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Root Shoot Relationships: An Effective Indicator of Soil Compaction and Water Stress for Coconut (*Cocos nucifera* L.) Seedlings

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ABSTRACT. An experiment was conducted to determine the root-shoot relationships of coconut seedlings in their first few months of establishment in different soil series in coconut growing areas under two soil watering regimes and two soil compaction levels with the objective of developing possible measures to rectify the high mortality rate during field establishment.

After six week of establishment of Six-month old CRIC 60 coconut seedlings which was grown under Weliketiya, Wilpattu and Mavillu soil series at two different soil compaction levels (bulk density 1.3 and 1.6 g.cm^{-3}) in pots in a green house environment, an eight-week water stress period was imposed. Growth and development of above and below ground components, and soil moisture contents were measured at the end of the experimental period.

The impact of water deficit on the growth of coconut seedlings greatly varied among soil series. Different soils had differential nutrient contents and organic carbon contents leading to different water holding capacities and nutritional capabilities. The changes in assimilate partitioning pattern favouring roots to reduce further water loss and capture more water to cope up with the water limited environment was common in all soil types. The high nutrient content (N, P, K and Mg), high cation exchange capacity and high organic carbon content in Wilpattu soil series were the main factors that contributed to a better seedling growth when compared to total biomass in seedlings grown in Weliketiya and Mavillu soil series. The physical obstruction under high soil compaction levels resulted in a reduced and poorly spread coconut root system, although sturdy roots succeeded in penetrating hardy soil mainly in Wilpattu series that contained some stored water in deeper layers. Therefore, improvement of Weliketiya and Mavillu soils with respect to the physical and chemical parameters would help in arresting the mortality rate and reduction in vegetative growth. Alleviation of high soil compaction to facilitate the root growth appears important in the establishment of coconut seedlings.

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INTRODUCTION

The dry periods which prevailed in Sri Lanka during the last two decades have adversely affected the National Replanting Programme (NRP) for coconut, which was in operation for four decades for systematic replacement of senile palms by new cultivars in order to maintain the sustainability of the crop. The annual demand for coconut seedlings has always been higher than the actual requirement in recent years in spite of the fact that around 33% of growers use their own seedlings for replanting. According to Liyanage (1998), the current demand for coconut seedlings is over 3 million although the actual requirement is only about 1.45 million per year. It was emphasized that the reason for this difference was due to the high mortality of coconut seedlings during the establishment phase resulting from the adverse conditions such as water stress. The degree of stress varies in different soils with various chemical and physical characteristics, especially with different soil compaction levels. This experiment was conducted to investigate the shoot and root growth of coconut seedlings in different coconut growing soils under two soil compaction levels and two soil water levels during first few months of establishment. Inherent characteristics of commonly available soils in coconut growing areas and their impact on growth and establishment of coconut seedlings were also studied.

MATERIALS AND METHODS

Experimental design

A three factor factorial experiment was conducted with in a completely randomized design (CRD) in a green house environment. The factors considered were water treatment with two moisture regimes of W_1 (watered up to field capacity maintaining an average of 20% moisture) and W_2 (continuous withholding of water for 8 weeks during which flaccidity was observed in most leaves and average soil moisture level declined to 1-2%), soil types with three different soil series namely Weliketiya, Wilpattu and Mavillu, and soil compaction with two levels of bulk densities of C_1 (1.3 $g.cm^{-3}$) and C_2 (1.6 $g.cm^{-3}$). Altogether, there were 12 treatment combinations and each treatment had 6 replicates.

Planting material

Six-month old, open pollinated CRIC 60 (*Tall* x *Tall*) coconut seedlings from the Isolated Seed Garden (ISG), Ambakelle, were assayed in this experiment at Coconut Research Institute, Sri Lanka, from January to May, 1998. Seedlings were selected from a healthy stock of seed coconuts, which exhibited over 90% germination. The primary selection for the uniformity of material was made on growth parameters of the seedlings such as height, girth at collar region and the number of leaves at the commencement of the experiment.

Soils and preparation of pots

Three soil types representing three main soil series *viz.* Weliketiya, Wilpattu and Mavillu (Somasiri *et al.*, 1994), inclusive of both surface and subsurface soils were collected from the Puttlam district. Galvanized iron pots (33 cm diameter and 85 cm height) were filled with air-dried soils free of foreign objects up to 75 cm height amounting to a total volume of 0.067 m^3 per pot. Soils in the pot were compacted to two compaction levels of bulk densities of 1.3 and 1.6 $g.cm^{-3}$. The relevant soil mass was compressed into the appropriate volume by equal number of hammerings using a weight of 750 g to achieve the require bulk density (dry mass of soil (g) = volume covered by the soil (cm^3) × bulk density ($g.cm^{-3}$)). These levels lie within the inherent compaction range of the soils in the field. All externally visible roots were removed from seedlings and the seed portion was dipped in 1% benomyl solution for 1 h to prevent possible fungal infections. Seedlings were planted in pots after applying coal tar on cut surfaces of roots and allowed to establish for six weeks in the glass house with soils under field capacity before imposing the water treatment.

Plant house conditions

The level of photosynthetically active radiation (PAR) in the green house varied from 600–950 $\mu mol\ m^{-2}s^{-1}$ during the day time while the day and night temperatures ranged from 30–34^{0}C and 28–30^{0}C, respectively. The daytime relative humidity (RH) varied from 25–45% and its variation was 14–27% during the night.

Analysis of soil

Soil chemical parameters namely electrical conductivity (EC), pH, cation exchange capacity (CEC) and macro-nutrient contents were determined using the methods illustrated by Black *et al.*, 1979 with six replicates per each soil category. Soil moisture content was measured using the gypsum resistance block method (Wellings *et al.*, 1985).

Investigations on shoot and root components

After uprooting seedlings, roots were separated in to three groups *viz.* primary roots, secondary roots and tertiary roots on the basis of their place of origin from the base. Root diameter (mm) was measured 2–3 cm away from the tip of 10 random samples of each group for all seedlings, using Starrett, Precision Vernior Calipers. Root lengths were also calculated by the modified line intersect method of Tennant (1975). Root and shoot dry weights were measured after oven drying at 60^{0}C.

Analysis of data

Data on soil, root and shoot parameters were subjected to an Analysis of Variance (ANOVA) using the Statistical Analysis System (SAS) computer package. Models were chosen for factorial analyses indicating all 2-way and 3-way interactions. Significant interactions were computed for further analysis. The mean separations were obtained by restricted Least Significant Difference (LSD).

RESULTS AND DISCUSSION

Soil comparison

Differences in the three soil series were clearly observed due to their nutrient and chemical status. The percentage organic carbon content was significantly higher ($P<0.001$) by 46.0% and 7.6% in Wilpattu and Mavillu series soils compared to the Weliketiya series soil which had the lowest organic carbon content (Table 1). A high percentage of water could be observed in Wilpattu soil both at the field capacity and even at the end of eight-week drying period. High organic carbon content could contribute retaining of water in the Wilpattu soil.

Wilpattu soil also contained significantly higher quantities of nitrogen, potassium, phosphorous and magnesium ($P<0.001$) compared that in both Mavillu and Weliketiya soils (Table 1). Hence, higher growth and development of coconut seedlings grown in Wilpattu series soil compared to the other two series of soils could be attributed to this factor. A significantly high electrical conductivity ($P<0.001$) and cation exchange capacity ($P<0.001$) were also found on in Wilpattu series (Table 1). This indicated the high capacity of Wilpattu series to retain more nutrients, reducing possible leaching.

Table 1. Nutrient status and chemical properties of different soil types used in the experiment.

Soil Series	Weliketiya	Wilpattu	Mavillu	LSD
Organic C%	0.26 ± 0.008	0.38 ± 0.007	0.28 ± 0.007	0.02***
N%	0.20 ± 0.004	0.34 ± 0.020	0.22 ± 0.008	0.05***
K (cmol/kg)	0.16 ± 0.004	0.23 ± 0.004	0.18 ± 0.005	0.01***
P (mg/g)	15.67 ± 0.18	30.35 ± 0.16	17.71 ± 0.05	0.44***
Ca (cmol/kg)	1.31 ± 0.020	4.25 ± 0.020	2.46 ± 0.020	0.07***
Mg (cmol/kg)	0.27 ± 0.008	0.41 ± 0.008	0.38 ± 0.010	0.03***
Soil pH	6.27 ± 0.010	7.32 ± 0.030	6.48 ± 0.030	0.08***
Conductivity (μs/cm)	4.37 ± 0.080	10.17 ± 0.05	7.55 ± 0.070	2.20***
CEC (cmol/kg)	3.27 ± 0.050	5.35 ± 0.070	4.06 ± 0.020	0.18***

*** Significant at $P<0.001$

Shoot and root dry weight and root/shoot ratio

All factors had a significant impact on both root and shoot dry weights and on the root-to-shoot ratio. Mean shoot and root dry weights declined by 37% and 28% respectively making a reduction in total biomass by 35% under water stress. In addition, a change in partitioning pattern occurred in favour of roots showing high root/shoot ratio (14%) compared to that of regularly watered seedlings (Table 2).

Table 2. Mean shoot and root dry weight, and root/shoot ratio (±SE) at the end of the experiment.

Treatment	Shoot weight (g)	Root weight (g)	Root/shoot ratio
Field capacity (moisture 20%)	226.0 ± 9.5†	46.98 ± 2.66†	0.21 ± 0.01†
Drying (moisture 1-2%)	143.3 ± 6.3	33.87 ± 1.47	0.24 ± 0.01
LSD	*19.5****	*3.11****	*0.02**
Weliketiya series	171.87±10.5	36.57 ± 2.81	0.22 ± 0.02
Wilpattu series	199.87±11.3	48.35 ± 2.59	0.26 ± 0.01
Mavillu series	175.77±9.9	36.35 ± 2.37	0.21 ± 0.01
LSD	*22.95**	*3.81****	*0.02***
Low compaction	174.19±10.2	49.36 ± 2.72	0.27 ± 0.01
High compaction	195.14±10.4	30.49 ± 1.53	0.17 ± 0.01
LSD	*19.5**	*3.11****	*0.02****

* Significant at P<0.05   ** P<0.01   *** P<0.001   NS- Not Significant

† Regularly watered throughout the experiment

The reduction in shoot dry weight, root dry weights and total biomass in seedlings with water deficit could be attributed to the reduced amount of assimilates available for partitioning for shoot and roots, due to reduced photosynthesis under extended water stress. In addition, the reduction in pressure potential in leaves would directly have an impact on cell expansion.

The well accepted theory of shifting the assimilate partitioning pattern in favour of roots is clearly illustrated by high root-to-shoot ratio in water stressed seedlings. Root/shoot ratio was high for drought imposed seedlings at both compaction levels and for low compaction at both watering levels (Table 3). The highest ratio was observed in seedlings grown under low compaction with water stress. This acquisition of high root/shoot ratio indicates a shift in the existing balance in partitioning of assimilates between root and shoot favouring more root growth under water deficits conditions.

Table 3. **Mean root/shoot ratio (± SE) at the end of the experiment as affected by levels of watering and soil compaction.**

Moisture regimes	Mean root/shoot ratio	
	Low compaction	High compaction
Field capacity (moisture 20%)	0.243 ± 0.016	0.182 ± 0.009
Drying (moisture 1–2%)	0.279 ± 0.013	0.218 ± 0.012
LSD	0.032**	0.028**

** Significant at P<0.01

Although biomass was predominantly directed to the shoot under sufficient supply of soil-borne resources , a lower rate of overall biomass production was associated with increased allocation to the roots under water stress. Therefore, the obvious adaptive advantage of prioritizing allocation of limited photosynthate to roots under such a situation is the maximization of water uptake.

When the seedling growth under different soils is considered, significantly high values for shoot dry weight, root dry weight and total dry mass with high root/shoot ratio were observed when grown in Wilpattu series soils (Table 2). Changes in root dry weight of seedlings grown in Wilpattu soil had significantly high root dry weight compared to those in other soils at both compaction levels (Table 4). The percentage reductions in root dry weight under high soil compaction were 40.7%, 25.8% and 35.0% in Weliketiya, Wilpattu and Mavillu soils respectively. These results indicated that the root growth was less affected in Wilpattu soil.

Table 4. **Mean root dry weight and soot dry weight (± SE) at the end of the drying cycle as affected by series of soil and levels of soil compaction.**

Soil Series	Mean root dry weight (g)		Mean shoot dry weight (g)	
	Low Compaction	Low Compaction	High Compaction	High Compaction
Weliketiya	45.92 ± 3.17	27.21 ± 1.46	169.6 ± 18.6	175.1 ± 19.5
Wilpattu	55.54 ± 3.90	41.16 ± 2.79	179.6 ± 13.1	220.2 ± 19.2
Mavillu	43.61 ± 3.57	30.09 ± 1.02	171.0 ± 18.4	205.2 ± 12.7
LSD	4.84***	5.21***	NS	33.8*

*, ***, Significant at P<0.05 and P<0.001 respectively

The higher root dry weight under both soil compaction levels in Wilpattu soil indicates its better supportive ability for root growth. This can be illustrated further by considering the soil moisture aspects under drying. According to the pattern observed in changing soil moisture content in the three different soil types, it was very clear that the Wilpattu soil had the high moisture content even at the inception of the drying cycle, when all soils were at their field capacities, due to its inherent high water holding capacity (Fig. 1). The lowest level was observed in Weliketiya series soil, which had the high draining ability due to high sand content with relatively more macropores and low organic carbon and clay content resulting in low water holding capacity. The Mavillu soil having the sandy loam texture was at the intermediate level. The same pattern had been maintained throughout the drying cycle.

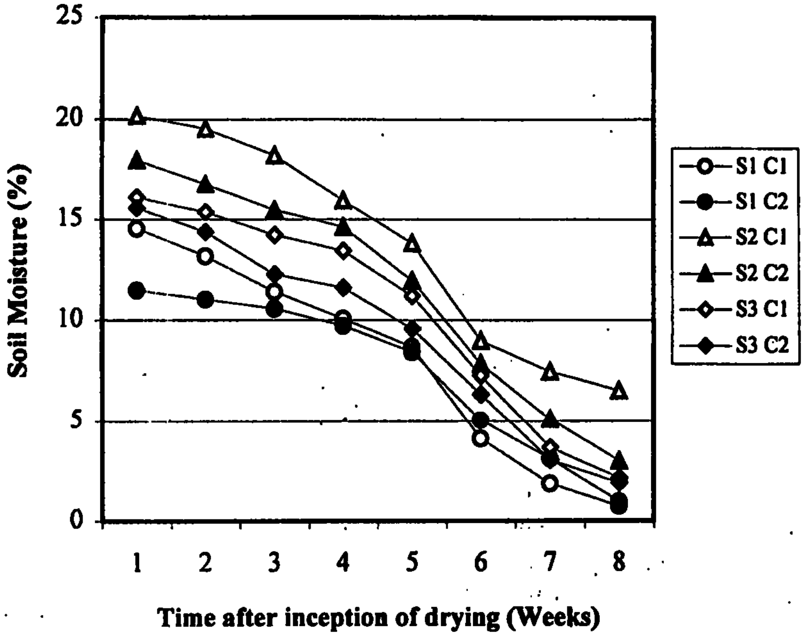

Fig. 1. **Changes in soil moisture content (%) with drying in different soils with different soil compaction levels under induced water stress.**
[Note: S1 - Weliketiya series; S2 - Wilpattu series; S3 - Mavillu series; C1 - Low compaction; C2 - High compaction]

Although the shoot dry weight did not differ significantly among seedlings in different soil types under low soil compaction, a significant increase was observed in both Wilpattu (22.6%) and Mavillu (19.9%) soils under the high soil compaction. The increase was not significant in Weliketiya series soil (Table 4). The highest shoot dry weight under high soil compaction was observed in seedlings grown in Wilpattu soil. Therefore, the acquisition of high overall biomass production was achieved by seedlings grown in Wilpattu series soil.

The Wilpattu soil held more water even under field capacity and has shown a comparatively gradual decline of water under drying, compared to the less amount of water available and rapid development of water deficit in other two soils. Therefore, the Wilpattu soil has possibly permitted sufficient time for seedlings to shift assimilates towards the root system favouring a high root to shoot ratio. In contrast, the other soils may have failed to provide the sufficient time for seedlings to shift their balance in favour of roots due to the rapid depletion of water. In addition, seedlings in Wilpattu soil have been able to obtain more water and procure the benefit of diverting more assimilates to the root system, since more water was available in deeper layers even at the end of drying cycle. Moreover, the high nutrient content and cation exchange capacity may also have contributed to this high dry matter accumulation in plants grown in this soil.

Soil compaction

When a soil is compacted the porosity is reduced. As a consequence, the amount of water that can be held by the soil would be reduced. In addition, plant roots would not grow deeper due to mechanical impedance exerted by the compact soil. This was the reason for the observed 38% reduction in root dry weight under high soil compaction compared to that under low soil compaction (Table 2). As a result a shallow, unspread root system would develop. Such roots have to extract water only from a small volume of compacted soils that contains a relatively small amount of water. Furthermore, water movements in the soil may also be restricted due to reduced porosity. Thus, the combined effect has caused the plants grown in such a soil, to experience a water deficit in a short period of time after discontinuation of the water supply. Hence, this condition is not favorable for the establishment of coconut seedlings. In addition, compacted soils restrict the rate of water infiltration and, soil water storage for subsequent uses by plants. According to Mathers *et al.* (1971) adequate soil aeration (O_2), which is essential for plant roots for proper functioning would also be restricted and amounts would not be sufficient for meeting their demand fully, when soil compaction occurs. Poor aeration under high compaction may also cause the accumulation of CO_2 in soil, which enhance root death or interfere with water uptake. Therefore, the alleviation of the high soil compaction appears to be important in the establishment and long-term survival and existence of coconut seedlings.

Total root length

Seedlings grown under field capacity have displayed a higher total root length at both compaction levels while the low soil compaction has favoured the root length within a particular watering level (Table 5). High soil compaction had a significant impact on the total root length in both watering levels.

Despite the increase in root/shoot ratio with respect to dry weights, the expected increase in root length was not clearly discernible in total root length after the imposition of water stress. Nevertheless, compared to the regularly watered seedlings where roots were observed in large numbers with short or intermediate long ones, only a few long roots which had grown through the entire depth of the soil column were clearly discernible in

Table 5. **Mean total root length (± SE) at the end of the experiment as affected by levels of watering, different series of soils and levels of soil compaction.**

Treatments	Mean total root length (m)	
	Low compaction	High compaction
Moisture regimes		
Field capacity (moisture 20%)	27.25 ± 1.67	17.46 ± 1.84
Drying (moisture 1-2%)	10.63 ± 1.54	8.85 ± 0.84
LSD	3.43**	3.21**
Soil Series		
Weliketiya	15.58 ± 2.03	8.11± 1.11
Wilpattu	24.66± 3.43	15.62± 2.36
Mavillu	16.58±3.20	11.14±2.06
LSD	4.27*	4.19*

*, **, Significant at $P<0.05$ and $P<0.01$ respectively

seedlings subjected to drying. The main attribute for this phenomenon is the development of a few long roots rather than a large number of short or intermediate long roots. Presence of a large number of roots is common when sufficient water and nutrients are available in the micro-environment (Taiz and Zeiger, 1991) as a measure to increase the root surface area available for water and nutrient absorption to assist the rapidly growing shoot with abundant assimilates. However, under initial water deficit conditions, which restricted to the upper soil layers, plants experience only mild stress and the root number tends to decrease due to reduction in root initiation. A few roots tend to elongate rapidly in order to explore deeper layers of soil for water at the expense of photosynthate partitioned from shoot. This was clearly evident in most water stressed plants where only a few roots had grown through the entire soil column up to the bottom of the pot.

Similar to root dry weights, seedlings grown in Wilpattu soil had maintained a significantly high mean total root length in comparison to those in other two soil types, at both compaction levels (Table 5). However, there was a significant reduction in root length under high soil compaction in all soils used.

The observation of high root length in Wilpattu soil under soil compaction is obvious because of its high nutrient contents. High organic carbon content, which contributed to high water holding capacity, has avoided quick drying allowing seedlings to have sufficient time to shift the partitioning pattern of photosynthate in favour of roots. However, the mechanical impedance of the soil against root elongation may have caused an evident reduction in root length under high compaction level.

Root diameter

The diameters of both primary and secondary roots were increased significantly under high soil compaction in both watering treatments (Table 6) and in all soil types (Table 7). The mean root diameter was significantly low in drying imposed seedlings than regularly watered (unstressed) seedlings in both primary and secondary roots (Table 6). Although the mean root diameter of secondary roots was almost similar in three different soils under low soil compaction it was significantly higher in seedlings grown in Wilpattu soils under high soil compaction (Table 7). The percentage increases in mean root diameter due to high soil compaction were 13.6%, 27.3% and 20.2% in Weliketiya, Wilpattu and Mavillu soils respectively. The possible attempt to penetrate the compacted soil by being sturdy with the increased radial growth has well succeeded in Wilpattu soil mainly due to its high organic matter and nutrient content.

Table 6. Mean root diameter (± SE) for primary and secondary roots at the end of the experiment, as affected by levels of watering and soil compaction.

Moisture regimes	Mean root diameter (mm)			
	Primary roots		Secondary roots	
	Low Compaction	High Compaction	Low Compaction	High Compaction
Field capacity (moisture 20%)	4.54 ± 0.048	4.57 ± 0.051	1.53 ± 0.024	1.68 ± 0.024
Drying (moisture 1-2%)	3.85 ± 0.050	4.27 ± 0.065	1.24 ± 0.015	1.62 ± 0.027
LSD	0.149***		0.063***	

*** Significant at P<0.001

Table 7. Mean root diameter (Mean ± SE) (mm) for secondary roots at the end of the experiment as affected by different series of soil and levels of soil compaction.

Soil Series	Mean root diameter (mm)	
	Low compaction	High compaction
Weliketiya	1.40 ± 0.030	1.59 ± 0.034
Wilpattu	1.39 ± 0.027	1.77 ± 0.029
Mavillu	1.38 ± 0.026	1.66 ± 0.030
LSD	0.06**	0.07**

** Significant at P < 0.01

Sturdy roots are more advantageous in penetrating the hard soil as it can exert more pressure against the mechanical impediment. Materechera *et al.* (1991) have shown that the high soil strength increased root diameter. However, the capacity for increased radial root growth has reduced significantly under the depletion of soil water at a particular soil compaction level because of the reduction of pressure potential which determines the root cell expansion.

CONCLUSIONS

The impact of water deficit on the growth of coconut seedlings greatly varied when they were grown in different soil series. Different soils had differential nutrient contents and organic carbon contents leading to different water holding capacities and nutrient status. This was the reason for observing differential impact of water stress on growth of coconut seedlings grown in different soils. The high nutrient content (N, P, K and Mg), high cation exchange capacity and high organic carbon content in Wilpattu soil series were the main factors that contributed to a better seedling growth compared to what observed in Weliketiya and Mavillu soils. Therefore, the improvement of Weliketiya and Mavillu soils with respect to the soil physical and chemical properties through management practices as addition of organic matter would obviously be beneficial in initial seedling growth and establishment through mitigation of the impact of water stress. That would reduce the impact of a drought on coconut seedlings grown on such soils where reduced cell expansion and photosynthetic rate produced a marked reduction in vegetative growth. The changes in assimilate partitioning pattern favouring root with a view to reducing further water loss and to capture more water to cope up with the water limited environment was common under all soil types.

The reduced and unspread root system due to the high soil compaction where the physical obstruction exerted by the soil itself had restricted elongation of roots. The possible penetration of the hardy soil by roots becoming sturdy was exhibited as a success mainly in Wilpattu soil where water was stored in deeper layers. However, the resulting seedling with a larger canopy being catered by a small root system would be more vulnerable in subsequent water deficit conditions. Hence, it appears imperative to alleviate this condition by adopting possible measures such as tillage and addition of organic matter to the soil through surface mulching and husk pits, though they were untested in this experiment. Although it was not tested in this experiment, it appears that the preparation of larger seed holes in field planting would facilitate root growth at a young stage preventing possible impacts of high soil compaction on root growth.

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