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# Economics of the Greenseeder Hand Planter

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## Core Ideas

- Break-even corn yield increase for a US$50 Greenseeder hand planter is 1.12%.
- A US$50 Greenseeder hand planter needs to use 12.19% fewer seeds, and reduces labor man-days by 38.66%.
- If used for fertilization, the Greenseeder hand planter could increase corn yields up to 10.82%.
- The Greenseeder hand planter would pay for itself if used to apply fertilizer alone.

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## ABSTRACT

Corn (*Zea mays* L.) yields in developing countries are lower than in developed countries, in part due to planting methods that involve hand dropping of multiple seeds per hill. The Greenseeder hand planter (GHP) was developed to reduce seeding rates and long-term health risks from using bare hands to drop pesticide-treated seeds. When used to apply fertilizer, it can prevent loss of N from ammonia volatilization. This research determines economic break-even levels of seed and labor savings, increases in corn yield, and reduced loss of N through reduced ammonia volatilization. A GHP used to plant 3 ha $yr^{-1}$ that costs US$50 would need to increase corn yields on average by about 1.12%, use 12.19% fewer seeds, or reduce labor man-days by 38.66% to equal expected net returns from traditional methods. Using the GHP to apply fertilizer would on average increase corn yields up to 10.82% $ha^{-1}$ due to reduced N loss from ammonia volatilization and thus fertilization alone could be enough to pay for the planter.

**Abbreviations:** ANOVA, analysis of variance; DIRTI-5, depreciation, interest, rent, repairs, taxes, and insurance; FAO, Food and Agriculture Organization; GHP, Greenseeder hand planter; JDP, John Deere planter; MLE, maximum likelihood estimation; OSU, Oklahoma State University; REML, residual maximum likelihood estimation; SSP, stick seeder planter; SSA, sub-Saharan Africa; ZNFU, Zambian National Farmers' Union.

Corn (*Zea mays* L.) is one of the most cultivated crops in the world. Corn originated from Mesoamerica and its production has spread throughout the world. Corn can be grown over a wide range of altitudes and latitudes (Shiferaw et al., 2011). Plant breeders have developed varieties that grow well under different biophysical environments. Thus, global corn production has increased over the years. Between 1961 and 2010, area allocated to corn production increased by more than 50% with about 73% of this growth in developing countries (Shiferaw et al., 2011). In 2010, corn was planted on about 73, 44, and 46% of the cultivated land in Africa, Latin America, and South Asia, respectively (Shiferaw et al., 2011) and on 35 million US hectares (USDA, 2016).

Although demand for corn in developing countries remains high (Borlaug, 2007; Shiferaw et al., 2011), its yields in developing countries are lower than in developed countries (Cairns et al., 2013; Chim et al., 2014). For example, since 1961 corn yields in the top five corn-producing countries in the world (United States, China, Brazil, Mexico, and Indonesia) have increased three-fold (from 1.84 Mg $ha^{-1}$ to more than 6.10 Mg $ha^{-1}$), whereas in developing regions of Africa, Asia, and Latin America, corn yields have stagnated at less than 2 Mg $ha^{-1}$ (FAO, 2011; Cairns et al., 2013). These yield differences are attributed to a number of factors including access to and use of localized seed genetics, fertilizer, pest management, and differences in seeding practices (Adjei et al., 2003; Aikins et al., 2010). In developed countries, mechanized planters that deliver and cover single seeds per drop at relatively precise depths and precise within-row spacing enhance yield potential (Omara et al., 2015). However, about 60% of corn area (29 million ha) in developing countries is planted with multiple seeds per hill by hand (Chim et al., 2014; Fisher, 2016; Dhillon et al., 2017).

Planting by hand usually involves using a heavy stick seeder planter (SSP) and/or hand hoe. Workers use the SSP to open a shallow hole about 5 cm deep, drop two to three seeds in the hole, cover the seeds with soil forming a small hill, and step on the hill, enhancing soil-to-seed contact (Adjei et al., 2003). The typical SSP is composed of a wooden shaft and a pointed metal tip that can be used to penetrate the soil and open a slot for seed placement (FAO, 2010). Aikins et al. (2010) explain that the whole process is labor-intensive and results in non-uniform plant stands, often with multiple plants emerging from each hill and competing for nutrients. For equivalent seeding rates, non-uniform spacing of seeds has been found to result in lower yields than uniform spacing (Epplin et al., 1996; Rutto et al., 2014). Although several hand planters have in the past been developed for corn farmers in developing countries, few of them drop one corn seed with a single strike (singulation) (Aikins et al., 2010; Dhillon et al., 2017, 2018). Researchers at Oklahoma State University (OSU) developed a singulating corn Greenseeder hand planter (GHP), hypothesized to reduce optimal seeding rates (Omara et al., 2015). Theoretically, use of a GHP relative to a SSP could result in equivalent or greater yields from fewer seeds purchased and planted per hectare.

The GHP includes a seed box that eliminates the need for the operator to handle each seed (see Fig. 1). Prior to planting, corn seeds are commonly coated with one or more pesticides such as imidacloprid (trade name Gaucho, 1-(6-chloro-3-pyridylmethyl)-*N*-nitroimidazolidin-2-ylideneamine), permethrin (trade name Kernel Guard Supreme or Profound, 3-(phenoxyphenyl) methyl (+,–)-cis, trans-3-(2,2-dichloroethenyl)-2,2-dimethyl cyclopropanecarboxylate), thiamethoxam (trade name Cruiser, 3-[(2-chloro-5-thiazolyl) methyl]tetrahydro-5-methyl-*N*-nitro-4*H*-1,3,5-oxadiazin-4-imine), as well as with biological agents (Paulsrud et al., 2001). Careless handling of coated seeds may result in deleterious health consequences. Thus, the GHP can reduce long-term health risks because it reduces operator exposure to treated seeds (Fisher, 2016; Dhillon et al., 2017). By changing the GHP's internal drum, the GHP can serve as a mid-season fertilizer applicator where the operator places fertilizer underneath the soil surface (Dhillon et al., 2017, 2018). The GHP is hypothesized to prevent loss of N from ammonia volatilization from urea fertilizers because it allows the operator to place fertilizer beneath the soil surface, which reduces urea's exposure to direct heat from the atmosphere (Dhillon et al., 2017). Developing countries experience higher loss of N via ammonia volatilization than industrialized countries due to high temperatures and widespread use of urea and ammonium bicarbonate (Bouwman and Boumans, 2002).

**Fig. 1. The Greenseeder hand planter (Oklahoma State University, 2016).**

The GHP is designed to release a single seed per location, which is intended to improve homogeneity of plant growth, decrease inter-plant nutrient competition, improve yield potential, and reduce seed cost per hectare (Chim et al., 2014; Fisher, 2016). To keep manufacturing costs low, the GHP does not yet meet this target. However, the most recent design comes closer than the version used in the experiments reported here.

This study seeks to determine the labor savings, seed savings, and the quantity of corn yield increase required for the GHP to be an economically viable alternative to the SSP. This study also determines the quantity of corn yield increase that would be realized due to reduced loss of N from ammonia volatilization if the GHP was used to apply urea fertilizer. In addition to these main objectives, we also determine the effect of using the GHP on corn yield per hectare relative to an ideal standard of near perfect seed singulation. Evaluation of the GHP technology could show whether the GHP would pay or not, which would be an important finding for farmers producing a vitally important food crop. These objectives are achieved by employing partial budgeting techniques and estimating a linear mixed effects model to data from designed field trials in Stillwater, OK, USA.

## THEORY

Farmers are expected to choose the planting method that maximizes expected net returns and improves their welfare. Biermacher et al. (2009) suggest that the expected profit maximizing framework is suitable to model behavioral decision and choice of farmers before the onset of the planting season. Assume that one of the farmer's objectives is to adopt a planting method that maximizes expected profit $\pi$ by comparing profit that is yielded by $m$ alternative methods. The farmer chooses a planting method $j$ over any alternative package $m$ such that:

$$\pi_j > \pi_m, m \neq j \qquad [1]$$

The adoption decision $D^*$ and the optimal expected profit $\pi_j^*$ from choosing a given planting method would be:

$$D^* = \begin{cases} 1 \text{ iff } E[\max E(\pi_j^*)] > E[\max_{m \neq j} E(\pi_m^*)] \\ \qquad \text{or } \eta_{i1} > 0, \text{ for } \forall m \neq j \\ 0 \text{ otherwise} \end{cases} \quad [2]$$

where $\eta_j = E[\max_{m \neq j}(\pi_j^* - \pi_m^*)] > 0$ (Bourguignon et al., 2007; Biermacher et al., 2009). By Eq. [2], a farmer whose objective is to maximize expected profit is expected to adopt a planting method whose expected profit is greater than all alternatives. The GHP considered here is attempting to drop a single seed per planting station as opposed to an SSP in which two or more seeds are dropped per hill. Thus, if the same number of seeds are planted per hectare, the theoretical expected yield would be greater for the GHP given the expected agronomic benefits of uniform plant spacing. Alternatively, if fewer seeds are planted per hectare with the GHP, total seed costs would be lower. Ignoring the potential value of farmer health benefits from using a GHP relative to a SSP, the farmer's optimization problem is mathematically:

$$\max_D E(\pi_i \mid \mathbf{x}) = \{D[pE(y_{\text{GHP}} \mid \mathbf{x}) - c_{\text{GHP}}] + [(1-D)(pE(y_{\text{SSP}} \mid \mathbf{x}) - c_{\text{SSP}}]\} \quad [3]$$

subject to

$$y_k = f(\mathbf{x}),\ k = \{\text{GHP,SSP}\},\ D \in \{1,0\}$$

where $p$ is the price of corn; $E(\pi_i)$ is expected profit (US$) per hectare; $D$ is the discrete choice variable that equals 1 if the farmer uses GHP, 0 otherwise; $y_{\text{GHP}}$ is corn yield from plots where the GHP was used; $y_{\text{SSP}}$ is corn yield from plots where the SSP was used; $c_{\text{GHP}}$ is cost of production from plots where the GHP was used; $c_{\text{SSP}}$ is cost of production from plots where the SSP was used; $y_k$ is corn production function; and $\mathbf{x}$ denotes a vector of inputs used in corn production.

## DATA AND PROCEDURES

### Agronomic Data

Plot-level agronomic data were generated from experiments conducted at the Efaw, Lake Carl Blackwell, and Stillwater Agronomy Research Stations in Payne County, Oklahoma, USA. Efaw has an Ashport silty clay loam soil (fine-silty, mixed, superactive, thermic Fluventic Haplustolls). The Lake Carl Blackwell plots have Pulaski fine-sandy loam soils (coarse-loamy, mixed, superactive, nonacid, thermic Udic Ustifluvents). Stillwater Agronomy Research Station has mostly Kirkland silt loam soils (fine, mixed, superactive, thermic Udertic Paleustolls) (Omara et al., 2015). These experiments were designed as randomized complete blocks. Each experiment comprised three replications and four plots per replication in each site year. The experiments were conducted at the Stillwater site in 2014, at Efaw in 2014 through 2016, and at Lake Carl Blackwell in 2015 and 2016.

Treatments consisted of planting methods: GHP, SSP, and a tractor-drawn John Deere planter (JDP). The GHP has an internal drum that can hold up to 1 kg of seed. It was designed to deliver a single seed per hill at a planting depth of about 5 cm (Omara et al., 2015). The SSP has a metal tip like those typically used in Central and South America. Its only function is to open a planting hole into which seeds are dropped and covered by foot (Chim et al., 2014). The SSP used in these field experiments managed 100% singulation (planter delivers a single seed with every strike), which implies that the SSP in this experiment did not simulate its actual applications in developing countries. Despite this severe limitation, the experimental dataset is used because it still provides helpful information.

Hybrid corn variety Pioneer P1498HR was planted on all plots with plant population of 74,000 seeds ha$^{-1}$. Inter-row spacing at all the stations was 76 cm while plant spacing was uniform at 18 cm. Plot size varied, ranging from 1.5 × 6 m to 3 × 6 m. Summary statistics of corn yield from each research station are shown in Table 1.

In addition, summary statistics from the research stations according to planter type are shown in Table 2. Other details of the field trials are in Dhillon et al. (2017).

### Economic Analysis

Partial budgeting was used to determine the economics of the GHP. Adopting a GHP would result in incremental changes at the farm, and a partial budget is a useful tool for a farmer when such a situation arises (Nuthall, 2011). Partial budgeting computes the overall impact by netting out the negative effects from positive effects. Positive effects include the monetary value of activities that would increase revenue and/or decrease costs, whereas negative effects are those that would decrease revenue and/or increase costs. In our partial budget, the added returns were the additional revenue that would result from using the GHP and reduced costs included seed and labor costs for SSP. The added costs included the GHP's annual operating costs whose computation relied on depreciation, interest on average value, repairs, taxes, and insurance (also called the DIRTI-5 by Lessley and Holik, 1987). Reduced revenues were zero.

The following assumptions were used in our partial budget. The market price of the GHP is assumed to range between $40 and

**Table 1. Descriptive statistics of corn yield (Mg ha$^{-1}$) according to planter type obtained in 2014, 2015, and 2016.**

| | 2014 | | 2015 | | 2016 | |
|---|---|---|---|---|---|---|
| Planter type | Mean | SD | Mean | SD | Mean | SD |
| SSP | 6.683 | 0.511 | 4.506 | 2.140 | 5.462 | 2.320 |
| GHP | 5.583 | 0.909 | 3.421 | 2.313 | 5.326 | 2.291 |
| JDP | 6.433 | 1.357 | 4.488 | 1.845 | 5.221 | 2.268 |

**Table 2. Descriptive statistics of corn yield (Mg ha$^{-1}$) by planter type from Efaw, Lake Carl Blackwell, and Stillwater agronomy research stations.**

| | Efaw | | Lake Carl Blackwell | | Stillwater | |
|---|---|---|---|---|---|---|
| Planter type | Mean | SD | Mean | SD | Mean | SD |
| SSP | 6.313 | 2.268 | 4.067 | 1.511 | 4.050 | 0.750 |
| GHP | 5.582 | 2.200 | 3.106 | 2.173 | 3.577 | 0.985 |
| JDP | 5.940 | 1.677 | 3.706 | 2.029 | 5.233 | 0.451 |

\$100 unit$^{-1}$. The \$100 is about what it costs now and the \$40 is what we hope it will cost under mass production. Omara et al. (2015) posit that if the market price of the GHP were \$40 unit$^{-1}$, it would be more marketable among smallholder farmers in the developing world.

We assume a useful life of 3 yr and that the GHP would be used to plant corn seed on up to 5 ha yr$^{-1}$. Following Haggblade and Tembo (2003), Ng'ombe et al. (2017), and Ng'ombe (2017), peasant farmers in Zambia and across sub-Saharan Africa (SSA) plant up to 5 ha of land annually—the typical holding size of land for farming by most farmers. An annual market interest rate of 6% was assumed, and the repairs, taxes, and insurance for the GHP are assumed to be zero. Price of corn is assumed to be \$175 Mg$^{-1}$ and labor cost was set at \$2.5 man-day$^{-1}$. A farmer is assumed to plant 1 ha of corn in 5 d, and 25 kg of corn seed is assumed to be planted on 1 ha of land. These assumptions and variable values were pulled from the standard nationally representative smallholder corn enterprise budget from Zambia. The corn enterprise budget was prepared by the Zambia National Farmers' Union (ZNFU) based on production practices by representative Zambian smallholder corn farmers in 2015 (ZNFU, 2015). Zambia is a developing country in SSA where planting by hand is common (Haggblade and Tembo, 2003). In addition, Zambia is one of the countries where the GHP has been distributed (see Fig. 2).

Bouwman and Boumans (2002) find that N loss from ammonia volatilization of urea fertilizers on average amounts to 18 and 7% in developing countries and industrialized countries, respectively. Funderburg (2009) reports a 20% N loss from ammonia volatilization to be common when urea fertilizers are applied on the soil surface. Jama et al. (2017) determine corn yield response to N use from 940 on-farm trials and demonstration sites consisting of at least 3220 site-year treatment combinations in southern Africa. Jama et al. (2017) classified the applied N rates as "half N" and "full N" based on recommended rates for each site. The half N and full N rates imply applying fertilizer containing N less than or equal to 50% and more than 50% of the recommended N rates, respectively (see Jama et al., 2017 for more details). Although Jama et al. (2017) did not estimate the traditional linear response stochastic plateau (Tembo et al., 2008; Boyer et al., 2013), their results corroborate the idea of the linear response stochastic plateau. They find that without N, farmers would on average realize 1.6 Mg of corn ha$^{-1}$, whereas the expected corn plateau is 4 Mg ha$^{-1}$, and that marginal physical productivity for corn is 0.025 Mg kg$^{-1}$.

Considering that agricultural producers are financially constrained and so the quantity of urea is limited, studies by Bouwman and Boumans (2002) and Jama et al. (2017) allow us to estimate the corn yield increase that would be realized due to reduced loss of N from ammonia volatilization if the farmer used the GHP to apply fertilizer. In our budget, the GHP potentially increases the amount of N by up to 18% (because it places fertilizer underneath the soil) and the amount of urea that a producer has is assumed to be constrained. Following Bouwman and Boumans (2002) and Jama et al. (2017), the percentage that the GHP would increase corn yield due to reduced N loss from ammonia volatilization, $y^*$, is:

$$y^* = [4 - (1.60 + 0.0259 \times \mathrm{Nrem})] \quad [4]$$

where Nrem is amount of N available after 18% loss from ammonia volatilization: Nrem = (Nplat − Nplat × 0.18), and Nplat is the amount of N required to produce corn at its plateau. Based on averages of Table 2 in Jama et al. (2017), Nrem is 75.95 kg N ha$^{-1}$ and Nplat is 92.66 kg N ha$^{-1}$.

## Statistical Analysis

The effect of using GHP on corn yield was estimated using the plot-level agronomic data. Dhillon et al. (2017) conducted the experiment for other experimental objectives. For this study, it would have been preferred to compare the GHP with actual farmer practices rather than an ideal situation under which the SSP was used. The data were used here because they are the only experimental data available and they do show how well the GHP compares vs. ideal planting methods. The data are cross-sectional time series and therefore could be prone to problems of non-spherical errors across seasons. Thus, the R-package lme4 (Bates et al., 2015) is used to estimate the linear mixed effects model. The R-package lme4 uses restricted maximum likelihood estimation (REML). For estimation of linear mixed effects models, REML is preferred to maximum likelihood estimation (MLE) because it yields unbiased covariance

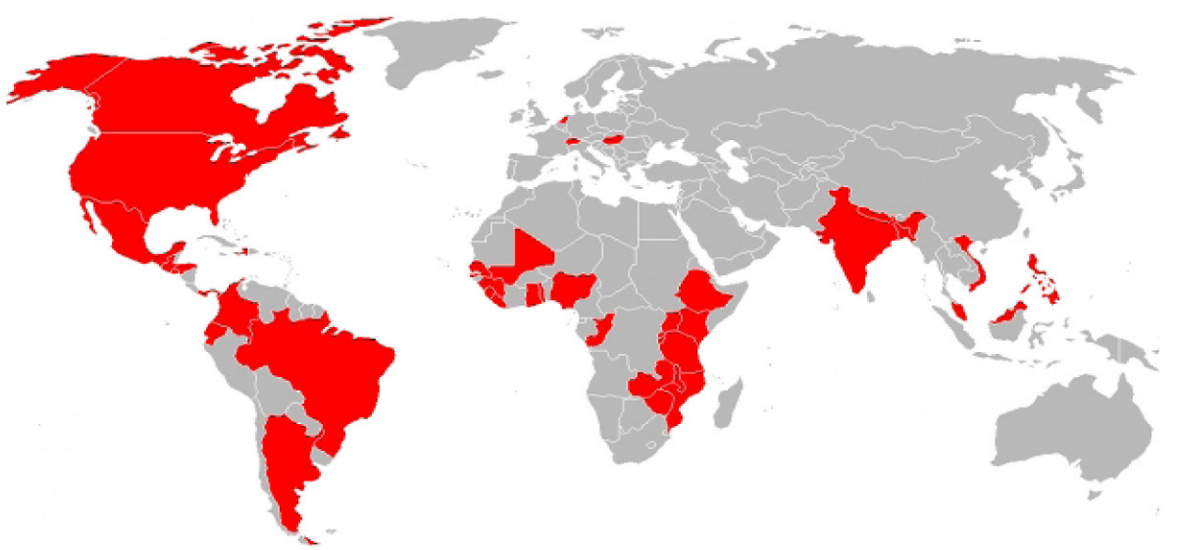

**Fig. 2. Distribution of the GHP across the world by 2016. (Oklahoma State University, 2016). Note: Countries marked in red have some farmers that received a GHP in previous 5 yr.**

parameters by accounting for the loss of degrees of freedom that results from parameter estimation of fixed effects (West et al., 2014). To determine the statistical significance of treatment main effects, we used the R-package lsmeans developed by Lenth (2016). Our linear mixed effects model's data generating process is:

$$y_{itk} = \mu + \tau_i + s_t + \varepsilon_{itk} \quad [5]$$

where $y_{itk}$ is corn yield with the $i$th planting method, from year $t$ and site $k$, $\mu$ is the overal mean, $\tau_i$ is the effect of the $i$th planting method, $s_t \sim N(0, \sigma_S^2)$ is the site-year random effect, $\varepsilon_{itk} \sim N(0, \sigma_\varepsilon^2)$ is a random error, and $\sigma_S^2$ and $\sigma_\varepsilon^2$ are mutually independent.

# RESULTS AND DISCUSSION

## Statistical Analysis

Several diagnostics were conducted to determine the plausibility of the linear mixed effects model selected. Based on the Shapiro-Wilk test, the null hypothesis of normality of the distribution of corn yield was not rejected at a 10% significance level ($P = 0.200$). Based on results from the Levene test, the null hypothesis of equal error variances across the treatments was not rejected ($P = 0.567$). The likelihood ratio test was used to determine significance of the fixed effects (based on the ANOVA function in R software, R Core Team, 2017) in the model. The null hypothesis of no fixed effects was rejected ($P < 0.001$). Parametric bootstrap of the $p$ value based on 1000 replications was used to determine statistical significance of site-year random effects. There was strong evidence to support the inclusion of site-year random effects in the model ($P < 0.001$). The estimated linear mixed effects regression model is shown in Table 3. The linear mixed effects model with seed size fixed effects was also estimated, but the results differed little from those reported above and therefore they are omitted.

Furthermore, actual mean differences among treatments were determined by conducting a post-hoc analysis and results are reported in Table 4. The SSP is the base treatment. Results in Table 4 indicate the GHP had significantly lower corn yield than the SSP. We find no statistically significant differences between mean corn yields from using the SSP and JDP. These findings corroborate with descriptive statistics in Table 1 for years 2014 and 2015, although in 2016 the GHP resulted in higher average corn yield than the JDP. Dhillon et al. (2018) document efforts to refine use of the hand planter and the improved performance in 2016 may partly result from learning in prior years.

The idealized SSP would result in about 0.742 Mg more corn yield ha$^{-1}$ than the GHP. The estimated JDP advantage over GHP of 0.611 Mg ha$^{-1}$ is not statistically different from zero.

**Table 3. Linear mixed effects regression results of corn yield (Mg ha$^{-1}$) response to planter type.**

| Variable name | Coefficient | SE |
|---|---|---|
| Intercept | 5.262** | 0.776 |
| GHP | −0.742** | 0.346 |
| JDP | −0.130 | 0.456 |
| Site-year random effect | 2.536** | 1.262 |
| Error variance | 3.388** | 1.357 |
| Log likelihood ratio | −408.344 | |
| Number of observations | | 193 |

** Statistically significant at the 1% level.

**Table 4. Least squares (LS) means of corn yield by planter type.**

| Planter *i* vs. planter *j* | Difference in least squares means |
|---|---|
| | Mg ha$^{-1}$ |
| SSP vs. JDP | 0.130 |
| SSP vs. GHP | 0.742** |
| JDP vs. GHP | 0.611 |

**Statistically significant at 1%.

## Economic Analysis

Using the partial budgeting approach, break-even values for corn yield, labor costs, the price of corn seed, and the purchased price of the GHP are discussed next. Results suggest that for a GHP priced at \$50 to be an economically viable alternative to the SSP, it should be able to increase corn yields by about 1.12% ha$^{-1}$ (equivalent to 28 kg). If the GHP can achieve the 20% yield increase projected by Omara et al. (2015) then it would unambiguously pay to adopt the hand planter. In terms of seed savings, results indicate that such a GHP would be an economically viable planting method if it reduced seeds by about 12.19% ha$^{-1}$. This finding also implies that for the GHP that costs \$50 to result in equivalent net returns as the SSP, it should enable the smallholder farmer to save corn seeds valued at about \$5.0 ha$^{-1}$ (assuming seeds are valued as \$1.5 kg$^{-1}$).

In terms of labor savings, results suggest that for the GHP valued at \$50 to generate equal net returns as the SSP, it is required to reduce labor man-days for planting by 38.66%. Stated differently, this implies that for the GHP to enable a farmer to break-even, it should reduce the amount of labor required for planting by at least about 39%. Since planting is done in one motion with the GHP, it does have some potential for labor saving. Our experience, however, is that there is little or no labor saving and certainly nothing close to 38.66%, so labor saving does not appear to be a sufficient motivation for adopting the GHP. In addition, the main part of the GHP is metal and contains the seeds so that it weighs more than the SSP, which makes it being a labor saving technology even more unlikely.

Since the value of the GHP depends on its production and transactions costs, its market price would perhaps be different from the one assumed above, which would ultimately alter our partial budgeting results. Considering such potential disparity and holding other factors fixed, break-even values of corn yield, labor, and seed at varying market prices of the GHP are presented in Table 5.

**Table 5. Break-even corn yield, corn seed, and labor savings.**

| Price of GHP | Break-even corn yield | Break-even amount of seed | Break-even amount of labor |
|---|---|---|---|
| \$ unit$^{-1}$ | Mg ha$^{-1}$ | kg ha$^{-1}$ | man-days ha$^{-1}$ |
| 40 | 0.022 | 2.578 | 1.547 |
| 45 | 0.025 | 2.900 | 1.740 |
| 50 | 0.028 | 3.222 | 1.933 |
| 55 | 0.030 | 3.544 | 2.127 |
| 60 | 0.033 | 3.867 | 2.320 |
| 65 | 0.036 | 4.189 | 2.513 |
| 70 | 0.039 | 4.511 | 2.706 |
| 75 | 0.041 | 4.833 | 2.900 |
| 80 | 0.044 | 5.156 | 3.093 |
| 85 | 0.047 | 5.478 | 3.287 |
| 90 | 0.050 | 5.800 | 3.480 |
| 95 | 0.052 | 6.122 | 3.673 |
| 100 | 0.055 | 6.444 | 3.867 |

Table 6. Average emergence rates (%) according to planter type obtained in 2014, 2015, and 2016.

| Planter type | 2014 | | 2015 | | 2016 | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | Mean | SD |
| SSP | 89.333 | 17.282 | 96.565 | 5.010 | 91.167 | 5.734 |
| GHP | 82.056 | 21.421 | 80.372 | 14.372 | 86.020 | 9.411 |
| JDP | 87.333 | 14.224 | 92.288 | 10.461 | 95.583 | 4.641 |

As mentioned before, it is assumed that the GHP's market price would range between \$40 and \$100 unit$^{-1}$. If the price of the GHP were \$95 unit$^{-1}$, for it to produce the same net returns as the SSP, the GHP would need to increase corn yields by about 2.08% ha$^{-1}$ or result in seed savings of 23.16% ha$^{-1}$, all other things being equal.

Similarly, it would have to reduce labor man-days required for planting corn by about 74%. If the market price of the GHP were \$40 per unit, the break-even values for seeds, labor, and corn yields would be 9.75% less seeds ha$^{-1}$, about 30.94% less man-days ha$^{-1}$, and 0.88% more corn yield ha$^{-1}$.

The smallholder farmer is assumed to be cash constrained and thus only able to purchase and apply a fixed amount of fertilizer per hectare. In terms of added corn yields due to 18% reduced N loss from ammonia volatilization, our findings show that a farmer would realize about 10.82% of additional corn per hectare (about 0.432 Mg ha$^{-1}$) if the GHP were used to apply fertilizer. Thus, using the GHP to apply fertilizer would provide about \$75.74 ha$^{-1}$, assuming fertilizer is limited. Therefore, using it to apply fertilizer on only 1 ha is sufficient to pay for the full cost of the GHP priced anywhere between \$40 and \$70 unit$^{-1}$.

Clearly from the linear mixed effects regression model, the GHP resulted in lower corn yields per hectare than the SSP, and a plausible reason for its lower corn yields could be due to the way it was designed. The GHP, like the SSP, is not designed to ensure or enhance seed to soil contact (see video, https://www.youtube.com/watch?v=VisKBsqcCWA). The SSP's operator used his/her foot to enhance soil-to-seed contact, whereas this was not done with the GHP. Another limitation of the experiment is that unlike conventional practice in developing countries, only one seed was dropped per hill with the SSP. A third limitation is that within-row spacing was uniform for all treatments. Thus, the seeding rate was held constant and findings from the experiment cannot be used to address the potential for seed savings with the GHP relative to the SSP.

Following Martin et al. (2005) and Rutto et al. (2014), lack of attention to seed-to-soil contact when the GHP plots were seeded or failure by the GHP to drop the seed may have contributed to lower emergence rates for GHP relative to SSP and JDP and the resultant lower crop yield on the GHP plots. As shown in Table 6, the GHP had the lowest corn emergence rates among the three treatments in all the years and possibly it did not always place a seed. As Dhillon et al. (2018) note, these findings have already been used to modify both the design and use of the hand planter.

## CONCLUSION

The GHP has the potential to improve yields and reduce costs for planting corn in developing countries. In terms of seed savings, a GHP valued at \$50 would be a break-even investment if it increased corn yields by 1.12% ha$^{-1}$ or saved about 12.19% of seeds ha$^{-1}$. If labor reduction were its only benefit, a reduction of labor man-days by 38.66% would be required for it to be economically as viable as the SSP. Since the GHP's market price would vary, if the GHP sold at \$95, break-even would require a 2.08% increase in yield, a 23.16% seed savings, or a 74% reduction in labor. In terms of added corn yields due to reduced loss of N from ammonia volatilization, the GHP seems to be a profitable venture, as it would result in about a 10.82% increase of corn per hectare, which is a staggering \$75.74 additional corn returns per hectare. With about \$74 more added revenue, the farmer would be able to pay for the GHP from using it on a single hectare. This result suggests that the economics of the GHP are more favorable for using it to apply fertilizer than for planting corn.

The GHP was compared with two ideal planting techniques. The GHP had lower corn yields than an SSP with perfect seed singulation. The GHP had lower corn emergence, which may be due to the GHP failing to drop a seed or incomplete seed and soil contact. The SSP was used in an ideal situation (up to 100% seed singulation), which is different from how farmers use it. Further research is needed to evaluate the GHP vs. actual farmer practice. Given the potential for the GHP to reduce seed costs, increase corn yield due to reduced loss of N from ammonia volatilization, and reduce potential health risk relative to the SSP, it is recommended that additional field trials be conducted with the following changes. First, either the GHP should be modified to enhance seed-to-soil contact when seeding, or the GHP operator should cover and step on the soil above each placed seed. Second, within-row distance between seed drops should be doubled in the SSP plots relative to within-row distance between seed drops in the GHP plots to more nearly simulate farmer practice. Third, two seeds should be dropped at each location in the SSP plots relative to one seed in GHP plots.

One limitation of our study is that consequences of physical contact between treated seed and SSP and GHP laborers were not determined. The GHP may reduce the negative consequences to operator health resulting from handling treated seed. Additional research would be required to quantify this potential benefit from using a GHP rather than SSP. Furthermore, due to uncertainty, producers may require a higher rate of return to adopt. Micro-dosing of fertilizer looks promising, but as Jama et al. (2017) argue, research is needed to demonstrate results in actual farmers' fields rather than only on field trials.

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