Published online September 6, 2018

Hand Planter for the Developing World: Factor Testing and Refinement

Jagmandeep S. Dhillon, P. Omara, E. Nambi, E. Eickhoff, F. Oyebiyi, G. Wehmeyer, A. Fornah, E. N. Ascencio, B. M. Figueiredo, R. Lemings, T. Lynch, J. Ringer, W. Kiner, R. K. Taylor, and W. R. Raun*

Core Ideas

- Developing world maize producers desperately need better planting methods.
- OSU hand planter delivers safety, convenience, and increased maize yields for producers managing highly marginal landscapes.
- Same area of maize planted in the USA (30 million ha) is planted in the developing world on highly marginal slopes.

J.S. Dhillon, P. Omara, E. Nambi, E. Eickhoff, F. Oyebiyi, G. Wehmeyer, A. Fornah, B.M. Figueiredo, R. Lemings, T. Lynch, and W.R. Raun, Plant and Soil Sciences, Oklahoma State Univ. Stillwater, OK 74078; E.N. Ascencio, San Salvador, El Salvador; J. Ringer, Horticulture and Landscape Architecture, Oklahoma State Univ., Stillwater, OK 74078; W. Kiner and R.K. Taylor, Biosystems and Agricultural Engineering, Oklahoma State Univ., Stillwater, OK 74078.

Received 20 Mar. 2018.
Accepted 30 July 2018.
*Corresponding author (bill.raun@okstate.edu).

Agrosyst. Geosci. Environ. 1:180002 (2018)
doi:10.2134/age2018.03.0002

ABSTRACT

Maize (*Zea mays* L.) production in the developing world takes place on marginal landscapes using indigenous planting methods that conflict with modern hybrids, and the chemically treated seeds being used. In 1987, a mechanical planter was imagined that could replace indigenous planting methods used in many developing countries where maize is produced on marginal landscapes. Over two decades, controlled variables were evaluated with the aim of delivering an improved planter capable of singulating maize seed with each planter strike, and that would ensure uniform plant stands. This hand planter, presently termed GreenSeeder was further designed to deliver mid-season fertilizer N via the use of an alternative internal drum. To secure singulation for each planter strike, many seed sizes, planter weights, brush strengths, drum cavity sizes, and operators were evaluated. Results showed that when seed size was large (<3000 seeds kg^{-1}) and the 260-20 internal drum was employed, the ability to singulate with no misses was high. When the 450S internal drum was used, seed sizes that were smaller (>3500 seeds kg^{-1}) had higher singulation and lower misses. An efficiency index encumbering these parameters was developed that was highly correlated with final grain yield. In-country design and manufacturing should account for ranges in seed size that work with the present design, drum cavity depth, and angle. Because this planter can easily accommodate mid-season fertilizer N application, adoption of this device should deliver increased grain yields and fertilizer N use efficiency.

Abbreviations: EI, efficiency index; OSU, Oklahoma State University.

Uniform seed establishment and plant stands are largely determined by the type of planting tools and planting techniques used (Liu et al., 2004). Diverse planting techniques are employed in different maize (*Zea mays* L.) production systems around the world to maximize grain yields (Sangoi, 2000). In maize production systems, the producer's main goal is to maximize grain yield to offset production costs while retaining a sizable return relative to the investments. In the developing world, maize production systems are characterized by low input use and poor management due to lack of knowledge and efficient planting tools (Omara et al., 2016). This results in lower grain yields compared with maize production in developed countries, where highly mechanized planters with nearly perfect seed placement are used to produce optimum grain yields. Design advancement and use of hand planters that suit developing world producers has progressed to some extent due to growing interests in conservation agriculture dubbed *minimum tillage* (Erenstein et al., 2012). The minimum tillage concept is not new, and it simulates the pre-historic planting practices where seed placement was accomplished by use of a stick to open a planting hole. In many developing world settings, such practices are still common (Derpsch, 1997; Omara et al., 2016; Dhillon et al., 2017). As such, it is important to note that minimum tillage saves energy and time required to perform land preparation accompanied with other soil protection benefits (Tabatabaeefar et al., 2009).

The adoption of minimum tillage in developing countries has been slow in part due to the unavailability of appropriate equipment or tools to be used (Friedrich et al., 2009).

Furthermore, limited maize planting tools have been designed and tested in different developing countries, resulting in even slower adoptions. In some instances researchers have reported flaws in performance due to poor quality control during commercial manufacturing of these planting tools (Aikins et al., 2010). Designing a viable planting tool that is durable and efficient requires putting into perspective conditions under which the tool will be used, and understanding the people using them (Friedrich et al., 2009). Furthermore, Harman et al. (2017) pointed out that the hand planter development should be gender specific, because women are largely responsible for laborious and manual jobs at crop establishment.

For more than three decades, research on the GreenSeeder hand planter, developed at Oklahoma State University (OSU), has progressed with field testing encompassing over 20 different countries in the developing world. The original concept for this work is embodied in Fig. 1, which was taken near Opico Quezaltepeque, El Salvador, in 1987. In this picture the producer is planting maize on a severe steep slope with good quality seed treated with chemicals for insect control. Extensive seed-to-skin contact is thus encountered, which leads to excessive and cumulative chemical exposure. This centuries-old planting method requires making a hole in the soil with a hardwood-metal-tipped planter [Gliricidia, *Gliricidia sepium* (Jacq.) Kunth, and Spanish elm, *Cordia alliodora* (Ruiz & Pav.) Oken] and then dropping two to three seeds into the hole by hand while moving forward. Producers in general cover the hole with their foot as they move forward 30 to 40 cm to make the next strike. The schism that has arisen is that chemicals were not previously used in this landscape, where maize has been planted for centuries.

From the initial prototype, the GreenSeeder hand planter has taken on different forms, with different components and parts being tested to perfect maize singulation (Fisher, 2016). This in turn has been sought to improve maize grain yields. Furthermore, the GreenSeeder is an all-terrain hand planter, which can be used in topographically steep slopes (hilly areas) that are not well-suited for mechanized planters (Dhillon et al., 2017). Over several sites, work by Chim et al. (2014) showed that planting one seed every 0.16 cm increased yields by an average of 1.15 Mg ha^{-1} (range: 0.33–2.46 Mg ha^{-1}) when compared with the farming practice of placing two to three seeds per hill, every 0.48 cm.

Allied work has also targeted planting sorghum [*Sorghum bicolor* (L.) Moench] and soybean [*Glycine max* (L.) Merr.], using this same planter with a modified internal drum. Sorghum, like maize, is a staple food that will be required to feed the world in the 21st century (Conway and Toenniessen, 1999). Work by Krishnareddy et al. (2009) showed that planting sorghum seeds less than 2.5 cm apart in clumps of four plants was a viable option to minimize tiller production, conserve water, and reduce plant water stress during later growth stages.

Fig. 1. Indigenous maize planting: metal tipped persimmon stick on sloped ground near Opico Quezaltepeque, El Salvador, 1987.

Women play a crucial role in agriculture production of developing world countries. Forty-three percent of the global agricultural work force is comprised of women (Mucavele, 2013). In developing countries alone, the percentage of female labor in agriculture is often greater, and over the past three decades, the role of women in production agriculture has risen. Sub-Saharan Africa represents the highest percentage with close to 50% of the agriculture labor force being women with East/Southeast Asia at 45% (Doss, 2011).

Recently, African countries have been implementing new land laws to increase the ownership rights of women to help this issue (Mucavele, 2013). African regions represent a very high percentage of women's labor, ranging from 30 to 80%. Women's role in agriculture of developing countries is undoubtedly significant. Often 40 to 50% of the agriculture labor force of such countries is comprised of women (Doss, 2011). When moving forward in helping developing countries improve their agriculture technology to strive and increase yields, women's roles must be considered heavily and technologies adapted to fit their needs.

The objective of this work was to describe and report on the various different changes that have been tested over time. The underlying objective behind developing the GreenSeeder was singulation, or dropping one seed with each strike. This led to the current prototype of the GreenSeeder hand planter that can be manufactured in the developing and developed world.

MATERIALS AND METHODS

Laboratory and field testing of the GreenSeeder hand planter was conducted from 2002 to 2017 at various locations near Oklahoma State University, located in Stillwater, OK. Initially a reciprocating drum was sought out, which could deliver single seeds with each strike. Once a reciprocating internal drum model/device had been developed (Koller et al., 2012), other variables and agronomic requirements were tested (Table 1).

The four independent variables that were tested and noted to influence the efficiency of maize seed delivery included seed size, drum cavity, operator, and internal brush strength. Several drums and

Table 1. Weights of planter components, and total weight of the GreenSeeder hand planter.

Planter component	Weight, g
Outer housing	246
Inner housing	190
Spring	48
Brush	2
Drum and lever assembly	43
Lever retainer washer and clip	3
Tip	347
Tip retainer clip	33
Seed resevoir PVC + collar	1267
Total (planter)	2179
Weight of seed (full)	1670 (3213 seeds kg^{-1})
Total (planter + seed)	3849

Table 2. Mean values for efficiency index (EI), multiples, singles, and misses for the different drums used within the OSU hand planter (cavity volume: 285-20, 0.60 mm; 450S, 0.86 mm; China, 1.26 mm).

Drum	*n*	EI	Multiples	Singles	Misses	Cavity volume
				—— mean ——		cm³
235-20	420	5.70	0.69	7.50	1.84	
235-25	455	5.16	1.01	6.95	2.05	
260-20	1035	6.47	1.33	7.36	1.32	
260-25	535	6.41	1.19	7.44	1.37	
260B	60	6.95	1.62	7.37	1.02	
260T	100	4.05	1.64	5.86	2.50	
260W	60	7.02	1.32	7.65	1.03	0.60
285-20	190	5.75	1.44	6.91	1.67	
285-25	80	2.46	1.45	5.20	3.35	
450S	2092	5.49	2.88	5.58	1.54	0.86
716M	230	4.86	1.09	6.73	2.18	
China	150	6.76	5.85	3.79	0.35	1.26
Agitate	60	8.12	1.15	8.35	0.50	
Small	75	7.81	1.11	8.23	0.67	

cavity sizes were tested and are included in Table 2. All variable testing reported here was conducted indoors where striking the hand planter against the ground was accomplished using multiple stacked rubber mats that had a similar resistance/stress load as that encountered in the field. This was required to facilitate counting of the seed(s) that fell, and/or blanks, for each strike. Each change in a single variable (e.g., seed size) was accomplished holding all other variables constant (brush strength, drum size, and operator). More comprehensive testing of inner and outer housing materials, component strength, and multiple planter configurations (all combined components), were ultimately tested so as to arrive at the current model that was employed to test the final four variables (seed size, drum cavity, operator, and brush strength).

Variables evaluated over the years have included but were not restricted to inner housing brush strength, brush length, drum cavity size, drum cavity depth, and pre-cavity agitation on the drum. Optimizing singulation has further evaluated the interaction of seed size (range between 2585 and 4050 seeds kg^{-1}) and the size/depth of the drum cavity. Other variables that were tested to eliminate the problem of misses included the following: seed bridging (vibrations and string with beads), operator strike style, drum scarification, drum position, spring tension, different housings, and seed volume in the reservoir. For most drums, two numbers were used to identify their differing characteristics. The first number is the depth (from the drum surface to the bottom of the drill-bit cutout), and the second is the cavity angle, measured from the center of the drill bit entry. As such, drum nomenclature (first number) reflects the depth of cut (cavity size) where 450S has a depth of 1.14 cm (0.450 in) and where the second number is the cavity angle (e.g., 260-20 would be 20°). Drum 235-20 would be 0.60 cm (0.235 in) and 20°, and 260-20 would be 0.66 cm (0.260 in) and 20°.

Seed sizes were grouped according to density (no. of seeds kg^{-1}) and this ranged from 2585 to 5012 seeds kg^{-1}. Results by seed size, for the efficiency index (EI), multiples, singles and misses, averaged over operator and drum are reported in Table 3. To determine possible ergonomic differences, six different operators were used in the testing and evaluation process of the GreenSeeder hand planter (Table 4) (more people were used, but where insufficient number of strikes were recorded to adequately test individual performance). Three

Table 3. Mean values for the efficiency index (EI), multiples, singles, and misses for seed sizes used to evaluate the OSU hand planter.

Seed size†	*n*	EI	Multiples	Singles	Misses
2585	150	5.07	2.07	6.03	1.90
2593	140	5.05	1.70	6.31	1.96
2761	310	5.66	1.46	6.83	1.71
2799	240	4.17	3.10	4.73	2.18
2865	150	6.43	2.10	6.70	1.20
3017	940	5.74	0.77	7.44	1.79
3263	260	7.42	1.95	7.34	0.72
3338	490	5.00	2.88	5.32	1.79
3449	130	3.70	1.35	5.92	2.73
3486	160	4.91	1.06	6.78	2.16
3577	522	6.44	2.45	6.42	1.13
3643	310	6.02	3.12	5.65	1.23
3846	1214	6.05	1.38	7.10	1.52
3968	230	6.51	5.72	3.77	0.51
4050	296	6.04	1.73	6.82	1.48

† Seed size = the number of seeds for every kg of seed.

brush types tested were stiff, medium, and soft. The break load was 279.52 N, and peak load 845.79 N for the medium brush stiffness employed. The brush is comprised of a galvanized steel-backed nylon conveyor strip (0.32 cm wide × 0.32 cm high backing, 1.9 cm overall height [0.125 × 0.125 × 0.75 in] manufactured by McMaster-Carr, Atlanta, GA).

The internal brush is required in this device so as to sweep off extra seed not held within the drum cavity. Extra seed, if not swept off the drum, could ultimately increase delivery of multiple seeds. Dependent variables recorded were singulation (only one seed delivered per strike), multiples (more than one seed per strike), and misses (no seed delivered per strike). Despite singulation being a good measure of efficient seed delivery, it does not provide a mathematical weight for blanks/misses that producers cannot tolerate. Blanks or misses encapsulate a system failure, and that is compounded by energy expenditure to plant (striking the soil) with a net negative consequence (lower seed density). Consequently, an EI value was computed that taxed misses accordingly:

$$\text{EI} = (\text{Singles} \times 0.95 + \text{Multiples} \times 0.6) - \text{Misses} \qquad [1]$$

Composite work over the years ultimately resulted in securing a US Patent for the OSU Hand Planter (Koller et al., 2017). Also, a manual for the current hand planter is available via the following link: nue.okstate.edu/Hand_Planter/Planter%20User's%20Manual%20EL.pdf (accessed 16 Aug. 2018).

With each advancing component and/or change that was made to the actual hand planter, mean separation was employed to be certain that the change/improvement delivered measurable

Table 4. Mean values for the efficiency index (EI), multiples, singles, and misses for operators evaluating the OSU hand planter.

Operator	*n*	EI	Multiples	Singles	Misses
			——	mean	——
Daniel	80	4.73	4.16	4.14	1.70
Jagman	500	6.06	2.64	6.07	1.29
Lawrence	810	5.60	2.61	5.86	1.53
Peter	1606	6.98	1.20	7.73	1.08
Rajen	1186	5.13	1.40	6.61	1.99
Sulu	270	6.46	1.28	7.39	1.33

differences. In general, Least Significant Difference mean separation at an α level of 0.05 was used to document each component being scrutinized (SAS, 9.4).

RESULTS AND DISCUSSION

Initial ideas for the development of a viable hand planter for the developing world came from work in Central America, beginning in 1987 when working with producers on highly eroded hillsides (work done by E. Ascencio and W. Raun, see Fig. 1). The needs for a new planter were predicated on the demands to remove chemically treated seed from the hands of producers in the developing world, whose method of planting maize required skin-to-seed contact. We also saw a need for more homogenous plant stands, both distance to and from each seed, and with a planter that delivered one seed per strike. Many mechanical changes have taken place over the past 15 yr that have led to the more refined design reported here. The resulting hand planter, including all components and weights in grams, is reported in Table 1. This also includes the weight of the maize seed (common seed size, 3213 seeds kg^{-1}) that will fit in the PVC handle.

Variables Evaluated

Despite notable progress over the years, the continual nemesis of "misses" (or blanks) slowed our group from moving forward. Avoiding misses has often been resolved when the planter was gently shaken following every two to three strikes, achieving >80% singulation (with a range of seed sizes, using the 450S and/or 260-20 drums). However, this was principally tied to certain operators (Peter and Lawrence) who had a seemingly ergonomic connection to the planter and who could consistently deliver higher singulation than other operators.

Although the focus has been on maximizing singulation, an overall acceptance of multiple seeds per strike has been preferred over the presence of any misses. This is simply because producers will not accept making a strike with any "new-age planter" that did not deliver a corresponding seed. Multiples instead of singles and with no misses would also be acceptable, given not having to handle the chemically treated seed, especially for women.

Seed Bridging

Seed bridging is the result of corn seed forming a bridge (many seeds joined together, or bridged, across the inner diameter) above the drum cavity, which subsequently prevents seed from dropping from the seed reservoir. Bridging was also found when ambient conditions were moist and the relative humidity was high (>40%). The occurrence of "sticky seed surfaces" resulted in multiple-layer-bridging, which required taking the planter apart to resolve the problem. Planter shaking (up and down) once every two to three strikes often assisted in decreasing bridging.

Several methods of external vibration were tested, including attaching various configurations of low-level vibration. External electronic vibration was used (attached to the outer housing) to assist in diminishing bridging and to decrease misses. Nonetheless, even with external vibration it did not completely resolve the problem.

Understanding that misses were the result of inner-housing seed bridging, ensuing testing took place to embed something inside the seed reservoir that would go up and down and break up bridging when it occurred. Initially, a spring-loaded cable was attached to the seed reservoir cap. It was then attached to a small cable that extended all the way down to the rotating drum. Beads were placed at the lower extremes of the cable (bottom to top, about 20 cm) so as to guarantee disturbance of any seed bridging that would take place just above the drum. Although this was cumbersome and an unlikely fix, this agitation completely eliminated misses, even if we used more (unwanted) moving parts.

External shaking of the hand planter also assisted in alleviating bridging, but this, too, is a planting nuisance for producers aiming to plant large areas. This also required visual inspection of seeds dropping to know when shaking was needed. Small nails placed diagonally inside the inner housing were also evaluated, but did not completely resolve seed bridging and associated misses.

Operator Strike Style

Over time, the influence of operator on planter performance has consistently been evaluated. Answers were sought for why certain individuals were able to deliver improved/increased singulation and diminished numbers of misses.

The ergonomics of how the planter was operated combined with the force exerted when striking the soil did show clear differences from one person to the next. For all operators included in this analysis, one stood out as being able to deliver higher singulation and decreased misses, and is identified as "Peter." Written communication from him is included below concerning his ability to achieve improved planter performance.

> When I started testing the planter I had varying results in the beginning, with high and sometimes low singulation. The inconsistencies in the results prompted me to [do a] self-audit. In the end, I noticed either striking the planter so hard, which rotated the internal drum so fast to occasionally catch the seeds, or striking the planter too soft didn't fully turn (less than 180 degrees) the drum to capture the seed. A more gentle strike simulating field planting would give just the right force needed to turn the drum to 180 degrees. This is achieved with minimal practice that producers can complete with ease.

In summary, a less mechanical, more-fluid ebb and flow did deliver better results (lower misses, higher singulation).

Drum Scarification

Another method that was employed to break up potential bridges was to rough up or scarify the trailing edge of the drum to loosen or impede bridging. If bridges form close to the surface of the drum (reverse side), just prior to having the cavity perpendicular to the tip, or soil surface, drum scarification was successful and did prevent misses.

Drum Position and Seed Release on the Upstroke vs. Downstroke

Early work was necessary to evaluate the ideal internal configuration that would allow seed to drop when the planter was depressed (going down) or whether this should take place as the planter/spring was relaxed (going up). The angle at which the internal drum/cavity was set dictates being able to catch the seed, and an ensuing forward 180° degree rotation to drop the seed.

Spring Strength and Tension

Once a finalized design was arrived at that employed an internal spring, several different spring tensions were tested. To compensate for hand planter weight and the weight of seed in the handle or reservoir, the highest tension was ultimately used. Other tensions were too soft, and complete compression resulted in the internal cavity compressing all the way to the point where the attachment-ring for the tip went up against the outer housing. The decision to use the higher tension was therefore necessary, which guaranteed spring relaxation.

Internal Brush

To sweep excess seed from the cavity before the seed is dropped, the GreenSeeder hand planter uses an internal brush that runs across the surface as the drum is rotated forward. The final brush used was the highest stiffness that could be purchased. Longer brush length and thickness were also tested, as was a plastic sweep that simulated the brush. The final brush used has a break load of 279.52 N, and peak load 845.79 N. The brush is comprised of a galvanized steel-backed nylon conveyor strip (0.32 cm wide × 0.32 cm high backing, 1.9 cm overall height [0.125 × 0.125 × 0.75 in] manufactured by McMaster-Carr, Atlanta, GA).

Housing and Planter Weight

The outer housing is a critical component of this planter. Various different thicknesses of the final aluminum housing were tested, only to arrive at a 0.32-cm (0.125-in) thickness. This was lighter than that originally tested (0.64 cm, or 0.25 in) but still allowed for solid pin and arm mounting. Using an internal spring (compressed and not compressed, or not relaxed and relaxed), when connected to the external arm, the inner drum is either catching seed or dropping seed. The aluminum welded arm connected to the external aluminum housing is a potential weakness of this design.

Seed Reservoir Volume and Planter Components

Weight for this planter depends on how full it is (seed). Actual weights for the components that make up the planter are reported in Table 1, in addition to an estimated seed weight, utilizing a seed size of 3213 seeds kg^{-1}.

Various different levels of seed were tested from near empty to completely full. For the final model presently manufactured, the seed reservoir holds approximately 1.67 kg of seed. Combined with the weight of the planter, and completely full with seed, our current planter weighs 3.849 kg. This will depend on the seed density, with the smaller seed weighing more and larger seed sizes weighing less. Differences in singulation and misses were generally small when planter weight or seed volume was altered.

Efficiency Index

The rationale for developing a planter EI comes from the need to weigh the three components that are being measured using this device. For each planter strike, misses (no seed), singles, and multiples (two or more) were measured. The desired result is to have only one seed that drops with each strike. Using our current design, we are unable to deliver this level of precision. As indicated earlier, our goal with this entire concept/planter is that misses are unacceptable. Nonetheless, the presence of the entire range (misses, singles, multiples) is almost always present, no matter what drum and/or seed is used. This is obviously a product of our present engineering and associated design. The challenge is to match the correct drum with producer seed size that minimizes misses and maximizes singles. Because developing world producers presently plant two to three seeds per hole/strike, the acceptance of multiples have been tolerated. The current index is computed as EI = (singles × 0.95 + multiples × 0.6) – misses (Eq. [1]). This metric/index places increased value on singulation and multiples while taxing results with misses.

Seed Size and Shape

In general, when seed size was smaller (more seeds kg^{-1}), increased numbers of multiples were found (Table 3). Averages for the different seed sizes showed that as the seed size decreased (more seeds kg^{-1}), misses also decreased (Table 3). Accordingly, singles and misses decreased when the seed sizes were smaller. Seed sizes 2865, 3263, and 3968 seeds kg^{-1} did stand out. It is hypothesized that some seed surfaces are smoother than others, and as such flow more easily within the confines of the planter. These less resistant seed surfaces may have been the cause for improving the EI.

An additional observation was made when testing flat seed vs. round seed with similar densities (seeds kg^{-1}). For flat and round seeds that were both near 3200 seeds kg^{-1}, round seed was found to have significantly lower misses and greater singles when compared with flat seed. This was expected, considering the continuity/consistency of seed surfaces and the importance this would have on seed flow.

For planter testing, the seed reservoir was kept half full. This amounted to 0.835 kg of seed (1.670 kg full), or approximately 2682 seeds. Testing different levels of seed in the reservoir were evaluated, but limited differences in any of the variables evaluated were found.

When drums were evaluated over users and seed sizes, and where more than 5000 strikes were recorded, the 260-20 drum had the highest number of singles (Table 2) and tended to outperform the 450S drum. The highest EI and singulation (n > 1000) was recorded for the 260-20 drum. Both the 260-20 and 450S drums averaged just over 1 miss for every 10 strikes. Future work must go back and review the 260W and 260-25 drums based on the positive results.

Over the years, many modifications of the hand planter have been required. Although changes have indeed taken place, more recent design and feature changes have been somewhat static due to an achieved planter reliability. When planter results from near-identical planters (2013, and again in 2017) were re-tested using Drum 260-20, results were very similar (Table 5). Seed sizes changed somewhat, but the comparisons coming from three seed sizes (tested in 2013 and tested again in 2017) differed by <50 g kg^{-1}

Table 5. Comparison of drum cavity 260-20 data collected in 2013 vs. that found in 2017.

2017					2013				
Seed size†	*n*	Misses	Singles	Multiples	Seed size	*n*	Misses	Singles	Multiples
3571	200	8.5A‡	69A	22.5A	3572	300	11AB	70ABC	19CD
3808	200	10A	64.5A	25.5A	3846	300	7ABC	71CD	22AB
4096	200	13A	68.5A	18.5A	4050	200	17A	73A	11AB

† Seed size = the number of seeds for every kg of seed.

‡ Means followed by the same letter were not significantly different at the alpha = 0.05 probability level.

Fig. 2. Current 2018 hand planter and planter components developed primarily for maize producers in the developing world, who are entrusted with management on incredibly marginal landscapes.

(3571 vs. 3572, 3808 vs. 3846, and 4096 vs. 4050, Table 5). The recorded singles and misses were found to be very similar when tested in 2013, and again in 2017. These results further validated the rigor and reproducibility of our testing procedures. Duplicating highly similar numbers for singulation and misses over this 4-yr period, and that encumbered different operators was encouraging (Table 5).

The authors recognize the presence of confounding effects when running through the exhaustive testing required over the years. No two variables could be evaluated while holding absolutely everything else constant. Much of this was because, improvements were made over time that rendered a previous iteration as untestable (e.g., altered brush strength). Nonetheless, for the creation of this planter, and those variables evaluated in Tables 2 to 5, the inconsistency of parts due to time was a necessary evil that afforded design improvements. Our most current hand planter is illustrated in Fig. 2 and it conveys much of the sophistication embedded in a design that would never have been envisioned 20 yr ago. This is further underscored coming from a very modest project budget and a host of different students and faculty working specifically on the OSU hand planter for the last two decades.

Once 80% singulation was achieved with a given planter change, field experiments were realized to holistically test the planter. Omara et al. (2016) deduced that maize producers in the developing world could increase yields by 20% using the OSU GreenSeeder. Omara et al. (2016) further noted the inability of a single drum to deliver singulation over a wide range of seed sizes and recommended testing for appropriate cavity size within a region to optimize seed singulation. Another field study conducted with OSU GreenSeeder noted similar emergence and yields between GreenSeeder-planted treatments and checks planted with a John Deere MaxEmerge Planter (Dhillon et al., 2017). Dhillon et al. (2017) also noted the ability of the planter to apply mid-season fertilizer N by simply changing the internal drum. Harman et al. (2017) evaluated seven different hand planters based on plant population establishment, economic viability, and usability, and inferred highest qualitative performance using the OSU GreenSeeder.

CONCLUSIONS

Using the OSU GreenSeeder removes chemically treated seeds from the hands of producers in the developing world, whose present method of planting continues to expose them to chemically treated seed via skin-to-seed contact. This applied mechanical device embodies "indigenous planting know how" for developing world maize landscapes, and for the producers who manage these difficult terrains.

By embedding an internal rotating drum with a modifiable drum cavity, this device enables early season maize planting capable of singulating a range of seed sizes. Also, this design accommodates mid-season fertilizer N application by simply changing the internal drum. We expect to see grain yield increases and improved N use efficiency where ever this device is adopted.

ACKNOWLEDGMENTS

The authors are grateful to Lawrence Aula, Daniel Aliddeki, Natasha Macnack, Sulochana Dhital, Rajen Bhajgain, Chris Raun, and Dhillon Davidson for help testing the hand planter over the years.

REFERENCES

Aikins, S.H.M., A. Bart-Plange, and S. Opoku-Barrour. 2010. Performance evaluation of Jab planters for maize planting and inorganic fertilizer application. J. Agric. Biol. Sci. 5(1):29–33.

Chim, B.K., P. Omara, J. Mullock, S. Dhital, N. Macnack, and W. Raun. 2014. Effect of seed distribution and population on maize (*Zea mays* L.) grain yield. Int. J. Agron. doi:10.1155/2014/125258

Conway, G., and Toenniessen, G. 1999. Feeding the world in the twenty-first century. Nature 402:C55–C58. doi:10.1038/35011545

Derpsch, R. 1997. History of crop production with and without tillage. JIRCAS Seminar on Soybean Research, MAG-GTZ Soil Conservation. p. 151–154.

Dhillon, J.S., B. Figueiredo, L. Aula, T. Lynch, R.K. Taylor, and W.R. Raun. 2017. Evaluation of drum cavity size and planter tip on singulation and plant emergence in maize (*Zea mays* L.). J. Plant Nutr. 40:2829–2840. doi:10.1080/01904167.2017.1382532

Doss, C. 2011. The role of women in agriculture. ESA Working Pap. 11-02. The Food and Agriculture Organization of the United Nations, Rome.

Erenstein, O., K. Sayre, P. Wall, J. Hellin, and J. Dixon. 2012. Conservation agriculture in maize and wheat based systems in the subtropics: Lessons from adaptation initiatives in South Asia, Mexico, and Southern Africa. J. Sustain. Agric. 36:180–206. doi:10.1080/10440046.2011.620230

Fisher, M. 2016. Greenseeder: Hand planter could boost productivity for world's poorest farmers. CSA News 6(3):4–8. doi:10.2134/csa2016-61-3-1

Friedrich, T., J. Kienzle, and A. Kassam. 2009. Conservation agriculture in developing countries: The role of mechanization. Innovation for Sustainable Agricultural Mechanization Club. July, 20.

Harman, R.M., N.S. Eash, J.E. Morrison, W.E. Hart, C.T. Sullivan, and D.M. Lambert. 2017. Finding the Technological Sweet Spot: The Smallholder Conservation Agriculture Maize Seeder. J. Sustain. Dev. 10:241–256. doi:10.5539/jsd.v10n5p241

Koller, A., W.R. Raun, and R.K. Taylor. 2012. Singulating hand planter and fertilizer applicator. Serial no. 61/799,338. Disclosure: 26 July.

Koller, A., R. Taylor, and W. Raun. 2017. Singulating hand planter and fertilizer applicator. US Patent 9635,801 B2. Date issued: 2 May.

Krishnareddy, S.R., B.A. Stewart, W.A. Payne, and C.A. Robinson. 2009. Grain sorghum tiller production in clump and uniform planting geometries. J. Crop Improv. doi:10.1080/15427520903303808

Liu, W., M. Tollenaar, G. Stewart, and W. Deen. 2004. Impact of planter type, planting speed, and tillage on stand uniformity and yield of corn. Agron. J. 96:1668–1672 doi:10.2134/agronj2004.1668

Mucavele, S. 2013. The role of rural women in agriculture. World Farmers' Organization, Rome. http://www.wfo-oma.com/women-in-agriculture/articles/the-role-of-rural-women-in-agriculture.html (accessed 16 Aug. 2018).

Omara, P., L. Aula, B. Raun, R. Taylor, A. Koller, E. Lam, J. Ringer, J. Mullock, S. Dhital, and N. Macnack. 2016. Hand planter for maize (*Zea mays* L.) in the developing world. J. Plant Nutr. 39:1233–1239. doi:10.1080/01904167.2015.1022186

Sangoi, L. 2000. Understanding plant density effects on maize growth and development: An important issue to maximize grain yield. Cienc. Rural 31:159–168. doi:10.1590/S0103-84782001000100027

Tabatabaeefar, A., H. Emamzadeh, M.G. Varnamkhasti, R. Rahimizadeh, and M. Karimi. 2009. Comparison of energy of tillage systems in wheat production. Energy 34:41–45. doi:10.1016/j.energy.2008.09.023