Nitrogen and/or Phosphorus Fertilization Effects on Organic Carbon and Mineral Contents in the Rhizosphere of Field Grown Sorghum[1]

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The effects of nitrogen (N) and/or phosphorus (P) fertilizers on the nutritional status in the rhizosphere were studied by monitoring throughout the growth period the concentrations of organic carbon (C), inorganic N, $NaHCO_3$ extractable P, exchangeable K, Ca, and Mg in sorghum (*Sorghum bicolor* L. Moench) down in an Alfisol field, and of all these elements except for extractable P, and exchangeable Ca in a Vertisol field in semi-arid tropical India. These concentrations were compared between the rhizosphere soil and bulk soil of sorghum grown in both fields.

Organic C content of the rhizosphere soil increased with plant age and was significantly higher than that in the bulk soil throughout the growth of sorghum, but it was not affected by the rates of N or P fertilizer. Inorganic N concentration in the rhizosphere soil was significantly higher than that in the bulk soil until maturity in sorghum. The content of available P in the rhizosphere soil was significantly higher than in the bulk soil after the middle of the growth stage. Its average concentration in the rhizosphere soil across growth stages was significantly higher than in the bulk soil, which contradicts the observation in many reports that there is a depletion of P in the rhizosphere soil. The concentration of three exchangeable cations, K, Ca, and Mg, showed different patterns in the rhizosphere and the bulk soils. The concentration of K was almost constantly higher in the rhizosphere soil than in the bulk soil, Ca concentration was not different between the two soils, and Mg concentration was significantly higher in the bulk soil than in the rhizosphere soil. The reasons for these discrepancies cannot be explained at present. The concentrations of these cations were not affected by the rate of N or P fertilizer except for Mg at a later growth stage. The differences between rhizosphere and bulk soils in Alfisol were similar to those in Vertisol with respect to the concentration of organic C, inorganic N, and exchangeable K and Mg.

Key Words: **mineral content, N/P fertilization, organic C content, rhizosphere, sorghum.**

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Growing roots alter the rhizosphere soil physically, chemically, and biologically through the interaction between the roots and their surrounding soil. One of the important processes in this interaction is the root uptake of nutrients and water, which may cause the accumulation or depletion of ions depending on their mobility and mode of uptake.

It is technically difficult to study events in the rhizosphere because the rhizosphere is defined as the close vicinity of the root within a radius of about 1 mm. To overcome the difficulty, several techniques have been proposed such as the use of a rhizobox (Youssef and Chino 1988) and chambers (Kuchenbuch and Jungk 1982; Helal and Sauerbeck 1984). These techniques are known to provide precise and accurate information on chemical and biological processes in the rhizosphere under controlled environmental conditions. On the other hand, little is known about the nutrient status in the rhizosphere of crop plants growing under field conditions. Although the measurements of rhizosphere processes in field-grown roots may not be as precise as the measurements using a rhizobox or a chamber, the data from such measurements can provide useful information that helps to develop effective plant nutrition strategies. If there is an accumulation of a nutrient in the rhizosphere, plant parameters, more than soil parameters, may account for the increased uptake of the nutrient. If there is a depletion, the reverse is probably true.

The objective of the present study is to analyze the influence of N and P fertilizer application on the nutrient status in the rhizosphere by monitoring throughout the growth period the concentrations of organic C, inorganic N, extractable P, and exchangeable cations in sorghum grown on an Alfisol and Vertisol. In both Alfisol and Vertisol fertilizer was applied by banding, a commonly used method for efficient use of fertilizer; but the study was carried out in greater detail with Alfisol than with Vertisol.

MATERIALS AND METHODS

Crop and soil. Sorghum (cv. CSH 11) was grown on an Alfisol (pH (1 : 2 soil/water ratio) 6.78, organic C 0.30%, $NaHCO_3$ extractable P 3.34 mg kg^{-1} soil, and inorganic N 22.9 mg kg^{-1} soil) and on a Vertisol (pH (1 : 2 soil/water ratio) 8.58, organic C 0.48%, $NaHCO_3$ extractable P 8.15 mg kg^{-1} soil, and inorganic N 24.7 mg kg^{-1} soil) at ICRISAT, Patancheru, Andhra Pradesh, India (17°36′N, 78°16′E, 545 m altitude). The experimental design on Alfisol consisted of three P treatments (0, 13, and 26 kg P ha^{-1}, referred to as 0 P, 13 P, and 26 P, respectively) as the main treatment and six N treatments (0, 30, 60, 90, 120, and 150 kg N ha^{-1}, referred to as 0 N, 30 N, 60 N, 90 N, 120 N, and 150 N, respectively) as the subtreatment with three replications. The design on Vertisol consisted of six N treatments (0, 30, 60, 90, 120, and 150 kg N ha^{-1}) which were equally fertilized with P at 13 kg P ha^{-1}. Urea was used as N fertilizer, and single superphosphate as P fertilizer. Both fertilizers were applied in the furrow on the top of the ridge before sowing. However, for N fertilizer doses higher than 60 kg N ha^{-1}, half the dose was applied before sowing, and the other half at 3 weeks after sowing.

Soil sampling and preparation. The plants were sampled six times: in the Alfisol field, 28, 44, 58, 71, 92, and 120 (maturity) d after sowing (DAS); and in the Vertisol field, 37, 50, 64, 78, 98, and 114 (harvest) DAS. The roots were sampled until a 90 cm depth. The soil that remained attached to the roots after shaking by wrist movement is referred to as rhizosphere soil. The rhizosphere soil was collected by tapping the roots on a plastic sheet. The soil attached to the root surface after tapping was brushed off very gently. The soils removed by tapping and brushing were combined as rhizosphere soil. The bulk soil was also taken from the soil until a 90 cm depth as close to the rooting zone as possible, but the fertilized ridge soil was excluded as far as possible. Both rhizosphere and bulk soils were air dried for two weeks, ground, and sieved through a 0.5 mm sieve.

Measurement of soil pH. The air-dried soil was used for the pH measurement because only small amounts of fresh rhizosphere soil were collected, and because precise adjustment of water to be added for the pH measurement was difficult with fresh rhizosphere soil.

Five hundred-milligram air-dried soil and 1.5 mL distilled water were placed in a 10-mL vial, and mixed by wrist movement. This 1 : 2 soil : water (w/w) suspension was allowed to stand for 2 h and was stirred with a mechanical stirrer. A combined micro-glass electrode (Radiometer, Denmark) was inserted into the suspension, and the pH was read immediately.

Organic C, inorganic N, $NaHCO_3$ extractable P (available P), exchangeable K, Ca, and Mg. Organic C was analyzed as described by Nelson and Sommers (1982), inorganic N by Keeney and Nelson (1982), and available P by Olsen and Sommers (1982). The contents of exchangeable K, Ca, and Mg were measured with an atomic absorption spectrophotometer (Spectra A 20, Varian, Australia) after extracting the soil with 1 N NH_4-OAc (pH 7.0).

Data presentation and statistical analysis. In this study, urea, which is rapidly degraded to inorganic N in the soil, was used as N fertilizer. Single superphosphate, which contains Ca, was used as P fertilizer. It was found that the rhizosphere soil showed very high values of inorganic N, and available P and exchangeable Ca concentrations in urea-applied treatments and single superphosphate-applied treatments, respectively. This phenomenon was more often observed in earlier growth stages than in later growth stages of sorghum, presumably due to the root contact with the fertilizers placed in the furrow on the ridge. For this reason, in the case of inorganic N, the data from only the 0 N treatment within each of 0 P, 13 P, and 26 P main treatments were used. In the case of available P and exchangeable Ca, only data from the 0 P treatment consisting of six N levels were used for statistical analysis, but the data from the 0 N, 60 N, 120 N, and 150 N treatments are presented in this paper.

In presenting the data of organic C, K, and Mg, the values from only two P levels (0 P and 13 P), and two N levels (0 N and 120 N) are shown in the tables of the present paper. However, statistical analyses were carried out using the data from all three P levels and all six N levels for both rhizosphere and bulk soils.

RESULTS AND DISCUSSION

Total biomass production of sorghum

The total biomass production of plants harvested at maturity from different N or P treatments in Alfisol and Vertisol is shown in Table 1. In the Alfisol field, sorghum responded to P up to 26 P, and to N up to 150 N. In the Vertisol field, sorghum responded to N up to 90 N. The productivity in the Vertisol field at 0 N was higher than that in the Alfisol field, but the responsiveness to N was higher in the Alfisol field than in the Vertisol field.

pH changes

The changes in pH with sorghum growth stages in the 0 P and 0 N treatments of Alfisol

Table 1. Total biomass production of sorghum at maturity in Alfisol and Vertisol fields, ICRISAT Asia Center, 1989.

Fertilizer treatment ($kg\ ha^{-1}$)		Total biomass production ($t\ ha^{-1}$)	
P	N	Alfisol	Vertisol
0	0	4.37	
0	30	5.72	
0	60	6.21	
0	90	6.67	
0	120	6.66	
0	150	7.43	
13	0	5.11	6.30
13	30	6.26	6.81
13	60	6.80	7.58
13	90	8.07	8.05
13	120	8.39	7.92
13	150	9.60	7.92
26	0	5.31	
26	30	6.60	
26	60	7.37	
26	90	8.59	
26	120	8.59	
26	150	9.83	
SE (P levels)		±0.593	
SE (N levels)		±0.328	±0.156
SE (P–N interaction)		±0.787	

Table 2. Changes in pH (water) with growth stages of sorghum in rhizosphere and bulk soils without P and N fertilizer treatment in Alfisol field, ICRISAT Asia Center, 1989.

Soil[a]	DAS						
	28	44	58	71	92	120	Mean
R	6.70	6.99	6.78	6.68	6.73	ND[b]	6.78
B	6.78	6.89	7.10	7.13*	7.11	ND	7.00**

[a] R, rhizosphere soil; B, bulk soil. [b] ND, not determined. * and ** Significant at 5% and 1%, respectively.

are shown in Table 2. Even at earlier growth stages, there were differences between rhizosphere soil and bulk soil, but they were not significant. The differences became more pronounced with the growth, and at 71 DAS the difference reached a value of 0.45 which is significant. Means across all growth stages were significantly different between rhizosphere soil and bulk soil.

There is ample evidence that rhizosphere pH results largely from the imbalance in plant uptake of cationic and anionic ions (Kirkby 1968; Grinsted et al. 1982). The excretion of organic acid also influences rhizosphere pH (Petersen and Bottger 1991). In this study, since the pH was measured only in the 0 P and 0 N treatments it is not possible to simply extrapolate the decrease in rhizosphere pH to other P and N treatments. Although Youssef and Chino (1989) found that rhizosphere pH was not affected by the N source or by N levels, but by the initial bulk soil pH, it remains to be determined whether or not sorghum roots in this Alfisol acidified the rhizosphere soil regardless of N fertilizer treatment.

Table 3. Organic C concentration (%) in rhizosphere and bulk soils from Alfisol and Vertisol fields of sorghum, ICRISAT Asia Center, 1989.

DAS	0 P				13 P				Source of significance[b]		
	0 N		120 N		0 N		120 N		S	S-P	S-N
	R[a]	B[a]	R	B	R	B	R	B			
Alfisol											
28	0.30	0.25	0.30	0.25	0.28	0.24	0.25	0.22	**	ns	ns
44	0.30	0.25	0.30	0.25	0.29	0.23	0.26	0.22	**	ns	ns
58	0.33	0.25	0.32	0.26	0.29	0.25	0.29	0.23	**	ns	ns
71	0.34	0.27	0.35	0.24	0.34	0.23	0.35	0.22	**	ns	ns
92	0.35	0.23	0.36	0.23	0.30	0.24	0.29	0.22	**	ns	ns
120	0.35	0.30	0.33	0.26	0.29	0.22	0.37	0.21	**	ns	ns
Mean	0.33	0.26	0.33	0.25	0.30	0.24	0.30	0.22	**	ns	ns
R−B	0.070**		0.079**		0.063**		0.082**				
Vertisol											
37					0.55	0.48	0.57	0.47	**		ns
50					0.56	0.45	0.58	0.46	**		ns
64					0.55	0.42	0.55	0.44	**		ns
78					0.62	0.38	0.57	0.43	**		ns
98					0.59	0.43	0.63	0.43	**		ns
114					0.65	0.41	0.72	0.36	**		ns
Mean					0.59	0.43	0.60	0.43	**		ns
R−B					0.159**		0.172**				

[a] R, rhizosphere soil; B, bulk soil; R−B, rhizosphere soil minus bulk soil. [b] S, soil; P, phosphorus; N, nitrogen; ANOVA was performed with all three P and six N levels in Alfisol experiment and with all six N levels in Vertisol experiment. * and ** Significant at 5% and 1%, respectively; ns, not significant at 5%.

Organic C

The level of organic C in the rhizosphere soil increased with sorghum growth in both Alfisol and Vertisol fields whereas organic C levels in the bulk soil remained almost constant in the Alfisol field, and decreased in the Vertisol field (Table 3). The rhizosphere soil showed a significantly higher concentration of organic C than the bulk soil, irrespective of growth stages, P or N levels. The accumulation of organic C is a well-known characteristic of the rhizosphere (Curl and Truelove 1986).

Most of organic C is considered to be released from the roots. It has been reported that N deficiency or P deficiency increases the release of organic C from the roots (Hoffland et al. 1989; Petersen and Bottger 1991). Ratnayake et al. (1978) demonstrated that the roots of sudangrass seedlings grown at low levels of P, released larger amounts of exudates than those grown at high levels of P. These studies used nutrient solution, quartz sand, or sterilized soil, which are considered to minimize or eliminate microbial activity. In the present study, sorghum did not show N or P deficiency symptoms in the 0 N or 0 P treatment, but sorghum responded to N or P fertilizer, which indicates that sorghum was under N or P stress to a certain extent. However, the content of organic C did not increase the 0 N or 0 P treatment. It is generally recognized that organic C released from the roots is the major source of substrate for microbial activity. Since the present study was conducted under field conditions where microorganisms are abundant, it is possible that increased organic C was lost as respiratory CO_2 in the 0 N or 0 P treatment due to increased microbial activity.

Table 4. Inorganic N concentration (mg kg^{-1} dry soil) in rhizosphere and bulk soils from Alfisol and Vertisol fields of sorghum, ICRISAT Asia Center, 1989.

DAS	0 P		13 P		26 P		Source of significance[b]	
	0 N		0 N		0 N			
	R[a]	B[a]	R	B	R	B	S	S-P
Alfisol								
28	23	14	20	25	23	30	ns	ns
44	18	11	13	12	21	11	**	ns
58	23	9	15	10	21	9	**	ns
71	14	11	13	10	11	10	ns	ns
92	11	7	11	9	9	10	ns	ns
120	11	9	11	9	9	9	ns	ns
Mean	17	10	14	13	16	13		
R−B	7*		1ns		3ns			
Vertisol								
37			58	28			**	
50			42	19			**	
64			23	16			**	
78			30	12			**	
98			17	10			**	
114			14	11			**	
Mean			30	16				
R−B			14**					

[a] R, rhizosphere soil; B, bulk soil; R−B, rhizosphere soil minus bulk soil. [b] S, soil; P, phosphorus. * and ** Significant at 5% and 1% respectively; ns, not significant at 5%.

Inorganic N

Inorganic N concentration in the rhizosphere soil was significantly higher than that in the bulk soils at earlier growth stages of sorghum in the Alfisol field, and throughout the growth stages in the Vertisol field (Table 4). The concentration of inorganic N in the rhizosphere decreased with the growth stages whereas that of organic C increased at the later growth stages.

Since it is well known that organic C can be first used for N immobilization, the concentration of inorganic N in the rhizosphere soil could be lower than in the bulk soils. However, the presence of predators of microorganisms, such as protozoa, in the rhizosphere, leads to N mineralization (Clarholm 1985). Robinson et al. (1989) analysed N mineralization in the rhizosphere in a theoretical analysis, and showed that greater amounts of N mineralization are theoretically possible at realistic soil C : N ratio if bacteria are grazed by predators. We observed several bacterial grazers such as protozoa, microarthropods, and nematodes in the Alfisol and Vertisol fields of the present study. At present, we assume that the accumulation of inorganic N was largely due to grazing of bacteria by their predators in the rhizosphere. It is possible that the grazing decreased at the later growth stages, which resulted in a lower concentration of inorganic N in the rhizosphere at later growth stages.

Available P

The concentration of available P in both rhizosphere and bulk soils did not differ significantly up to 44 DAS (Table 5). However, after 44 DAS the concentrations of P in the rhizosphere soil were significantly higher than those in bulk soil except at 92 DAS. Averages across growth stages were still significantly different between the two soils.

Table 5. Sodium bicarbonate extractable P concentration (mg kg^{-1} dry soil) in rhizosphere and bulk soils from an Alfisol field of sorghum, ICRISAT Asia Center, 1989.

DAS	0 P								Source of significance[b]	
	0 N		60 N		120 N		150 N			
	R[a]	B[a]	R	B	R	B	R	B	S	S-N
28	7.7	6.1	7.6	5.9	7.6	7.1	6.5	6.8	ns	ns
44	6.2	7.3	6.3	7.1	7.0	5.6	7.4	6.2	ns	ns
58	6.3	2.0	4.7	1.2	4.9	2.4	4.6	1.2	**	ns
71	7.5	7.2	5.2	2.3	5.3	1.3	4.9	2.3	**	ns
92	4.6	4.6	3.5	1.8	3.5	2.5	2.8	3.3	ns	ns
120	4.3	4.8	4.0	2.2	5.4	2.9	5.3	2.0	**	ns
Mean	6.1	5.3	5.2	3.4	5.6	3.6	5.2	3.6	*	ns
R−B	0.8[ns]		1.8[ns]		2.0[ns]		1.6[ns]			

[a] R, rhizosphere soil; B, bulk soil; R−B, rhizosphere soil minus bulk soil. [b] S, soil; N, nitrogen; ANOVA was performed with all six N levels. * and ** Significant at 5% and 1%, respectively; ns, not significant at 5%.

It is assumed that P estimated by $NaHCO_3$ in the present study consists mainly of inorganic P. Depletion of inorganic P in the rhizosphere has been widely reported (e.g. Gahoonia and Nielsen 1992). The results in this study are not in agreement with the usual observations on the depletion of inorganic P in the rhizosphere. On the other hand, Tarafdar and Jungk (1989) reported that the inorganic P levels adjacent to the root surface (up to 0.4 mm) of wheat and clover were unexpectedly higher than in the bulk soils. They suggested that the increase in the level of inorganic P very close to the root surface may be due to mineralization of organic P at a rate higher than plant uptake. At present, we do not know if this is also the case for the rhizosphere of sorghum. The kinetics of P mineralization and P plant uptake need to be studied to confirm this assumption.

Exchangeable K, Ca, and Mg

The concentration of exchangeable K increased with the plant age especially in the Alfisol field (Table 6). The concentration was significantly higher in the rhizosphere soil, in Alfisol and Vertisol fields but it was not affected by the N or P level. The concentration of exchangeable Ca was higher in both rhizosphere and bulk soils at very early growth stages (28 DAS), and afterwards it declined and leveled off (Table 7). No significant difference was observed in averages of exchangeable Ca across the plant growth stages between rhizosphere and bulk soils although significant differences were observed at three growth stages (58, 71, and 120 DAS). The concentration of exchangeable Mg was generally low in the rhizosphere of both Alfisol and Vertisol fields except at the early growth stages of sorghum (Table 8). This decrease continued up to maturity. Averages of Mg concentration across the growth stages significantly differed between rhizosphere and bulk soils. At later growth stages, the concentration of Mg in both rhizosphere and bulk soils significantly decreased with increasing P levels (92 and 120 DAS) and N levels (92 DAS).

It has been recognized that in the case of transport of cations such as K, Ca, and Mg, mass flow is more important than diffusion. This phenomenon indicates that an accumulation of these cations in the rhizosphere soil may occur depending on plant uptake, but a depletion gradient of these cations in the rhizosphere cannot be expected. In fact, the study (Youssef and Chino 1987) using rhizoboxes specially designed for experiments on the rhizosphere demonstrated the accumulation of these cations in the rhizosphere soil. How-

Table 6. Exchangeable K concentration (mg kg^{-1} dry soil) in rhizosphere and bulk soils from Alfisol and Vertisol fields of sorghum, ICRISAT Asia Center, 1989.

DAS	0 P				13 P				Source of significance[b]		
	0 N		120 N		0 N		120 N				
	R[a]	B[a]	R	B	R	B	R	B	S	S-P	S-N
Alfisol											
28	49	36	60	48	67	56	58	54	**	ns	ns
44	79	60	78	59	69	51	76	55	**	ns	ns
58	114	25	113	18	108	34	99	39	**	ns	ns
71	56	54	67	50	57	49	64	51	ns	ns	ns
92	116	75	104	77	99	69	90	62	**	ns	ns
120	127	87	127	89	145	79	152	87	**	ns	ns
Mean	90	56	92	57	91	57	90	58	**	ns	ns
R−B	34**		35**		34**		32**				
Vertisol											
37					160	157	193	99	**		ns
50					180	60	162	62	**		ns
64					137	93	175	88	**		ns
78					197	95	166	96	**		ns
98					180	84	180	75	**		ns
114					188	85	197	68	**		ns
Mean					174	96	179	81	**		ns
R−B					78**		98**				

[a] R, rhizosphere soil; B, bulk soil; R−B, rhizosphere soil minus bulk soil. [b] S, soil; P, phosphorus; N, nitrogen; ANOVA was performed with all three P and N levels in Alfisol experiment and with all six N levels in Vertisol experiment. ** Significant at 1%; ns, not significant at 5%.

Table 7. Exchangeable Ca concentration (mg g^{-1} dry soil) in rhizosphere and bulk soils from an Alfisol field of sorghum, ICRISAT Asia Center, 1989.

DAS	0 P								Source of significance[b]	
	0 N		60 N		120 N		150 N			
	R[a]	B[a]	R	B	R	B	R	B	S	S-N
28	9.46	8.71	6.95	8.58	9.82	6.10	7.53	5.71	ns	ns
44	1.90	1.67	1.25	1.29	1.55	1.64	1.30	1.54	ns	ns
58	1.35	1.85	1.14	1.54	1.44	1.86	1.20	1.60	*	ns
71	0.62	1.82	0.45	1.66	1.62	1.94	1.31	1.69	ns	ns
92	1.25	1.45	1.15	1.80	1.20	1.54	0.47	1.30	*	ns
120	1.34	2.64	1.20	2.68	1.35	2.40	1.26	1.74	*	ns
Mean	2.65	3.02	1.87	2.93	2.83	2.58	2.18	2.26	ns	ns
R−B	-0.37^{ns}		-1.06^{ns}		0.25^{ns}		-0.04^{ns}			

[a] R, rhizosphere soil; B, bulk soil; R−B, rhizosphere soil minus bulk soil. [b] S, soil; N, nitrogen; ANOVA was performed with all six N levels. * Significant at 5%; ns, not significant at 5%.

ever, a few reports indicated that in some cases the concentration of these cations decreased in the rhizosphere compared to their concentration in bulk soil (Weiming and Zhiyu 1987; Miyasaka et al. 1992). In general, the accumulation or depletion of a nutrient results from the imbalance between plant uptake and nutrient transport (diffusion and mass flow). However, in the case of K, Ca, and Mg, other aspects such as their interactions in terms of exchange reactions, and the concentrations of anions coexisting with these cations have to be taken into account at the root surface (Bouldin 1989). In the present study, the concentra-

Table 8. Exchangeable Mg concentration (mg kg^{-1} dry soil) in rhizosphere and bulk soils from Alfisol and Vertisol fields of sorghum, ICRISAT Asia Center, 1989.

DAS	0 P				13 P				Source of significance[b]		
	0 N		120 N		0 N		120 N				
	R[a]	B[a]	R	B	R	B	R	B	S	S-P	S-N
Alfisol											
28	223	210	259	214	245	203	255	207	**	ns	ns
44	233	260	229	261	211	228	218	203	ns	ns	ns
58	231	349	251	367	237	260	219	290	**	ns	ns
71	200	283	204	275	178	235	182	236	**	ns	ns
92	199	229	186	271	207	219	214	233	**	**	**
120	210	364	221	311	240	269	195	300	**	**	ns
Mean	216	282	225	283	220	236	214	245	**	*	ns
R−B	−66**		−58**		−16*		−31**				
Vertisol											
37					452	361	355	342	ns		ns
50					394	458	421	413	ns		ns
64					393	474	473	443	*		ns
78					463	636	461	536	**		ns
98					458	550	372	383	**		ns
114					367	437	353	305	**		*
Mean					421	486	406	404	**		ns
R−B					−65**		2[ns]				

[a] R, rhizosphere soil; B, bulk soil; R−B, rhizosphere soil minus bulk soil. [b] S, soil; P, phosphorus; N, nitrogen; ANOVA was performed with all three P and N levels in Alfisol experiment and with all six N levels in Vertisol experiment. * and ** Significant at 5% and 1%, respectively; ns, not significant at 5%.

tions of three cations, K, Ca, and Mg, showed different patterns in the rhizosphere and bulk soils. However, as we did not study the interaction between these cations or the concentration of anions, further studies are required to analyse in more detail the contrasting behavior of these cations.

CONCLUSION

Despite the problems associated with monitoring organic C and mineral contents in the rhizosphere under field conditions, useful information was obtained regarding plant nutrient status in the rhizosphere in the present study. The concentration of organic C was consistently higher in the rhizosphere soil than in the bulk soil, and was not affected by P or N fertilizer. Despite this higher concentration of organic C in the rhizosphere soil, the concentration of inorganic N that is subject to immobilization in the presence of organic C was significantly higher in the rhizosphere than in the bulk soil, presumably, due to increased N mineralization associated with the grazing of rhizosphere microorganisms by their predators. Accumulation of $NaHCO_3$ extractable P in the rhizosphere soil was observed and the extent of the accumulation was not affected by N fertilizer. Exchangeable K, Ca, and Mg behaved differently in the rhizosphere. Accumulation of K was observed in the rhizosphere, levels of Ca did not significantly differ between the rhizosphere and bulk soils, and depletion of Mg was observed in the rhizosphere soil. Patterns of accumulation or depletion of organic C, inorganic N, and exchangeable K and Mg in the rhizosphere in an Alfisol were similar to those in a Vertisol. These findings provide a better understanding of chemical and biological processes in the rhizosphere, with the ultimate goal of increasing plant nutrient uptake under field conditions.

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