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Small-Scale Mechanical Harvesting and Tractor-Caused Soil Compaction Reduce Early Growth in Sugarcane

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Abstract: Sugarcane is an important crop for sugar and biofuel production worldwide. It is mostly grown on hilly area by smallholders in China, which makes harvesting by a combine harvester impractical. Harvesting sugarcane by a small-scale harvester could be more practical. However, information about the impact of small-scale mechanical harvesting on soil compaction (SC), early growth and cane yield, and its yield components is still limited. The scarcity of quantitative information is equally true for the genotype and harvesting method interaction for traits describing early growth and final yield in sugarcane. Field experiments were conducted in a plant and two consequent ratoon crops (RCs) during 2016–2018 in Kaiyuan, Yunnan Province, China, to determine the impact of small-scale mechanical harvesting followed by tractor passages (SMH) on SC, sugarcane early growth and yield, and yield components, and to determine the genotype x treatment (harvesting methods, GT) interactions. The results indicated that, when compared to manual harvesting (MH), SMH significantly ($p < 0.05$) increased SC at 5, 10, and 20 cm depths by 0.6, 0.71, and 0.69 MPa for the first ratoon crop (RC), respectively; and increased by 1.4, 2.02, and 1.72 MPa at 10, 20, and 30 cm depths for the second RC, respectively. The amounts of underground bud bank (UBB) in RCs were nearly nine times the buds for establishing the plant crop (PC); positive correlations between the UBB and seedling counts were observed, with the highest correlations ($r = 0.8453$) occurring in May for the second RC. As compared with MH, stool damage and gaps were significantly higher in SMH; meanwhile, the UBB was lower in two RCs; the amount of seedlings, plant height, and height uniformity were significantly lower in SMH. Cane yield declined more in SMH, particularly declining by 20.59% from the first RC to the second RC. With respect to sugarcane production by SMH, the existence of significant GT interactions for stool damage, gaps, early seedling, millable stalks, and height uniformity at the maturing stage suggested that genotype selection trials should be conducted under the SMH rather than in MH.

Keywords: sugarcane; small-scale mechanical harvest; early growth; soil compaction; stool damage

1. Introduction

Sugarcane (*Saccharum* spp. hybrid) is a globally important crop for sugar and biofuel production. China is one of the largest sugarcane producers in the world, which produced 105 million tons of millable canes in 2017 [1]. In China, sugarcane is grown mostly in the hilly areas of Guangxi, Yunnan, and northern Guangdong provinces. A survey of 38 counties in Yunnan Province indicated that 71% of sugarcane was grown on slopes >6°, including 16% on slopes >25° [2]. Further, most sugarcane is grown by small land-holders averaging 0.6 ha per grower [3]. The geographical complexity and small land-holders make conventional combine harvesting impracticable. Only 2% of sugarcane in China was mechanically harvested during the 2017–2018 milling season [4].

Small-scale mechanical harvesting is an alternative for the sugarcane growing areas with a labor shortage. A single worker can manually harvest 1–2 t day^{-1}, compared to 200–300 t day^{-1} for a combine harvester [5]. A small-scale harvester 4GZ-9 (total weight 1140 kg) was designed for harvesting sugarcane in a hilly area in Guangxi province. Its capacity was chopping down 7.5–10 t of whole stalk per hr (in the sugarcane field yielding 75 t ha^{-1}), aided with a small-scale leaf and cane top removing machine; the clean stalk harvesting capacity was approximately 4 t hr^{-1}. To harvest 1000 t of sugarcane, the costs for manual harvesting (MH) and small-scale mechanical harvesting using a 4GZ-9 harvester were 150,000 and 31,250 RMB, respectively. Thus, the cost of small-scale harvesting was 21% of MH [6]. While MH creates more jobs for laborers [7], the labor pool for sugarcane harvest is shrinking, and farm workers receive much lower wages than they may earn in other industries or in cities [6]. It is imperative that the sugarcane industry develop small-scale harvester technology to ensure the sustainability of sugarcane production.

The harvesting process is an external disturbance to sugarcane growth in consequent ratoon crop (RC), and the strength of disturbance differs with harvesting methods, so the strength is a key factor to determine whether harvesting is done by hand or by machine. Combine harvesting increases soil compaction (SC) [8,9] and stool damage for consequent RC [10]. Tractor-caused compaction significantly increases in a soil depth of 10–20 cm, causing decreased sprouting by 11%–28%, and decreased plant height by 9%–12% [11]. Thus, sugarcane yield can be negatively affected by mechanical harvesting [12,13]. As the number of mechanical harvests and tractor passages increases, the cane yield tends to decrease compared to treatment without tractor passages [14].

Sugarcane is a vegetative crop that allows several ratoon crops (RCs) after the plant crop (PC) is harvested. Post-harvest buds that survive underground on the stool sprout to produce stalks in the consequent RC. According to the concept of underground bud bank (UBB) of other vegetative grasses [15], the total amount of buds that remain in a certain area after harvesting a previous crop becomes the UBB in sugarcane. Mechanical harvesting and tractor passages can have adverse effects on soil structure and may also negatively affect the constitution of the UBB by damaging ratoon stools compared to MH. SC significantly decreases the concentration and plant uptake of N, P, and K in wheat [16], reduces leaf area and dry matter accumulation in sugar beet and field bean [17], and significantly decreases sugarcane root growth [12,18]. The compacted soil may also induce stress on the sprouting and early growth of the subsequent RCs in sugarcane. Added passages of field equipment during transportation of millable cane also contribute to SC.

There have been limited studies on the UBB of sugarcane, even though this is an essential source for sprouting and early crop establishment. There has also been limited information on the impact of small-scale harvesting equipment on early growth and cane yield in the RC of sugarcane; if the UBB and ratoon sprouting is related to the harvest method, changing from MH to small-scale harvesting will result in changes to the UBB and ratoon sprouting; if SC is related to early sugarcane growth, harvest methods that compact soil should affect early sugarcane growth. There is no information on the genotype × treatment (GT) interaction if MH and small-scale mechanical harvesting followed by tractor passages (SMH) are considered as two treatments.

To our understanding, there is no literature reporting the GT interaction dealing with this specific interaction between genotype and treatments of MH and SMH. If the sugarcane production changes to SMH, will the genotype selected from trials under MH management suit the SMH? However, to serve a specific production system, for example, breeding for rain-fed production conditions had been expected to be conducted under the targeted condition even complicated by irregular weather conditions. Reported findings of litter or no interaction between genotype and treatments of water regimes, i.e., irrigated and rain-fed conditions for cane yield and components suggested that a genotype selection trial conducted under irrigated conditions might also be suited for rain-fed conditions [19–21]. Current sugarcane breeding programs are conducted under MH in China with the aim of supporting sugarcane production under MH. So, understanding the genotype and harvesting method (MH and SMH) interaction may help improve the breeding program for production with SMH.

The objectives of this study were to determine if the SMH impacts SC, UBB, early growth, and cane yield in RCs, and to determine the GT interactions for traits describing early growth and final cane yield in sugarcane.

2. Materials and Methods

2.1. Field Sites, Plant Materials, and Experimental Conditions

The field experiments were conducted in Kaiyuan City (103°15′ E, 23°42′ N) of Yunnan Province, in the south-west of China. The soil texture was clay loam, and the field was a paddy field without water stress. The experiment was in a split-plot design with the harvest method (MH vs. small-scale mechanical harvesting followed by tractor passages, SMH) as the main plot, and sugarcane genotype (YZ05-51 [22], FN39, GT32, YT93-159, and ROC22) as the subplot, and genotypes were randomly arranged in each of the four replications within each treatment. There were a total of 40 subplots, with 20 subplots in each treatment. Each subplot had 7 rows with 8 m in length and 1.2 m inter-row spacing. Four sides of the field experiment were surrounded by at least one guard row. The third and fourth rows of each subplot were used to measure yield components and traits describing early growth, the fifth and sixth rows were used to observe the UBB and collect samples for cane juice analysis, and the others were used as guard rows within each subplot. The experiments were conducted in one PC and two consecutive RCs from 2016 to 2018. The PC was planted on 2 February 2016. The growth periods were 386, 386, and 355 days for the PC, first RC, and second RC, respectively (Table 1). Standard locally-established commercial cultivation practices were used, with an exception of no inter-tillage for the entire study duration. For each crop, fertilizers urea (n = 46%), superphosphate (available P_2O_5 = 16%), and potassium sulfate (K_2O = 52%) were applied at the rates of 750 kg ha^{-1}, 750 kg ha^{-1}, and 150 kg ha^{-1}, respectively; and flood irrigation was applied six times per crop. Investigation on millable stalks, plant height, and stalk diameter in the lodged sugarcane field was more difficult than the field without lodging, particularly the measurements on plant height. The experimental field was fixed with bamboo sticks from October to the time of harvest for each crop to diminish experimental errors caused by lodging.

Table 1. Some site details, weather conditions, and management of field experiments.

Attributes	Crop		
	PC	First RC	Second RC
Location	103°15′ E, 23°42′ N		
Soil texture	Clay loam		
Accumulated rainfall (mm)	737.75	939.90	1038.40
Mean monthly max temp (°C)	31.43	30.98	30.80
Mean monthly min temp (°C)	11.37	10.77	11.11
Planting date	2 February 2016		
Harvest dates	22 February 2017	15 March 2018	5 March 2019
Growth period (day)	386	386	355

2.2. Harvest and Compaction Treatment

Each crop was harvested from the end of February to the middle of March after approximately 12 months of growth (Table 1). Manually harvested subplots were harvested by hand. Stalks were cut close to the ground using a sharp sickle following standard commercial practices. Leaves and tops were removed with a sickle. Mechanical harvesting was conducted using a reciprocating harvester (type 4GZW–0.8, product standard: Q/YYH01–2012, Yunnan Yunhai Machinery Co. Ltd., Kunming, Yunnan Province, China) (Figure 1), with a frequency of 4–7 cuts s^{-1}. Leaves and tops were removed manually with a sickle. Post-harvest compaction of mechanically harvesting subplots was carried out by rolling the stool bed five times with a tractor (Figure 1) (tread width = 20 cm). This was done to emulate compaction that might occur during sugarcane transportation in a hilly area after small-scale machine harvesting. The tractor was loaded with sand to a total weight of 7 t, a weight similar to that of a fully-loaded tractor. The same driver and tractor were used to mechanically harvest all the crops and apply SC treatments.

Figure 1. Mechanical harvest treatment was conducted by a reciprocating sugarcane harvester (**left**), followed by a tractor passage (**right**).

2.3. Measurements of the Traits Related to Early Growth of Sugarcane

Sugarcane was planted at approximately 10 cm below the soil surface. SC was measured at 10 cm depth intervals using a penetrometer (DS/TYD-2, manufactured by Zhejiang Tuo Pu Yun Nong Technology Co. Ltd., Hangzhou, Zhejiang Province, China) with a compaction limit of 500 N cm^{-2} and a maximum depth of 45 cm. Within each treatment, the subplots with cultivar ROC22 (4 replications in each treatment) were measured. SC was measured shortly after SC treatment at the depths of 5, 10, and 20 cm for the first RC, and at the depths of 10, 20, and 30 cm for the second RC. The measured soil depths were determined by the soil surface and scale on the penetrometer. The SC at each depth was represented by the average of four readings from the penetrometer. The readings were originally in units of N cm^{-2} and were converted to a more commonly used unit, MPa, following the conversion formula 1 MPa = 100 N cm^{-2}.

The UBB (×1000 buds ha^{-1}) of sugarcane consisted of the number of buds that remained underground on the stool after crop harvest, and the number of millable stalks of the previous crop. The number of underground buds per stool was determined immediately after each harvest and compaction treatment. The stools containing more than three underground stalks were excavated using a hoe, the adhering soil was removed by dipping into water for approximately 2 h and washing, and the number of underground buds was then counted on each stool.

Stool damage was investigated shortly after each harvest and SC treatment. The remaining stalks with a broken depth >5 cm were considered as damaged [23,24]. Stool damage (%) was calculated from the number of damaged stalks and total remaining stools. Due to a relatively high planting density, the gaps >40 cm were measured before harvest.

The number of seedlings (×1000 seedlings ha^{-1}) was recorded two times for each crop during April and May. The amount was determined through the seedling counts, including all the main shoots and tillers on the third and fourth rows of each subplot.

Plant height was measured during the grand growth period (June to September in Kaiyuan condition) and maturing stages (November to February) for both RCs. In the first RC, the plant height in June (booming growth) and November (maturing) was measured. In the second RC, plant height was measured three times, i.e., May, June, and July 2018. The measurement at the maturing stage was the same as the first RC in November. For each subplot, 10 stalks were chosen randomly for measuring the plant height from the soil surface to the top visible dewlap. The height uniformity of each subplot was determined by a coefficient of variation of the height of 10 stalks (C.V.) using the formula [25]:

$$\text{Height uniformity} = 1/\text{C.V.} \tag{1}$$

2.4. Yield Component and Cane Yield Measurement

The cane yield components, including millable stalks, plant height, and stalk diameter, were investigated in November when the sugarcane crop stopped vegetative growth and turned into the maturing stage. A total of 10 plants were chosen randomly from the third and the fourth rows of each subplot for determination of plant height and stalk diameter. The amount of millable stalks >1 m [26] was counted on the third and fourth rows within the subplot. These measurements were done in the plant and two RCs; however, plant height and stalk diameter in PC was not measured because there was no harvest treatment. The cane yields (t ha^{-1}) of the three crops were estimated from the fresh weight of all stalks in the third and the fourth rows recorded at harvest. For conducting juice analysis, i.e., to determine fiber (%), juice purity (%), and sucrose content (%) during the maturing stage [27], a sample bundle including 6 randomly cut stalks were taken from each subplot. The sampling lasted from November to February at both RCs. Meanwhile, within each crop, single stalk weight was determined by the total weight of 4 sample bundles (24 stalks) cut from each subplot. Considering that the long-time interval of sampling may affect the subsequent RCs [28], samples for juice analysis were taken from the sixth row rather than the two rows for determining yield and its components. Within the sixth row, the portion with worse growth may have been impacted by sampling during previous crops and was not considered for sampling.

2.5. Statistical Analysis

Plant uniformity for each subplot in each crop was calculated using Microsoft Excel 2010, as described by Ma et al. [25]. The variables, such as single stalk weight, fiber content, purity, and sucrose content, were averaged for each subplot across four monthly samples (November to February) in each crop because the date × subplot interactions were not significant. Analysis of variance for each variable, i.e., millable stalks, plant height, height uniformity, stalk diameter, cane yield, stool damage, gaps, amount of seedlings, single stalk weight, fiber, purity, and sucrose content were processed by the split-plot design model for determining the effects of treatment, genotype, and genotype × treatment (GT) interactions. In the split-plot design model of the software Statistix V8, treatment, genotype, and replication were used as the main-plot factor, subplot factor, and replication variable, respectively. The SC between the two main plots and soil depths were analyzed using the LSD all-pairwise comparisons test. Pearson correlations between the amounts of the UBB and seedlings in the two RCs were calculated using analytical software Statistix V8 (Tallahassee, FL 32312 USA) [29].

3. Results

3.1. Soil Compaction

It was found that SMH resulted in significantly greater SC than MH at all soil depths under both RCs (Figure 2). SC in the SMH treatment at 5 and 10 cm soil depths in the first RC, and at 10 and 20 cm depths in the second RC were more than twice of that in the MH treatment. The soil layers tested contained virtually all the possible depths where the UBB was present. In the first RC, SC was 1.70 and 2.36 MPa at 10 and 20 cm depths, respectively. In the second RC, the SC increased to 2.10 and 3.32 MPa, relatively. In the SMH of the second RC, SC reached 4.48 MPa, which was close to the limit of the penetrometer (500 N cm^{-2} = 5.0 MPa). However, SC was relatively lower in the MH treatment. At the depth of 10 cm, the SC was 0.99 and 0.70 MPa for the first and second RCs, respectively. At the depth of 20 cm, the SC was 1.67 and 1.30 MPa for the first and the second RCs, respectively. As compared with the MH, the SMH posed significant SC stress.

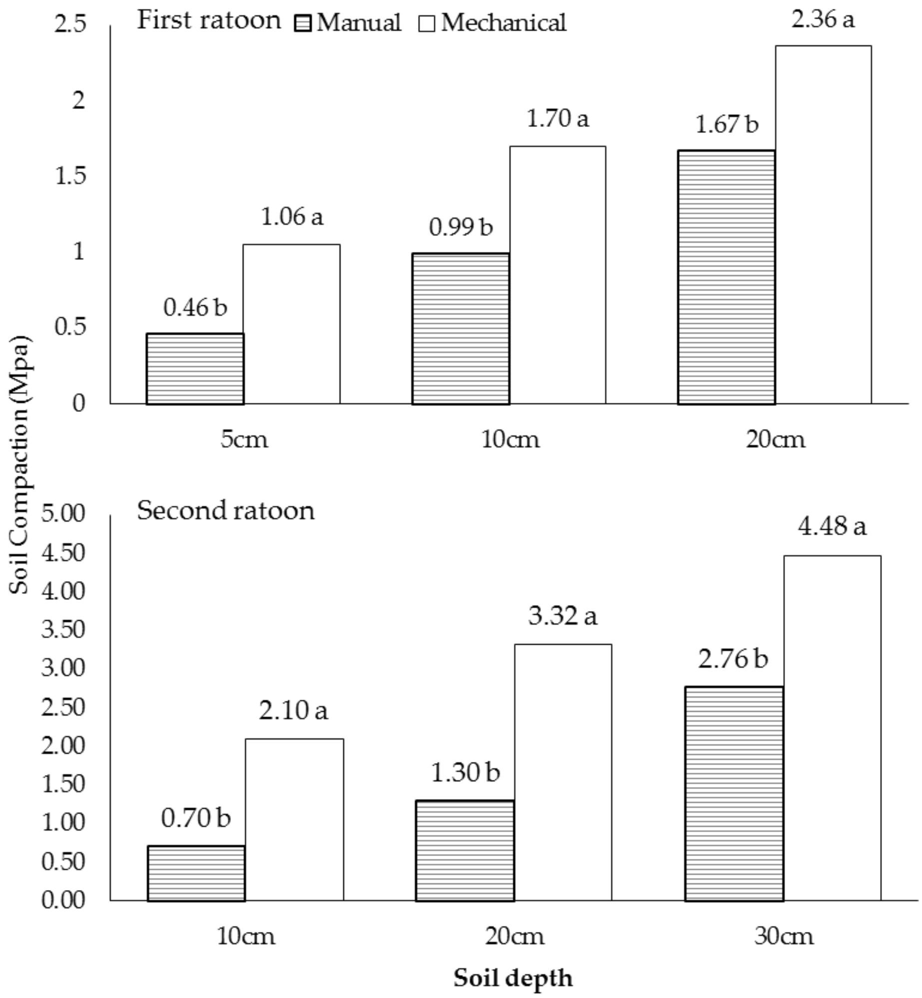

Figure 2. Soil compaction (SC) for manual harvesting (MH) and small-scale mechanical harvesting followed by tractor passages (SMH) at two ratoon crops (RCs), bars within a ratoon crop (RC) and depth followed by the same letter do not differ at $p < 0.05$ (LSD test).

3.2. Stool Damage and Gaps

SMH caused significantly ($p < 0.001$) more stool damage than MH in the RCs (Table 2). The genotype and GT interaction effects also were significant ($p < 0.05$). There was more stool damage observed at the second RC for both treatments as compared with the first RC.

Gaps increased sharply with SMH and across RCs. Gaps in the MH increased from 118.49 m ha^{-1} in the first RC to 445.30 m ha^{-1} in the second RC and increased from 463.54 to 1070.3 m ha^{-1} in the SMH. Compared to the MH, gaps were significantly greater with the SMH. SMH had a significant ($p < 0.05$) adverse effect on gaps for both RCs. The effects of genotype and GT interaction were not significant in the first RC, but both effects were significant ($p < 0.05$) in the second RC.

3.3. Underground Bud Bank, Ratoon Sprouting, and Their Correlations

The number of buds per stool was relatively low in the SMH and was not significantly affected by treatment or GT interaction in either RC (Table 3). However, there was a significant ($p < 0.01$) genotype effect in the second RC. The number of buds ha^{-1} was affected by the number of millable stalks in the previous crop and the number of underground buds that remain on the stool. SMH caused a significant ($p < 0.05$) decrease in the number of buds ha^{-1} in the second RC. The genotype effect was significant ($p < 0.001$) in both RCs, while the GT interaction was not significant.

Treatment effects were significant ($p < 0.05$) for April and May evaluations for both RCs, but not for the PC (Table 4). There were also significant ($p < 0.01$) genotype effects for all the seedling counts. Significant ($p < 0.05$) GT interactions were found for both RCs with respect to the seedling counts in April; however, GT interactions were not significant for the seedling counts in May.

There tended to be a positive correlation between the UBB and number of seedlings in RCs (Table 5). Positive correlations across all the 40 subplots were significant ($p < 0.05$), with the highest correlation ($r = 0.8453$) occurring in May for the second RC. Under the SMH, the correlation was significant ($p < 0.05$) with the seedling counts in May for the first RC and was significant with the seedling counts in April and May for the second RC. With MH, a significant correlation ($r = 0.7970$) between the UBB and number of seedlings was observed in May in the second RC. From April to May in the second RC, there was a tendency to increase for MH.

3.4. Plant Height and Height Uniformity at Grand Growth and Maturing Stages

The data presented in Table 6 showed that SMH had significant ($p < 0.05$) adverse effects on plant height for most measurement dates. There were highly significant ($p < 0.001$) genotype effects for all the measurement dates during the grand growth period and maturing stage. However, plant height was largely unaffected by the GT interaction. SMH also caused a significant ($p < 0.05$) reduction in height uniformity compared to MH. The genotype effect was also significant for all measurement dates. Significant GT interactions were observed at the maturing stage of both RCs, and for the June 2017 measurement at the grand growth stage of the first RC.

3.5. Cane Yield and Its Components

The PC was untreated, and therefore, as expected, no significant treatment or GT interaction effects were found for the sugarcane yield and millable stalks; the only significant effect ($p < 0.001$) was found for genotype (Table 7). Cane yield and millable stalks were significantly ($p < 0.05$) lower in the SMH treatments compared to the MH in one or both RCs. The GT interaction was not significant for cane yield in either RC, but it was significant for millable stalks in the second RC.

Plant height was significantly reduced by the SMH in the second RC, but not in the first RC. Stalk diameter, however, was greater in the SMH than the MH, and the difference was significant in the second RC. Purity was significantly ($p < 0.05$) lower in the SMH in both RCs. The genotype effect was significant for all the yield-related measured traits. The GT interaction was not significant for cane yield and most of the yield components for either RC. Significant GT interaction was observed merely for the number of millable stalks in the second RC. The treatment effect was not significant on the traits with respect to single stalk weight, fiber content, and sucrose content.

Table 2. Summary of statistical analyses of stool damage and gaps in MH and SMH in two ratoon crops (RCs), and mean square for treatment, genotype, genotype × treatment interaction (GT), and experimental error.

Crop	Treatment		Mean Square			
	MH	SMH	Treatment	Genotype	GT	Error
			Stool damage (%)			
First RC	5.22	36.88	10,024.20 ***	89.60 *	93.50 *	28.30
Second RC	9.12	74.02	42,118.80 ***	92.10 *	134.10 **	30.90
			Gaps (m ha^{-1})			
First RC	118.49	463.54	1,190,609 *	362,506 (ns)	226,381 (ns)	158,889
Second RC	445.30	1070.30	3,906,250 *	2,417,772 ***	1,096,429 **	193,244

ns, *, **, and *** refer to no statistical significance, and statistical significance at $p < 0.05$, 0.01, and 0.001, respectively.

Table 3. Summary of statistical analyses of buds per stool and 1000 buds per ha in MH and SMH in two ratoon crops (RCs), and mean square for treatment, genotype, genotype × treatment interaction (GT), and experimental error.

Crop	Treatment		Mean Square			
	MH	SMH	Treatment	Genotype	GT	Error
			Buds per stool			
First RC	18.99	17.33	27.81 (ns)	8.98 (ns)	17.73 (ns)	15.45
Second RC	18.08	17.18	8.20 (ns)	25.49 **	3.78 (ns)	5.29
			1000 buds ha^{-1}			
First RC	1103	1124	4410 (ns)	156,430 ***	5205 (ns)	9024
Second RC	1161	1086.30	55,840 *	365,136 ***	6980 (ns)	5937

ns, *, **, and *** refer to no statistical significance, and statistical significance at $p < 0.05$, 0.01, and 0.001, respectively.

Table 4. Summary of statistical analyses of seedlings in April and May in MH and SMH in a plant and two ratoon crops (RCs), and mean square for treatment, genotype, genotype × treatment interaction (GT), and experimental error.

Crop	Treatment		Mean Square			
	MH	SMH	Treatment	Genotype	GT	Error
Seedlings in April (1000 seedlings ha^{-1})						
Plant crop (PC)	63.96	58.82	264.30 (ns)	572.20 ***	73.54 (ns)	74.96
First RC	80.71	72.52	670.11 *	3512.84 ***	81.69 *	28.16
Second RC	69.89	39.32	9341.28 *	1294.24 ***	356.98 **	54.14
Seedlings in May (1000 seedlings ha^{-1})						
PC	102.64	100.30	54.90 (ns)	2818.30 ***	441.31 (ns)	221.62
First RC	110.15	98.99	1244.23 *	4605.70 ***	277.33 (ns)	152.94
Second RC	124.19	106.55	3113.46 *	9297.23 ***	232.66 (ns)	157.27

ns, *, **, and *** refer to no statistical significance, and statistical significance at $p < 0.05$, 0.01, and 0.001, respectively.

Table 5. Pearson correlations of underground bud bank and seedlings in two ratoon crops (RCs), for all subplots, $n = 40$; for MH or SMH treatment, $n = 20$.

Crop	Month of Seedlings Count	Correlation		
		All Subplots	MH	SMH
First RC	April 2017	0.3816 *	0.3960 (ns)	0.4143 (ns)
	May 2017	0.3937 *	0.3934 (ns)	0.4677 *
Second RC	April 2018	0.4930 **	0.3907 (ns)	0.6699 **
	May 2018	0.8453 ***	0.7970 ***	0.8743 ***

ns, *, **, and *** refer to no significant correlation, and significant correlations at $p < 0.05$, 0.01, and 0.001, respectively.

Table 6. Summary of statistical analyses of plant height and height uniformity in MH and SMH in two ratoon crops (RCs), and mean square for treatment, genotype, genotype × treatment interaction (GT), and experimental error.

Crop	Date	Treatment		Mean Square			
		MH	SMH	Treatment	Genotype	GT	Error
				Plant height (cm)			
First RC	30 June 2017	95.90	81.64	2033.48 *	3981.39 ***	57.92 (ns)	61.54
	15 November 2017	295.70	287.72	637.60 (ns)	16,824.60 ***	78.60 (ns)	86.90
Second RC	24 May 2018	26.79	20.17	437.91 ***	154.00 ***	2.87 (ns)	5.23
	20 June 2018	69.34	48.86	4194.3 ***	1393.26 ***	61.73 (ns)	52.47
	25 July 2018	119.51	98.02	4621.21 **	3553.72 ***	518.02 ***	58.28
	30 Nov 2018	264.91	240.36	6027 **	18,408.80 ***	109.90 (ns)	210.9
				Height uniformity			
First RC	30 June 2017	7.81	5.27	64.34 **	34.60 ***	15.75 *	4.34
	15 November 2017	19.54	16.93	68.00 *	373.81 ***	199.89 ***	22.06
Second RC	24 May 2018	4.93	3.77	13.47 *	4.35 **	1.09 (ns)	0.68
	20 June 2018	7.91	5.04	81.97 **	8.99 ***	2.40 (ns)	1.16
	25 July 2018	7.16	5.73	20.56 *	29.77 ***	1.23 (ns)	2.98
	30 November 2018	21.27	13.18	653.63 *	159.17 **	69.29 *	13.16

ns, *, **, and *** refer to no statistical significance, and statistical significance at $p < 0.05$, 0.01, and 0.001, respectively.

Table 7. Summary of statistical analyses of cane yield, millable stalks, plant height, stalk diameter, single stalk weight, fiber, purity, sucrose content in MH and SMH in a plant crop (PC) and two ratoon crops (RCs), and mean square for treatment, genotype, genotype × treatment interaction (GT), and experimental error.

Crop	Treatment		Mean Square			
	MH	SMH	Treatment	Genotype	GT	Error
			Cane yield (t ha^{-1})			
PC	106.36	103.26	95.57 (ns)	2228.69 ***	167.71 (ns)	143.42
First RC	108.49	102.15	402.43 (ns)	4052.10 ***	42.73 (ns)	44.09
Second RC	96.17	81.12	2265.93 *	5574.91 ***	30.47 (ns)	82.18
			Millable stalks (×1000) ha^{-1}			
First RC	60.76	61.90	13.12 (ns)	375.95 ***	15.63 (ns)	28.48
Second RC	65.57	61.07	203.09 *	350.53 ***	29.91 (ns)	20.41
First RC	69.53	61.54	639.12 **	1038.24 ***	90.21 *	25.28
			Plant height (cm)			
First RC	295.70	287.72	637.60 (ns)	16824.60 ***	78.60 (ns)	86.90
Second RC	264.91	240.36	6027 **	18408.80 ***	109.90 (ns)	210.90
			Stalk diameter (cm)			
First RC	2.77	2.91	0.20 (ns)	0.13 ***	0.003 (ns)	0.01
Second RC	2.768	2.94	0.299 *	0.097 **	0.01 (ns)	0.02
			Single stalk weight (kg)			
First RC	1.77	1.71	0.05 (ns)	0.43 ***	0.02 (ns)	0.05
Second RC	1.35	1.29	0.04 (ns)	0.25 ***	0.01 (ns)	0.03
			Fiber (%)			
First RC	13.32	13.70	1.43 (ns)	4.77 ***	0.27 (ns)	0.43
Second RC	13.27	13.61	1.16 (ns)	4.83 ***	0.74 (ns)	0.37
			Purity (%)			
First RC	86.97	86.23	5.44 *	6.60 ***	0.49 (ns)	0.53
Second RC	85.62	84.21	20.09 *	18.22 ***	0.74 (ns)	2.21
			Sucrose content (%)			
First RC	15.21	15.42	0.43 (ns)	1.25 ***	0.22 (ns)	0.17
Second RC	13.79	13.39	1.56 (ns)	2.91 ***	0.15 (ns)	0.25

ns, *, **, and *** refer to no statistical significance, and statistical significance at $p < 0.05$, 0.01, and 0.001, respectively.

4. Discussion

As compared with MH, the SMH significantly increased the stool damage for the consequent RCs and caused significantly greater SC. Under the condition of more gaps and greater SC, the increased stool damage led to more gaps in the RCs, and the greater SC restricted the germination of the UBB, and early crop growth in sugarcane. The SMH had adverse effects on early growth, cane yield, and most of the yield components. Currently, most sugarcane breeding trials are still conducted under MH in China. The important findings in this study related to significant GT interaction for stool damage, gaps, and seedlings in an earlier period (April), and height uniformity at the maturing stage and final millable stalks suggested that the genotype selection trial done under the MH system may not suit the production system with SMH well. As compared with the number of buds for establishing the plant cane, buds in the UBB were more than enough for establishing an RC. More focus for better RC establishment should be on improving the soil condition for germination of the UBB.

4.1. Soil Compaction, Stool Damage, and Gaps

Sugarcane is a perennial C4 grass, and after the PC is harvested, the underground buds regenerate the RCs. RCs are extremely important in the economics of sugarcane production, and the proper management of RC is fundamental to sustainable production. In Australia, Cuba, Philippines, and Mauritius, six to eight RCs are commonly harvested from a single sugarcane planting [30]. However, as the number of RCs increases, gaps increase, which tends to reduce sugarcane yield and, ultimately, necessitates replanting.

In this study, we found that the SMH tended to increase SC sharply compared to the MH. The subplots subjected to SMH showed significantly greater SC at all the soil depths from 5 to 30 cm (Figure 2). As the sugarcane planting depth was approximately 10 cm, the vertical distribution of the UBB in RCs was within the depth of 0–10 cm, where the SC would be greater due to the SMH. An increase in SC would physically constrain bud sprouting and restrict water absorbance by the buds, and SC is a major limitation to root elongation and root dry weight [31]. On sandy loam, the SC at 10 cm depth was 1.98 MPa in MH plots and increased to 2.95 MPa in the plots harvested by a combine harvester (CASE7000) [32]. In this study, at the same depth of 10 cm, the SC was 1.70 and 2.10 MPa for the SMH in the first RC and second RC, respectively. Even with a much lower SC by SMH than the combine harvester, root elongation rate ceased at root penetration resistances of about 1.0 MPa [33]. The SC was close to or greater than 1.0 MPa in the MH plots 10 cm or below in this study (Figure 2). This is probably why farmers tend to relieve the ratoon stools after the previous crop is manually harvested in Yunnan. In this study, the tractor rolled directly on the row for the specific purpose of maximizing potential SC and crop damage. In sugarcane production, reducing traffic over the row mitigates the adverse effects of compaction on RCs in the mechanical harvesting [14].

Significant genotype differences were found under mechanical harvesting conducted by a combine harvester [10], which implied the possibility of selecting genotype for less stool damage under the harvesting conditions. In this study, significant genotype differences for stool damage in two RCs and for gaps in the second RC suggested the possibility for selecting genotype for less stool damage and gaps under the SMH. However, the significant GT interaction for stool damage in both RCs and for gaps in the second RC (Table 2) suggested that genotypes selected in a manual harvesting system might not be suited for SMH with respect to stool damage and gaps.

4.2. Underground Bud Banks and Sprouting

The sprouting of the UBB is the initial stage in establishing an RC. The UBB of sugarcane consisted of the number of remaining stools in the soil and the number of buds on the underground part of stools (buds per stool). In this study, the numbers of buds per stool were lower with the SMH in two RCs, and between the first and second RCs, the buds per stool tended to decline regardless of the harvesting method. There was no significant treatment effect on the number of buds (×1000) ha^{-1} in the first

RC because no treatment applied to the PC, i.e., the amount of remaining stalks in soil had not been impacted by harvesting treatment. The significant difference in the second RC was mainly due to the significant effects on millable stalks in the first RC. With MH, the UBB increased by 58,000 buds ha^{-1} from the first to the second RC, but it decreased by 37,700 buds ha^{-1} with the SMH. The planting density for the PC was approximately 120,000 buds ha^{-1}, and the UBB ranged from 1.09 million to 1.16 million in the two RCs (Table 3). This was nearly nine times the buds used for establishing the PC. To maintain a suitable number of seedlings for the RC, it is more important to relieve SC for promoting the germination of the buds in UBB. A significant genotype effect was observed in the second RC for buds per stool (Table 3), and a significant genotype effect was observed in two RCs for UBB. Lack of significant GT interaction for bud per stool and UBB suggested the genotype with higher buds per stool or UBB in MH may perform relatively high in SMH.

The seedling counts, a trait describing the sprouting of RC, were significantly impacted by treatment and genotype (Table 4). The SMH significantly increased SC (Figure 2), stool damage, and gaps compared to the MH (Table 2). A significantly negative correlation (r^2 = 0.91) between SC and ratoon sprouting [32] indicates that increased SC poses a great negative impact on the sprouting in RC. In addition, a lower saturated hydraulic conductivity in compacted soil [14] may have affected the sprouting of the dormant underground buds. As compared to MH, the number of seedlings was reduced by 5537 seedlings ha^{-1} in the mechanical harvesting conducted by combine harvester [34]. Seedling counts in April and May were significantly lower in the SMH and significantly affected by genotype. An interesting finding was that significant GT interaction for seedling counts was observed in April, and it became not significant in May for both RCs. This is similar to the GT interaction for ratoon sprouting, which was in a declining trend from one month to three months after the harvest of the previous crop [26]. In sugarcane, the number of seedlings consisted of the shoots from the UBB and the tillers generated later. Typically, in sugarcane production, late tillers are prone to senesce and contribute less to the final amount of millable stalks than early-produced tillers [35]. The impact of GT interaction on tillers was significant for the earlier observation (seedling counts in April) after the harvest of the previous crop, and it was not significant for the later observation (seedling counts in May). The observation on earlier sprouting (April) reflected the interaction better than the observation made later (May).

Larger numbers in the UBB generate more seedlings for the RC. Correlations across all subplots were significant for all seedlings counts in April and May for two RCs (Table 5). In most cases, the trait correlations in April were lower than those in May because the late sprouting generated seedlings as well. As compared with the MH, the correlations were much higher in the SMH. Although the bud amount of UBB was more than adequate for the establishment of the RC in the SMH, the SC adversely affected the spouting, which may have led to a lower emergence rate. Therefore, the bud amount is more important, and the correlations were much higher under SMH.

4.3. Plant Height and Height Uniformity

Stalk elongation is a sensitive trait reflecting the environmental stress in sugarcane; a decrease in plant height under water stress conditions is used as a parameter for evaluating drought tolerance in sugarcane [36]. Regardless of water or nutrient availability, water and nutrient uptake by plant roots are impacted by SC, which resulted in a significantly reduced plant height for most of the measurements (Table 6). As compared with MH, the plant height in the combine harvesting treatment decreased by 6.21% and 6.84% during June and July, respectively, and no obvious differences were observed at the maturing stage during November and December [34]. In this study, the plant height in SMH decreased by 14.87%–29.54% from May to July, and the decrease was merely 2.70% and 9.27% in November for first RC and second RC, respectively. This might mean that SMH impacts more on the early growth than final height. The plant height was mostly impacted by the treatment and genotype; merely one measurement at the grand growth stage was significantly affected by the interaction in this study.

The height uniformity was considered as a trait presenting individual uniformity among the whole crop with respect to plant height and was used in the evaluation of 11 maize cultivars developed from 1950 to 2010 for yield stability [25]. Sugarcane stalk is the part that accumulates sugar and the right part to be harvested. Higher uniformity in plant height indicates relatively higher uniformity in tillers growth and contributes to higher harvest quality. Under SMH, more gaps cause uneven competition among stools, and the increased SC may also stress more on the tiller plants whose roots developed later and shorter than the main shoots. Moreover, the soil was compacted more in topsoil where the roots of later tillers may distribute in. In the SMH, the height uniformities across all measurements that started from grand growth to maturing were significantly lower than the MH, and significant GT interaction was observed at the maturing stage in two RCs (Table 6), which suggested that selecting genotypes under MH for SMH could be difficult for height uniformity.

4.4. Cane Yield and Its Components Responses to Small-Scale Mechanical Harvest

Cane yield tends to decline with an increased number of RCs and declines faster in poor soils [37]. As compared with favorable growth conditions in irrigated fields, rain-fed fields showed sharper declines in cane yield (6–7 t ha^{-1} for each crop) [38]. In this study, as compared with the MH treatment, more compacted soil in SMH could be a less favorable growth condition. Cane yield increased slightly from the plant to the first RC and decreased by 11.36% from the first to second RC with the MH, while all decline trends were observed from the plant to the first and second RCs with the SMH, which particularly decreased 20.59% from the first to the second RC. The SMH had an adverse effect on the cane yield in two RCs, and a significant effect was found on the second RC. No significant GT interaction for the final cane yield in two RCs was in accordance with the findings by Jackson et al. [26]. However, the previous study [26] aimed at determining the GT interaction for final cane yield under combine harvesting in dry conditions and wet conditions.

The stalk diameter was significantly larger with SMH in the second RC (Table 7), which was possibly caused by less competition for light under more gaps conditions, and plants beside the gaps received more light, particularly when the gaps increased from 463 m ha^{-1} in the first RC to 1070.30 m ha^{-1} in the second RC (Table 2). Purity was significantly lower with SMH in two RCs, which may be caused by poorer height uniformity; shorter plants may not reach maturing and resulted in a dilution of the sucrose content [39] and purity. The sugar content was not significantly affected by the treatment because sugar content is a trait that varies little across environments [37].

In this study, genotypes had significant effects on cane yield and yield components in the plant and two RCs. The GT interaction had a significant effect on merely one trait, i.e., millable stalks in the second RC. However, millable stalk is an essential component for cane yield and contributes directly to the UBB. The existing significant GT interaction for millable stalks suggested that conducting genotype selection trials under MH may not be suited for SMH. In addition, under MH conditions, stool damage and gaps of genotype may perform differently from those under SMH.

5. Conclusions

As compared with MH, the treatment with SMH significantly increased SC and caused significantly greater gaps and stool damage, which negatively impacted the sprouting of the buds in underground bud bank (UBB) and plant growth, and therefore, decreased the final cane yield. Even small-scale harvesting equipment should avoid rolling over the stool and bed directly for minimizing the damage to the RC stool and soil compaction. Significant differences among genotypes were detected for all traits in this study, and particularly, the significant differences for stool damages suggested the possibility for selecting genotypes for SMH. Moreover, the existing significant GT interactions for stool damage, gaps, early seedling counts, millable stalks, and height uniformity suggested that conducting sugarcane genotype selection trials under traditional MH may not be suitable for sugarcane production under SMH. The UBB of RC for sprouting was nearly nine times the buds used for establishing PC, and therefore, relieving the compacted soil for better sprouting of the UBB may help establish better

RC. In addition, further understanding of the constitution and regulation of UBB may help prolong ratoon years.

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