J. Bamboo and Rattan, Vol. 3, No. 2, pp. 81–90 (2004)

Root morphology and development in rattans. 3. Root system development in *Calamus thwaitesii* Becc. and *Calamus rotang* L. in relation to the physical properties of a degraded lateritic soil

V. K. JAYASREE[1], M. P. SUJATHA[2], C. RENUKA[2,*] and P. RUGMINI[2]

[1] *SreeKrishna College, Guruvayur, Thrissur, Kerala, India*
[2] *Kerala Forest Research Institute, Peechi, Thrissur, Kerala 680653, India*

Abstract—The suitability of any vegetation to a particular soil is greatly controlled by the establishment and proliferation of the root system in that soil, which in turn is decided by the nature and properties of the soil. As part of an attempt to introduce *Calamus* from natural forests to degraded lateritic soils of Kerala, this study was conducted to evaluate the root system development of two species of *Calamus*, *viz.*, *Calamus thwaitesii* and *C. rotang*, grown in a degraded lateritic soil at Palappilly range in the Chalakkudy Forest Division of the State. Both species had been planted in plots of 90 m × 4.5 m size with a spacing of 1.5 m × 1.5 m. For collecting soil samples, five 3-year-old plants from each species were selected from the central row of each plot. Root parameters such as root length, rooting density, total root weight and fine root weight were determined in soil core samples collected from different depths (0–15 cm, 15–40 cm and 40–60 cm) and radial distances from the base of the plant (0 cm, 10 cm and 30 cm) at three randomly selected sampling points around a single plant. Various physical properties of these soil samples were determined using standard procedures and their relation with root parameters were determined. Results revealed that radial distance from the plant inversely affected the root growth in both the species especially within a soil depth of 0–60 cm rather than at different soil layers considered separately. Depth of soil also had an inverse relationship with root growth in both the species. Among the different soil physical properties, soil moisture and gravel were negatively correlated with all the root parameters while positive correlation was seen with sand. No definite relationship was observed with the bulk density in both the species.

Key words: *Calamus*; root development; lateritic soil; physical properties.

---

[*] To whom correspondence should be addressed. E-mail: renuka@kfri.org

INTRODUCTION

The rattan resources of Kerala State, India, are restricted to remote areas and they are reduced at an alarming rate due to over-exploitation. This necessitates effective measures to conserve and propagate this endangered resource. Ecosystem conservation together with large-scale cultivation of rattans will guarantee enough raw material for the industry, as well as the conservation of the species and genetic diversity. Most of the forests of the State are degrading in nature and hence large scale cultivation of rattan is possible only through their introduction from fertile natural habitat to degraded edaphic environment.

The suitability of a new edaphic environment for a particular species is greatly influenced by the establishment and proliferation of the species root system in that soil which in turn is decided by the nature and properties of the soil. Root systems are important for water and nutrient uptake, sources of endogenous hormones, and ultimately have direct influence on seedling growth and development. Root systems and root morphological components (tap roots, basal roots, adventitious roots and lateral roots) although genetically controlled, are very variable in growth and development even in optimum environments. Therefore, fluctuating soil environments may have major impacts on root growth. Even though much information regarding the development of root system in relation to the physical properties of soils in various agricultural crops is available [1–3] no such information is available in *Calamus*. Hence the present study mainly focus to find out the growth and development of the root systems of two species of *Calamus* (*C. rotang* and *C. thwaitesii*) in relation to the physical properties of a degraded lateritic soil.

STUDY AREA AND METHODS

The study area, species, and details of plots remain the same as detailed in the previous two papers [2, 4]. For collecting soil samples, 5 plants of about three years old from each species were selected from the central row of the plot. Soil samples were collected using a 4-cm-diameter core from four different depths (0–15 cm, 15–30 cm, 30–45 cm and 40–60 cm) at 0, 10 and 30 cm away from the base of the plant. There were three randomly selected sampling points around a single plant in order to get fragments of the roots, which spread, in all directions. Thus, there was a total of 28 samples from a single plant (12 at 10 cm from the base, 12 at 30 cm away from the base and 4 at immediately below the base of the plant) and thus 140 samples from 5 plants for each species. Separate soil samples (28 per plant) were also collected for estimating soil moisture.

Soil samples, brought directly from the field, were air dried in the shade for 4–5 days and were weighed. Root fragments were separated from each sample and used for determining different root parameters such as root length, total root weight, fine root weight and rooting density. Soil was then sieved through a 2-mm sieve and gravel content was measured. The 2-mm sieved soil samples were used for laboratory analyses.

Soil moisture was estimated using a gravimetric method. Important physical properties such as texture (international pipette method) and bulk density (core method) were estimated following the procedures described by Black *et al.* [3]. The root fragments separated from the soil samples were weighed to obtain total root weight. They were then sieved through a 2-mm sieve to extract the fine roots, which were also weighed to obtain the fine root weight.

Length of all the roots in the samples was estimated using Newman's line intersection method. For this a transparent plastic trough was placed over a 1 cm^2 graph paper. Root fragments of each soil sample along with a certain amount of water was then poured into the trough. These were then arranged in such a manner that they did not touch one another. Since the lines of the graph paper are visible through the transparent trough, the number of intersections of the root pieces with the horizontal and vertical lines on the graph paper could be counted. Root length was calculated using the formula $R = 11/14N$, where N comprises all intercepts of roots with total length of vertical and horizontal grid lines. R is measured in terms of grid units.

Rooting density in each soil sample was calculated from the root length using the formula l/v, where l is the total root length in each sample and v is the volume of the soil present in that core sample.

RESULTS AND DISCUSSION

Results of the study are presented and discussed in the following three sections.

- Root growth as influenced by variation in radial distance from the plant.
- Root growth as influenced by the variation in the depth of soil.
- Root growth as influenced by the physical properties of the soil.

The observations recorded under these three sections are shown in Tables 1–4. The double asterisk denotes significance at the 1% level.

Root growth as influenced by variation in radial distance from the plant

The mean values of various root parameters (Table 1), *viz*., root length, total root weight, fine root weight and rooting density at different radial distances from the plant (0, 10 and 30 cm) revealed that *C. rotang* attained the maximum values for these parameters at the base of the plant and only total root weight was decreasing significantly with increase in radial distance. When different soil layers were considered separately, in the surface layer (0–15 cm) all the root parameters were decreasing significantly with increase in lateral distance. However, the soil at the two depths (15–30 cm and 30–45 cm) showed maximum rooting density at 10 cm away from the plant and minimum at the base of the plant.

In *C. thwaitesii* also, the maximum mean values of all the root parameters were recorded at the base of the plant and most of them were decreasing significantly

Table 1.
Mean values of root parameters at different radial distances and depths from the base of the plant ($n = 5$)

Root parameters	RD (cm)	Depth (cm)									
		C. rotang					*C. thwaitesii*				
		0–15	15–30	30–45	45–60	0–60	0–15	15–30	30–45	45–60	0–60
Root length (cm)	0	127.0	18.7	16.2	11.9	43.5	189.4	76.1	7.1	14.8	71.8
	10	101.6	37.1	21.4	11.3	42.8	100.5	43.2	16.9	11.8	43.1
	30	75.7	21.0	20.0	9.3	31.5	91.6	32.6	10.6	23.1	39.5
	0–30	94.1	27.5	20.1	10.5		109.4	43.4	12.8	17.1	
Total root weight (g)	0	3.4	0.1	0.1	0.1	0.9	4.1	0.4	0.03	0.05	1.1
	10	1.14	0.3	0.1	0.1	0.4	0.4	0.2	0.1	0.03	0.2
	30	0.5	0.3	0.1	0.04	0.2	0.4	0.2	0.1	0.05	0.2
	0–30	1.2	0.2	0.1	0.1		0.9	0.2	0.1	0.04	
Fine root weight (g)	0	0.2	0.04	0.02	0.03	0.1	0.4	0.1	0.01	0.03	0.1
	10	0.2	0.04	0.03	0.01	0.1	0.2	0.1	0.03	0.03	0.1
	30	0.1	0.04	0.02	0.02	0.05	0.2	0.1	0.03	0.02	0.1
	0–30	0.2	0.04	0.02	0.02		0.23	0.1	0.03	0.02	
Rooting density ($\mathrm{cm\,cm^{-3}}$)	0	0.7	0.1	0.1	0.1	0.2	1.0	0.4	0.04	0.1	0.4
	10	0.5	0.2	0.1	0.1	0.2	0.5	0.2	0.1	0.1	0.2
	30	0.4	0.1	0.1	0.05	0.2	0.5	0.1	0.1	0.1	0.2
	0–30	0.5	0.2	0.1	0.1		0.6	0.2	0.1	0.1	

RD, radial distance.

Table 2.
Correlation between soil physical properties and root parameters within a depth of 0–60 cm and up to a radial distance of 30 cm

Soil properties	Root parameters							
	C. rotang				*C. thwaitesii*			
	RL	TRW	FRW	ROD	RL	TRW	FRW	ROD
Soil moisture	−0.3040**	−0.2894**	−0.3362**	−0.3007**	−0.2285**	−0.1282	−0.1126	−0.2485**
Bulk density	−0.0996	−0.1853*	−0.1595	−0.1158	−0.1321	−0.1057	−0.1059	−0.1557
Gravel	−0.3279**	−0.2553**	−0.3656**	−0.3204**	−0.5608**	−0.2393**	−0.3949**	−0.5221**
Sand	0.4530**	0.3931**	−0.3383**	0.4446**	0.4450**	0.2497**	0.4886**	0.4217**
Silt	−0.1945*	−0.2522**	−0.1463	−0.1850*	0.2222**	−0.1067	−0.2725**	−0.2114*
Clay	−0.1369	−0.0187	−0.1097	−0.142	−0.0517	−0.0346	−0.0396	−0.048

RL, root length; TRW, total root weight; FRW, fine root weight; ROD, rooting density.
* Significant at 5%.
** Significant at 1%.

with increase in the lateral distance. About 46% of rooting density was observed at the basal region of the plant within 60 cm depth, 29% at 10 cm radial distance and 25% at 30 cm radial distance (calculated from Table 1). A similar decrease of

Table 3.
Correlation between soil physical properties and root parameters at different distances from the base of the plant

Distance from the base of the plant (cm)	Soil physical properties	Root parameters							
		C. rotang				C. thwaitesii			
		RL	TRW	FRW	ROD	RL	TRW	FRW	ROD
0	Moisture	−0.4828*	−0.4926*	−0.4851*	−0.4834*	−0.2881	−0.3893	−0.0087	−0.2873
	Bulk density	−0.3273	−0.3855	−0.3092	−0.3130	−0.4491*	−0.1601	−0.1524	−0.4481
	Gravel	−0.5790**	−0.5120*	−0.5674**	−0.5572*	−0.6168**	−0.3643	−0.6726**	−0.6173
	Sand	0.5123*	0.4570*	0.3455	0.4769*	0.5096*	0.4464*	0.6612**	0.5101*
	Silt	−0.3597	−0.3444	−0.2599	−0.3256	0.4056	−0.1622	−0.4531*	−0.4064
	Clay	0.0408	0.0681	0.0516	0.0259	0.1545	−0.0761	0.0065	0.5130
10	Moisture	−0.4106**	−0.3894**	−0.4494**	−0.4099**	−0.2288	−0.2121	−0.0923	−0.2272
	Bulk density	−0.2397	−0.3077*	−0.2794*	−0.2571*	−0.0254	−0.0810	−0.0997	−0.0310
	Gravel	−0.4406**	−0.3206*	−0.4771**	−0.4339**	−0.5277**	−0.4379**	−0.4820**	−0.5089**
	Sand	0.5655**	0.5213**	0.4468**	0.5549**	0.6164**	0.5862**	0.6375**	0.6151**
	Silt	−0.2155	−0.2605	−0.1343	−0.2150	−0.2235	−0.0905	−0.2563	−0.2091
	Clay	−0.1697	−0.0830	−0.1768	−0.1623	−0.0156	−0.1503	0.0117	−0.0311
30	Moisture	−0.1104	−0.0510	−0.0947	−0.1063	−0.3206*	−0.0434	−0.2774*	−0.4191**
	Bulk density	0.1392	0.0689	0.0811	0.1063	−0.0769	−0.1738	−0.0963	−0.1374
	Gravel	−0.1498	−0.1865	−0.1869	−0.1441	−0.6607**	−0.3152*	−0.2759*	0.5465**
	Sand	0.3297*	0.4069**	0.2309	0.3357**	0.4284**	0.3161*	0.4285**	0.3619**
	Silt	0.0173	−0.1673*	0.0813	0.0292	−0.1006	−0.1416	−0.2251	0.0922
	Clay	−0.3665**	−0.2163	−0.3782**	−0.3887**	−0.3108*	−0.1407	−0.1472	−0.2529

Abbreviations as in Table 2.
[*] Significant at 5%.
[**] Significant at 1%.

root growth with increase in radial distance was seen in both surface (0–15 cm) and subsurface (15–30 cm) layers.

The study in general reveals that root growth in both the species had an inverse relationship with the radial distance especially within a soil depth of 0–60 cm and 0–15 cm.

Root growth as influenced by the variation in the depth of soil

In *C. rotang,* at all the lateral distances, maximum mean values for all the root parameters were recorded (Table 1) at the surface layer (0–15 cm) of the soil and they were decreasing significantly with increase in depth of soil. Similar observations were recorded in *C. thwaitesii* also. Thus, in both the species soil depth had an inverse effect on root growth.

Root growth as influenced by physical properties of the soil

Soil moisture. In general, the content of soil moisture varied from 6.03 to 7.9% in soil around *C. rotang* within a depth of 0–60 cm and up to a radial distance of 30 cm. In this volume of soil highly significant and negative relation of soil moisture with root parameters such as root length ($r = -0.3040^{**}$), total root weight ($r = -0.2894^{**}$), fine root weight ($r = -0.3362^{**}$) and rooting density ($r = -0.3007^{**}$) were observed. In soil around *C. thwaitesii,* moisture was found to have a highly significant and negative correlation with root length ($r = -0.2285^{**}$) and rooting density ($r = -0.2485^{**}$) (Table 2).

When different lateral distances were considered separately, the influence of soil moisture on root growth was negative and highly significant at the base of the plant and also at 10 cm away in *C. rotang* (Table 3). But in *C. thwaitesii* significant and negative correlation of root growth with soil moisture was observed only at a radial distance of 30 cm.

Among the different depths, significant relation of soil moisture on root growth was more pronounced at 45–60 cm depth in *C. rotang* and at 15–30 cm depth in *C. thwaitesii*. Soil moisture shows a highly significant negative correlation with root parameters in both species of *Calamus.* Hence a higher root growth occurs in *Calamus* at regions where soil moisture is comparatively less. This could be well explained since root growth in both these species is found to be more at the surface layer where moisture is comparatively less. Even though both the species were grown in the same area with uniform climate and soil conditions, soil moisture values with respect to *C. thwaitesii* were found to be significantly higher than *C. rotang*. This indicates that water consumption is comparatively less in *C. thwaitesii* and hence would be a better species in areas of water shortage. In this study, *C. rotang* has lesser root length compared to that of *C. thwaitesii*. Soil moisture stress can be suggested as a reason for this. *C. thwaitesii*, which does not require much moisture overcomes this without having an inverse effect on the root length. This is in fact supported by the work of Korikanthmath [5]. They have noted that soil moisture stress imposed on cardamom seedlings resulted in reduced root length.

Gravel. Results revealed a relatively higher content of gravel in soil around both *C. thwaitesii* (32.2–41.7%) and *C. rotang* (24.6–39.8%) within a depth of 0–60 cm and up to a radial distance of 30 cm. In this volume of soil highly significant and negative relation of gravel with root length ($r = -0.3279^{**}$), total root weight ($r = -0.2553^{**}$), fine root weight ($r = -0.3656^{**}$) and rooting density ($r = -0.3204^{**}$) was observed in *C. rotang*. Similar relation with all the root parameters viz., root length ($r = -0.5608^{**}$), total root weight ($r = -0.2393^{**}$), fine root weight ($r = -0.3949^{**}$) and rooting density ($r = -0.5221^{**}$) was observed in *C. thwaitesii* also (Table 2).

At all lateral distances in both the species, gravel showed significant and negative relationship with root growth. On considering different soil depths, in surface and subsurface layers, root growth of *C. thwaitesii* had significant and negative relationship with gravel.

Thus, in general a high negative correlation of gravel with root growth was observed in both species of *Calamus*. Presence of gravel in the soil usually cause hindrance to the growth of roots. The results of the present study also support the above statement.

Soil texture. Among the soil separates, sand was found to have a highly significant and positive relation with all the root parameters such as as root length ($r = 0.4530^{**}$, 0.4450^{**}), total root weight ($r = 0.3931^{**}$, 0.2497^{**}), fine root weight ($r = 0.3383^{**}$, 0.4886^{**}) and rooting density ($r = 0.4446^{**}$, 0.4217^{**}) in both *C. rotang* and *C. thwaitesii*, respectively. Silt was found to exert significant and negative impact on root length ($r = -0.1945^{*}$), total root weight ($r = -0.2522^{**}$) and rooting density ($r = -0.1850^{**}$) in *C. rotang*, while in *C. thwaitesii* its influence was noticed on root length ($r = -0.2222^{**}$), fine root weight ($r = -0.2725^{**}$) and rooting density ($r = -0.2114^{*}$) (Table 2). Among different lateral distances, sand had more pronounced influence on root growth at 10 cm away from the plant in both the species (Table 3).

The correlation coefficient between root parameters and soil properties at different soil depths revealed a significant and negative relationship for sand with fine root weight ($r = -0.3814^{*}$) at 15–30 cm depth in *C. rotang*, while highly significant and positive relationship for sand with total root weight ($r = 0.4335^{**}$) and fine root weight ($r = 0.5400^{**}$) at 30–45 cm depth was found in *C. thwaitesii* (Table 4).

Thus, in general sand shows a highly significant positive correlation with root growth in both species of *Calamus*. It increases porosity of the soil thereby enhancing root growth as is seen in the present study. In the case of silt, it is highly and negatively significant at 10 cm radial distance in *C. rotang*, while in *C. thwaitesii* it shows high negative correlation with root growth at the base of the

Table 4.
Correlation between soil physical properties on root parameters at different soil depths

Depth (cm)	Soil physical properties	Root parameters							
		C. rotang				*C. thwaitesii*			
		RL	TRW	FRW	ROD	RL	TRW	FRW	ROD
0–15	Moisture	−0.1007	−0.2751	−0.2263	−0.0880	−0.0539	−0.0458	0.1154	−0.0907
	Bulk density	−0.0013	−0.3200	−0.2346	0.0224	−0.0462	−0.1249	0.0448	−0.5420
	Gravel	−0.1774	−0.1384	0.2583	−0.1674	−0.5485**	−0.0573	−0.2197	−0.4237*
	Sand	0.1169	0.1778	−0.0399	−0.0807	0.1136	−0.0266	0.2923	−0.1394
	Silt	−0.1195	−0.2859	−0.0899	−0.0852	−0.3054	−0.0105	−0.3931*	−0.0890
	Clay	0.0653	0.2443	0.1596	0.0488	0.2605	0.0855	0.1314	0.2462
15–30	Moisture	0.0978	0.3201	−0.0859	−0.0898	0.0764	0.3524*	0.1806	0.0761
	Bulk density	−0.0105	−0.2137	0.0877	−0.0501	−0.0122	0.1839	0.0669	−0.0135
	Gravel	0.0526	0.1855	−0.1157	0.1288	−0.3975*	−0.3119	−0.3192	−0.3986*
	Sand	0.1398	0.2961	−0.3814*	0.0904	0.0566	0.2105	0.2519	0.0588
	Silt	−0.1220	−0.1306	0.3567*	−0.0517	0.0701	0.1501	0.0422	0.0716
	Clay	0.0756	−0.0385	−0.2292	−0.0094	−0.0933	−0.2361	−0.1450	−0.0956
30–45	Moisture	−0.1737	−0.2372	−0.0029	−0.1514	0.0220	−0.0954	−0.2597	0.0627
	Bulk density	0.3722*	0.3439*	−0.0047	0.2393	−0.2489	−0.5395**	−0.5353**	−0.2543
	Gravel	0.2520	−0.3565*	0.2628	0.2821	−0.1981	−0.1256	−0.2049	−0.2107
	Sand	0.1578	−0.1484	−0.0672	0.1395	0.3077	0.4335**	0.5400**	0.3077
	Silt	0.1154	−0.2183	−0.1352	0.1102	−0.0428	−0.2042	−0.3170	−0.0428
	Clay	−0.1552	0.1334	0.0661	−0.1374	0.1102	0.0246	0.1090	−0.1124
45–60	Moisture	0.0269	−0.1494	−0.2789	−0.4149*	0.1100	−0.0716	−0.0971	−0.1180
	Bulk density	−0.0424	−0.0329	0.2294	0.0629	−0.0882	−0.0716	−0.1634	−0.2566
	Gravel	−0.0883	0.0227	0.0105	−0.0806	−0.2668	−0.0977	−0.1253	−0.1105
	Sand	−0.0767	0.1017	0.1200	−0.0261	−0.0561	0.1316	0.1538	0.0482
	Silt	0.0555	−0.3146	−0.1345	−0.0034	0.1398	0.0349	−0.0181	0.0570
	Clay	−0.0081	0.2820	0.0663	0.0224	−0.1536	−0.1733	−0.1160	−0.1285

Abbreviations as in Table 2.

*Significant at 5%.

**Significant at 1%.

plant and also at 10 cm radial distance. Lower porosity is suggested as one of the reasons for inhibition of root growth [6] and is applicable in the case of silt.

Bulk density. The significant and negative influence of bulk density on root growth was observed only in the case of total root weight ($r = -0.1853^*$) in *C. rotang* and no significant relation was observed with any of the root parameters in the case of *C. thwaitesii* (Table 2). At a lateral distance of 10 cm also root growth was significantly and negatively influenced by bulk density in *C. rotang* (Table 3).

Bulk density in this study is not correlating with any of the root parameters in *C. rotang*. This might be due to the fact that the seedlings of *Calamus* have not grown to produce roots to such an extent as to find any correlation with the bulk density of the soil. However, bulk density is found to show an increase with soil depth as well as lateral distance from the plant. Studies by Petcu *et al.* [7], Nune and Bisbal [8], Lav–Bhushan *et al.* [9], Goodman and Ennos [10] and Imhoff *et al.* [6] support the above statement.

The above results in general reveal that any species will have its own root architecture which is genetically controlled. If there is no much hindrance in the soil, the same architecture will be expressed by the plant. In the present study, there was no hindrance in the soil and hence the plant could express its own root architecture [2]. The results, thus, show that more root growth occurs closer to the base of the plant at a depth of 0–15 cm. In the given soil, each property of soil has its own trend already. Thus, both inherent root architecture and variation of soil properties at different depths have an over all effect on the rooting pattern.

CONCLUSIONS

Results revealed that the root growth in both the species was inversely correlated with radial distance from the plant especially within a soil depth of 0–60 cm rather than at different soil layers considered separately. Root growth in both the species also had an inverse relationship with the depth of soil. Among the different soil physical properties, soil moisture and gravel were negatively correlated with root growth while positive correlation was seen with sand. Results also suggest that it is advisable to grow *C. rotang* and *C. thwaitesii* on degraded lateritic soil, provided there is no much physical hindrance to root growth as seen in the present study.

REFERENCES

1. J. Pabin, J. Lipiec, S. Wlodek, A. Biskupski and A. Kaus, Critical soil bulk density and strength for pea seedling root growth as related to other soil factors, *Soil Till. Res.* **46** (3–4), 203–208 (1998).
2. V. K. Jayasree, C. Renuka and P. Rugmini, Root morphology and development in rattans. 1. A quantitative study of the roots in two species of *Calamus* L., *J. Bamboo and Rattan* **2** (2), 135–151 (2003).

3. C. A. Black, D. D. Evans, L. E. Ensminger, J. L. White and F. E. Clark, *Methods of Soil Analysis*, Part I. American Society of Agronomists, Madison, WI (1965).
4. V. K. Jayasree, C. Renuka and P. Rugmini, Root morphology and development in rattans. 2. Soil requirements and efficiency of the root systems of *Calamus thwaitesii* Becc. and Hook. f. and *C. rotang* Linn. in the seedling stage, *J. Bamboo and Rattan* **3** (1), 3–12 (2004).
5. V. S. Korikanthmath, Effect of moisture stress on growth of cardamom (*Elettaria cardamomum* Maton.), in: *Water and Nutrient Management for Sustainable Production and Quality of Spices*, S. J. A. Gowda, K. S. Krishnamurthy, A. K. Sadanandan, K. S. Krishnamurthty and K. Kandiannan (Eds), pp. 158–160. Indian Society for spices, Calicut, India (1998).
6. S. Imhoff, A. Pires da Silva and C. A. Tormena, Spatial heterogeneity of soil properties in areas under elephant–grass short–duration grazing system, *Plant and Soil* **219** (1–2), 161–168 (2000).
7. G. Petcu, G. E. Petcu, M. Terbea, I. Chirnogeanu and D. Musat, Some aspects of mineral nutrition of maize in relations to physical and chemical properties of soil, *Probleme de Agrofitotehnie Teoretica Si Aplicata* **19** (2), 29–40 (1997).
8. U. M. C. Nune and E. C. de-Bisbal, Effect of soil compaction on some morphological parameters of maize root development, *Agronomia Tropical Maracay* **49** (1), 93–106 (1999).
9. P. K. Lav-Bhushan, P. K. Sharma and L. Bhushan, Effect of depth, bulk density and aeration status of root zone on productivity of wheat, *J. Ind. Soc. Soil Sc*i. **47** (1), 29–34 (1999).
10. A. M. Goodman and A. R. Ennos, The effects of soil bulk density on the morphology and anchorage mechanics of the root systems of sunflower and maize, *Ann. Bot*. **83** (3), 293–302 (1999).