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RESEARCH ARTICLE

Growth of Root System and the Patterns of Soil Moisture Utilization in Sugarcane under Rain-fed and Irrigated Conditions in Sri Lanka

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Abstract The objective of this study was to investigate the effects of soil moisture deficits on the growth of root system and its effect on soil moisture utilization in sugarcane to identify relationship of root growth with drought tolerance of sugarcane varieties. An experiment with eight sugarcane varieties under rain-fed and irrigated conditions in a split-plot design was conducted from 2002 to 2007 at the Sugarcane Research Institute, Uda Walawe, Sri Lanka (6°21′N, 80°48′E). Root length densities (RLD) and soil moisture contents at different depths of the 1 m soil profile were measured. The variety SL 88 116 showed the highest RLD values of 1.49 in top (0–30 cm), 0.33 in middle (30–60 cm) and 0.65 cm cm^{-3} in entire (0–100 cm) layers of soil profile, and SL 83 06 showed the highest RLD of 0.14 cm cm^{-3} in the bottom (60–100 cm) layer of soil profile under rain-fed conditions. RLD of all varieties except SL 88 116 under irrigation were significantly ($P < 0.05$) greater (15–63%) than under rain-fed conditions. The rain-fed cane yield showed a significant ($P < 0.05$) positive correlation with RLD in the middle soil layer. Varieties with higher root length densities in the 30–60 cm soil layer survive better during significant water deficit periods in the top soil layer (0–30 cm), and such varieties produce high sugarcane yields in the rain-fed environments of Sri Lanka.

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Introduction

Sugarcane is commercially grown mainly under rain-fed conditions in the dry and intermediate zones of Sri Lanka where a prolonged dry period could occur in both *Maha* (main rainy season from October to February) and *Yala* (minor rainy season from April to June) seasons (Panabokke 1996). Water scarcity in this region limits the cultivation both under rain-fed and irrigated conditions, causing reduction of cane yield. Therefore, drought tolerance is an essential trait in sugarcane required for achieving high cane yield in Sri Lanka.

A deep and extensive root system has been regarded as a trait which would allow a crop to withstand a prolonged absence of significant rainfall or irrigation by absorbing water from deeper layers of the soil profile (Passioura 1983; Yadava 1993). Moreover, increasing the growth of root system in a water stressed crop as compared to well-watered conditions is a response of the plant to water stress by increasing its water absorption capacity. However, an extensive root system may not necessarily increase productivity as a higher proportion of photosynthates may have to be diverted into the root at the expense of shoot (Passioura 1983). Most of the water stressed plants increase their root dry weight above that of well- watered plants only during early stages of water stress. As time progressed and water stress increased, root dry weight of water stressed plants become lower than that of the well-watered plants. Therefore, it is argued that an extensive root system is useful only as a survival mechanism rather than to prevent significant drought-induced yield reductions (De Costa 2001). Similar situations exist in the growth of sugarcane (Gascho and Shih 1983; Evensen et al. 1997; Nixon and Simmonds 2004) and maize (Kang et al. 2002) roots under different water regimes. However, significant genotypic variations in the matured sugarcane root systems are found (Evans 1935), and rooting depth and the drought resistance is based on the inherent genetic makeup of the variety (Stevanson and McIntosh 1935). Smith et al. (2005) critically reviewed the available information on the growth and development, size and distribution of the sugarcane root system and their effects on growth and biomass partitioning of sugarcane, and whole plant physiology including control of assimilation and growth in response to changes in the environment. Moreover, they suggested that extraction of water and nutrients from depth should also be addressed, to improve utilization of available resources and reduce the risk of off-site impacts.

In root studies, mapping root intersections in a soil profile by the trench profile method (Bohm 1976) has the advantage of being feasible in the field which shows the root distributions in soil (Tardieu 1988; Vepraskas and Hoyt 1988). However, it does not provide direct information on spatial distribution of Root length density (RLD), which is linked to the root architecture, and determines water and nutrient uptakes (Gregory 2006; Lynch 1995). Direct empirical relationships between the root intersection density (number of root intersections per m^2 of soil profile) and RLD have been tested for wheat (Drew and Saker 1980) and maize (Chopart and Siband 1999), but the relationships obtained with this approach were not very robust. This study aimed to determine the genotypic variation in depth and distribution of root growth and its effects on the patterns of soil moisture utilization, and their relationships to drought tolerance and productivity of sugarcane under different growing environments in Sri Lanka using spatial distribution of RLD.

Materials and Methods

A field experiment was conducted from April 2002 to February 2007 at the Sugarcane Research Institute (SRI), Uda Walawe, Sri Lanka (6°21′N latitude, 80°48′E longitude and 76 m altitude) where the annual average rainfall was about 1450 mm with a distinctly bimodal distribution (Panabokke 1996). The average annual minimum and maximum temperatures ranged between 22 and 32°C. The evaporation from a free water surface averaged about 5 mm per day (Sanmuganathan 1992). The soil had been classified as Ranna series of Reddish Brown Earths (RBE), great group of Rhodustalfs (order Alfisols, suborder Ustalfa) soils and has a sandy clay loam texture (De Alwis and Panabokke 1972; United States Department of Agriculture (USDA) 1975). It was moderately well drained with a pH of 6.5–6.7. The bulk density of the soil ranged from 1.59 to 1.85 g cm^{-3}. The respective soil water contents at saturation, field capacity and permanent wilting point were 30, 20% (10 kPa) and 8% (1500 kPa), respectively (Sanmuganathan 1992).

The experiment was conducted in a split-plot design with two factors, which contained 16 treatment combinations, composed of two main plot treatments as ‘irrigated’ (‘well-watered’) and ‘rain-fed’ (‘water-stressed’) and eight commercial sugarcane (*Saccharum* hybrid L.) varieties (i.e. SL 71 03, SL 71 30, SL 83 06, SL 86 13, SL 88 116, SLI 121, M 438/59 and Co 775) as subplot treatments. The irrigated treatment received irrigation (2 m^3 of water per irrigation) at 5–10 day intervals so that its soil water potential in the top 1 m was maintained above −0.05 MPa. One metre deep trenches were made between irrigated and rain-fed plots to avoid the lateral movement of water. Each treatment combination was replicated thrice. Plot size was 9 × 8.22 m^2, each of which contained six furrows spaced at 1.37 m. The sugarcane was planted and maintained under recommended procedures (Sugarcane Research Institute of Sri Lanka 1991).

Soil moisture content in each plot was measured gravimetrically at fortnightly down to 1 m depth at 20 cm intervals. Daily rainfall (mm) and pan-evaporation (mm) were obtained from the SRI meteorological station which was less than 200 m from the experimental site. RLD down to 1 m soil depth at 10 cm intervals was measured at 184 and 276 days after planting (DAP) by core sampler method (Schuurman and Goedewaagen 1971). Soil samples were taken within a diameter of 30 cm around the plant using a core sampler. At 184 DAP, soil samples were taken between stools within the cane row in the furrow while soil samples were taken from in between cane rows in the ridge at 276 DAP to determine the growing depth and distribution of sugarcane root system under rain-fed and irrigated conditions. Root separation from soil was done using a root washer. Root length was measured by the grid method (Marsh 1971) and RLD was calculated as root length per unit soil volume in top (0–30 cm), middle (30–60 cm) and bottom (60–100 cm) layers of 1 m soil profile.

Significance of treatment differences was tested by analysis of variance (ANOVA). Means were separated by using the least significant difference (LSD). Correlation between yield and RLD was determined by simple correlation analysis. The SAS statistical package was used to analyse the data.

Results and Discussion

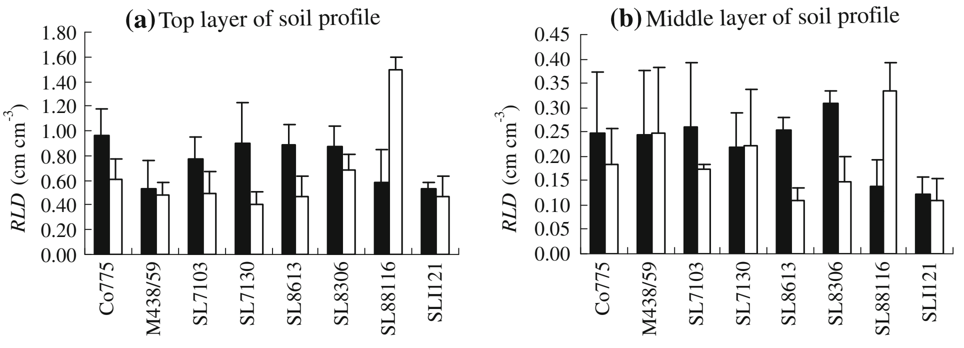
Soil Moisture Conditions in the Two Water Regimes

The entire seasonal, average soil moisture content in the top 1 m of the soil profile of the irrigated plots (22.3 cm) was greater than that of the rain-fed plots (18.2 cm) during the first 12 months of the experiment. There was a substantially lower rainfall (72 mm) than the 75% probable rainfall (197 mm) between the second and fourth months (i.e., June and August), and significantly higher pan evaporation (734 mm) than the actual rainfall (126 mm) between the second and fifth months (i.e., June and September) of the crop. There were two water deficit periods which had higher monthly pan-evaporation than the monthly rainfall in between *Yala* and *Maha* season from June to September and in between *Maha* and *Yala* season in January and February. Accordingly, the rain-fed experimental plots experienced significant soil moisture deficits during the periods from 3 to 6 months after planting (MAP) (July–October) and 9 and 10 MAP (January and February). In contrast, the soil water potential in the irrigated plots was maintained above −0.05 MPa throughout the season. It created a substantial difference in the average soil moisture content in the top 1 m of the soil profile between the two water regimes. However, the actual total rainfall (1871 mm) was greater than the annual average rainfall (1450 mm) and total pan evaporation (1629 mm) during the first 12 months of the experiment at the experimental site.

Impacts of Water Regimes on Root Growth

The measured RLD of sugarcane in the furrow and in the ridge varied significantly between varieties ($P < 0.05$) and between different soil layers ($P < 0.0001$) in the top 1 m of the soil profile under irrigated and rain-fed conditions. Moreover, a majority of varieties had a greater RLD in the furrow (Fig. 1) than in the ridge (Fig. 2) in 1 m soil profile under the two water regimes. However, RLD in the ridge and furrow showed a broadly similar pattern of variation in all the layers of soil profile (Figs. 1, 2). The top soil layer (0–30 cm) had greater RLD than the middle layer (30–60 cm) which in turn had greater RLD than the bottom layer (60–100 cm) consistently in all varieties in the furrow and the ridge and under the two water regimes. It indicates that the bulk of the roots of sugarcane is in the shallow layers of soil. Nixon and Simmonds (2004) also showed that, in the plant crop, 39–45% of roots to 60 cm depth occurred within the top 15 cm, and 65–74% within the top 30 cm of soil.

In the top and middle layers and entire soil profile, the majority of varieties had greater RLD under irrigated conditions than under rain-fed conditions (Figs. 1a, b, d and 2a, b, d). It showed that irrigated sugarcane had a strong root system and the bulk of it is within 60 cm soil depth compared to the rain-fed sugarcane which showed reduction of RLD under severe dry soil condition as reported by Kang et al. (2002). Gascho and Shih (1983) recorded that most of the roots of irrigated sugarcane were in the upper 20 cm of the soil. Similarly, Evensen et al. (1997) observed that the root system of sugarcane under irrigated conditions was mainly restricted to the top 46 cm of the soil profile and that it contained about 90% of total root biomass at 184 DAP.



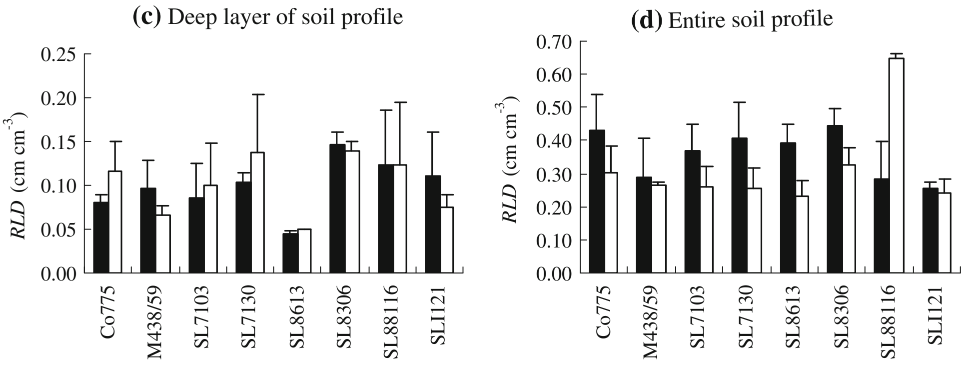


Fig. 1 Root length density (RLD) in different layers of the soil profile within the cane row in between stools in different sugarcane varieties under irrigated (*solid bars*) and rain-fed (*open bars*) conditions. *Error bars* indicate the respective standard error of means where $n = 3$

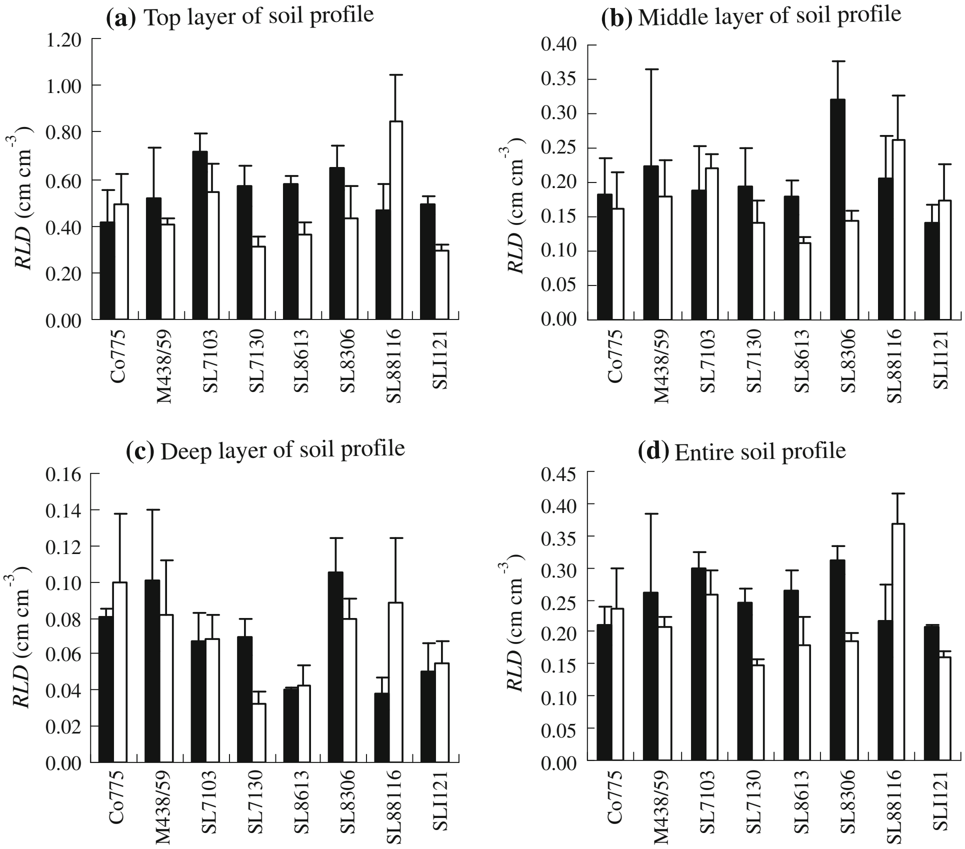


Fig. 2 Root length density (RLD) in different layers of the soil profile in between cane rows in the ridge in different sugarcane varieties under irrigated (*solid bars*) and rain-fed (*open bars*) conditions. *Error bars* indicate the respective standard error of means where $n = 3$

However, in the bottom layer, a majority of varieties had greater RLD under rain-fed conditions than under irrigation (Figs. 1c, 2c). It revealed that water deficit in upper layers induces rooting depth to extract moisture in deep soil layers. These results agree with those of Gascho and Shih (1983), in which irrigated sugarcane on clayey soil exploited soil water to a depth of 90 cm while rain-fed cane on the same soil removed water from a depth of at least 120 cm.

Varietal Variation in Root Length Densities in Different Soil Layers

Within each layer, there was a significant ($P < 0.05$) interactive effect of variety and water regime on RLD. In the top soil layer, under rain-fed conditions, the highest RLD of 1.492 cm cm^{-3} in the furrow and 0.849 cm cm^{-3} in the ridge were observed in the variety SL 88 116. The lowest RLD of 0.406 cm cm^{-3} in the furrow and 0.292 cm cm^{-3} in the ridge were observed in the varieties SL 71 30 and SLI 121, respectively. Under irrigated conditions, the highest RLD of 0.967 cm cm^{-3} in the furrow and 0.713 cm cm^{-3} in the ridge were observed in the varieties Co 775 and SL 71 03 respectively. The lowest RLD of 0.527 cm cm^{-3} in the furrow and 0.410 cm cm^{-3} in the ridge were observed in the varieties M 438/59 and Co 775, respectively. Except for SL 88 116 and Co 775, the majority of varieties had lower RLD under rain-fed conditions than under irrigated conditions (Fig. 1a, 2a).

In the middle soil layer, under rain-fed conditions, similar to the top soil layer, the highest RLD of 0.333 cm cm^{-3} in the furrow and 0.261 cm cm^{-3} in the ridge were observed in the SL 88 116. The lowest RLD of 0.110 cm cm^{-3} in the furrow and 0.113 cm cm^{-3} in the ridge were observed in the SL 86 13. Under irrigated conditions, the highest RLD of 0.307 cm cm^{-3} in the furrow and 0.321 cm cm^{-3} in the ridge were observed in the SL 83 06. The lowest RLD of 0.121 cm cm^{-3} in the furrow and 0.141 cm cm^{-3} in the ridge were observed in the SLI 121 (Fig. 1b, 2b).

In the bottom layer, the variety SL 8306 showed the highest RLD values of 0.105 cm cm^{-3} in the ridge under irrigated conditions and 0.146 and 0.139 cm cm^{-3} in the furrow under irrigated and rain-fed conditions, respectively. Co775 showed the highest RLD of 0.099 cm cm^{-3} in the ridge under rain-fed conditions. It is notable that SL 88 116 had substantially greater *RLD* under rain-fed conditions in the top, middle and entire soil layers in the furrow and ridge. Also, it had comparatively high levels of RLD in the bottom layer under both rain-fed and irrigated conditions (Fig. 1c, 2c). This superior rooting ability of SL 88 116 was probably due to its inherent genetic make-up.

This allowed water absorption from deeper layers of soil. However, the variety SL 86 13 showed the lowest RLD of 0.045 and 0.050 cm cm^{-3} under irrigated and rain-fed conditions respectively (Fig. 1c, 2.c).

Moreover, there was a significant ($P < 0.05$) interactive effect of variety and water regime on RLD of the entire soil profile (0–100 cm) as well. The comparative variation pattern of RLD in the entire soil profile was similar to that shown for the top soil layer. In all varieties, except SL 88 116 and Co775, there was a lower RLD under rain-fed conditions compared to the irrigated conditions. In contrast, RLD of the variety SL 88 116 over the entire soil profile increased significantly ($P < 0.05$) to the highest value of 0.65 cm cm^{-3} under rain-fed conditions. Under irrigated conditions, the highest and the lowest RLD in the entire soil profile were observed in the varieties SL 83 06 and SLI 121, respectively. It is notable that SLI 121 and SL 86 13 showed comparatively low levels of RLD in the entire soil profile under both rain-fed and irrigated conditions (Fig. 1d, 2d).

Patterns of Soil Moisture Utilization

When averaged across varieties, there was a significant ($P < 0.05$) difference in soil moisture content (SMC) between the rain-fed and irrigated treatments on 20 days out of all 26 days of measurement, except 35, 250, 298, 311, 357 and 392 DAP. In the rain-fed crops, average SMC in the total soil profile showed a continuous decline from 23 to 10 cm m^{-1} from 35 to 173 DAP (Fig. 3). It was less than the permanent wilting point (PWP) of 12 cm m^{-1} from 159 to 173 DAP. Moreover, it was less than the 50% depletion level of available moisture in RBE soil of 16 cm m^{-1} from 96 to 201 DAP. Similarly, the lowest SMC under rain-fed conditions and the maximum difference in SMC between irrigated and rain-fed conditions were observed at 173 DAP. Following an increase in SMC from 10 cm m^{-1} to 22 cm m^{-1} from 173 DAP until 229 DAP due to mid-seasonal rainfall, there were further periods of prolonged soil moisture depletion from 250 to 311 DAP and from 392 to 451 DAP (Fig. 3).

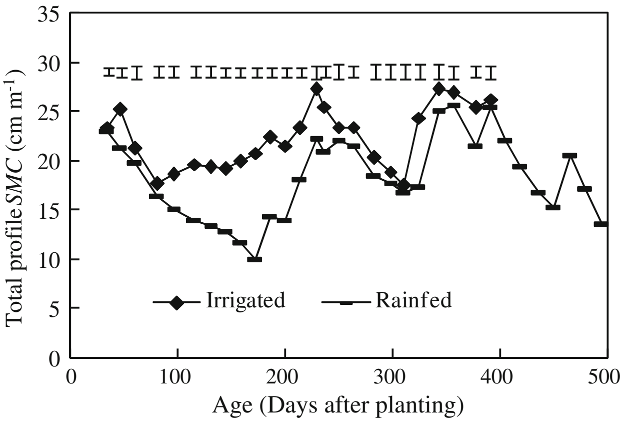


Fig. 3 Variation of mean soil moisture content (SMC) in the top 1 m of the soil profile during the cropping period when averaged across varieties under irrigated and rain-fed conditions. *Note*: Each data point in the graph is the average of 120 observations (eight varieties in three replicates and five levels of soil depth). Error bars indicate the respective *LSD* of means

Except for a short period between 47 and 82 DAP, the irrigated crops did not show soil moisture depletion until 229 DAP. Similar to the rain-fed crops, the irrigated crops also experienced a period of soil moisture depletion from 229 to 311 DAP as irrigation was withheld from 176 to318 DAP with the onset of *Maha* rains assuming that rainfall fulfils the latter-stage water requirement of sugarcane. Irrigation was re-started at end of the *Maha* rains at 318 DAP, and it was continued whenever needed. From then onwards, SMC in the irrigated crops was continuously high until their harvest. The average total profile SMC in the irrigated crops was greater than 17 cm m^{-1} throughout the cropping period (Fig. 3).

Varietal Variation in Soil Moisture Utilization

Within each water regime, all varieties experienced a common overall pattern of SMC in the top 1 m of the soil profile during the respective cropping periods. There was no significant variation in SMC between the varieties within a water regime on majority of measurement dates covering a major portion of the cropping period (Fig. 4). However, under rain-fed conditions, significant varietal variation in SMC was shown only during the period between 145 and 187 DAP (Fig. 4b). This coincided with the prolonged period of soil moisture depletion that was experienced during the first half of the cropping period. The varietal variation in SMC shown during this period probably reflected the varying transpiration rates of different varieties (De Silva 2007). Varieties having greater transpiration rates and higher total evapotranspiration depleted soil moisture to a greater extent, resulting in severe water stress (Wiedenfeld 2000). Under irrigated conditions, significant varietal variation in SMC was shown only during the period between 284 and 325 DAP, which again coincided with the period of soil moisture depletion during the latter part of their life span (Fig. 4a). This also probably reflected the varietal variation in root length densities and transpiration rates.

When the *SMC* of individual varieties were analysed separately (Fig. 5a–h), there was a significant difference in SMC between the rain-fed and irrigated treatments in all varieties during a major portion of the cropping period. In all varieties, the rain-fed treatment had a substantially lower SMC than the irrigated treatment, during the period

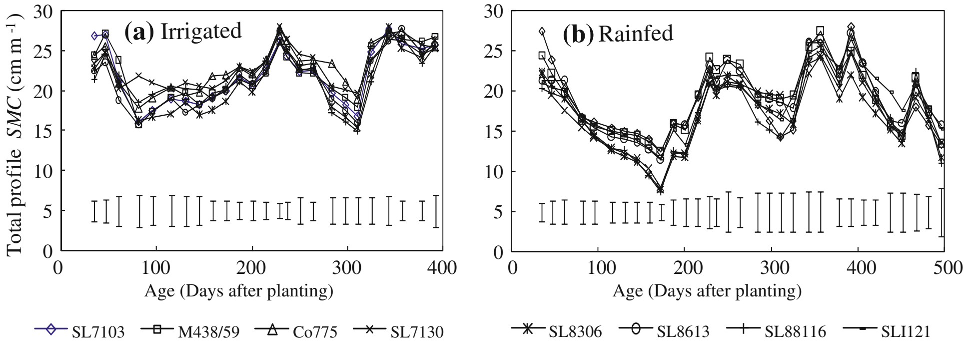


Fig. 4 Variation of soil moisture content (SMC) in the top 1 m of the soil profile during the cropping period in different sugarcane varieties under irrigated (**a**) and rain-fed (**b**) conditions. *Note:* Each data point in the graphs is the average of 15 observations (three replicates and five levels of soil depth). *Error bars* indicate the respective LSD of means

between 96 and 230 DAP which was the grand growth stage of the crop. On the other hand, after 230 DAP, slight differences could be noted between varieties during the period showing a clear difference in SMC between the two water regimes. For example, in SL 71 30 and Co 775 (Fig. 5b, g), significant variation between the two treatments persisted until late stage of the crop. In contrast, in SL 71 03 and M 438/59 (Fig. 5a, h), the variation in SMC between the respective irrigated and the rain-fed treatments did not persist for long beyond 230 DAP. When the seasonal minimum SMC was recorded at 173 DAP, under rain-fed conditions, the variety SL 88 116 showed the lowest total profile soil moisture content of 7.56 cm m^{-1} while M 438/59 showed the highest value (12.49 cm m^{-1}). At that stage, SMC in all the varieties except M 438/59 and SL 7103 were below the PWP of 12 cm m^{-1}.

RLD, Soil Moisture Utilization and Productivity

Under rain-fed conditions, the variety SL 88 116 which had the highest RLD in the top, middle and entire soil layers in the furrow and ridge (Fig. 1, 2), consistently, depleted more soil moisture during prolonged dry spell (Fig. 5e). Also, it had high leaf stomatal conductance and transpiration rate under water stress during the period from 159 to 167 DAP and thereby achieved the highest biomass production at the end of cropping period (De Silva 2007). The varieties SLI 121 and SL 86 13 which had low RLD in middle and bottom layers in furrow and ridge depleted less soil moisture during the early water deficit (Fig. 5c, f) and produced lowest biomass at end of the cropping period (De Silva 2007). Under irrigated conditions, the variety SL 83 06 which had high RLD in middle, bottom and entire soil profile showed the lowest seasonal SMC at 311 DAP when the irrigated crop also experienced a period of soil moisture deficit. The variety SLI 121 which had the lowest root length densities in middle and entire soil profile recorded the highest SMC at the same stage under irrigated conditions. Consequently, each variety showed clear correlation between RLD and soil moisture depletion patterns under each water regime.

Moreover, total profile RLD showed a positive correlation with cane yield ($r = 0.21$ with $P = 0.14$) when both irrigated and rain-fed data were pooled in the correlation analysis. A higher total RLD allowed greater water absorption and thereby achieved higher cane yields through increased stomatal conductance and water use. On the other hand, the rain-fed cane yield showed a significant ($P < 0.05$) positive correlation with RLD in the middle soil layer ($r = 0.42$ with $P = 0.04$) and a moderate correlation with total RLD ($r = 0.26$ with $P = 0.23$) (De Silva 2007). Therefore, as a mechanism to achieve higher yields under rain-fed conditions, it is highly probable that higher RLD in the middle soil layer was used as a means of absorbing water to maintain plant functions during periods of significant soil water deficits in the top soil layer.

Conclusions

The present study showed that there is an adequate genotypic variation in the depth and spatial distribution of root system, and the depth of soil moisture extraction which determine cane yields under different sugarcane-growing environments of Sri Lanka. Moreover, the growth pattern and the shape of the developed root system of sugarcane was dependent on water availability at different depths of soil during the root development, severity of soil drying and the interaction between soil moisture status and varieties. Sugarcane developed a stronger root system within the top 60 cm of the soil profile under well-watered conditions compared to the water stressed conditions. On the other hand, the amount of soil moisture extraction, one of the traits that allows the sugarcane crop to withstand drought under rain-fed conditions, was mainly dependant on root system developed in the middle soil layer from 30 to 60 cm. Also, there was a strong correlation among RLD in different layers of the soil profile, soil moisture extraction and cane yield under both conditions. Therefore, higher RLD in upper 60 cm of soil layer could be used as selection criteria to select high-yielding varieties under irrigated conditions while higher RLD in 30–60 cm of

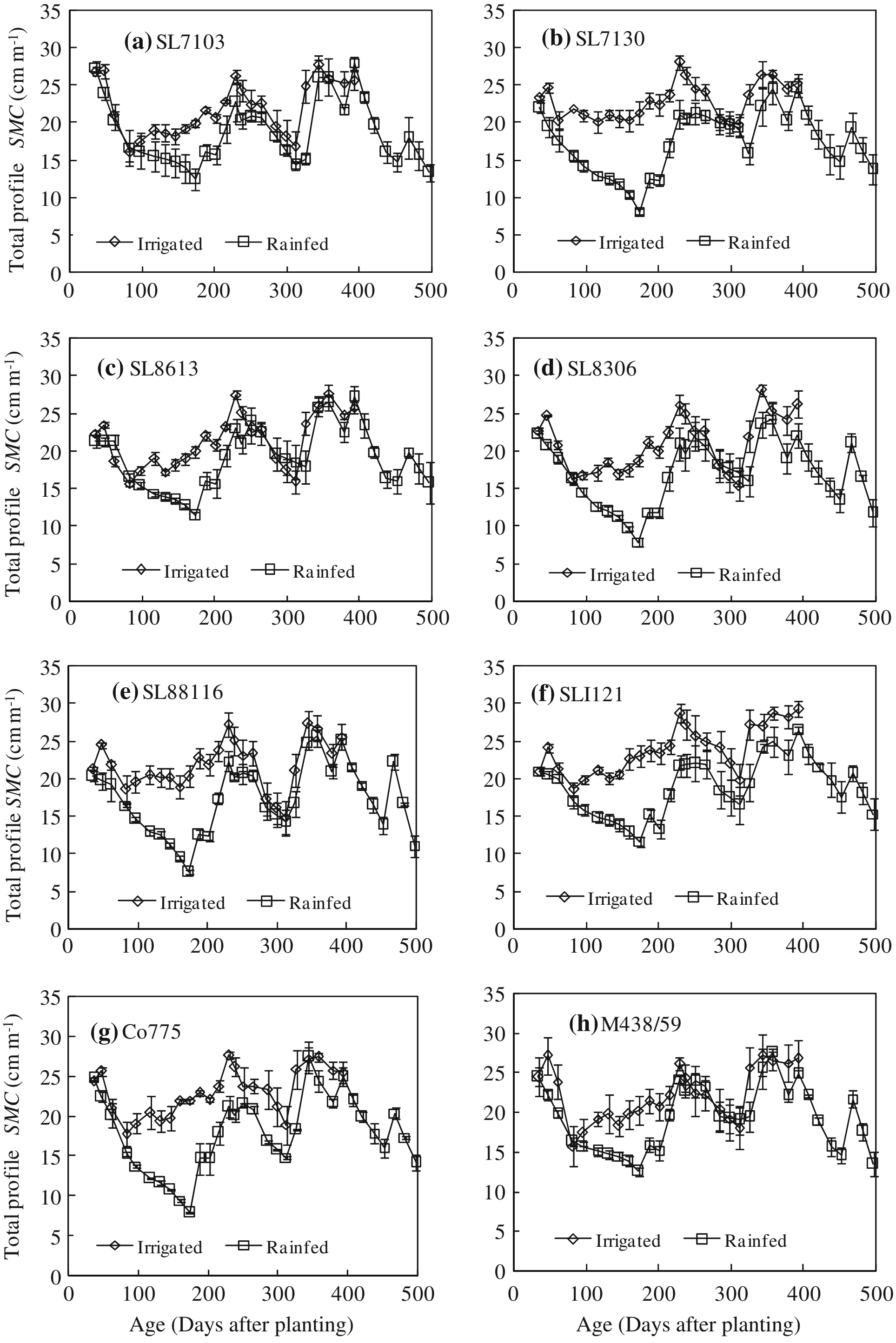


Fig. 5 Variation of soil moisture content (SMC) in the top 1 m of the soil profile during the cropping period in different sugarcane varieties (**a**–**h**) under irrigated and rain-fed conditions. *Note*: Each data point in the graphs is the average of 15 observations (three replicates and five levels of soil depth). *Error bars* indicate the standard error of the mean

middle soil layer could be used as selection criteria to select drought tolerant sugarcane varieties for rain-fed conditions.

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