

# Variations in Root Distribution Patterns and Cane Yield of 16 Elite Sugarcane Clones Grown Under Varied Soil Conditions

Sawettachat Set-Tow<sup>1</sup> · Patcharin Songsri<sup>1,2</sup> · Nuntawoot Jongrunklang<sup>1,2</sup>

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**Abstract** Response to drought of sugarcane for root traits is considered to be an important mechanism in which the crop can maintain cane yield under drought conditions. The objective of this study was, therefore, to investigate root distribution patterns of sugarcane and their relationships with cane yields under rain-fed conditions. Thirteen elite sugarcane clones (KK06-501, KK07-478, NSUT08-22-3-13, RT2004-085, CSB06-2-15, CSB06-2-21, CSB06-4-162, CSB06-5-20, TBy27-1385, TBy28-0348, MPT02-458, MPT03-166 and 91-2-527) and three check varieties (KK3, LK92-11 and Kps01-12) were planted in a randomized complete block design with four replications at two locations. Root length density (RLD) was measured via the auger method at 4, 6 and 8 months after planting (MAP) at two positions between plants and between rows. Cane yield was measured at 12 MAP. RLD in the upper soil layers was measured at 0–20 cm and 20–40 cm below the soil surface, whereas RLD in the lower soil layers was measured at 40–60, 60–80 and 80–100 cm below the soil surface. Sugarcane genotypes were significantly different for RLD and cane yield in both locations, and the RLDs of the 13 sugarcane varieties grown under rain-fed conditions were classified into four patterns. The sugarcane varieties changed their root distribution patterns when evaluated at 6 and 8 MAP. KK3 was predominant and most interesting as it had consistently high yield in both locations and high

root length density in the lower soil layers in response to drought.

**Keywords** Auger method · Root length density · Drought stress · Recovery · Root depth

## Abbreviations

DAP Days after planting  
LSD Least significant difference  
MAP Months after planting  
RLD Root length density

## Introduction

Sugarcane is cultivated mainly in tropical environments under rain-fed conditions primarily for the production of sugar (FAO 2016). In Thailand and most tropical regions of Southeast Asia, sugarcane is generally planted in the late rainy season. Sugarcane is germinated using stored soil moisture and minimum rainfall. The germinated plants then encounter a drought period for 2–4 months until the start of the rainy season. Yield loss by drought could be as high as 60% of its productivity (Robertson et al. 1999). Yield loss has also been associated with the reductions in germination, stalk diameter, leaf area and biomass (Jangpromma et al. 2012).

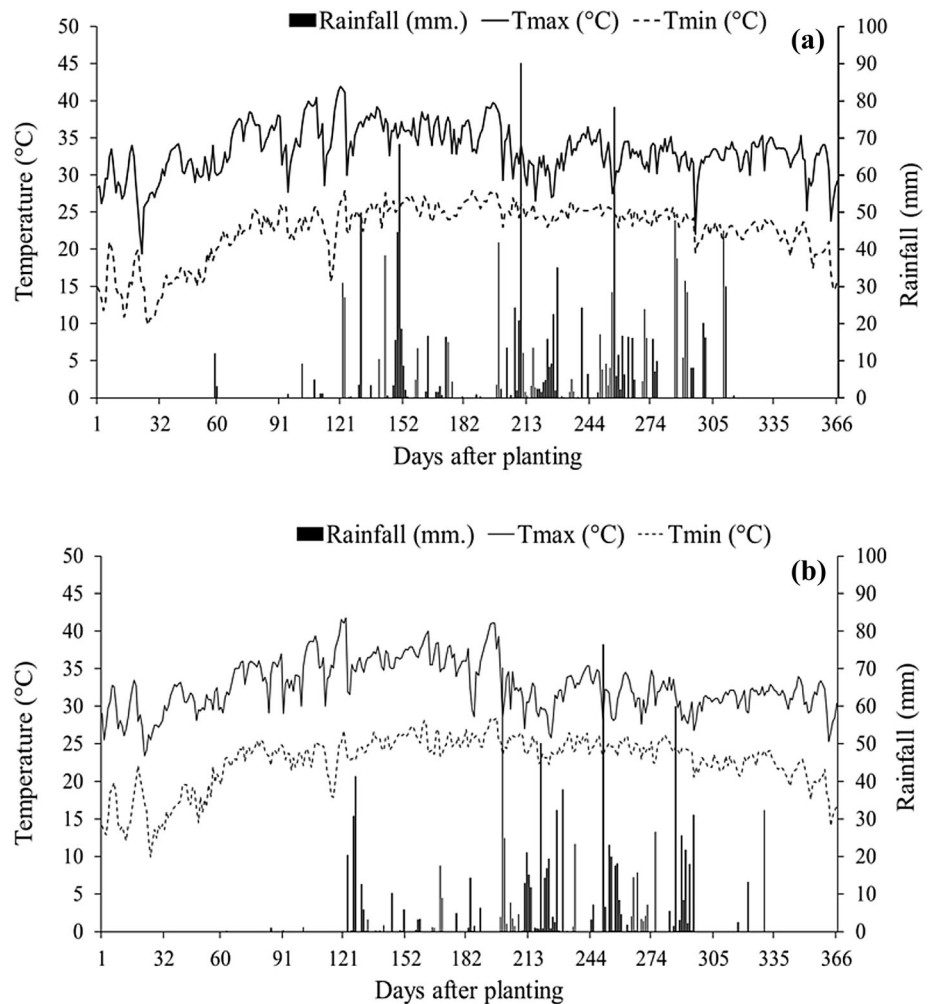
The use of drought-resistant varieties represents a promising strategy for sustaining yield under drought conditions. A better understanding of the mechanisms underlying drought tolerance is a key factor for the success in drought resistance breeding (Xiong et al. 2006). To achieve this goal, root responses of sugarcane genotypes to drought within the early growth stages must be clearly identified.

✉ Patcharin Songsri  
patcharinso@kku.ac.th

<sup>1</sup> Department of Agronomy, Faculty of Agriculture, Khon Kaen University, Khon Kaen 40002, Thailand

<sup>2</sup> Northeast Thailand Cane and Sugar Research Center, Khon Kaen University, Khon Kaen 40002, Thailand

**Fig. 1** Rainfall and minimum and maximum temperatures during the experimental period at the Nong Saeng location (a) and Kuchinarai location (b)



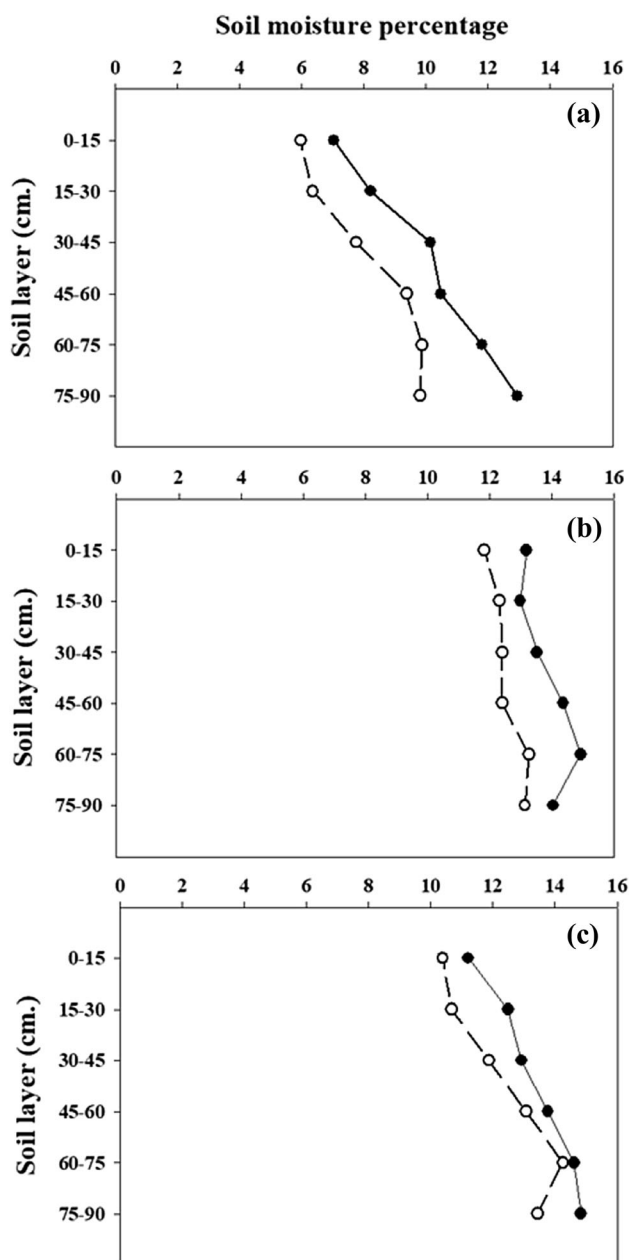
Drought resistance may be enhanced by improving a crop's ability to extract water from the soil. Plants such as peanuts (Songsri et al. 2008), chickpeas (Serraj et al. 2004), bread wheat (Gesimba et al. 2004), rice (Wang et al. 2009) and *Arabidopsis thaliana* (Xiong et al. 2006) are capable of modifying their roots in response to drought in order to take up more water. In sugarcane, drought increases root growth into the lower soil layers to mine more water, whereas the roots of a well-irrigated crop are distributed mainly in the upper soil layers (Laclau and Laclau 2009). Root growth deep into the lower soil layers in response to drought might allow plants to mine more available water in the subsoil (Songsri et al. 2008). According to Smith et al. 2005, drought-tolerant cultivars tend to expand root systems deep into the lower soil layers, thereby creating a viable selection criterion for drought tolerance and water use efficiency. RLD in the lower soil layers and root surface areas were closely related to the uptake of nutrients and water in the lower soil layers (Jongrungrklang et al. 2011; Inman-Bamber et al. 2012).

Drought responses for root growth into the lower soil layers, RLD and root distribution under rain-fed conditions have not been clearly investigated in sugarcane. Further studies on the changes in root distribution patterns during drought period, drought recovery period and maturity stage are required. The objective of this study was to investigate the root distribution patterns of sugarcane and their relationships with cane yield under rain-fed conditions. The information obtained in this study is important for explaining drought resistance mechanisms and improving sugarcane genotypes for cultivation under rain-fed conditions.

## Materials and Methods

### Experimental Details

Sixteen sugarcane genotypes from several sugarcane breeding organizations in Thailand were used in this study.



**Fig. 2** Soil moisture contents at Nong Saeng location (filled circle) and Kuchinarai location (empty circle), measured at soil depths of 0–15, 15–30, 30–45, 45–60, 60–75 and 75–90; at 4 (a), 6 (b) and 8 (c) MAP of the 16 sugarcane genotypes grown under rain-fed conditions

KK06-501, KK07-478 and KK3 were developed by the Khon Kaen Field Crop Research Center. NSUT08-22-3-13 and RT2004-085 were kindly provided by Thailand's Department of Agriculture. CSB06-2-15, CSB06-2-21, CSB06-4-162, CSB06-5-20 and LK92-11 were generously donated by the Office of Cane and Sugar Board. TBy27-1385, TBy28-0348 and Kps01-12 were obtained from Kasetsart University, Kamphaeng Saen Campus. MPT02-458 and MPT03-166 were provided by the Mitr Phol

Innovation and Research Center, and 91-2-527 is an elite breeding clone from the Suphan Buri Field Crops Research Center. LK92-11, Kps01-12 and KK3 genotypes were used as standard checks as KK3 and Kps01-12 are drought-tolerant cultivars with adequate root traits under drought conditions, and LK92-11 was identified as a moderately drought-tolerant cultivar based on both growth and cane yield (Office of the Cane and Sugar Board 2015). The 16 sugarcane genotypes were planted under rain-fed conditions in randomized complete block design with four replications at two locations in Nong Saeng District, Udon Thani, Thailand (17° 10' 3" N, 102° 46' 50" E and 175 m a.s.l.) and Kuchinarai District, Kalasin, Thailand (16° 32' 18" N, 104° 3' 18" E and 200 m a.s.l.) from November 2014 to December 2015. The soil texture at the Nong Saeng location was sandy loam (70% sand, 19.7% silt and 10.3% clay), whereas the soil texture at the Kuchinarai location was sandy (89.68% sand, 9.31% silt and 1.01% clay). The plots (6 × 8 m) contained four rows, spaced 150 cm between rows and 50 cm between plants within each row.

### Crop Management

Soil was prepared conventionally by plowing three times. The germinated sets of sugarcane were planted in the flat plots without soil ridges. Immediately after planting, irrigated water was supplied to the plots by furrow irrigation to ensure uniform germination of the crop. Chemical fertilizer (15–15–15: N–P–K) was applied at the rate of 312.5 kg/ha. Post-emergence weed control was carried out twice at 45 and 75 days after planting (DAP) through the application of Ametryn (N2-ethyl-N4-isopropyl-6-methylthio-1,3,5-triazine-2,4-diamine, 80% WP) at the rate of 4 kg/ha. Weed control was also carried out manually at 4, 6 and 8 MAP.

### Weather Data and Soil Moisture Content

Soil moisture content was collected at 4, 6 and 8 MAP by hand auger sampling at 0–15, 15–30, 30–45, 45–60, 60–75 and 75–90 cm below the soil surface. The data for rainfall, minimum temperature and maximum temperature were recorded daily throughout the experiment period by the nearest meteorological station (approximate distance of 5 km).

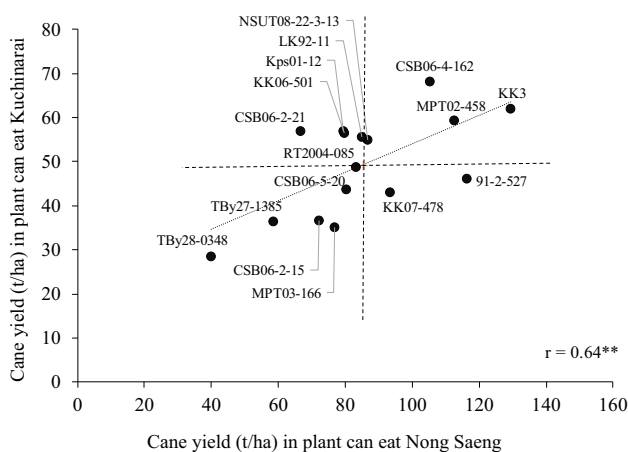
### Root Traits

RLD was measured at 4, 6 and 8 MAP via the auger method. The auger consisted of a coring tube (Welbank et al. 1974) with a diameter of 69 mm and a length of 1.15 m. The auger was designed to reduce compaction in

**Table 1** Mean squares for cane yield at two locations and root length density (RLD) between rows in the upper soil layers (0–40 cm) and lower soil layers (40–100 cm) of the 16 sugarcane advance varieties grown under rain-fed conditions, evaluated at 4, 6 and 8 MAP

Source of variation	RLD cm/cm <sup>3</sup> at 4 months		RLD cm/cm <sup>3</sup> at 6 months		RLD cm/cm <sup>3</sup> at 8 months		Cane yield (ton/ha)
	Upper (0–40 cm)	Lower (40–100 cm)	Upper (0–40 cm)	Lower (40–100 cm)	Upper (0–40 cm)	Lower (40–100 cm)	
Location (L)	13.32**	0.76**	1.92**	0.01**	7.24**	0.40**	958.93**
Rep./L	0.08	0.02	0.01	0.00	0.21	0.03	0.65
Genotype (G)	0.20**	0.03**	0.07**	0.02**	0.11**	0.02**	32.19**
G × L	0.12**	0.02*	0.05**	0.02**	0.07**	0.01**	14.41**
Pooled error	0.14	0.01	0.03	0.01	0.08	0.01	0.76
C.V. (%)	34.93	30.34	33.79	27.57	22.66	30.56	8.32

\*\* and \* = significant at 0.01 and 0.05 probability levels, respectively



**Fig. 3** Relationships between cane yield at 12 MAP of the 16 sugarcane genotypes grown under rain-fed conditions at Nong Saeng and Kuchinarai locations. The broken lines are the means of all sugarcane genotypes in each location to separate into four groups

the inner tube by improving the cutting edge and reducing the tube thickness (Welbank et al. 1974; Ford et al. 2006; Jongrunklang et al. 2011). RLD was collected from two positions between rows and between plants within a row at distances of 150 and 50 cm, respectively. Root samples were collected from a depth of 100 cm and separated into five layers consisting of 0–20, 20–40, 40–60, 60–80 and 80–100 cm. The root samples of each pot were washed thoroughly in tap water to remove excess soil from the roots and then scanned using an Epson Perfection V700 Photo Scanner (Epson, Suwa, Japan). Lastly, RLD was calculated as follows:

$$RLD \text{ (cm/cm}^3\text{)} = \frac{\text{Root length (cm)}}{\text{Soil volume (cm}^3\text{)}} \tag{1}$$

**Cane Yield**

The cane yield was recorded at 12 MAP from the two middle rows within the harvest area of 24 m<sup>2</sup>, and the total sugar cane produced was reported as cane yield per hectare.

**Table 2** Mean squares for root length density (RLD) between plants in the upper soil layers (0–40 cm) and lower soil layers (40–100 cm) of the 16 sugarcane advance varieties grown under rain-fed conditions evaluated at 4, 6 and 8 MAP

Source of variation	RLD cm/cm <sup>3</sup>		RLD cm/cm <sup>3</sup>		RLD cm/cm <sup>3</sup>	
	at 4 months		at 6 months		at 8 months	
	Upper (0–40 cm)	Lower (40–100 cm)	Upper (0–40 cm)	Lower (40–100 cm)	Upper (0–40 cm)	Lower (40–100 cm)
Location (L)	3.92**	0.14 ns	4.09**	0.00 ns	6.56**	0.64**
Rep./L	0.07	0.02	0.14	< 0.00	0.01	< 0.00
Genotype (G)	0.99**	0.06**	0.08*	0.02**	0.11**	0.03**
G × L	0.36**	0.03**	0.22**	0.01**	0.08**	0.02**
Pooled error	0.08	0.01	0.04	< 0.00	0.02	< 0.00
C.V. (%)	24.13	25.56	22.66	27.57	22.66	30.56

\*\* , \* and ns = significant at 0.01, 0.05 probability levels and not significant, respectively

**Table 3** Root length density (RLD) between plants in the upper soil layers (0–40 cm) and lower soil layers (40–100 cm) of the 16 sugarcane advance genotypes grown under rain-fed conditions evaluated at 4, 6 and 8 MAP at Nong Saeng location

genotypes	RLD cm/cm <sup>3</sup> between plants at 4 months		RLD cm/cm <sup>3</sup> between plants at 6 months		RLD cm/cm <sup>3</sup> between plants at 8 months	
	Upper (0–40 cm)	Lower (40–100 cm)	Upper (0–40 cm)	Lower (40–100 cm)	Upper (0–40 cm)	Lower (40–100 cm)
KK06-501	0.79 efg	0.28 c–f	1.00 b–e	0.15 f	0.27 d–h	0.20 abc
KK07-478	0.33 gh	0.11 g	0.84 de	0.16 ef	0.26 e–h	0.13 def
NSUT08-22-3-13	1.03 def	0.19 efg	1.15 a–d	0.14 f	0.35 b–e	0.23 a
RT2004-085	1.30 bcd	0.19 efg	0.91 cde	0.19 def	0.46 b	0.17 cd
CSB06-2-15	0.24 h	0.18 fg	0.72 de	0.12 f	0.15 h	0.10 fg
CSB06-2-21	1.66 abc	0.29 cde	0.91 cde	0.22 b–f	0.38 bcd	0.10 fg
CSB06-4-162	0.59 fgh	0.18 fg	0.92 cde	0.31 abc	0.21 gh	0.09 fg
CSB06-5-20	1.72 ab	0.32 cd	1.49 a	0.33 ab	0.18 gh	0.05 g
TBy27-1385	0.92 def	0.31 cd	1.40 ab	0.29 a–d	0.26 e–h	0.09 fg
TBy28-0348	0.97 def	0.12 g	1.10 a–d	0.20 c–f	0.84 a	0.17 bcd
MPT02-458	2.05 a	0.48 ab	0.88 de	0.21 c–f	0.23 e–h	0.09 fg
MPT03-166	0.95 def	0.37 bc	1.38 ab	0.38 a	0.29 d–g	0.22 ab
91-2-527	1.01 def	0.11 g	1.43 ab	0.15 f	0.34 c–f	0.11 ef
KK3	0.32 h	0.12 g	1.34 abc	0.22 b–f	0.44 bc	0.11 f
LK92-11	0.92 def	0.24 def	0.64 e	0.11 f	0.20 gh	0.10 fg
KPS01-12	1.23 cde	0.53 a	1.54 a	0.28 a–e	0.23 fgh	0.16 cde
Mean	1.00	0.25	1.10	0.22	0.32	0.13
<i>F</i> test	**	**	**	**	**	**
C.V. (%)	28.26	25.15	23.95	31.53	22.03	23.24

\*\* = significant at 0.01 probability level

Means followed by the same letter(s) in the same column are not significantly different by LSD at  $P \leq 0.05$

## Statistical Analysis

Analysis of variance was performed for all characters using Statistix 10<sup>®</sup> in accordance with the randomized complete block design. Error variances for each location were tested for homogeneity using Bartlett's test (Gomez and Gomez 1984). Although error variances were homogeneous, the combined analysis of variance showed high genotype by environment interactions for all characters. The authors then decided to report a separate analysis of variance for each location. Means were separated by least significant difference (LSD) at 0.05 probability level (Gomez and Gomez 1984), and the correlations between RLD and cane yield were performed.

## Results

**Meteorological data and soil moisture content** Rainfall as well as the daily minimum and maximum temperatures was obtained from the nearest weather stations. The total rainfall at Nong Saeng was recorded at 1521.9 mm/year, and the average minimum and maximum temperatures

were 22.7 °C and 33.7 °C, respectively (Fig. 1a). The total rainfall at the Kuchinarai location was 1148.5 mm/year, and the average minimum and maximum temperatures were 22.6 °C and 32.7 °C, respectively (Fig. 1b).

Soil moisture content was recorded at surface levels of 0–15, 15–30, 30–45, 45–60, 60–75 and 75–90 cm. The average soil moisture contents at 4, 6 and 8 MAP at Nong Saeng were 10.1, 13.8 and 13.0%, respectively. The average soil moisture contents at 4, 6 and 8 MAP at Kuchinarai were 8.4, 12.5 and 12.3%, respectively (Fig. 2). The results indicated that the soil moisture contents differed in each growth stage at each location. The soil moisture contents at 4, 6 and 8 MAP at Nong Saeng were higher than those at Kuchinarai. Notably, the soil moisture contents at both locations increased with the depth of the soil profile, and the soil moisture content at 4 MAP was lower than that at 6 and 8 MAP, especially in the upper soil layers (0–30 cm).

## Cane Yield

Sugarcane genotypes were significantly different for cane yield, and the interaction between genotype and location was also significant for this trait (Table 1). KK3, MPT02-

**Table 4** Root length density (RLD) between plants in the upper soil layers (0–40 cm) and lower soil layers (40–100 cm) of the 16 sugarcane advance genotypes grown under rain-fed conditions evaluated at 4, 6 and 8 MAP at Kuchinarai location

Genotypes	RLD cm/cm <sup>3</sup> between plants at 4 months		RLD cm/cm <sup>3</sup> between plants at 6 months		RLD cm/cm <sup>3</sup> between plants at 8 months	
	Upper (0–40 cm)	Lower (40–100 cm)	Upper (0–40 cm)	Lower (40–100 cm)	Upper (0–40 cm)	Lower (40–100 cm)
KK06-501	1.65 abc	0.38 b–e	0.80 ab	0.17 f–ij	0.76 c–g	0.42 b
KK07-478	0.96 d	0.16 h	0.80 ab	0.35 ab	1.06 ab	0.59 a
NSUT08-22-3-13	1.59 bc	0.36 b–f	0.52 ef	0.11 j	0.96 bcd	0.25 cd
RT2004-085	1.21 cd	0.43 abcd	0.68 bcde	0.22 d–g	1.02 abc	0.42 b
CSB06-2-15	1.19 cd	0.34 c–g	0.80 ab	0.15 g–j	0.92 b–e	0.33 bc
CSB06-2-21	2.13 a	0.53 a	0.58 c–f	0.11 j	0.99 a–d	0.17 de
CSB06-4-162	0.82 d	0.22 fgh	0.80 ab	0.36 a	0.82 b–g	0.30 bcd
CSB06-5-20	1.28 cd	0.21 gh	0.61 c–f	0.22 e–i	0.59 fg	0.09 e
TBy27-1385	1.57 bc	0.47 abc	0.63 b–f	0.31 a–d	0.71 d–g	0.34 bc
TBy28-0348	2.11 a	0.30 d–h	0.66 bcde	0.23 d–g	0.85 b–f	0.31 bcd
MPT02-458	1.85 ab	0.49 ab	0.93 a	0.22 e–h	0.65 efg	0.23 cde
MPT03-166	0.89 d	0.22 fgh	0.76 abc	0.27 b–e	1.25 a	0.25 cd
91-2-527	1.54 bc	0.23 fgh	0.57 def	0.13 hij	0.74 c–g	0.25 cd
KK3	0.97 d	0.27 e–h	0.72 bcd	0.25 c–f	0.74 c–g	0.43 b
LK92-11	1.81 ab	0.39 b–e	0.75 a–d	0.32 abc	0.83 b–g	0.21 cde
KPS01-12	0.91 d	0.26 e–h	0.44 f	0.13 ij	0.55 g	0.17 de
Mean	1.41	0.33	0.69	0.2	0.84	0.30
<i>F</i> test	**	**	**	**	**	**
C.V. (%)	21.18	25.44	16.36	23.14	20.45	29.51

\*\* = significant at 0.01 probability level

Means followed by the same letter(s) in the same column are not significantly different by LSD at  $P \leq 0.05$

458 and CSB06-4-162 produced consistently high cane yields at both locations, whereas 91-2-527 had high cane yield at Nong Saeng location, and CSB06-2-21, KK06-501, Kps01-12, LK92-11 and NSUT08-22-3-13 had high cane yield at Kuchinarai location (Fig. 3). At Nong Saeng location, KK3 had the highest yield of 129t/ha followed by 91-2-527, MPT02-458 and CSB06-4-162 with cane yields of 116, 112 and 105 t/ha, respectively. At the Kuchinarai location, CSB06-4-162 had the highest yield of 68 t/ha followed by KK3, MPT02-458, CSB06-2-21, KK06-501, Kps01-12, LK92-11 and NSUT08-22-3-13 with yields of 62, 59, 57, 57, 56, 56 and 55t/ha, respectively.

**Root Distribution Patterns at 4 MAP**

Sugarcane genotypes were significantly different ( $P \leq 0.05$  to 0.01) for RLD in the upper and lower soil layers, at both positions between plants (Tables 2, 3 and 4) and between rows (Tables 1, 5 and 6). Sugarcane genotypes also presented different distribution patterns of RLD at 4, 6 and 8 MAP and were subsequently classified into distinct groups based on the distribution patterns of RLD.

In sandy loam soil at Nong Saeng location, sugarcane genotypes were classified into four groups based on RLD in the upper soil layers. CSB06-2-21 was the only genotype in Group I with high RLD between plants and between rows. Group II contained 91-2-527, MPT02-458, CSB06-5-20, RT2004-085 and TBy28-0348, which were characterized by high RLD between plants and low RLD between rows (Fig. 4). KK06-501, TBy27-1385, LK92-11, NSUT08-22-3-13, Kps01-12 and MPT03-166 formed Group III, which presented moderate RLD between plants and low RLD between rows. Group IV consisting of KK3, CSB06-2-15, KK07-478 and CSB06-4-162 had low RLD between plants and between rows.

In sandy soil at Kuchinarai location, sugarcane genotypes were divided into two groups (Fig. 5). Group I consisted of CSB06-2-21, MPT02-458, LK92-11, KK06-501, 91-2-527 and TBy28-0348, which had high RLD between plants and between rows. Group II including KK3, RT2004-085, CSB06-2-15, CSB06-4-162, NSUT08-22-3-13, KK07-478, Kps01-12, MPT03-166, TBy27-1385 and CSB06-5-20 demonstrated moderate RLD between plants and high RLDs between rows.

**Table 5** Root length density (RLD) between rows in the upper soil layers (0–40 cm) and lower soil layers (40–100 cm) of the 16 sugarcane advance genotypes grown under rain-fed conditions evaluated at 4, 6 and 8 MAP at Nong Saeng location

Genotypes	RLD cm/cm <sup>3</sup> between rows at 4 months		RLD cm/cm <sup>3</sup> between rows at 6 months		RLD cm/cm <sup>3</sup> between rows at 8 months	
	Upper (0–40 cm)	Lower (40–100 cm)	Upper (0–40 cm)	Lower (40–100 cm)	Upper (0–40 cm)	Lower (40–100 cm)
KK06-501	0.27 def	0.09 ef	0.35 c	0.16 c–f	0.08 e	0.07 def
KK07-478	0.19 efg	0.15 bc	0.35 c	0.08 f	0.12 cde	0.07 def
NSUT08-22-3-13	0.07 g	0.08 efg	0.19 e	0.15 c–f	0.10 e	0.07 def
RT2004-085	0.23 efg	0.08 efg	0.30 cd	0.23 bc	0.22 a–d	0.10 c–f
CSB06-2-15	0.14 fg	0.05 fgh	0.31 cd	0.10 def	0.18 b–e	0.12 b–e
CSB06-2-21	0.86 a	0.10 de	0.62 a	0.20 cd	0.33 a	0.14 bcd
CSB06-4-162	0.25 efg	0.19 b	0.67 a	0.31 b	0.23 abc	0.33 a
CSB06-5-20	0.25 efg	0.04 gh	0.31 cd	0.10 ef	0.17 b–e	0.03 f
TBy27-1385	0.14 fg	0.01 h	0.35 c	0.19 cde	0.10 de	0.13 b–e
TBy28-0348	0.24 efg	0.18 b	0.14 e	0.14 c–f	0.20 b–e	0.18 b
MPT02-458	0.62 b	0.15 bcd	0.22 de	0.43 a	0.08 e	0.11 b–e
MPT03-166	0.21 efg	0.15 bcd	0.49 b	0.30 b	0.24 abc	0.16 bc
91-2-527	0.44 bcd	0.18 b	0.46 b	0.14 c–f	0.12 cde	0.06 ef
KK3	0.51 bc	0.11 cde	0.35 c	0.15 c–f	0.26 ab	0.09 c–f
LK92-11	0.24 efg	0.04 fgh	0.35 c	0.10 def	0.13 cde	0.06 ef
KPS01-12	0.36 cde	0.32 a	0.34 c	0.22 bc	0.19 b–e	0.13 b–e
Mean	0.31	0.12	0.36	0.19	0.17	0.12
<i>F</i> test	**	**	**	**	**	**
C.V. (%)	35.02	23.64	17.09	31.46	43.1	36.91

\*\* = significant at 0.01 probability level

Means followed by the same letter(s) in the same column are not significantly different by LSD at  $P \leq 0.05$

### Root Distribution Patterns at 6 MAP

At Nong Saeng, sugarcane genotypes were divided into five groups. 91-2-527, TBy27-1385, Kps01-12, NSUT08-22-3-13, KK06-501, TBy28-0348 and CSB06-4-162 were classified in Group I based on root distribution patterns (Fig. 6). This group had high RLD between plants and between rows in the upper soil layer. In this group, the root distribution patterns between plants and between rows did not extend in the same direction. Group II had three genotypes (KK3, MPT03-166 and CSB06-5-20), which were characterized by high RLD between plants and between rows in both the upper and lower soil layers. Root distribution patterns between plants and between rows did not extend in the same direction. Group III containing MPT02-458, RT2004-085 and KK07-478 had intermediate RLD between plants and low RLD between rows in the upper soil layers. Root distribution patterns between plants and between rows spread in the same direction. Group IV, with the single LK92-11 genotype, showed low RLD between plants and between rows. Group V had two genotypes (CSB06-2-15 and CSB06-2-21) with RLD between plants and moderate RLD between rows, in the upper soil layers.

At Kuchinarai, the sugarcane genotypes were divided into two groups (Fig. 7). Group I consisting of KK06-501, KK07-478, NSUT08-22-3-13, RT2004-085, CSB06-2-15, CSB06-2-21, CSB06-4-162, TBy27-1385, TBy28-0348, MPT02-458, 91-2-527, KK3 and LK92-11 demonstrated high RLD between plants and between rows in the upper soil layers. Group II comprising CSB06-5-20, MPT03-166 and Kps01-12 had low RLD between plants and between rows in the upper soil layers.

### Root Distribution Patterns at 8 MAP

At Nong Saeng, sugarcane genotypes were classified into four groups based on root distribution patterns of RLD (Fig. 8). Group I contained RT2004-085, MPT03-166, 91-2-527 and KK3, which showed high RLD between plants and between rows in the upper soil layers. Group II, with only the TBy28-0348 genotype, presented varied RLD, which was intermediate between plants and high between rows in the upper soil layers. Root distribution patterns between plants and between rows did not extend in the same direction. Group III had three genotypes including NSUT08-22-3-13, Kps01-12 and KK07-478. This group was predominant for its intermediate RLD between plants

**Table 6** Root length density (RLD) between rows in the upper soil layers (0–40 cm) and lower soil layers (40–100 cm) of the 16 sugarcane advance genotypes grown under rain-fed conditions evaluated at 4, 6 and 8 MAP at Kuchinarai location

Genotypes	RLD cm/cm <sup>3</sup> between rows at 4 months		RLD cm/cm <sup>3</sup> between rows at 6 months		RLD cm/cm <sup>3</sup> between rows at 8 months	
	Upper (0–40 cm)	Lower (40–100 cm)	Upper (0–40 cm)	Lower (40–100 cm)	Upper (0–40 cm)	Lower (40–100 cm)
KK06-501	0.87	0.27 e–h	0.81 ab	0.27 bc	0.72 cde	0.24 def
KK07-478	1.36	0.31 c–g	0.48 d–g	0.32 b	1.16 ab	0.30 b–e
NSUT08-22-3-13	1.14	0.52 a	0.38 fg	0.11 f	0.37 e	0.24 def
RT2004-085	1.25	0.50 ab	0.69 a–d	0.21 c–f	0.60 de	0.36 abc
CSB06-2-15	1.04	0.46 abc	0.76 abc	0.21 c–f	0.36 e	0.17 fg
CSB06-2-21	1.36	0.27 e–h	0.68 a–d	0.26 bcd	1.15 ab	0.24 d–g
CSB06-4-162	1.12	0.36 b–f	0.65 a–e	0.14 ef	1.02 bc	0.40 ab
CSB06-5-20	0.78	0.16 h	0.33 g	0.18 c–f	1.15 ab	0.29 b–e
TBy27-1385	0.96	0.22 fgh	0.87 a	0.27 bcd	0.81 bcd	0.19 efg
TBy28-0348	0.86	0.18 gh	0.61 b–e	0.17 def	0.72 cde	0.45 a
MPT02-458	1.16	0.24 fgh	0.56 c–f	0.23 b–e	0.82 bcd	0.26 c–f
MPT03-166	1.13	0.22 fgh	0.63 b–e	0.11 f	0.55 de	0.12 g
91-2-527	0.89	0.39 a–e	0.43 efg	0.24 b–e	0.42 e	0.20 d–g
KK3	1.19	0.32 c–g	0.74 abc	0.43 a	1.39 a	0.31 bcd
LK92-11	1.17	0.30 d–h	0.76 abc	0.15 ef	0.50 de	0.31 bcd
KPS01-12	1.09	0.43 a–d	0.63 b–e	0.17 def	0.86 bcd	0.20 d–g
Mean	1.08	0.32	0.63	0.22	0.79	0.27
<i>F</i> test	ns	**	**	**	**	**
C.V. (%)	26.18	27.79	21.43	28.22	28.38	25.72

\*\* and ns = significant at 0.01 probability level and not significant, respectively

Means followed by the same letter(s) in the same column are not significantly different by LSD at  $P \leq 0.05$

and high RLD between rows in the upper soil layers. Root distribution patterns between plants and between rows spread in the same direction. Group IV had eight genotypes including MPT02-458, CSB06-2-21, KK06-501, LK92-11, TBy27-1385, CSB06-5-20, CSB06-4-162 and CSB06-2-15. This group presented low RLD between plants and between rows in the upper soil layers. Root distribution patterns between plants and between rows spread in the same direction.

At Kuchinarai, the resulting root distribution patterns separated the sugarcane genotypes into four groups (Fig. 9). Group I including KK3, RT2004-085, CSB06-2-15, CSB06-2-21 and LK92-11 was characterized by high RLD between plants and between rows in the upper soil layers. The root distribution patterns between plants and between rows were found to spread in the same direction. Group II had five genotypes (CSB06-4-162, MPT03-166, NSUT08-22-3-13, 91-2-527 and Kps01-12), which showed high RLD between plants and low RLD between rows in the upper soil layers. Root distribution patterns between plants and between rows did not extend in the same direction. Group III consisted of TBy27-1385, KK07-478, CSB06-5-20 and KK06-501, which showed high RLD between plants and intermediate RLD between rows in the

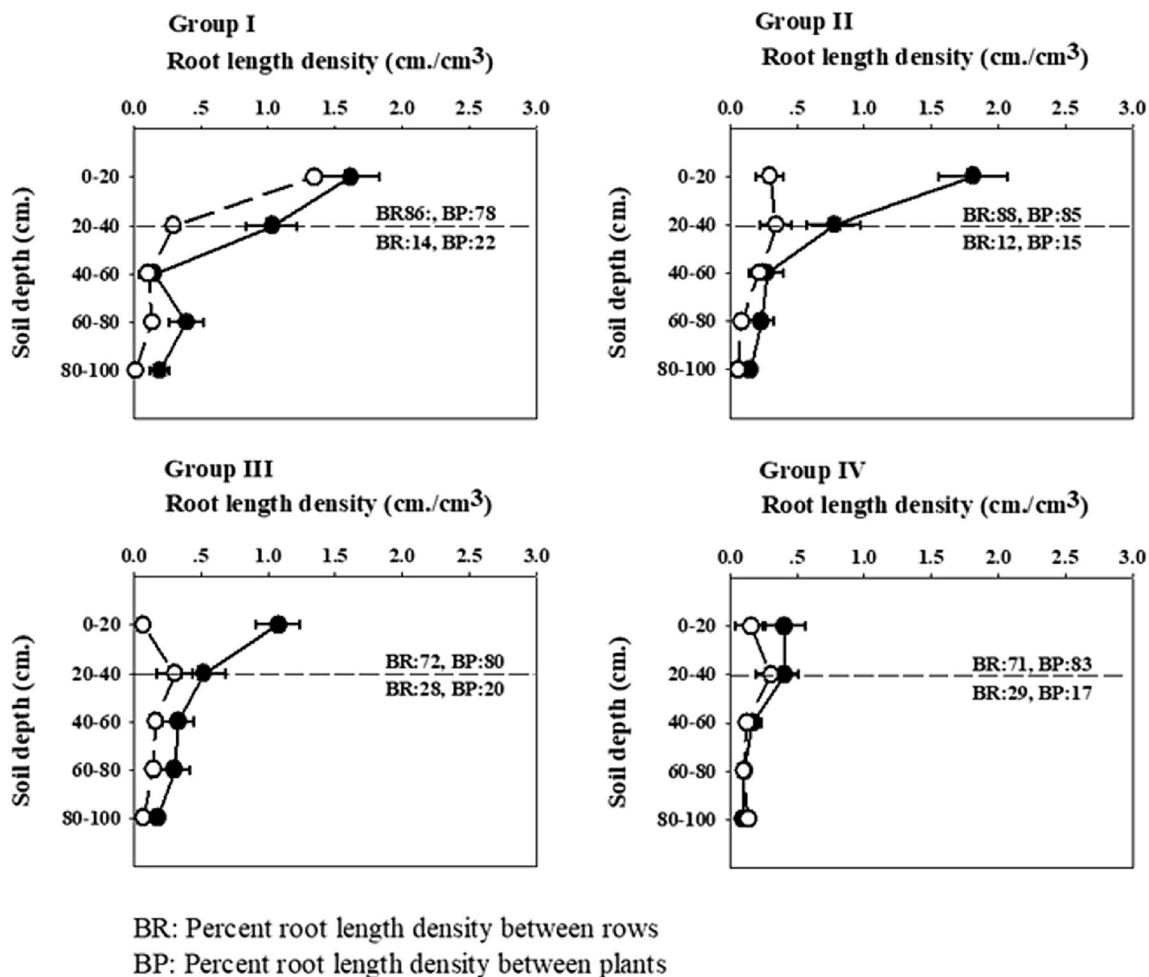
upper soil layers. Root distribution patterns between plants and between rows spread in the same direction. Group IV had two genotypes (TBy28-034 and MPT02-458), which were characterized by intermediate RLD between plants and low RLD between rows in the upper soil layers. Root distribution patterns between plants and between rows spread in the same direction.

## Discussion

Cane yield is an important selection criterion in sugarcane breeding. In this study, the sugarcane varieties and locations were significantly different for cane yield. The differences in cane yield between the two locations may be possibly due to the difference in soil fertility and moisture. The loamy soil at Nong Saeng was subjected to higher rainfall than that of the sandy soil of Kuchinarai, thereby producing higher cane yields. Notably, KK3, MPT02-458 and 91-2-527 produced high cane yields at both locations.

During drought stress period, varied root distribution patterns were observed among sugarcane varieties. A deep root system is a complicated trait, comprising root growth angle (RGA) and maximum root length (Araki et al. 2002;





**Fig. 4** Root length densities (cm/cm<sup>3</sup>) between plants (filled circle) and between rows (empty circle) of the 16 sugarcane genotypes grown under rain-fed conditions, evaluated at 4 MAP at the Nong Saeng location. Group I (CSB06-2-21); Group II (91-2-527, MPT02-458, CSB06-5-20, RT2004-085 and TBy28-0348); Group III (KK06-

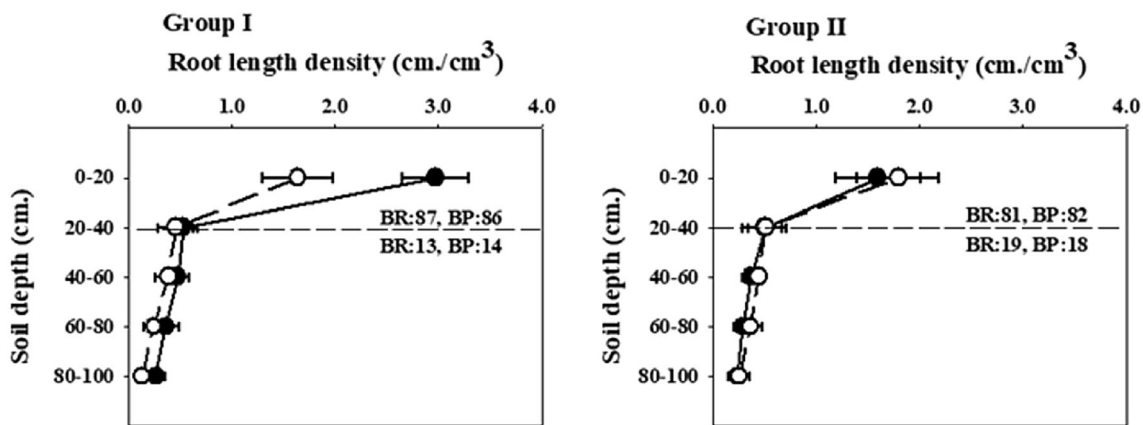
501, TBy27-1385, LK92-11, NSUT08-22-3-13, Kps01-12 and MPT03-166); Group IV (KK3, CSB06-2-15, KK07-478 and CSB06-4-162) (The bar stands for standard error (SE) indicating that the difference between two means is statistically significant at  $P \leq 0.01$ )

Uga et al. 2013). The RGA defines the direction of root elongation in the soil, which affects the area in which roots take up water and nutrients (Uga et al. 2015).

MPT02-458 had high RLD in the upper and lower soil layers, whereas 91-2-527 showed high RLD in the upper soil layers only. The results in this study agreed with those of Khonghintaing et al. (2017), who reported that sugarcane increased root lengths in the early season drought. The authors further reported that under most severe drought (105 DAP), KK3 reduced shoot dry weight, leaf dry weight, stalk dry weight, stalk diameter and root growth. In contrast to MPT02-458, KK3 produced low RLD in both the upper and lower soil layers in positions between plants and between rows. According to Jangpromma et al. (2012), drought reduces root length, root volume, root surface area and root dry weight in some varieties.

Jangpromma et al. (2012) further stated that the maintenance of water uptake may be enhanced through the improvement in the root/shoot ratio, which can be maintained through the development of drought-resistant cultivars, and sugarcane varieties were capable of maintaining a high root/shoot ratio under water stress conditions. Plants may have one or several mechanisms of drought resistance or avoidance in order to achieve high yields under water deficit conditions (Songsri et al. 2008).

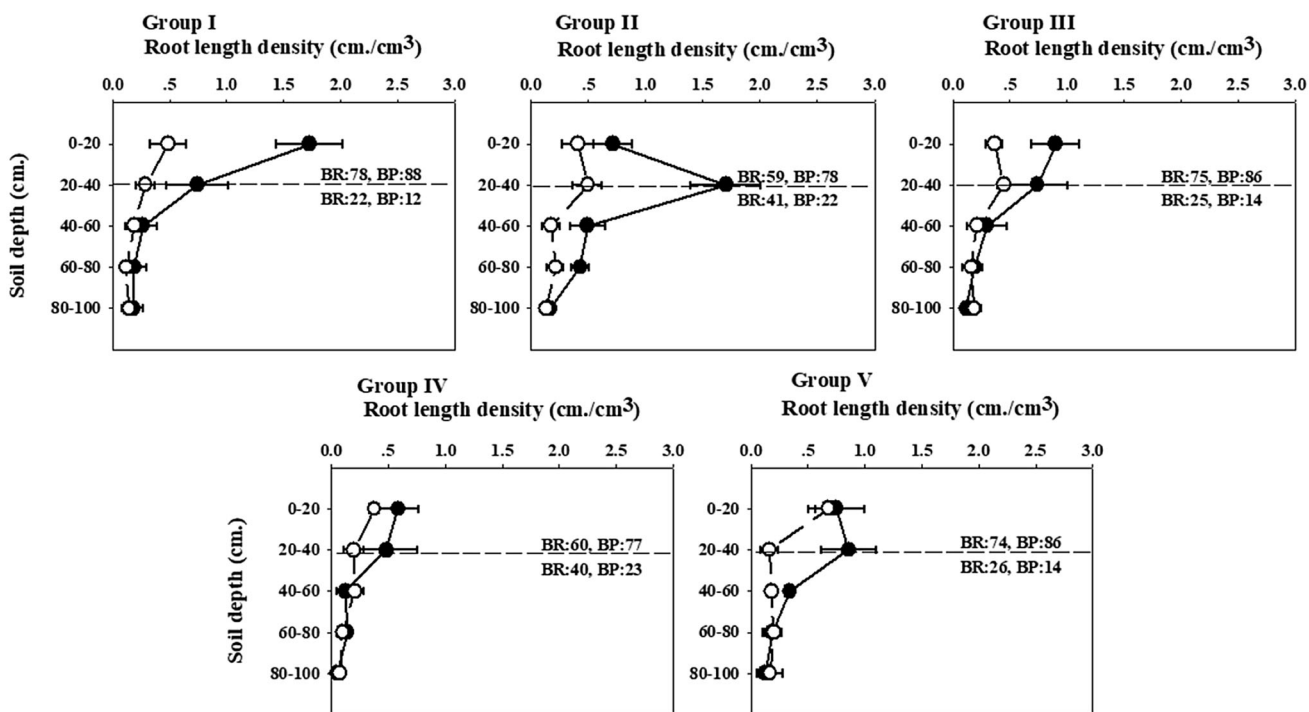
Within the recovery period (6 MAP), KK3 and MPT02-458 presented high RLDs in the upper and lower soil layers, whereas 91-2-527 had high RLD in only the upper soil layers. We observed that root distribution changed in accordance with the change in soil moisture content. Changes in the root system, such as deeper roots and higher root surface areas, increased nutrient uptake and the ability



BR: Percent root length density between rows  
BP: Percent root length density between plants

**Fig. 5** Root length densities (cm/cm<sup>3</sup>) between plants (filled circle) and between rows (empty circle) of the 16 sugarcane genotypes grown under rain-fed conditions, evaluated at 4 MAP at the Kuchinarai location. Group I (CSB06-2-21, MPT02-458, LK92-11, KK06-501, 91-2-527 and TBy28-0348); Group II (KK3, RT2004-085,

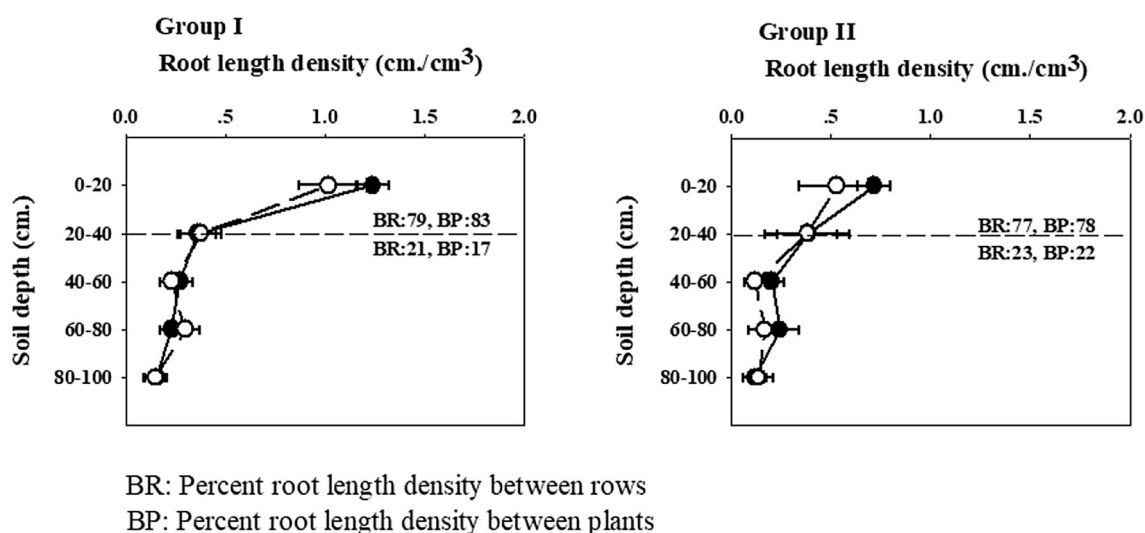
CSB06-2-15, CSB06-4-162, NSUT08-22-3-13, KK07-478, Kps01-12, MPT03-166, TBy27-1385 and CSB06-5-20) (The bar stands for standard error (SE) indicating that the difference between two means is statistically significant at  $P \leq 0.01$ )



BR: Percent root length density between rows  
BP: Percent root length density between plants

**Fig. 6** Root length densities (cm/cm<sup>3</sup>) between plants (filled circle) and between rows (empty circle) of the 16 sugarcane genotypes grown under rain-fed conditions, evaluated at 6 MAP at the Nong Saeng location. Group I (91-2-527, TBy27-1385, Kps01-12, NSUT08- 22-3-13, KK06-501, TBy28-0348 and CSB06-4-162);

Group II (KK3, MPT03-166 and CSB06-5-20); Group III (MPT02-458, RT2004-085 and KK07-478); Group IV (LK92-11); Group V (CSB06-2-15 and CSB06-2-21) (The bar stands for standard error (SE) indicating that the difference between two means is statistically significant at  $P \leq 0.01$ )



**Fig. 7** Root length densities (cm/cm<sup>3</sup>) between plants (filled circle) and between rows (empty circle) of the 16 sugarcane genotypes grown under rain-fed conditions, evaluated at 6 MAP at the Kuchinarai location. Group I (KK06-501, KK07-478, NSUT08-22-3-13, RT2004-085, CSB06-2-15, CSB06-2-21, CSB06-4-162,

TBy27-1385, TBy28-0348, MPT02-458, 91-2-527, KK3 and LK92-11); Group II (CSB06-5-20, MPT03-166 and Kps01-12) (The bar stands for standard error (SE) indicating that the difference between two means is statistically significant at  $P \leq 0.01$ )

of a plant to uptake water (Jongrunklang et al. 2011; Inman-Bamber et al. 2012).

At the full growth period (8 MAP), KK3 and 91-2-527 characterized by adequate soil moisture in the upper soil layers and enhanced root growth at the soil's surface demonstrated high RLD in the upper soil layers. Root patterns proved that the sugarcane had enough water for plant growth. The full growth period is an important phase of sugarcane for bulking yield. At this period, the assimilation products obtained through photosynthesis are transported to the shoot. When soil moisture is sufficient for plant growth, it is not necessary for the sugarcane plant to invest in additional roots.

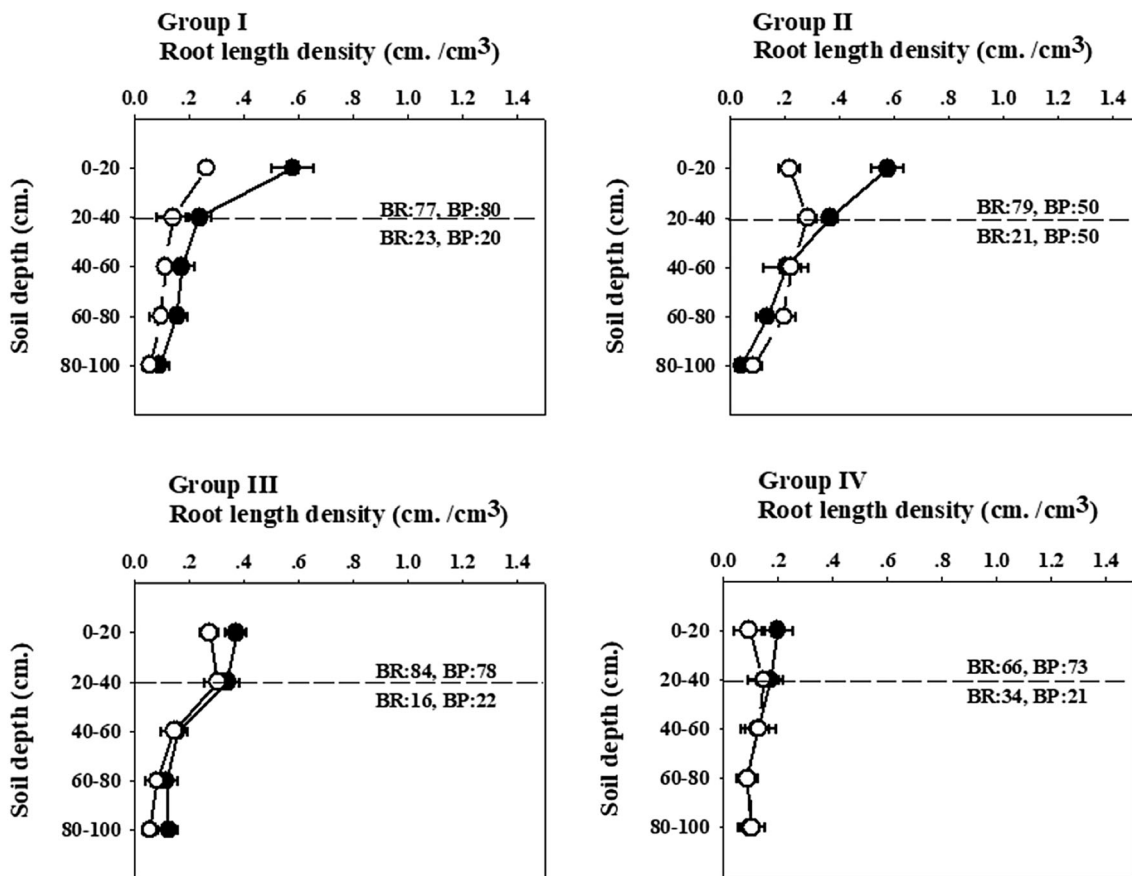
At Kuchinarai, CSB06-4-162 and KK3 genotypes had the highest cane yield, and all sugarcane varieties responded differently to soil moisture for RLDs. During drought stress period, several patterns of RLDs were observed among all varieties. The genotypes with high cane yields had high RLDs in both the upper layer soils (lower or far-vertical root angles) and deeper soil layers (higher or near-vertical root angles), whereas CSB06-4-162 and KK3 with low RLDs in the lower soil layers had high RLDs under stress conditions.

The results agreed with the previous observations. Jongrunklanga et al. (2013) reported that drought stress increased root systems in their search for more water within low soil moisture environments. In sandy soil, soil moisture content increased with the depth of the soil profile, thereby increasing sugarcane root activity at lower soil

layers after a reduction in soil surface moisture content (Inman-Bamber et al. 2003).

During the recovery period (6 MAP), CSB06-4-162 and KK3 did not produce adjunct roots in the upper soil layers, but they increased RLDs in the lower soil layers. During the full growth period, these varieties increased RLDs in both the upper and lower soil layers. This may be a result of the plant water use for stalk growth. According to Ohashi et al. 2014, some sugarcane genotypes are capable of increasing the cumulative root density of a ratoon crop until 205 days after harvest (about 7 months). This behavior illustrates that lower, more effective root depth also enables better use of rainfall.

In this study, several of the sugarcane genotypes characterized by higher RLDs in the lower soil layers in drought stress periods showed a putative drought avoidance mechanism in obtaining acceptable yields under rain-fed conditions. These genotypes were stabilized under drought stress, as they increased root growth in the lower soil layers in water stress periods and maintained RLDs until soil moisture was restored in the upcoming rainy season. However, additional mechanisms of drought resistance or avoidance to achieve high yields under rain-fed conditions also exist. The modification of the root distribution pattern is another mechanism, which allows sugarcane to achieve high cane yields under drought stress. Breeding for yield stability of sugarcane under water deficit conditions by selection of root growth in deep soil might accelerate the



BR: Percent root length density between rows  
 BP: Percent root length density between plants

**Fig. 8** Root length densities (cm/cm<sup>3</sup>) between plants (filled circle) and between rows (empty circle) of the 16 sugarcane genotypes grown under rain-fed conditions, evaluated at 8 MAP at the Nong Saeng location. Group I (RT2004-085, MPT03-166, 91-2-527 and KK3); Group II (TBy28-0348); Group III (NSUT08-22-3-13, Kps01-

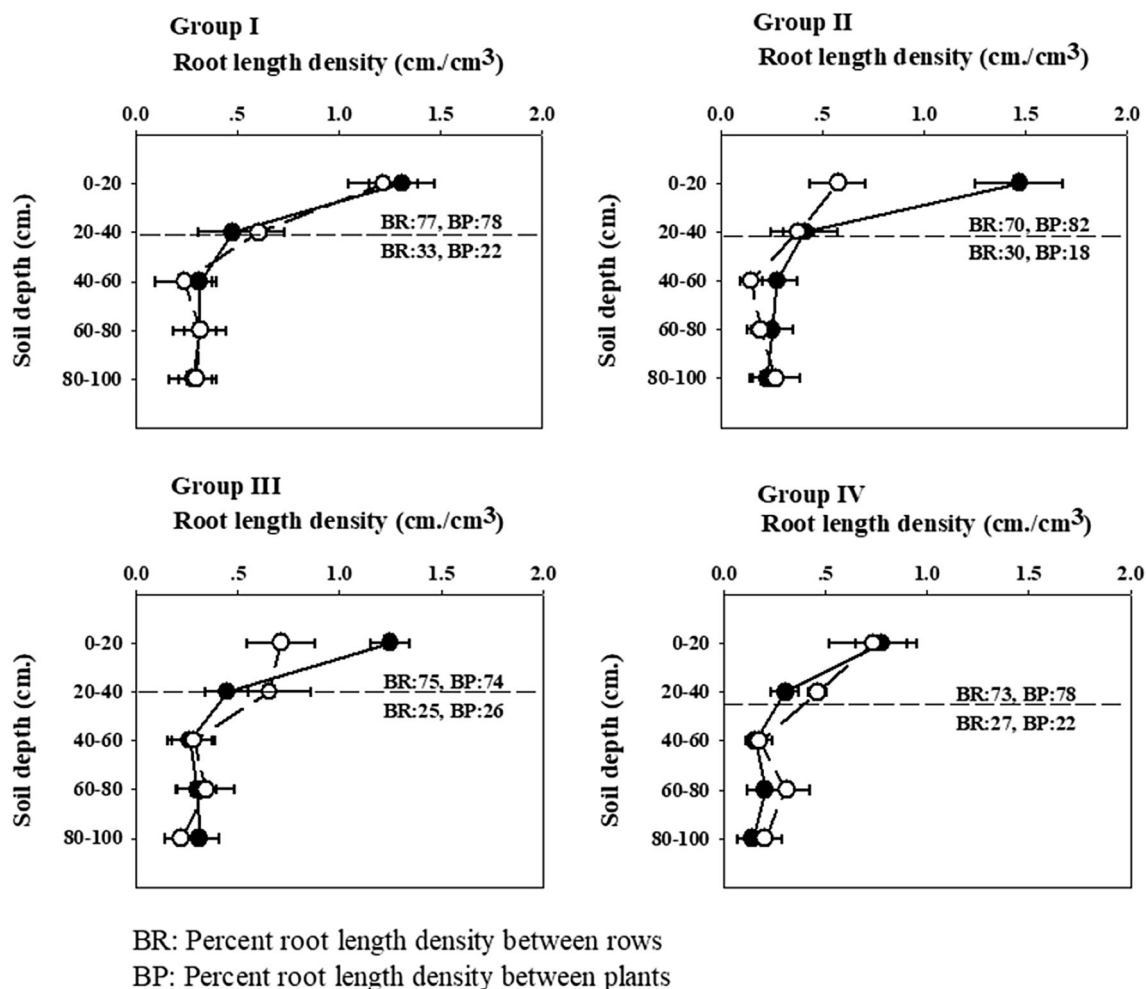
12 and KK07-478); Group IV (MPT02-458, CSB06-2-21, KK06-501, LK92-11, TBy27-1385, CSB06-5-20, CSB06-4-162 and CSB06-2-15) (The bar stands for standard error (SE) indicating that the difference between two means is statistically significant at  $P \leq 0.01$ )

progress of breeding programs for adaptation to specific water deficit environments.

**Conclusion**

Sugarcane breeding clones and checks were significantly different in both locations. KK3, MPT02-458 and CSB06-

4-162 produced high cane yields in sandy loam soil in Nong Saeng and sandy soil in Kuchinarai. Sugarcane genotypes were found to change their root distribution patterns in both the recovery period and full growth periods. KK3 had the highest cane yield in both locations, and the genotypes showed root adaptation as indicated by high RLD in the deeper subsoil levels at the recovery and full growth periods.



**Fig. 9** Root length densities (cm/cm<sup>3</sup>) between plants (filled circle) and between rows (empty circle) of the 16 sugarcane genotypes grown under rain-fed conditions, evaluated at 8 MAP at the Kuchinarai location. Group I (KK3, RT2004-085, CSB06-2-15, CSB06-2-21 and LK92-11); Group II (MPT03-166, NSUT08-22-3-

13, CSB06-4-162, 91-2-527 and Kps01-12); Group III (TBy27-1385, KK07-478, CSB06-5-20 and KK06-501); Group IV (TBy28-034 and MPT02-458) (The bar stands for standard error (SE) indicating that the difference between two means is statistically significant at  $P \leq 0.01$ )

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**Author Contribution** Sawettachat Set-tow carried out the whole experiment and made manuscript draft and was responsible for the main experimental assignments, data analysis and manuscript preparation; P. Songsri guided in working concepts and advised in physiological and rooting traits; N. Jongrungrklang guided in working concepts.

#### Compliance with Ethical Standard

**Conflict of interest** The authors declare that they have no conflict of interest.

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