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BREEDING AND GENETICS

Accuracy, Precision, and Harvesting Efficiency of a Cotton Plot Picker Installed with an Automatic Weighing System in a Cotton Breeding Program

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ABSTRACT

Many cotton breeding programs in the U.S. have installed an automatic weighing system in a cotton plot picker to increase operating efficiency in recent years. However, no experimental data are available to document the reliability of such a system. The objective of this study was to evaluate the accuracy, precision, and harvesting efficiency of a two-row cotton plot picker installed with an automatic weighing system with two scales based on results from replicated field tests from 2013 to 2016. Three tests each year, each containing 32 genotypes were arranged in a randomized complete block design in two-row plots by 10 m in length. The 2013 to 2015 results showed a highly significant positive correlation in seedcotton weights between the two rows of the same plot for each genotype harvested and weighed by the two scales in the picker, indicating that the two scales are consistent and reliable. In three tests in 2016, one row of each two-row plot was harvested by the picker, and seedcotton weight was compared with another row harvested by hand. A highly significant positive correlation was detected between the two harvesting methods that had similar coefficients of variation (16.14% for hand harvest vs. 16.90% for mechanical harvest). The two-row plot picker harvested a total of 368 single-row plots (10-m long) in six hours daily, whereas hand harvest by one person averaged two plots in four hours. An average of 417 kg ha^{-1} was lost due to the mechanical harvest.

In cotton breeding programs, yield is one of the most important breeding objectives. Each year, seedcotton from thousands of small field plots of 10 to 15 m (30-50 ft) in length is separately harvested and weighed to estimate yields for experimental lines and commercial cultivars. This harvest was done by hand in the U.S. before the 1970s, and is a common practice in cotton breeding programs in other countries. Since the 1970s until the mid-2000s, mechanical harvesting of seedcotton from small plots has become a reality in cotton breeding in the U.S. A one- or two-row cotton picker with a crew of three or five people was modified to catch seedcotton from each plot in a labeled bag or sack; the filled sack was removed and weighed by two to three people on the ground. The weighed seedcotton was emptied into a cotton wagon or trailer. The emptied bags were cleaned, labeled, and arranged for the cotton picker based on the next harvest order. Therefore, the entire operation was labor intensive and time-consuming, in addition to posing environmental, health, and safety hazards to the crew such as dust and danger from working on the back of the picker.

To tackle these issues, an automatic weighing system can be installed in a cotton plot picker to determine and electronically record seedcotton weight in each plot (Eaton, 2003; Marsh, 2006). In recent years, many cotton breeding programs in the U.S. including those from cotton seed companies have installed such a system to increase the operating efficiency and ensure the safety of workers in experimental farms (e.g., Zhang et al., 2016), and cuts the manpower need to one tractor driver for the entire operation. Breeding program tests compared plot seedcotton weight by the automatic weighing system followed by manual weighing on a scale, which gave breeders confidence in the reliability of the system; however, no experimental data to validate the automatic weighing system from a cotton breeding program has been published.

In the New Mexico Cotton Breeding Program, a two-row cotton plot picker was installed with an automatic weighing system (Cotton-Picking 920i, Master Scales, Greenwood, MS) by the Southwestern Cotton Ginning Research Laboratory, USDA-ARS, in 2010. The objective of this study was to evaluate the automatic weighing system for its accuracy, precision, and efficiency.

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MATERIALS AND METHODS

From 2013 to 2016, relevant experimental data from three replicated field tests (National Variety Test [NV], High Quality Test [HQ], and Regional Breeders Testing Network [RB]) were collected each year. Each test comprised 32 genotypes (commercial cultivars and advanced breeding lines) with four replications, except for trial 16NV with three replications. The plot size was two-rows × 10 to 11 m with a row-spacing of 0.92 m. Seeds were planted in early May each year at a seeding rate of 10 seed m^{-1} using a four-row plot planter. Crop management followed local recommendations except that no insecticides were applied. At crop maturity, 20 open bolls (with one boll per plant in the middle of the plant) were hand harvested from each plot and ginned using a 20-saw laboratory gin for measurements of boll weight and lint percentage. Each plot was then harvested by a two-row Case IH 1822 plot picker that was installed with an automatic weighing and computer system (Cotton-Picking 920i) by Master Scales in 2010. In this system, seedcotton from each of the two rows for the same genotype was separately harvested and electronically weighed and recorded. The number of hours used in harvesting the plots was recorded each day.

To evaluate the accuracy and precision of the automatic weighing system, one of the two rows in each plot was hand harvested before mechanical picking in the three replicated field tests in 2016. A cotton sack labeled with the plot identification was placed at the first row of each plot. Hand harvesting was done by a crew of eight students for 4 hr in the afternoon each day, and seedcotton in the sacks was taken to a shop and weighed by two students the following morning. The students were trained to minimize the trash when hand harvesting seedcotton, and the process was monitored to ensure a similar level of cleanness in seedcotton. The number of plots harvested and the number of working hours was recorded each day. Based on an analysis of variance for each test, the mean squares for experimental errors between the two harvest methods were compared for each test using an F-test.

Seedcotton weight in each of the two rows in each plot was used to perform a simple regression analysis for each field test in 2013 to 2015 to determine if the two rows of the two-row plots produced a similar yield. In 2016, the seedcotton weight harvested by hand and the picker in each plot were converted to seedcotton yield (SCY, kg ha^{-1}) and lint yield (LY, kg ha^{-1} = SCY × lint percentage) and used to perform an analysis of variance for each of the three replicated tests (i.e., 16HQ, 16RB, and 16NV). LY estimated by hand harvest and mechanical harvest in each plot also was used to perform a simple regression analysis on a plot or genotype basis between the two harvest methods.

To evaluate consistency in selection between the two harvesting methods, the genotypic means for 32 genotypes in each of the three field tests in 2016 were ranked from the highest (1) to the lowest (32). Whereas the rankings between the two harvesting methods were used to perform a simple correlation analysis, the absolute ranking difference between the two harvest methods for each genotype was used to perform a paired *t*-test.

RESULTS

Correlation between Two Scales in the Automatic Weighing System. The two-row cotton plot picker in the New Mexico Cotton Breeding Program installed with an automatic weighing and computer system was used to harvest and weigh each of the two rows for each plot (genotype) in three tests in 2013. The coefficients of correlation in seedcotton weights between the two rows were 0.7832, 0.7933, and 0.8205 on a plot basis (n = 128, $p < 0.0001$). The results showed that the seedcotton weights were highly correlated between the two rows (Fig. 1a, 1b, and 1c).

In 2014, as Fig. 2a, 2b, and 2c show, the coefficients of correlation in seedcotton weight were reduced to 0.6476, 0.5578, and 0.6526 for the three tests, though the correlation between the two rows of each plot in each test was still highly significant (n = 128, $p < 0.0001$). In 2015, higher correlations in seedcotton weight between the two rows of each plot were observed for trial 15NV (r = 0.9177, $p < 0.0001$), 15RB (r = 0.9362, $p < 0.0001$), and 15HQ (r = 0.9103, $p < 0.0001$), and results are shown in Fig. 3a, 3b, and 3c. The exact reasons for the lower correlations between the two rows of the two-row plots in 2014 are unknown, but uneven row lengths between the two rows of the same plots or variable missing plants could have played a role. However, the results from the 3 yrs consistently show that similar seedcotton yields were produced from two rows of the two-row plots based on the highly significant correlations between two rows in seedcotton weight.

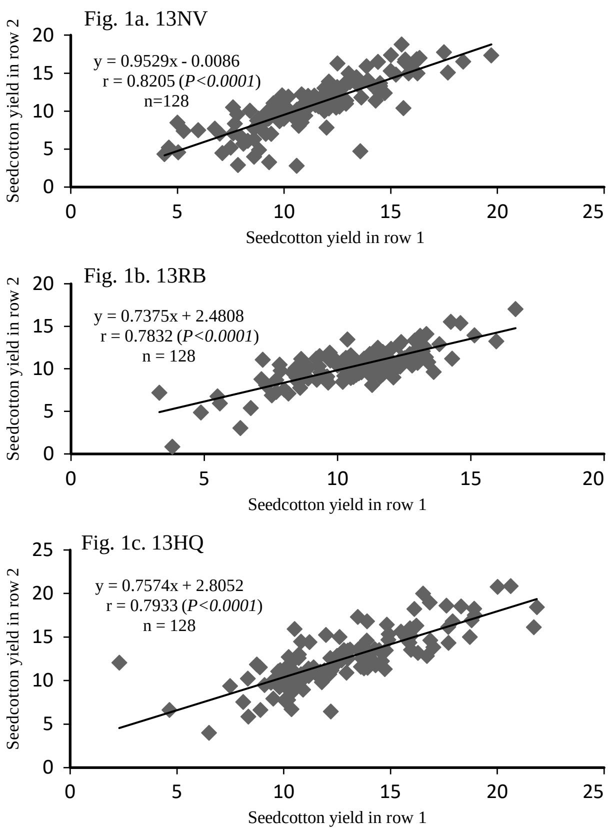
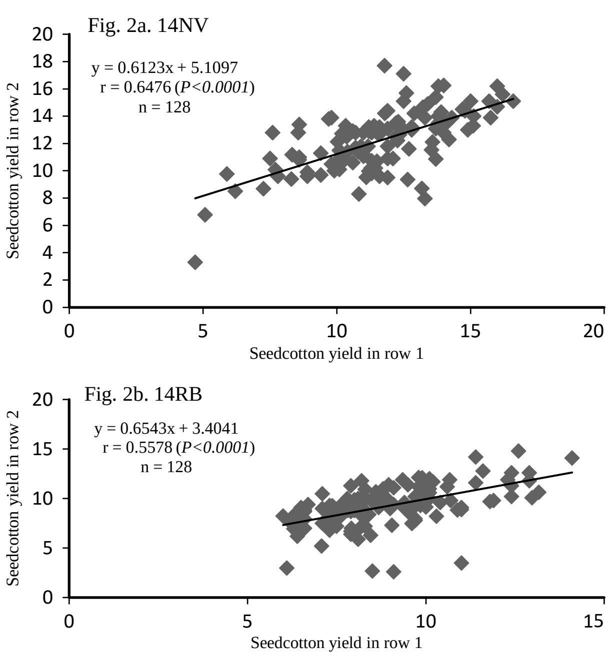


Figure 1. Correlation (based on plots) in seedcotton weight between two rows of the same plot harvested by a cotton plot picker in three replicated tests (each with a randomized complete block design, two-row plots of 10 m in length, and four replications) in 2013. 1a. 32 genotypes tested in trial 13NV. 1b. 32 genotypes tested in trial 13RB. 1c. 32 genotypes tested in trial 13HQ.



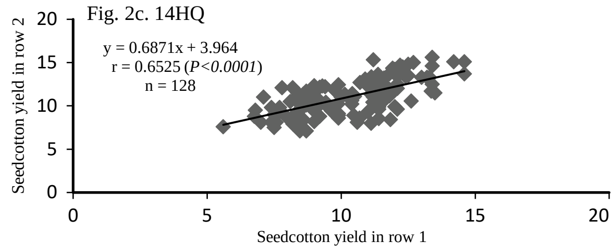


Fig. 2. Correlation (based on plots) in seedcotton weight between two rows of the same plot harvested by a cotton plot picker in three replicated tests (each with a randomized complete block design, two-row plots of 10 m in length, and four replications) in 2014. 2a. 32 genotypes tested in trial 14NV. 2b. 32 genotypes tested in trial 14RB. 2c. 32 genotypes tested in trial 14HQ.

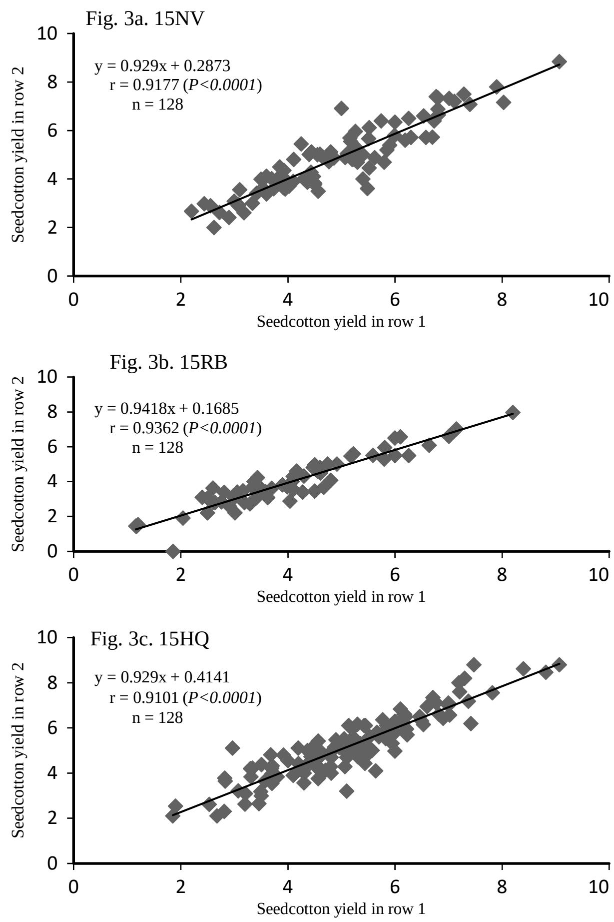


Fig. 3. Correlation (based on plots) in seedcotton weight between two rows of the same plot harvested by a cotton plot picker in three replicated tests (each with a randomized complete block design, two-row plots of 10 m in length, and four replications) in 2015. 3a. 32 genotypes tested in trial 15NV. 2b. 32 genotypes tested in trial 15RB. 3c. 32 genotypes tested in trial 15HQ .

Correlation between Hand Harvest and Mechanical Harvest with the Automatic Weighing System. After consistency from the two scales was established based on the close correlation in seedcotton weights between the two scales based on the results from 2013 to 2015, correlation between cotton yields harvested by two harvesting systems (hand and picker) in 2016 was analyzed (Fig. 4a, 4b, and 4c). The coefficients of correlation were 0.7633 for 16NV, 0.6740 for 16RB, and 0.5944 for 16HQ, and were highly significant (p < 0.0001). The consistent results among the three tests indicate that the mechanically harvested cotton yield is overall consistent with that from hand harvest.

Precision. The precision from the automatic weighing system in the picker was further evaluated from an analysis of variance (Table 1). As the LY harvested by hand was overall higher than that harvested by the cotton picker, the mean square in each test for the experimental error was also higher. The mean square of the experimental error from hand harvest in only one test (16HQ) was significantly higher than that from the picker with the automatic weighing system, as the F value (1.66) between the two error mean squares was highly significant ($F_{0.01}$ = 1.63). However, the coefficients of variation (CV) for the three tests ranged from 14.00 to 17.66% with an average of 16.14% for hand harvest, as compared to 16.08 to 18.48% with an average of 16.90% for the mechanical harvest with the automatic weighing system. Therefore, the cotton plot picker with the automatic weighing system produced similar precision to hand picking.

Accuracy. The accuracy of the automatic weighing system was further evaluated by comparing LY with that from hand harvest (Table 2). The overall LY for the three tests from hand picking ranged from 2,290 to 2,503 kg ha^{-1} with an average of 2,389 kg ha^{-1}, as compared to 1,885 to 2,085 kg ha^{-1} for mechanical picking with an average of 1,972 kg ha^{-1} for the three tests in 2016. The plot picker had an average of yield loss of 417 kg ha^{-1} (range 345-487 kg ha^{-1}), amounting to 17.46% of the total LY harvested by hand. Some seedcotton was left unharvested by the cotton picker.

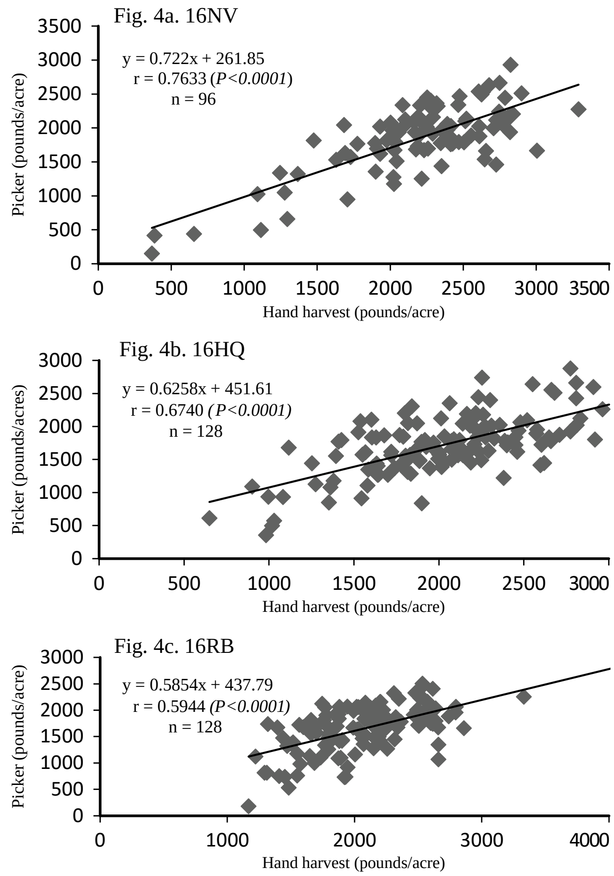


Fig. 4. Correlation (based on plots) in lint yield between hand harvest (one row) and mechanical harvest (another) of the same plot in three replicated tests (each with a randomized complete block design, two-row plots of 10 m in length, and four replications) in 2016. 4a. 32 genotypes tested in trial 16NV. 4b. 32 genotypes tested in trial 16RB. 4c. 32 genotypes tested in trial 16HQ.

Table 2. Overall mean lint yields harvested by hand and a plot cotton picker in three replicated field tests, Las Crcues, NM, 2016

Test	Hand	Picker	Difference
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
16NV	2503	2084	419
16RB	2373	1885	487
16HQ	2290	1945	345
Mean	2389	1972	417

Table 1. Mean squares and coefficient of variation (CV) for lint yield harvested by hand and a picker, based on an analysis of variance for each of the three field tests conducted in Las Cruces, NM, 2016

Source of variation	16NV		16RB		16HQ	
	Hand	Picker	Hand	Picker	Hand	Picker
Rep	426866	244540	160836	28614	579367	113225
Genotype	652920	585903	413067	487672	553428	613514
Error	95555	89062	122978	94361	127281	76716
CV (%)	14.00	16.08	16.76	18.48	17.66	16.15

Selection for High-Yielding Genotypes by Ranking. Similar to the results based on plot weights in LY, the coefficients of correlation in LY between hand picking and mechanical picking based on genotypes were highly significant ($r = 0.8608$ for 16NV, 0.7884 for 16RB, and 0.8425 for 16HQ; $r_{0.01} = 0.4629$, $n = 32$). Because various selection pressures are used to select top breeding lines to advance to the next stage of testing in a cotton breeding program, the reliability of the automatic weighing system in measuring plot yields was further evaluated based on rankings from the average yield for each genotype tested in 2016. The results are shown in Fig. 5a, 5b, and 5c.

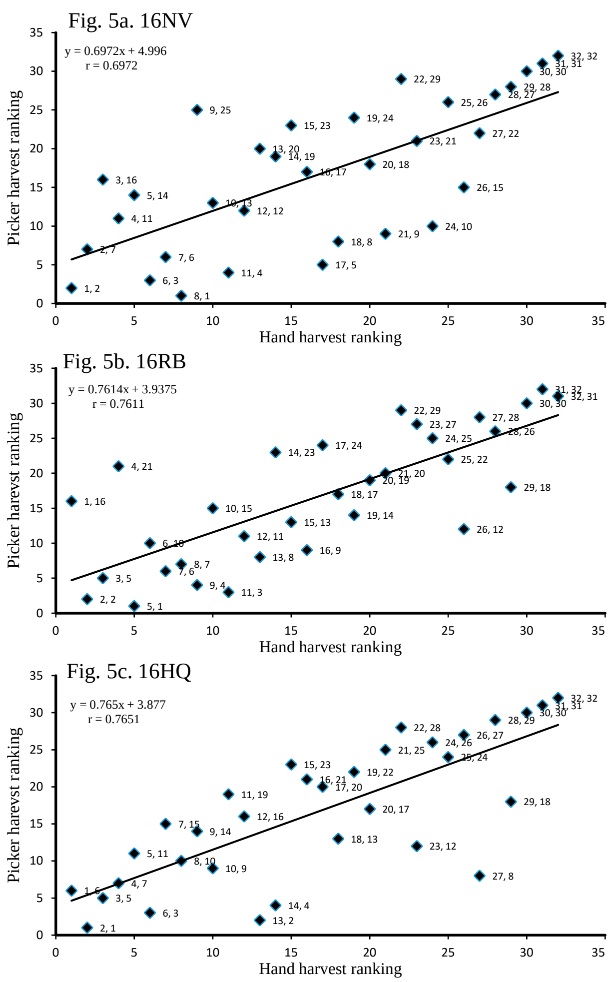


Fig. 5. Correlation (based on genotypes) in ranking based on seedcotton weight between hand harvest (one row) and mechanical harvest (another) of the same plot in three replicated tests (each with a randomized complete block design, two-row plots of 10 m in length, and four replications) in 2016. 4a. 32 genotypes tested in trial 16NV. 4b. 32 genotypes tested in trial 16RB. 4c. 32 genotypes tested in trial 16HQ.

In 16NV, 12 lines (37.5%) had a ranking difference within 0 to 2 between the two picking methods, and six genotypes had a ranking difference between 2 and 5, whereas 14 genotypes had a ranking difference of 5 or above (5-16). A *t*-test for the paired comparison showed that the rankings were significantly different between the two harvesting methods ($t = 4.26$; $t_{0.01} = 2.45$, $n = 32$). Similar results were obtained from trials 16RB and 16HQ. In 16RB, 15 lines (46.9%) had a ranking difference within 0 to 2, and eight genotypes had a ranking difference between 2 and 5, whereas nine genotypes had a ranking difference of 5 or above (5-17). Overall, the rankings were also significantly different between the two harvesting methods ($t = 3.98$; $t_{0.01} = 2.45$, $n = 32$). In 16HQ, 11 lines (34.4%) had a ranking difference within 0 and 2, and 11 genotypes differed in ranking between 2 and 5, whereas 10 genotypes had a ranking difference of 5 or above (5-19). Across the test, the ranking difference was significantly different between the two harvesting methods ($t = 4.18$; $t_{0.01} = 2.45$, $n = 32$). Therefore, an overall ranking difference between the two picking methods existed in each of the three replicated field tests, although an overall congruence in ranking between the two picking methods was observed based on the significant coefficients of correlation, ranging from 0.6972 to 0.7651 ($r_{0.01} = 0.4629$, $n = 32$) (Fig. 5a, 5b, and 5c).

Of the 32 genotypes tested in each test, the top five yielders as determined by the picker were also among the top 25th percentile (top eight) genotypes identified by hand picking, accounting for 62.5% of the top eight genotypes selected by hand picking. Similar results were noted for the 25th percentile bottom yielding genotypes, as five to six bottom yielders by the picker were also among the eight lowest yielding genotypes (75.1-100%) selected by hand picking. However, the middle portion of genotypes in yields was not congruent between the two harvesting methods, as only 37.5% of the genotypes were in the second 25th percentile (25.1-50%), whereas 45.8% of the genotypes were in the same third 25th percentile (50.1-75%).

In conclusion, the selection for top 25th percentile yielders based on machine picking is overall consistently with hand harvest. However, it should be noted that, only one top genotype was in common between the two harvesting methods in each of the three tests if selection for only top 10% (i.e., three genotypes out of 32 in each test) was conducted.

Therefore, two-thirds of the top three genotypes as determined by hand harvesting could be missed based on the machine picking data alone.

Harvesting Efficiency. In 2016, the field was divided into 23 blocks each with rows 10 m in length and a 2-m alley. Excluding the time for breaks and transportation of the picker and waiting time for dew to dry in the morning, 6 hr were used in the field to mechanically harvest cotton each day. On average, the two-row cotton plot picker made eight passes in harvest, i.e., 16 rows harvested, giving a total of 368 single-row plots or 184 two-row plots (each 10 m in length) harvested and weighed by just one operator (the picker driver) in 1 d (Table 3). As a comparison, eight students harvested 17 single-row plots (10-m long each) in 4 hr each day (Table 3). The higher the cotton yield, the fewer plots can be harvested by hand, as this was the case for the 2016 crop with high productivity. In addition, we noted that trash content, yield loss, and picking efficiency varied from person to person. However, the cotton plot picker should be more consistent among plots in trash content and yield loss, and the number of plots harvested by a cotton plot picker is unlikely dependent on the crop productivity.

Table 3. Harvesting efficiency of a two-row cotton plot picker installed with an automatic weighing and computer system in comparison with hand harvesting

	Picker	Hand
No. single row plots day^{-1}	368	17
No. hours day^{-1}	6	4
No. workers	1	8
Plot length (m)	10	10

SUMMARY AND DISCUSSION

This study represents the first published report to document the accuracy, precision, and harvesting efficiency of a two-row cotton plot picker installed with an automatic weighing system using two high-precision scales. Based on the results from a total of nine replicated field tests (each with 32 genotypes and four replications) from 2013 to 2015, the two scales are consistent and reliable in measuring plot seedcotton weights harvested by the two-row plot picker. The seedcotton weights between the two rows of the same plot (genotype) harvested and weighed by the two scales in the picker were highly significant and positively correlated in each of the nine field tests. Furthermore, seedcotton weights picked mechanically and weighed automatically were also overall highly significant and positively correlated with the seedcotton weights picked by hand in each of the three replicated field tests in 2016. The experimental errors as estimated by coefficients of variation were similar between the two harvesting methods, indicating a similar precision in measuring plot yields. The two-row plot picker is understandably more efficient with more than 180 two-row plots (10-m long each) harvested and weighed in 6 hr.

Although the overall congruence between the two harvesting methods was detected, there was still a practical problem when selections for top yielders are made in breeding. As compared with the hand-picking results, only one-third to one-half of the tested genotypes (based on means from four replications) picked by the plot picker had similar yield rankings (within a ranking difference below 2). The consistency between the two harvesting methods would be even lower for single-row plots with no replications such as a progeny-row test on numerous lines (~1000). Furthermore, approximately 60% (five genotypes) of the lines in the top 25th percentile (eight of 32 genotypes) in this study were congruent between the two harvesting methods. However, if only 10% of the topmost yielders (three lines in each of the three field tests in 2016) were selected based on mechanical picking, only one top line would be selected, as compared with the hand harvesting results.

Several other issues are related to mechanical harvest, but not necessarily related to the automatic weighing system. First, as our results show in this study, a cotton picker leaves a substantial amount of unpicked seedcotton behind depending on varietal characteristics, leading to variable yield loss. A heavy storm during a harvesting season would exacerbate the situation. In our 2016 study, hand picking was performed in a span of one week, which was followed by mechanical picking after a storm. Storm damage resulted in a greater yield loss in some plots than others, depending on the level of varietal storm resistance associated with boll-opening characteristics. This could lead to inconsistent results in yields between the two harvesting methods for some cultivars or breeding lines. To avoid the problem related to cotton genetics, a breeder is advised to mechanically harvest his or her plots once the cotton crop is mature to reduce any seedcotton loss due to a storm.

As with any other field experiments, a good field test should consider the number of replications, randomization, and blocking control. In addition, steps should be taken to increase the precision and reliability associated with mechanical picking and automatic weighing. For example, two-row plots should be preferred over single-row plots if a two-row plot picker is used, as any systematic differences in weighing between the two scales can be evened out. Because the high-precision scales need a minimal weight to provide relatively high precision in weight measurements, expected crop productivity in a breeding program should be taken into consideration when determining the plot size.

Based on our experiences, the scales in the automatic weighing system need to be regularly calibrated to ensure consistency in weighing, and seedcotton dropped off the scales after weighing needs to be monitored and timely removed to avoid its piling up to block the scales. As with other mechanical and electronic equipment, routine maintenance and repair should be performed.

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