil profile are determinants of root growth and distribution, particularly in the subsoil layers. Poor root development in the subsoil under field conditions can be due to: (a) an inherent branching pattern, (b) toxic soil conditions in this zone, or (c) a relative preference for more favourable conditions in the topsoil. Improvements in subsoil chemical properties can be achieved through lime or gypsum applications.

In the study presented here, the effects of P, N and K fertilisation, as well as lime and gypsum application, on the growth of both shoots and roots of *B. ruziziensis* and *B. dictyoneura* were investigated. The main objective was to clarify whether P deficiency limits plant growth under field conditions, and whether P deficiency is caused by low availability of P in the soil or by Al toxicity. We measured shoot and root growth as well as plant nutrient concentrations in shoot dry matter of the 2 species at 4 months after sowing.

Materials and methods

Experimental design

The field experiment was set up in March 1992 in a savanna at the CORPOICA/CIAT research station Carimagua in eastern Colombia at the 'Alegría' site (71°5′ W, 4°5′ N; 150 masl; 2300 mm annual precipitation). The soil (Oxisol) was a sandy loam with pH (H_2O) 5.1 and [$cmol_c$/kg] Al 0.7, Ca 0.13, Mg 0.08 and K 0.03, and with 336 mg/kg total N and 2 mg/kg P (Bray II). The Carimagua Oxisol is considered representative for large savanna extensions in Colombia (Guimarães *et al.* 2004). The experiment was sown after burning the native savanna vegetation and with conventional soil preparation of 2 passes of a chisel plough.

To examine the effect of pH and Al saturation on shoot and root growth, the natural soil Al saturation of 77% in the top soil (control) was compared with 2 Al saturation-reducing soil amelioration treatments: lime (500 kg/ha calcium carbonate) and gypsum (1200 kg/ha gypsum). These levels of lime and gypsum were based on results of preliminary experiments.

To examine the influence of applied nutrients on root and shoot growth, 2 fertilisation levels were superimposed on the control, lime and gypsum treatments. These levels were based on local recommendations for improved pastures (low fertilisation) and crop production (high fertilisation) (Rao *et al.* 1992) and were as follows (kg applied/ha at the beginning of the experiment):

Low fertilisation: N 0; P 20; K 20; Ca 40; Mg 14; S 10; Zn 2; Cu 2; B 0.1; Mo 0.1

High fertilisation: N 40; P 50; K 100; Ca 100; Mg 28; S 20; Zn 2; Cu 2; B 0.1; Mo 0.1

The experiment was carried out in a split-split-plot design. The main factor was the amelioration levels (control, lime, gypsum) and the subfactor was the fertilisation levels (low and high). The 2 species tested were *Brachiaria dictyoneura* cv. Llanero (accession CIAT 6133; now reclassified as *B. humidicola*) and commercial *B. ruziziensis* (comparable with accession CIAT 655) as sub-subplots. The individual subplots of plant species were 6 × 6 m with 3 replicates. Both species were established as seed with a row-to-row spacing of 50 cm and plant-to-plant spacing within rows of 12.5 cm.

Sampling

To determine dry matter and nutrient concentrations in shoots, above-ground plant samples were collected from a 1.5 × 1.5 m fixed-quadrat sample area in each subplot using a cutting height of 15 cm. At harvest, 2 root samples were taken from within plant rows and 2 from between plant rows in each plot, using an auger. Root length and root mass in the samples were determined to assess nutrient uptake capacity per unit root length. The specific root length, *i.e.*, the relation of root length to root dry matter (an indicator of aluminium toxicity, Sartain and Kamprath 1975), was also measured. For measuring root length, each sample obtained from within a plant row was combined with a sample from between plant rows. Roots were washed using 200 μm mesh sieves. Dead roots and organic detritus were separated by hand, and the length of living roots was then determined with a root-length scanner (Rao *et al.* 1996a). Along with root sampling, soil samples were taken for subsequent analyses.

Nutrient analyses

Plant samples (shoot and root samples) were dried to constant weight at 60°C and ground. Soil samples were air-dried and sieved to 2 mm. The soil was extracted with 1N potassium chloride. Soil pH was determined in water (1:1). Plant and soil nutrients were analysed according to methods described by Salinas and García (1985): For determination of N and P, plant samples were ashed in a sulphuric acid (96%): perchloric acid (70%) mixture (1:2) at 370°C and measured colorimetrically. After ashing samples in a perchloric acid (70%): nitric acid (65%) mixture (2:3) at 220°C, K, Ca, Mg, Mn, zinc (Zn), copper (Cu) and Al were determined by atomic absorption spectrometry and sulphur (S) colorimetrically according to Tabatabai and Bremner (1970).

Statistical analysis

Two-factor analysis of variance, regression, standard error and mean comparisons (Student-Newmann-Keuls test) were computed with SIGMASTAT. Correlation coefficients were tested after Fisher (1958) for significance.

Results

Effects of lime and gypsum applications on soil chemical characteristics

Four months after seeding, lime application had increased soil pH and had markedly decreased Al saturation in the 10-cm topsoil layer (Table 1). Gypsum application had not influenced pH but had clearly decreased Al saturation along the whole soil profile. The stronger depth effect of gypsum compared with lime had been expected, because of better solubility and higher mobility of the gypsum down the soil profile.

Shoot dry matter

Increased fertilisation significantly ($P<0.0001$) increased shoot dry matter of both species in the control, lime and gypsum plots (Figure 1). However, in control plots, the response by *B. ruziziensis* was much greater than that of *B. dictyoneura.*

At both fertilisation levels, both species produced significantly more shoot dry matter in lime and gypsum plots than in control plots (*B. ruziziensis* $P<0.05$; *B. dictyoneura* $P<0.01$). Lime and gypsum application combined with low fertilisation resulted in strongly increased shoot production of both species, while combined with high fertilisation, the response was lower in *B. ruziziensis* than in *B. dictyoneura.* Nevertheless, the fertilisation effect surpassed the effect of lime and gypsum applications for both species. Shoot dry matter production of both species did not differ significantly between lime and gypsum plots. In all treatments, *B. ruziziensis* produced significantly more shoot dry matter than *B. dictyoneura* ($P<0.05$).

Root length density and specific root length

In all treatments, root length density (RLD) decreased logarithmically with soil depth (Figure 2).

Roots were found down to 60 cm profile depth. In the top 10 cm and on average of the total 60 cm soil depth, RLD of *B. ruziziensis* was lower than that of *B. dictyoneura*. In both species, increased fertilisation led to increased root production in the topsoil on control, lime and gypsum plots. Surprisingly, lime and gypsum application resulted in a decrease of RLD in both species compared with the control, although shoot dry matter increased (Figures 1 and 2) and Al saturation in the soil decreased (Table 1).

The specific root length is a measure of fineness of the root system. It was clearly higher for *B. ruziziensis* in control plots than in lime and gypsum plots, but when the individual soil horizons were considered, the differences between control, lime and gypsum plots were statistically not significant for both species (Figure 3).

Al toxicity did not limit root growth on control plots. This is because in the topsoil, the

Table 1. Soil chemical properties in different profile depths at Carimagua (Alegría site) 4 months after seeding [pH (H_2O) and aluminium saturation, calculated on the basis of cation concentration (1M KCl) for control, lime and gypsum plots, are means of low and high fertilisation, for both *Brachiaria* species].

Depth	Control				Lime				Gypsum			
	pH	Al	Ca	Mg	pH	Al	Ca	Mg	pH	Al	Ca	Mg
(cm)		(%)				(%)				(%)		
0–10	4.9	76	17	6	5.2	49	42	9	4.9	66	28	6
10–20	4.8	84	12	4	4.9	79	16	5	4.9	81	16	3
20–40	4.8	87	9	4	4.9	83	13	4	4.8	80	17	3
40–60	4.8	87	9	4	5.0	86	11	3	4.9	80	16	4

specific root length was even lower on the lime and gypsum plots than on the control plots. Additionally, in the subsoil, the specific root length on gypsum plots was similar to or lower than that on control plots. The specific root length of *B. dictyoneura* decreased with increasing soil depth in all treatments, indicating a decrease in the proportion of fine roots.

Plant nutrient concentrations in shoots

B. ruziziensis. With increased fertilisation, the concentrations of most nutrients in the shoots decreased (Table 2).

Compared with the control, lime application increased Ca, Mg and P concentrations in the shoot biomass at both fertilisation levels,

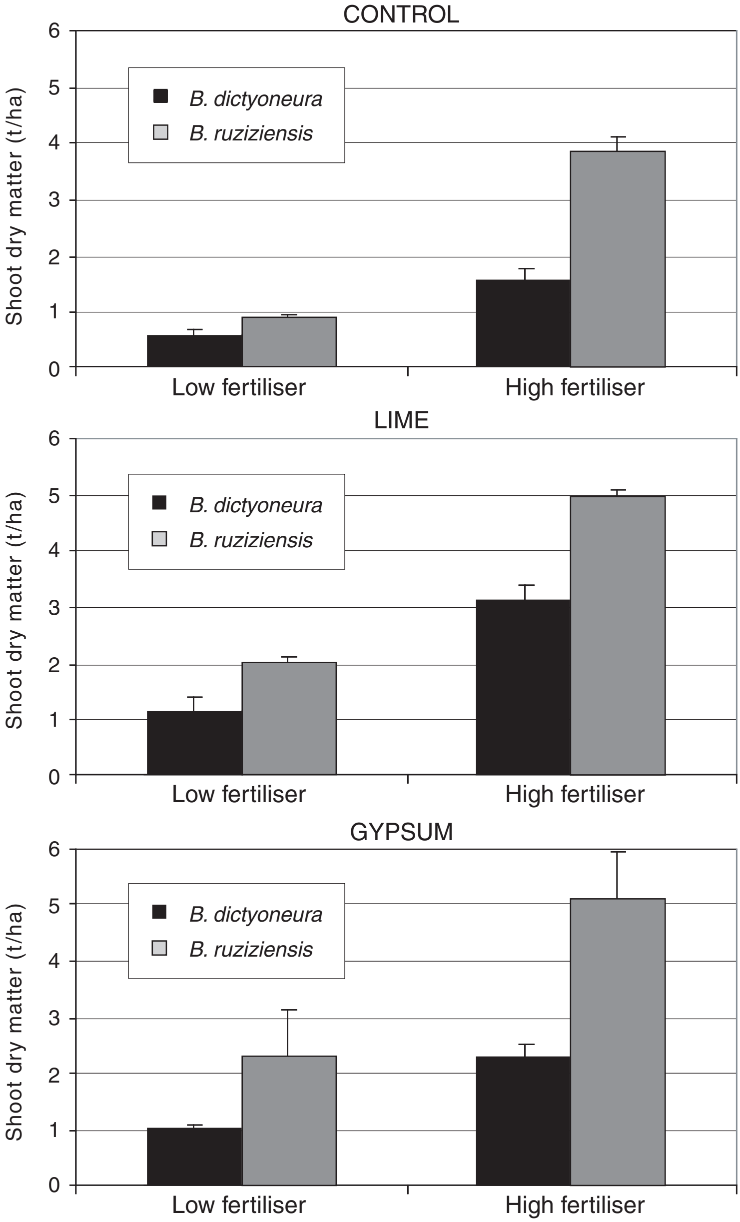

Figure 1. Shoot dry matter production of 4-month-old *B. ruziziensis* and *B. dictyoneura* as influenced by lime and gypsum application with low and high fertiliser input. Standard error values are presented as a bar.

but reduced N, K and S concentrations. Gypsum application increased mainly Ca concentration. A significant increase in Mg and S concentrations occurred especially at low fertilisation. The growth-enhancing effect of gypsum led to decreased N, P and K concentrations compared with the control.

B. dictyoneura. In general, nutrient concentrations in shoot dry matter of this species decreased with higher fertilisation, although this was less pronounced than in *B. ruziziensis* (Table 2). With lime application, there was no clear tendency towards an increase of Ca, Mg and P concentrations at both fertilisation levels, compared with the control. In contrast, gypsum application increased Ca, S and P concentrations consistently at both fertilisation levels.

In all treatments, Ca concentrations in shoot dry matter of *B. dictyoneura* were lower than those of *B. ruziziensis*. Except for slightly higher N concentrations in *B. dictyoneura*, other nutrients did not show any species-related difference.

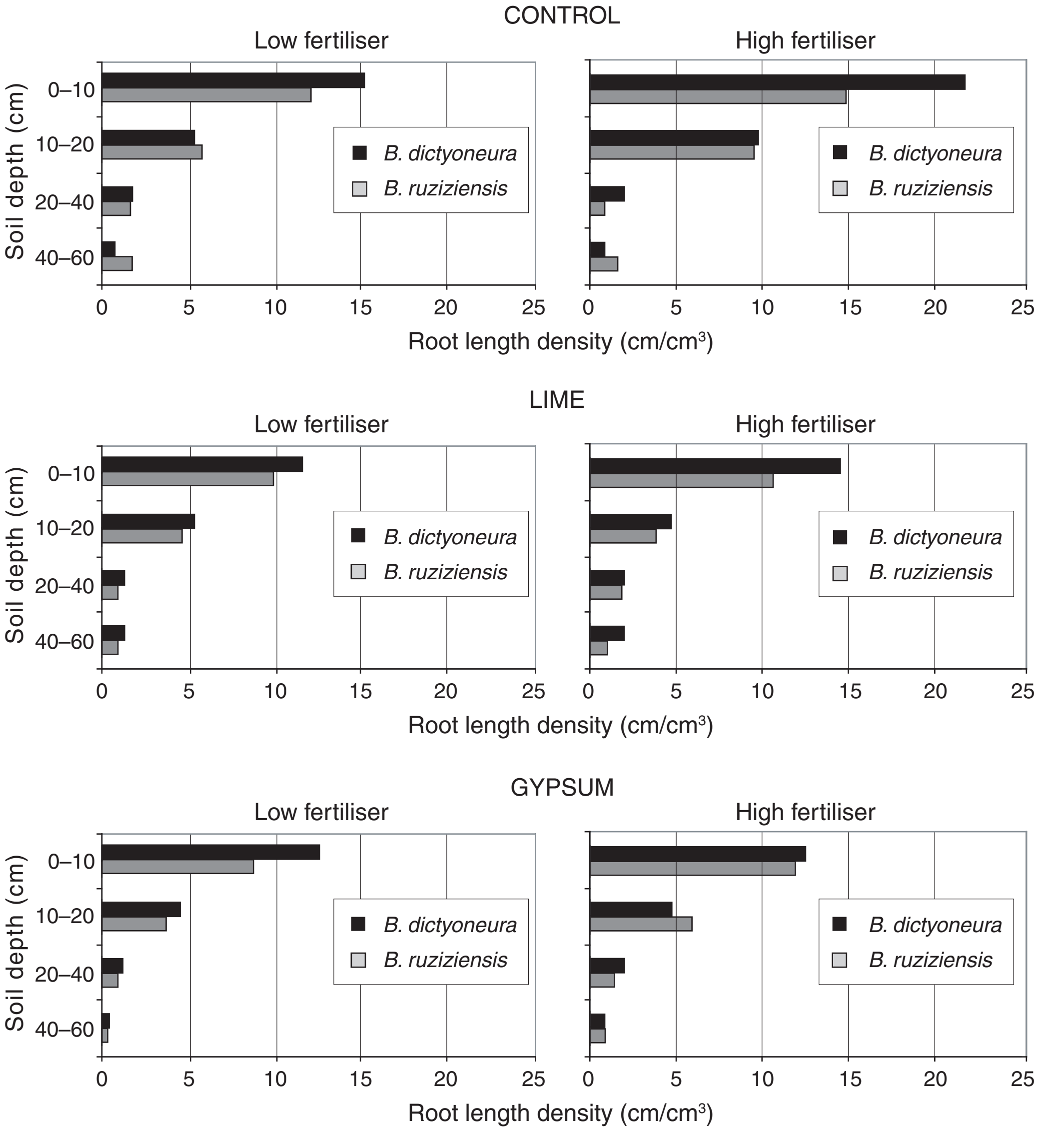

Figure 2. Root length density across soil layers of 4-month-old *B. ruziziensis* and *B. dictyoneura* as influenced by lime and gypsum application with low and high fertiliser input.

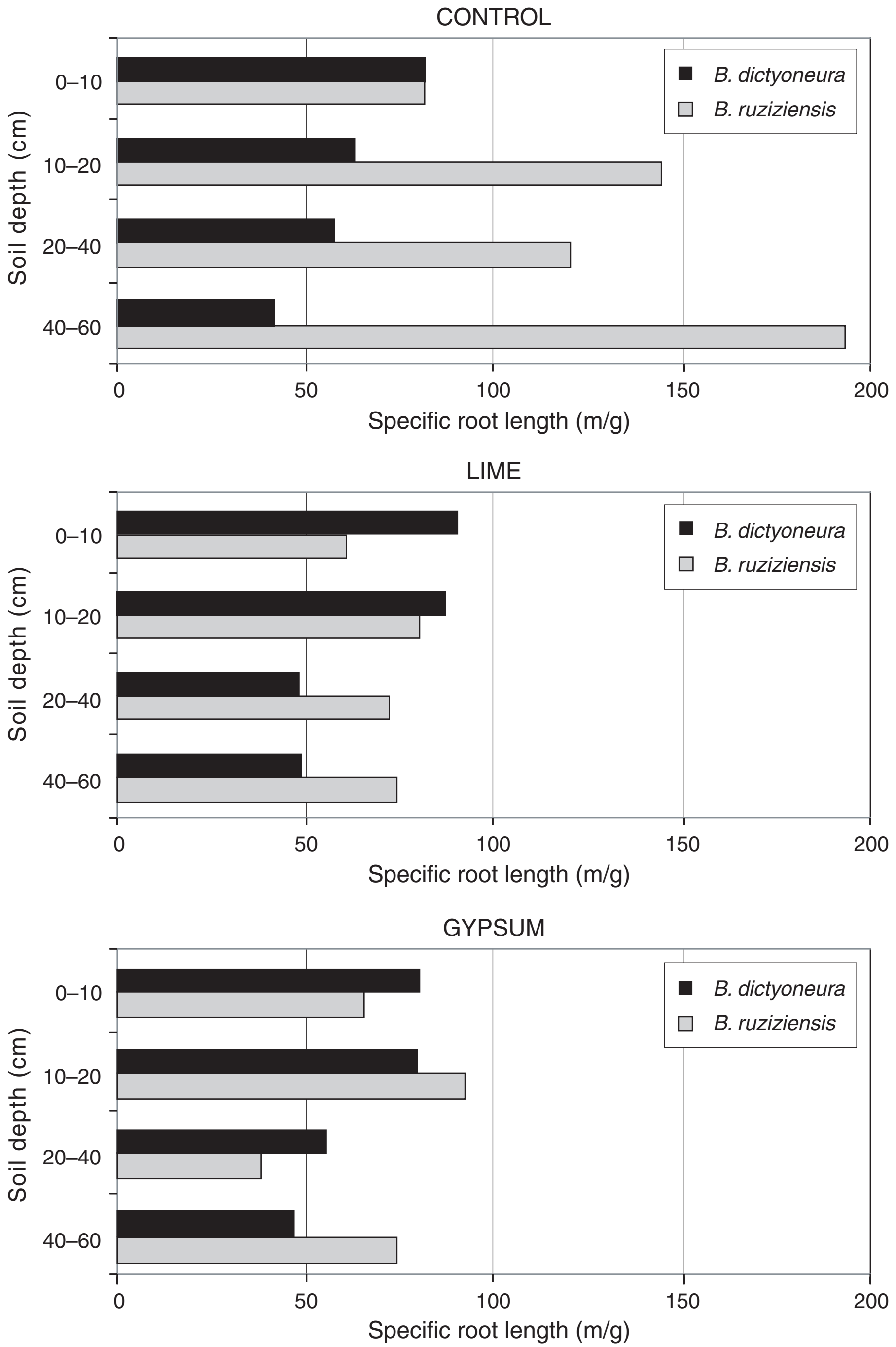

Figure 3. Specific root length across soil layers of 4-month-old *B. ruziziensis* and *B. dictyoneura* as influenced by lime and gypsum application. Values are means of low and high fertiliser input.

Discussion

Implications of high soil aluminium content for plant growth

The present field experiment showed that, in soils with high Al saturation (76–87%), *B. ruziziensis* and *B. dictyoneura* are capable of developing root systems that do not show symptoms of Al toxicity. Four findings support this:

1. Even in control plots, higher fertilisation resulted in a significant increase in root length density of both species (Figure 2), although soil Al saturation was not modified by fertilisation.
2. Application of lime and gypsum led to a decrease, rather than an increase, in root length of both species (Figure 2). An increase, however, would have been expected on the basis of experiences with *Sorghum bicolor*, where Ritchey *et al*. (1989) found that lime and gypsum applications increased root length of plants whose growth was limited by Al toxicity.
3. The specific root length of both species did not differ significantly between control and lime and/or gypsum plots (Figure 3). When Al toxicity affects root growth, lime application should increase specific root length as shown for *Sorghum bicolor* (Tan *et al*. 1991). A reduction in Al concentration in nutrient solution also increased specific root length of *Glycine max* (Sartain and Kamprath 1975; Klotz and Horst 1988).
4. The decrease in root length density with increasing soil depth was in line with the general logarithmic decrease, described by Greenwood *et al*. (1982), which occurs in most crops that grow without chemical or physical restrictions in the rooting zone (Wiesler and Horst 1994). An inhibition of root growth, caused by Al toxicity in the subsoil as schematically presented by Marschner (1991), was not observed.

At the experimental site, growth of both species was not limited by Al toxicity when low amounts of nutrients were applied to control plots. Consequently, both species displayed similar levels of Al tolerance when nutrients were supplied in low amounts. This was consistent with greenhouse

Table 2. Nutrient concentrations in shoot dry matter (DM) of *B. ruziziensis* and *B. dictyoneura* as influenced by lime and gypsum application with low or high fertiliser input at the time of establishment. Critical nutrient concentrations of different *Brachiaria* species for 80% (CIAT 1981) and 100% (Mesa *et al.* 1988) of maximum shoot growth rate are presented for comparison.

Treatment	Nutrient concentrations in shoot DM					
	N	P	K	Ca	Mg	S
	(g/kg)					
B. ruziziensis						
Control						
low fertiliser	14	1.1	21	2.9	2.3	0.6
high fertiliser	12	1.0	11	2.6	1.8	0.5
Lime						
low fertiliser	10	1.2	14	3.1	3.2	0.4
high fertiliser	11	1.1	9	2.7	2.4	0.3
Gypsum						
low fertiliser	13	1.0	13	3.9	3.0	0.7
high fertiliser	10	0.8	9	4.0	2.2	0.5
B. dictyoneura						
Control						
low fertiliser	15	1.0	19	1.6	2.8	0.6
high fertiliser	16	1.0	14	1.5	2.6	0.4
Lime						
low fertiliser	14	1.0	14	1.9	4.3	0.4
high fertiliser	13	1.3	12	1.4	2.1	0.6
Gypsum						
low fertiliser	17	1.2	16	1.9	3.1	0.8
high fertiliser	14	1.2	12	1.9	2.3	0.6
	Critical nutrient concentrations in shoot DM					
B. humidicola (CIAT 1981)	–	0.8	7	2.1	–	1.4
B. brizantha (CIAT 1981)	–	0.9	8	3.7	–	–
B. decumbens (CIAT 1981)	–	1.0	8	3.7	–	1.6
B. decumbens (Mesa *et al*. 1988)	12	1.1	24	–	–	–

experiments of Rao *et al*. (1996b), where Al tolerance of *B. ruziziensis* did not differ from that of *B. brizantha* or *B. decumbens*. With increasing soil Al content, root length of *B. ruziziensis* decreased even less than that of the other species in the presence of adequate supply of nutrients. Only the highest Al concentrations, 7 times higher than in the present experiment, caused a significant decrease in root length. However, exposure to toxic concentrations of Al in nutrient solution in the absence of adequate nutrient supply markedly reduced the root elongation of *B. ruziziensis* compared with *B. decumbens* (Wenzl *et al*. 2001). Inadequate nutrient supply may be one of the main factors that contribute to poor persistence of *B. ruziziensis* in infertile acid soils, that receive no maintenance fertiliser applications; this should be further elucidated in a long-term experiment.

Nutrient-uptake capacity

The recommendation to use *B. dictyoneura* on the infertile soils of the Colombian savanna (Miles and Lapointe 1992) and *B. ruziziensis* only on better soils (Lapointe and Miles 1992), suggests that the former species has a higher nutrient-uptake efficiency than the latter when grown on infertile acid soils. However, in the present experiment at low fertiliser input, *B. ruziziensis* produced more shoot dry matter than *B. dictyoneura* with similar or higher P and Ca concentrations, despite lower root length (Figures 1 and 2). Consequently, uptake of Ca and P per unit root length was more efficient for *B. ruziziensis*. This was not due to greater surface area per unit root length, because the values of specific root length were either similar to or higher than those of *B. dictyoneura*. Therefore, in this respect, *B. ruziziensis* can be considered more nutrient-efficient per unit root length in acid soils with low Ca and P contents than *B. dictyoneura,* when established with low fertiliser input.

Growth limitation by nutrients

The increased shoot growth with high fertiliser application (Figure 1) resulted in a diluting effect on nutrient concentrations in forage. Only Mg concentrations in shoot material can be considered adequate, when compared with the concentration of 2–6 mg/g shoot recommended by Bergmann (1986) for pasture grasses in temperate zones. Comparing with the critical concentrations proposed by CIAT (1981) and Mesa *et al.* (1988), Ca and especially S concentrations in shoot dry matter must be considered as low. At 4 months after sowing, Ca concentrations in shoot dry matter were low for both *B. ruziziensis* and *B. dictyoneura* (Table 2), and both lime and gypsum applications led to significantly increased shoot dry matter production, compared with control plots (Figure 1). This suggests that increase in Ca supply in sandy loam Oxisols could improve growth of the two *Brachiaria* grasses tested.

Conclusions

Results from this field experiment using recommended levels of fertiliser application to a sandy loam Oxisol showed that growth limitations of *B. ruziziensis* and *B. dictyoneura* (syn. *B. humidicola*) in Carimagua did not result from either P deficiency or Al toxicity. Considering both shoot and root growth, as well as nutrient uptake, it is more likely that in both species plant growth could be improved by increase in Ca supply to soil. *B. ruziziensis,* despite lower root length, produced more shoot dry matter than *B. dictyoneura* with similar or higher P and Ca concentrations. Therefore, Ca or P uptake efficiency per unit root length was greater in *B. ruziziensis* than in *B. dictyoneura,* so *B. ruziziensis* appears more nutrient-efficient than *B. dictyoneura* during pasture establishment on sandy loam acid soils with low Ca and P contents. This ability of *B. ruziziensis* may contribute to its rapid establishment during the first year of pasture growth.

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