RESEARCH ARTICLE

SABRAO Journal
of Breeding and Genetics
51 (1) 80-92, 2019

COMPARISON OF YIELD COMPONENTS OF SUGARCANE VARITIES GROWN UNDER NATURAL SHORT- AND LONG-TERM WATER-LOGGED CONDITIONS IN THAILAND

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SUMMARY

Against the background of a changing climate, water logging is a major problem for sugarcane production and results in reduced productivity. Various sugarcane genotypes cultivated in waterlogged areas show different acclimations of yield component traits. Understanding such traits under these conditions could be useful in the selection of suitable sugarcane cultivars. Therefore, the objectives of this study was to evaluate cane yield and millable cane, stalk weight, stalk length, and sugar yield of 12 sugarcane varieties in upland (short water logging period) and lowland (long water logging period) areas. Yield, sugar yield, stalk length, stalk diameter, millable cane, and weight per stalk were measured at 12 months after planting. Under both conditions, the tested sugarcane genotypes were differed in terms of yield, millable cane, single stalk weight, stalk length, stalk diameter, and sugar yield. Long water logging periods induced cane yield reduction and decreased single stalk weight. KK3, Kps01-12, and TBy28-0941 showed consistently high productivity across short and long water logging conditions. A positive correlation between single stalk weight and cane yield was existed, and this trait could be used as criteria selection for high productive cultivars under flooding conditions. Millable stalk number could also be used as a surrogate trait under these conditions.

Key words: Single stalk weight, millable cane, stalk length, flooding, sugar yield

Key findings: The twelve sugarcane genotypes used in this study were significantly differed in terms of yield, yield components, and sugar yield under short-term and long-term water logging conditions. Long periods of water logging result in lower cane yield, sugar yield, single stalk weight and stalk length compared to those obtained under short-term water logging. Single stalk weight contributes to high cane yield and could be used as a selection characteristic for improving cane productivity under water-logged field conditions.

Manuscript received: October 11, 2018; Decision on manuscript: January 22, 2019;
Accepted: February 22, 2019.

Communicating Editor: Dr. Sathiyamoorthy Meiyalaghan

INTRODUCTION

Currently, global sugar consumption is increasing, results in increased demands on sugar mills (Office of the Cane and Sugar Board, Thailand, 2016). Inevitably, this leads to the expansion of the sugarcane cultivation area, and sugarcane is increasingly cultivated in unsuitable areas such as water-logged lowlands. Moreover, global warming and climatic changes significantly affect agricultural production, resulting in decreased crop productivity. Flooding, as a main consequence of climate change, has significantly impacts on sugarcane yields, and it can reduce sugarcane yield up to 45% (Gomathi *et al*., 2015; Zhao and Yang-Rui, 2015), and in this sense, sugarcane cultivars tolerant to water-logging need to be established.

Yield and yield components of sugarcane could be influenced by numerous factors viz. genotype, environment, amount and period of water logging, and growth stage of sugarcane are related to yield and yield components under water logged conditions (Gomathi *et al.*, 2015), and water logging can affect every growth development stage of sugarcane (Hidaka and Karim,2007). In sugarcane, flooding induces stem dry weight and height reductions (up to 15-45%), leaf discoloration, and decreases in leaf number and length (Gomathi and Chandran, 2009; Gomathi *et al.*, 2010, 2015; Hidaka and Karim, 2007). Leaf biomass as well as stalk and total dry matter can be decreased by 42.63, 45.16, and 44.69%, respectively, under water logging conditions (Gomathi and Chandran, 2010). In addition, plant height, tiller number, leaf area index, and total biomass can be reduced by up to 13.0, 21.6, 26.52, and 42.5%, respectively (Gomathi *et al.*, 2015). In addition, in sugarcane, flooding also reduced the exhibition of physiological characteristics such as photosynthetic rate and CO_2 assimilation through stomatal closure (Hidaka and Karim, 2007; Jaiphong *et al.*, 2016). Thus, the water-logged resistant sugarcane cultivar could maintain photosynthetic rate and transpiration rate when subjected under flooding condition.

Cultivars resistant to water logging show satisfactory stem height, tillering, and yield characteristics under flooding (Carlos *et al.*, 2013). However, crops tolerant to water logging need to maintain their oxygen absorption and transportation to the roots, thereby avoiding damages from O_2 deficiency (Taiz and Zeiger, 2002). Moreover, damages due to water logging depend upon the genotypes, environmental conditions, developmental stage, the duration of the stress period (Joseph *et al.*, 2011). Therefore, different sugarcane cultivars might respond differently to water logging and soil types, especially when grown in different lowland and upland fields with sandy and clayey soils.

However, information about yield and yield components of diverse sugarcane cultivars under different natural water logging conditions in the field is scarce. In this context, the objective of this study was to evaluate cane yield, millable cane, stalk weight, stalk length, and sugar yield of 12 sugarcane varieties cultivated in upland (short water logging duration) and lowland (long water logging duration) areas, with the aim to provide information for the selection of sugarcane cultivars resistant to water logging and to identify the adaptation potential of various yield components to water logging conditions.

MATERIALS AND METHODS

Experimental design

Two field experiments were conducted in lowland and upland areas during the growing season from December 2015 to January 2017. In the upland area, the experiment on sandy soil at with a short water logging period was conducted at the Borabue District, Maha Sara kham Province, Thailand (16°07'21.0"N, 103°09'12.6"E), with 22% of the field capacity and lower organic matter (0.34-0.52%) compared to the lowland trial. The lowland field experiment, with a longer water logging period, was conducted at Amphoe Mueang Maha Sarakham, Maha Sarakham Province, Thailand (16°11'33.7"N, 103°12'43.8"E). The soil was clayey, with 43% of field capacity and an organic matter level of 2.28-2.53%. Each field experiment was arranged in a randomized complete block design with four replications. Plot size was 30 m^2, with 5 rows and a row length of 6 m. Between-row spacing was 120 cm, with a spacing of 50 cm between plants. Both experiments were conducted under rain-fed conditions. The water logging period in the upland area was around 3 months (196 to 290 days after planting) and that in the lowland area around 4.5 months (152 to 290 days after planting). Obviously, the water logging conditions of both fields were occurred during elongation stage as describe by Vasantha *et al.* (2014).

Planting material

Twelve sugarcane lines from the Thai sugarcane breeding program were used. Seven commercial sugarcane cultivars, namely KK3, LK92-11, K88-92, K93-219, UT12, UT13, and Kps01-12, were selected for this study. Cultivars KK3, LK92-11, and K88-92 have been identified by Khonghintaisong *et al.* (2018) as drought-tolerant cultivars with a good adaptation of rooting and physiological traits under water stress conditions. Cultivar K93-219 is resistant to water logging conditions (Office of the Cane and Sugar Board Thailand, 2016), while UT12 has been selected and evaluated under irrigation conditions. Cultivar UT13 has been improved from the wild-type genotype (Office of the Cane and Sugar Board Thailand, 2016) to adapt to environmental stress. Cultivar Kps01-12 has a large adaptation capacity and a high productivity in numerous locations. Five elite sugarcane lines, namely KKU99-02, KKU99-03, KK06-501, TBy28-0941, and MP-458, were also used in this experiment. Of these, KKU99-02, KKU99-03, KK06-501, and MP-458 were evaluated in northeastern Thailand (with frequent droughts and sandy soil) and TBy28-0941 in central Thailand (wet conditions and clayey soil).

Crop management

Prior to cultivation, the fields were prepared through rough ploughing and, later, ploughing in regular furrows. Three eye sets of each genotype were manually planted. Fertilizer was applied as base dressing with 46.9kg N, 46.9 kg P, and 46.9 kg K ha^{-1}. Additionally, 46.9 kg N, 46.9 kg P, and 46.9 kg K ha^{-1} were applied as top dressing with two equal split applications at the tillering stages (3 and 4 months after planting). Weed, insect, and disease controls were performed as necessary to keep the plants free from pests throughout the experimental period.

Data collection

Rainfall, relative humidity (RH), maximum and minimum temperature, and solar radiation were recorded daily from planting until harvesting by a weather station located 10 km away from the experimental fields. Water logging was recorded every 15 days after flooding events.

At the final harvest, all canes in each plot were harvested. All stalks were counted for the determination of millable canes and then cut at ground level; stalk fresh weight per plot was recorded. A sub-sample of six stalks per plot was randomly taken to determine the yield components, i.e., stalk length and stalk diameter. In six stalks, stalk length was measured using a measuring tape. A Vernier caliper was used to measure the diameter of these six stalks; the reading region was defined as one-third of the stalk length (from the base to the top). Subsequently, juice was extracted from these six stalks to determine commercial cane sugar (CCS) yield. Sugar yield per plot was calculated based on cane yield and CCS value, using the following equation:

$$\text{Sugar yield} = \text{Cane yield} \times \text{CCS} / 100$$

Statistical analysis

All statistical analyses were conducted using the software package Statistix 8. The measured data were subjected to analysis of variance according to a RCB design. Comparisons among varieties for yield and yield components were performed based on the Duncan's multiple range test (DMRT) (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

Meteorological conditions and water logging period

Minimum daily air temperature ranged from 9 to 30°C, maximum temperature from 19 to 40°C, and humidity from 59 to 91% during the growing season. Accumulation of rainfall was 1411.3 mm throughout the experimental period, and rainfall during water logging (140-316 days after planting) ranged from 5 to 105 mm (Figure 1). Due to rainfall during these experiments, the water logging period in the upland area was around 3 months (196 to 290 days after planting) and that in the lowland area around 4.5 months (152 to 290 days after planting). The natural water logging in lowland and upland in this experiment also confirmed different conditions between both fields.

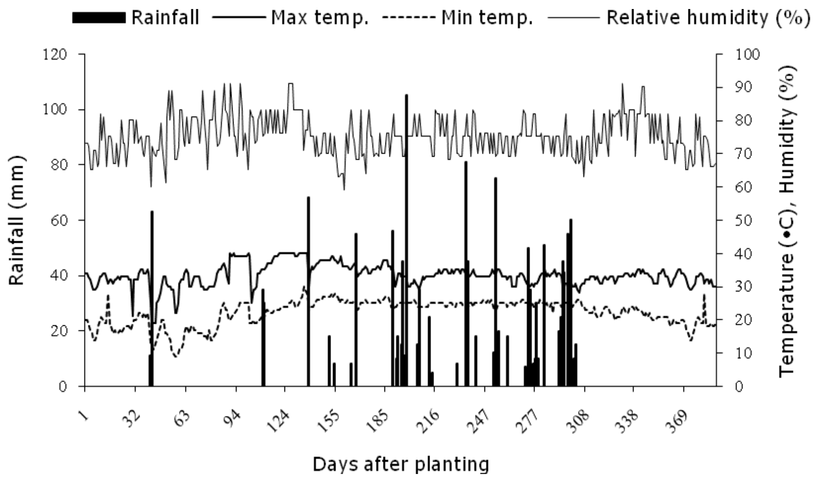

Figure 1. Rainfall (mm), maximum temperature (°C), minimum temperature (°C), and humidity (%) during the experimental period (1-366 days after planting).

Genotype and location interactions

Significant genotype × environment (G × E) interactions were found for cane yield, sugar yield, CCS, stalk weight, and stalk diameter, whereas no interaction was observed for millable cane and stalk length (Table 1). All traits revealed significant differences among genotypes, except for sugar yield. The different locations (upland and lowland) significantly differed in cane yield, sugar yield, CCS, stalk weight, millable cane, and stalk length, but not in stalk diameter (Table 1).

Traits impacted by G × E interactions are not desirable traits in breeding programs. A large G × E interaction may result in failure to identify the performance of genotypes across environments, leading to a low efficiency for line select in multi-location trails (Wen and Zhu, 2005). In this research, millable cane stalk length and stalk diameter could be used as trait selection criteria. Stalk diameter values of sugarcane rather depend on genetic variation than on environmental impacts. Although the main effects on stalk diameter are based on genetics, a G × E interaction is present under normal (rainfall), well-watered, and drought-stress conditions (Esayas *et al.*, 2016; da Silva *et al.*, 2008). Water logging might affect internode elongation; the transduction factor is simulated by flooding, which activates genes producing biochemical substrates involved in elongation. Thus, the response of stalk length depends on genetic and environmental variations. In addition, sugar yields did not differ among the various cultivars, and a G × E interaction was found for this trait. This might be due to the variation in the response of genotypes subjected to different water logging periods, indicating that sugar yield performance in this study was primarily based on environment. Generally, flooding decreases cane yield and CCS (Navnit *et al.*, 2015), and different flooding conditions induce different responses of these traits (Wen and Zhu, 2005).

Table 1. Mean squares from combined analysis for yield and yield components of 12 sugarcane varieties in upland and lowland areas.

Source of variation	Df	Yield and yield component						
		Cane yield	Millable canes	Sugar yield	CCS	Single stalk weight	Stalk length	Stalk diameter
Environment (E)	1	85162.5**	1.28×10^{10}ns	2087.9**	17.94**	60.33**	58,193.8**	0.26ns
Replication/E	6	803.3	3.61×10^{8}	15.70	1.16	0.19	1,833.8	0.11
Variety (G)	11	457.5**	4.10×10^{8}**	9.7ns	6.45*	0.65**	3422.6**	0.10**
G*E	11	837.4**	8.68×10^{7}ns	25.6**	5.59*	0.46**	1,264.3ns	0.21**
Pool error	66	130.2	8.38×10^{7}	5.30	2.63	0.15	684.2	0.03

ns, * and ** = non-significant, significant at $P < 0.05$ and 0.01.

Table 2. Cane yield, sugar yield and CCS of 12 sugarcane varieties under short-term (SWC) and long-term(LWC) water logging conditions.

Varieties	Cane yield (t ha-1)		Sugar yield (t ccs ha-1)		CCS	
	Short	Long	Short	Long	Short	Long
K93-219	150.8 a	68.8 bcd	17.7 abc	9.8 Bcd	11.7 d	14.2
UT13	141.9 ab	57.4 cde	22.0 a	7.6 De	15.5 abc	13.1
KK3	139.3 ab	83.5 ab	20.8 ab	11.9 Ab	14.9 abc	14.5
TBy28-0941	135.0 ab	76.8 b	18.4 abc	9.3 Bcd	13.6 c	12.3
KK06-501	134.7 ab	41.8 e	21.5 a	5.2 E	15.9 ab	12.3
Kps01-12	132.7 abc	73.2 bc	20.2 ab	10.6 Bcd	15.2 abc	14.6
UT12	130.2 bcd	53.0 de	20.1 ab	7.8 De	15.5 abc	14.7
KKU99-02	127.8 bcd	73.6 bc	20.3 ab	10.7 Bcd	15.8 ab	14.5
K88-92	119.2 b-e	85.7 a	16.9 bc	12.2 A	14.1 bc	14.6
KKU99-03	116.1 cde	71.3 bc	16.6 bc	8.6 Cd	14.3 abc	11.6
MP-458	114.0 de	78.4 ab	18.3 abc	11.7 Abc	16.1 a	14.9
LK92-11	108.4 e	72.1 bc	15.5 c	11.1 Abc	14.3 abc	15.2
Means	129.2	69.6	19.0	9.7	14.7	13.9
F-test	**	**	*	**	**	ns
CV (%)	8.8	16.5	13.6	20.4	8.0	14.2

ns, * and ** = non-significant, significant at $P < 0.05$ and 0.01, respectively. Means within a column with different letters are significantly different (0.05 probability level).

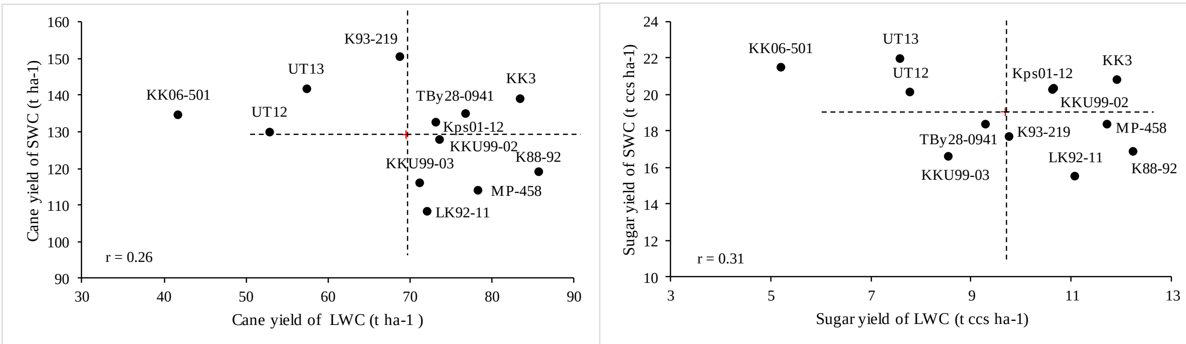

Figure 2. Correlations between cane yield under short-term water logging conditions (SWC) and cane yield under long-term water logging conditions (LWC), sugar yield under short-term water logging conditions (SWC) and sugar yield under long-term water logging conditions (LWC) for 12 sugarcane varieties.

Cane yields under water logged conditions

Sugarcane grown under short-term water-logged conditions showed higher cane yield compared to plants cultivated under long periods of water logging (129.2 t ha^{-1} vs. 69.6 t ha^{-1} (Table 2). The six cultivars with the highest productivity in the upland experiment were K93-219, UT13, KK3, TBy28-0941, KK06-501, and Kps01-12. In the lowland experiment, the six cultivars K88-92, KK3, MP-458, TBy28-0941, KKU99-02, and Kps01-12 had the highest yields, i.e., 85.7, 83.5, 78.4, 76.8 73.6 and 73.2 t ha^{-1}, respectively (Table 2). The genotypes KK3, Kps01-12, and TBy28-0941 were appropriate for both flooding conditions and showed high yields in the upland and the lowland areas (Figure 2).

Cane yield decreased when sugarcane was grown under water logging conditions. After flooding, the soil was hypoxic, impeding aerobic respiration and facilitating fermentation, thereby resulting in low energy levels (Taiz and Zeiger, 2002; Drew, 1997; Gomathi *et al*., 2014). Thus, water logging significantly reduces biomass accumulation. Long periods of water logging result in lower yields compared to those obtained under short-term water logging. This is also valid for sugarcane, where yields are significantly reduced even after 7 days of flooding (Islam *et al.*, 2011a). Sugarcane varieties tolerant to long-term water logging (120 days) show higher cane yield productivity than other cultivars (Islam *et al.*, 2011b). In addition, growth stage of sugarcane is related to responses of yield and yield components under water logging conditions (Gomathi and Chandran, 2009).

Sugar yield and CCS under water-logged conditions

In the upland experiment, means of sugar yield and CCS were higher than those in the lowland field. In the upland area, high values of sugar yield were mainly found for the genotypes UT13, KK06-501, KK3, KKU99-02, Kps01-12, and UT12, with 22.0, 21.5, 20.8, 20.3, 20.2, and 20.1 t CCS^{-1} respectively. In the lowland

Table 3. Stalk length, single stalk weight, stalk diameter, and millable canes of 12 sugarcane varieties under short-term (SWC) and long-term (LWC) water logging conditions.

Varieties	Millable canes (no. ha^{-1})				Single stalk weight (kg)				Stalk length (cm)				Stalk diameter (cm)			
	Short		Long		Short		Long		Short		Long		Short		Long	
K93-219	45833	de	47917	e	3.4	a	1.5	a	331.5	de	289.8	c	3.0	bc	3.7	a
UT13	56771	abc	54688	d	2.5	cd	1.1	bcd	362.5	a-d	305.0	abc	2.8	c	3.1	cd
KK3	57292	ab	74479	a	2.5	cd	1.1	a-d	328.5	de	297.5	bc	3.2	ab	3.0	d
TBy28-0941	57292	ab	63021	c	2.4	cd	1.2	abc	338.7	b-e	299.2	bc	3.2	ab	2.9	d
KK06-501	51823	bcd	53646	d	2.6	bcd	1.0	cd	389.8	ab	303.3	abc	3.0	bc	3.1	cd
Kps01-12	41146	e	48438	e	3.4	ab	1.4	abc	388.7	ab	324.6	ab	3.0	bc	3.4	abc
UT12	46354	cde	63542	c	2.9	abc	0.9	d	334.8	cde	283.6	c	3.0	bc	3.0	d
KKU99-02	57813	ab	57813	d	2.2	cd	1.3	abc	365.8	a-d	311.1	abc	3.1	ab	3.2	bcd
K88-92	65625	a	72396	ab	1.8	d	1.2	a-d	398.1	a	305.7	abc	3.0	bc	3.0	d
KKU99-03	46094	cde	57292	d	2.5	cd	1.3	abc	345.8	a-e	328.1	ab	3.3	a	2.9	d
MP-458	52604	bcd	57813	d	2.2	cd	1.4	ab	382.8	abc	334.1	a	2.9	bd	3.5	ab
LK92-11	54688	bcd	69792	ab	2.0	d	1.1	bcd	299.9	e	294.1	bc	2.9	bd	3.1	cd
Mean	52778		60069		2.5		1.2		356		306		3.0		3.1	
F-test	**		*		**		**		**		*		**		**	
CV (%)	12.6		18.5		20.0		18.2		8.6		6.8		5.6		6.4	

* and **= significant at $P < 0.05$ and 0.01, respectively. Means within a column with different letters are significantly different (0.05 probability level).

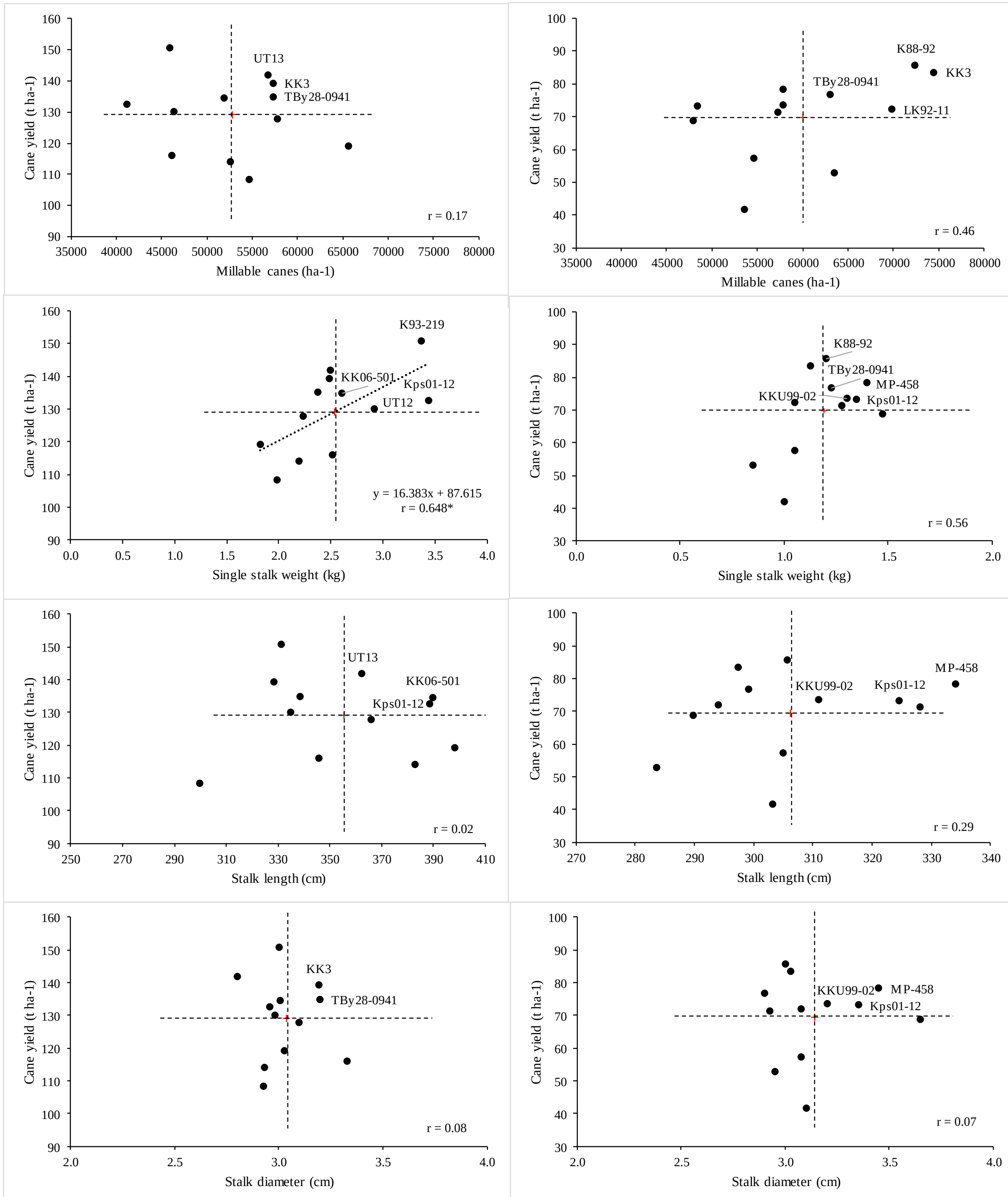

Figure 3. Correlations between stalk height, stalk weight, stalk diameter, and millable canes for 12 sugarcane varieties under short-term (SWC) and long-term (LWC) water logging conditions.

experiment, the cultivars K88-92, KK3, MP-458, and LK92-11 showed high sugar yield values, obtaining 12.2, 11.9, 11.7, and 11.1 t CCS^{-1} respectively. In the upland experiment, high values of CCS were found for the genotypes MP-458, KK06-501, KKU99-02, UT13, UT12, and Kps01-12, with 16.1, 15.9, 15.8, 15.5, 15.5,and 15.2 respectively, whereas no statistically significant differences were found in the lowland area (Table 2). Cultivars KK3, KKU99-02, and Kps01-12 showed high values of sugar yield in both conditions (Figure 2). Cultivar KK3 seems likely that cane yield was a major parameter which induces a high sugar yield, whereas KKU99-02 had high sugar yield via high values of CCS. In addition, cane yield and CCS value contributed to high sugar yield of Kps01-12, it provided a high performance of the both traits.

Genotypes resistant to water logging could maintain high sugar yield and CCS values during flooding. In field experiments, high sugar yield and CCS values were observed in resistant genotypes over a flooding period of 120 days (Islam *et al.*, 2011a; 2011b). Water logging significantly reduces sucrose accumulation due to it is changes in monosaccharide concentrations (Gomathi and Chandran, 2013). Flooding leads to increase fiber percent and non-sugars and yellowing of leaves in anaerobic situation during water-logging environment (Malik and Tomer, 2003).

Yield components under water logged conditions

In both short- and long-term water logging conditions, yields traits such as millable cane, single stalk weight, stalk length, and stalk diameter differed significantly among cultivars (Table 3). Cultivars KK3, K88-92, TBy28-0941, and LK92-11 had consistently high millable cane yields in both conditions, whereas K93-219 showed high single stalk weight in both conditions. In addition, there was relationship between single stalk weight and cane yield under short-term water logging (Figure 3). High cane weight under short-term water logging contributed to high cane yields. Although the G × E interaction had no impact on cane yield, KK3 and TBy28-0941 showed high millable cane yields. Under short water logged period, yield component characters of the top sixth high yields of sugarcane genotypes differently responded. Cultivars UT13, KK3, and TBy28-0941 were characterized by high stalk numbers, resulting in a high productivity under water-logged conditions, whereas K93-219, KK06-501, and Kps01-12 were identified as cultivars with a high stalk weight (Figure 3). In the experiment with long-term water logging, the cultivars with the highest millable cane amount were KK3, TBy28-0941 and K88-92, and TBy28-0941, K88-92, MP 458, KKU99-02 and Kps01-12, which were also genotypes with high stalk weight. In addition, the natural water logging in lowland and upland in this experiment also shown different root and shoot characteristics between both fields (Figures 4 and 5).

The use of the millable cane and stalk length not affected by G × E interaction might be a suitableselection criterion for improving cane productivity under water-logged conditions. Millable cane amount may be mainly controlled by genetic effect more than environment effects. Cane yield was positively

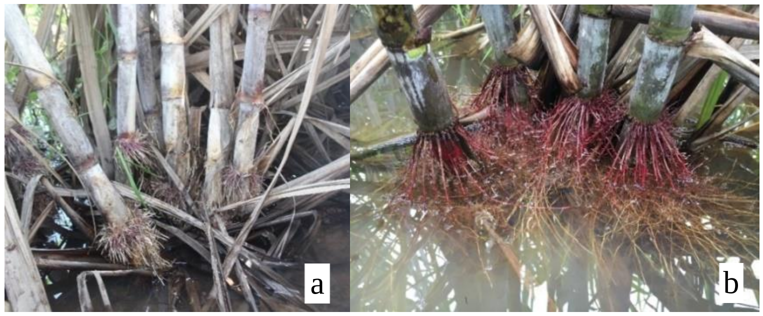

Figure 4. Root characteristics under waterlogged conditions in an upland field (a) and in a lowland field (b).

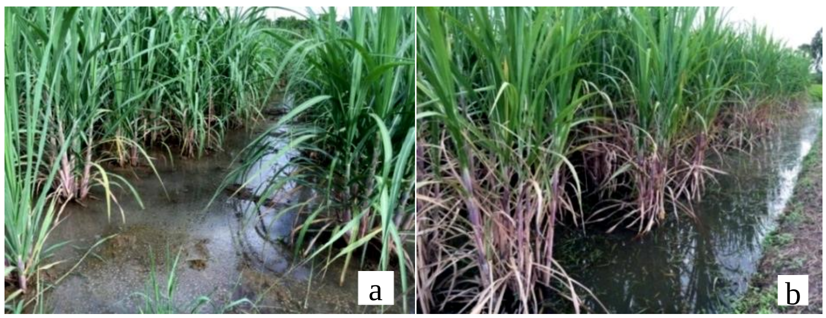

Figure 5. Water logging conditions in an upland field (a) and in a lowland field (b).

correlated with its component namely millable stalk numbers, millable stalk height internodes per stalk and single weight, but negative association with millable stalk diameter, Pol in juice and purity (Ahmed *et al.*, 2010). Similarly, the weight of millable stalks directly contributes to cane yield (Tyagi and Lai, 2007), as yield is positively and highly significantly correlated with single cane weight, stalk length, and millable cane number under irrigation conditions (Chaudhary and Joshi, 2005).

Almost all genotypes revealed higher millable stalk yield under long-term water-logged conditions. This could also be explained by the higher soil fertility in the lowland area compared to the upland site. The sugarcane used in this study already had an established stalk number prior to being subjected to flooding (about 6 months after planting); thus, the amount of millable cane did not depend on the duration of the water logging period. However, long periods of flooding significantly decreased stalk weight, consequently reducing cane productivity. The reduction in stalk weight of the different sugarcane genotypes might be related to space formation in the stalk, as the stalk diameter did not differ between the two conditions.

CONCLUSIONS

Under two different water logging conditions (short-term and long-term), the 12 sugarcane genotypes used in this study differed in stalk yield, millable cane, single stalk weight, stalk length, stalk diameter, and sugar yield. Long-term flooding resulted in a higher cane yield reduction and decreased stalk weight. The cultivars KK3, Kps01-12, and TBy28-0941 were suitable for planting under both conditions and showed high cane productivity. In contrast, the cultivars K93-219, UT13, KK3, TBy28-0941, KK06-501, and Kps01-12 performed well under short-term flooding, while the genotypes K88-92, KK3, MP-458, TBy28-0941, KKU99-02, and Kps01-12 showed high yields under long-term water logging. A positive correlation between single stalk weight and cane yield was existed, and these traits could be used as selection characteristics to improve cane productivity under flooding conditions. Millable stalk number could also be used as a selection trait in these environments, indicating high-yield genotypes. These results can be used to support breeding programs and the selection of high-yield sugarcane cultivars under water-logged conditions.

ACKNOWLEDGEMENT

We thank the Northeast Thailand Cane and Sugar Research Center, Faculty of Agriculture, Khon Kaen University, Thailand Research Fund (TRG5880086, RDG5950044 and RDG60T0165 for providing financial support for data collection and IRG5780003 for providing financial support for manuscript preparation). The research was funded in part by the Government of Thailand’s Grants to Khon Kaen University (KKU) (FY2018 and FY2019) and the Thailand Research Fund for providing financial support through the Senior Research Scholar Project of Prof. Dr. Sanun Jogloy (Project no. RTA6180002).

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