Research Article

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Simulation for Design and Material Selection of a Deep Placement Fertilizer Applicator for Soybean Cultivation

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Abstract: The optimal design of a subsoiler implement is a complex work that includes optimal design, material properties, structural reliability, random variables, soil properties, soil tillage equipment, and optimum safety measures. The main objectives of this study were to design and simulate the deep placement fertilizer applicator (DPFA) by using the finite element method (FEM). FEM simulation software was used to select the optimum material properties and improve the safety factor by considering a range of loads on DPFA. Three applied forces in a static simulation (4500, 5000 and 6000 N) were considered as were three application depths of fertilizers (0.15, 0.20, and 0.25 m), to improve the safety measures of the design. The simulation results showed that the best material property for DPFA is the AISI 4135 QT carbon steel materials. This yields a high strength of 780 MPa and an ultimate tensile strength of 950 MPa (Young's Modulus of 207 GPa and with Poisson's Ratio of 0.33). The static simulation for 6000 N shows that the DPFA model had a maximum stress and strain of 379.9 MPa and 25.6×10^{-4} mm/mm respectively, with a contact pressure of 207 MPa, and a maximum displacement of 3.1 mm. The study results can provide theoretical and technical support for the development of agricultural tools, especially for DPFA in selecting optimum material properties and improving safety factors.

Keywords: Deep placement fertilizer technology, Fertilizer applicator, Chisel plow, FEM, Material selection

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1 Introduction

The development of new technologies and methods in crop growth is one of the important roles in sustainable agriculture. To do this, farmers in developing countries are looking for new technology to increase labor-saving, crop yields and the quality thereof, by reducing the amount of fertilizer used. In addition, this should decrease environmental damage to the atmosphere and water [1].

Deep placement fertilizer technology (DPFT) is an innovative and cost-effective practice, which serves not only in the reduction of wastage and excessive use of fertilizer but also in the even distribution of nutrients in the soil and the mitigation of the negative impact on the environment induced by fertilizer [2]. Furthermore, the subsoil tillage may greatly improve crop growth and increase the utilization rate of soil nutrients by providing free air and water exchange through the tillage of compacted soil layers [3].

In several developed and developing countries, especially Japan, China and Bangladesh, the multiple benefits of DPFT have been confirmed by experts. In Japan, it has been proven that the deep application of controlled-release fertilizers such as coated urea and lime nitrogen, as well as phosphorus and potassium at depths of 20 cm, has a positive effect on growth, seed quality and the yield of soybean plants. This is achieved by the promotion of fertilizer fixation, especially through the reproductive stages (R1 – R6) [4–7]. In China and Bangladesh, several types of research endeavors were carried out on nitrogen fertilizer efficiency, the environmental impacts of this fertilizer, and the crop productivity of deep placement application in rice fields. It has been established that deep fertilizer placement from 5 to 20 cm have significantly increased overall nitrogen use efficiency by 20 – 50% and grain yields by 5 – 25% on average compared to broadcast fertilizer application (shallow soil application). In addition, nitrogen deep

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placement application significantly decreased mean nitrogen concentration by 60%, and pH by 3% in floodwater [8–10].

Besides the benefits of DPFT, labor-intensive work is still required for deep fertilizer placement in some cases, whether it be of a small or large scale of agricultural practices. Therefore, to implement DPFT during the sowing of crops in different scales of agriculture, the development of mechanized deep fertilizer technologies, and new optimized deep placement fertilizer applicators (DPFA), are necessary to be developed for subsoiling fertilizer application, and tillage purposes [8]. Consequently, deep placement fertilizer machinery and subsoilers have been successfully developed and improved recently. For example, the research by Fujii *et al.* [1] was the evaluation of tillage efficiency and power requirements of a rotary tillage implement combined with a deep placement fertilizer applicator. Zeng *et al.* discussed in [11] the method of modeling a deep tillage tool with heterogeneous soil by a discrete element model (DEM). It was found that the better performance of the deep tillage tool achieved at 5 – 20 mm deeper than the hardpan layer, where it has a greater bulk density than the topsoil layer. Hang *et al.* [12] developed a subsoiling model by DEM for soil disturbance in different tine spacing of the subsoiler. It was later verified in a discrete element simulation, as well as in a field test with a loamy clay soil. Ebrahimi *et al.* [13] and Topakci *et al.* [14] conducted practical research on life estimation and optimization of a deep tillage tool by the Finite Element Method (FEM) and through the performance of field experiments. Sandakov *et al.* [15] optimized a chisel plow model by decreasing the mass and increasing its service life in an FEM (simulation software). Moreover, several interesting studies on developing deep placement fertilizer applicators and subsoilers were published [16–19]. However, the studies of developed machinery and subsoilers still have limited applied knowledge of DPFT utilization and optimization of DPFA. Especially in design optimization, selecting material properties, and optimum safety factors depending on working depths.

The main purpose of this study is to design and simulate a DPFA to select the optimum material properties and develop better safety measures. Furthermore, the designed DPFA will be implemented in the development of a seeder prototype for soybean (*Glycine max* (L.) Merr.) cultivation in Primorsky Krai (PK), Russia.

The FEM simulation software was used as the main technique for testing, which is commonly used to design and develop parts for machines and machine prototypes [20]. To analyze the mechanical behavior of the DPFA and to select the optimum material properties, several types of FEM analyses were used, including structural

and stress analysis depending on different loads [14, 19]. In this study, the FEM was used to select the optimum material properties and optimize safety factors by considering a range of loads on the DPFA, which are already generated on the most commonly used subsoilers in agricultural machinery.

2 Materials and Methods

2.1 Prototype and Technology

The technological concept of a new prototype seeder is to perform a deep application of controlled-release fertilizers with simultaneous soybean sowing for large scale agriculture. According to previous research, the average fertilizer application depth to achieve better crop yield and quality, as well as environment protection varies from 10 to 20 cm depths [4–10]. Therefore, three main fertilizer application depths of 0.15, 0.20, and 0.25 m have been considered as the main technological aspects for the prototype and DPFA design. Figure 1 shows the main technological principal of the prototype.

Figure 1: The mechanism of DPFA with simultaneous soybean sowing

The prototype is equipped with the DPFA which provides subsoil tillage and deep application of controlled-release (slow-release) fertilizers at depths of 0.15 – 0.25 m., with simultaneous wide-row sowing of soybeans and application of fertilizers (base fertilizer) at the same soybean sowing depth (0.04 – 0.06 m). Thus, this method of fertilizer application will allow plants to grow throughout the entire growing season by providing all-time essential nutrients. Figure 2 illustrates a schematic diagram of the prototype.

1, 2 – lower and upper frame parts; 3 – hitch linkage; 4 – fertilizer hopper; 5 – fertilizer pipe; 6 – DPFA; 7 – DPFA's knife; 8 – seed-feeding mechanism; 9 – suspension; 10 – driving wheel; 11 – reduction gear; 12 – fertilizer hopper shaft; 13 – fertilizer hopper shaft drive chain; 14 – DPFA bolt connectors; 15 – frame parts connecting plate.

Figure 2: Schematic diagram of the prototype

Furthermore, this seeder prototype can be potentially used for other crops for example Maize (*Zea mays* L.). In addition, the prototype without seed-feeding mechanisms can be used for deep soil chiseling with fertilizer application before sowing crops by other agricultural types of machinery. Moreover, the DPFA itself could be adopted for any agricultural machinery.

2.2 Design of the DPFA

The design of the DPFA was based on a chisel plow model by Sandakov *et al.* [15], which was proposed for grain production in Russia. The model was designed and analyzed in a FEM simulation by static analysis with a total applied force of 5000 N. The chisel plow model has an optimum shape with four holes of a shank for a frame attachment. The knife of the chisel plow has a fixation to the shank by two bolts connection under a down part of the vertical plane of the chisel plow. Figure 3 shows the overall view of the chisel plow.

The material properties of the chisel plow are specified in Table 1.

However, it was targeted to design a new DPFA plow, which would not only be satisfactory with technical issues for soybean cultivation, but meet the issues of conserving resources due to its streamline design.

Figure 3: Chisel plow

2.3 Study Methods

The main study tasks were to design a new DPFA by improving the shape of the chisel plow. From selecting optimum material properties for its further manufacture, and developing a fertilizer pipe, which will be attached to the plow, and simultaneously perform deep tillage and deep placement fertilizer application. Furthermore, since the maximum subsoiling operating depth is expected to be 0.25 m, it was targeted to have a minimum safety factor (SF) between 2 and 2.5 for its material property. This minimum SF will not allow the DPFA to bend or break due to unpredictable working conditions in soil (e.g. mixed soil struc-

Table 1: Material properties of the original chisel plow

Chisel plow part	Shank	Knife
Properties, Unit	Steel	Steel
Density (kg/m^3)	7850	7820
Young's modulus (Pa)	2.12×10^{11}	2.11×10^{11}
Yield strength (Pa)	3.45×10^8	7.85×10^8
Tangent modulus (Pa)	7.94×10^{10}	7.94×10^{10}
Tensile yield stress (MPa)	470	735
Ultimate strength (MPa)	660	981
Poisson's ratio	0.31	0.29
Mass (kg)	10.75	1.29

Source: [15]

ture with different objects in the soil, a heavy soil property etc.). Moreover, this SF will promote an increasing effect to the DPFA's service life.

In this study, the FEM allowed us to simulate the behavior of the DPFA under operating conditions by using a static analysis system called, AutoCAD Fusion 360, Autodesk, Inc. This simulation software shows the results of the analysis as a 3D televised model by generating specified areas with a different range of colors to visualize material behavior under different types of analysis [14].

The methods in this study have four main stages. First, the design of a 3D model with the needed overall dimensions and generated mesh are completed in the 3D simulation program. The second stage is the selection of material properties in the 3D simulation program with optimum yield and ultimate strength to control the optimum safety factor (SF). For ductile materials, the SF is expected to be checked for both yield and ultimate strengths. Since the yield strengths calculation will define the SF until the part starts to deform plasticity, however, the ultimate strengths result will define the SF until it reaches part failure. Therefore, in this study the SF will be assumed and calculated

Figure 4: Flow chart of the DPFA design algorithm

automatically in the 3D simulation program. This mechanical method is normalized and is used in the mechanical engineering industry to determine the elastic deflection for ductile materials [21, 22].

The third and final stage is the use of static analysis by exploiting a range of loads with different constraints (boundary condition) to the selected geometry, and the analysis of the results from the simulation so as to define material properties with an optimum SF for further manufacture. According to the study by Topakci *et al.* [14], the maximum draft force of each subsoil tine had 12.773 kN at the working depth of 0.45 – 0.75 m. In the study by Sandakov *et al.* [15], in the static analysis the total applied force of 5000 N was simulated on the chisel plow. In addition, the soil moisture content and soil compactness were important to consider since it will have a significant effect on the resistance forces in field experiments [23]. Unfortunately, there are no existing studies on draft force and soil resistance properties such as soil compactness and assumptions related to soil moisture in PK, Russia. Therefore, in this study for the static analysis of the DPFA was considered. A maximum force of 6000 N was applied for the depth of 0.25 m based on the result of Topakci *et al.* and Sandakov *et al.* [14, 15]. Moreover, for the static simulation, the depths of 0.15 and 0.20 m were considered, and forces of 4500 and 5000 N were applied, respectively. As a result, based on the described method, objective's function and optimization algorithm were developed and represented in Figure 4.

This algorithm presents graphically the information introduced in the section of study methods as a block diagram, which can be used as one of the technical methods to optimize the DPFA.

3 Results and Discussion

3.1 Design of DPFA

At the first stage of the study, the DPFA was designed, to satisfy the technical requirements of the deep fertilizer application for soybean cultivation. The main issue was to perform deep tillage and simultaneously apply fertilizers into the soil at the depth of 0.15, 0.20 and 0.25 m. Second, the developed fertilizer pipe of fertilizer transportation should not increase the tractive resistance made by the chisel plow. Therefore, the total width of the fertilizer pipe was designed at 18 mm, which is less than the total thickness of the shank (24 mm). Moreover, the fertilizer pipe has a round inlet and square outlet, and from the top

to the bottom of the fertilizer pipe, the pipe has a truncated shape reduced by 10 mm. Figure 5 shows a schematic diagram of the designed DPFA with overall dimensions, (mm). In addition, Figure 6 illustrates a schematic diagram of the designed fertilizer pipe with sections views in order to reveal the inside shape.

Moreover, the DPFA was designed with five fixation holes to adjust to the three depths for the seeder prototype. Thus, it was convenient to simulate accurately the different applicable depths by different boundary conditions.

a – height of the frame connector; b – width of the shank; h – height of the shank; K – length of the knife; k – width of the knife; R – radius of curvature of the shank; d – penetration angle; F – inlet of the fertilizer pipe; t – thickness of the shank.

Figure 5: Schematic diagram of the DPFA

A – zoomed view of the square outlet; B-B – section view of the middle of the pipe; C-C – section view of the inlet

Note: Fertilizer pipe thickness – 2 mm.

Figure 6: Schematic diagram of the fertilizer pipe

Furthermore, the knife fixation to the shank and the fixation of the fertilizer pipe to the shank were not conducted in this study since this is the first DPFA prototype. These fixations were simulated as if it was fixed by an arc welding and had a full body connection. However, the different material properties of the knife, chisel shank and fertilizer pipe were considered.

3.2 FEM Simulation

Once the design was completed, a finite element model of the DPFA for soybean cultivation was done. The mesh sensitivity analysis was conducted to acquire the optimum mesh size and achieve the proper accuracy of computations. However, in the study by Kamal *et al.* [24], was discussed that the stress values did not change by an appreciable amount by decreasing the mesh size, however, there was an exponential increase in the nodes and elements number, that has resulted in a rise of the processing time and data storage requirements without much significance in the accuracy of the stress results. Thus, the mesh of the DPFA model was meshed and calculated automatically by the Fusion 360 software based on Model-Based Size (Average Element Size) 1–10%. Additionally, all edges of the DPFA model were filleted (rounded) by the radius of 2 mm to reduce the stress concentrations. The numerical model is shown in Figure 7, consists of 116,134 nodes and 66,221 elements. In Table 2 is summarized the result of the used mesh.

Figure 7: Finite element model and meshing construction of the DPFA

As the maximum load will be evenly distributed throughout the subsoil area of the DPFA, however, in the boundary condition of the simulation, the different load

Table 2: Mesh characteristics

Base Mesh (Solids): 116,134 nodes, 66,221 elements
Average Element Size (% of model size):
Scale Mesh Size per part: 10
Max. Adjacent Mesh Size Ratio: 1.5
Max. Aspect Ratio: 10
Max. Turn Angle on Curves (Deg.): 60
Min. Element Size (% of average size): 20
Element order: Parabolic
Number of Tetrahedra: 66,386 (100% of elements (100% of volume)):
Face Angle: min - 0.652, max - 177
Dihedral Angle: min - 0.724, max - 178
Worst Shape Ratio: 202 on element 11,976
Worst Aspect Ratio: 25.7 on element 8,107, shortest edge: 0.000144, longest: 0.048
Lowest Collapse Ratio: 0.00799 on element 11,976
Worst Jacobian Ratio: 1 on element 1

was applied on the maximum load surface of the knife. The principal of the boundary condition is shown in Figure 8. The boundary conditions of the static simulation are given in Figure 9.

Max. Load – load applied to the surface of the knife (4500, 5000 and 6000 N); Depth – subsoil area.

Figure 8: The overall view of boundary conditions

The next steps were the selection of the material properties to achieve the defined SF through multiple experiments within the simulation in accordance with the DPFA design algorithm (Fig. 4). Thus, as the maximum subsoiling operating depth of the DPFA is 0.25 m with the greatest

Note: Load is applied in the opposite to the forward direction of the DPFA.

Figure 9: Boundary conditions

a) – Depth – 0.15 m, load – 4500 N; b) – Depth – 0.20 m, load – 5000 N; c) – Depth – 0.25 m, load – 6000 N; the diameter of bolts connector is 19 mm.

Note: Depth – 0.25 m; Force loaded – 6000 N.

Figure 10: Results of the static analysis of the DPFA

a) – Safety factor; b) – Displacement; c) – Stress; d) – Strain Equivalent; e) – Reaction Force; f) – Contact Pressure.

static force of 6000 N (which requires the optimum safety factor of $2 \leq SF \leq 2.5$), making the result of the static analysis for this case was presented graphically. The end results of the simulation with the final selected material property and various behaviors of the materials are shown in figure 10.

According to the static simulation results (Figure 10, (a)), the minimum SF is 2.3 per body under loaded force of 6000 N. The SF is a ratio of the maximum strength of the selected material to the stress calculated in the simulation, and shows the calculation result based on the yield strength. Thus, this SF target meets the set optimum SF ($2 \leq SF \leq 2.5$), and the DPFA design is not expected to bend or break with the current force load and analysis criteria. In addition, the simulation shows the minimum SF of 3.1 for the depth of 0.15 m and a force load of 4500 N, as well as 2.8 for 0.20 m with 5000 N respectively. Table 3 summarizes the optimum material properties for the DPFA used in the static stimulation.

Table 3: Material properties used in the simulation

DPFA part	Shank	Fertilizer pipe
Properties, Unit	Steel AISI 4135 QT	Steel
Density (kg/m ³)	7860	7850
Young's modulus (GPa)	207	205
Yield strength (MPa)	780	207
Ultimate Tensile Strength (MPa)	950	345
Modulus of Elasticity (GPa)	205	185
Bulk Modulus (GPa)	160	160
Shear Modulus (GPa)	80	75
Poisson's Ratio	0.33	0.29
Mass (kg)	11.2	0.58

According to Table 3, one of the suitable materials for the chisel shank, as part of the main DPFA body, was chosen to achieve the set SF is the AISI 4135 QT steel. However, this is the general recommendation based on the simulation conditions. And the further selected material for the manufacture of the DPFA may not be appropriate to a particular industry or application due to specific working conditions or other factors relevant to cultural expectations by way of farming. Therefore, different types of material properties were used for the static stimulation where the yield strength was varied from 350 to 900 MPa, and the ultimate strength was varied from 420 to 1000 MPa. Thus, it

Table 4: Full result summary of 0.25 m by 6000 N loaded force

Category	Minimum	Maximum
Safety Factor (Per Body)	2.374	15
Stress Von Mises (MPa)	0.00124	379.9
1st Principal	-98.81	488.7
3rd Principal	-382.3	141.1
Normal XX	-177.7	278
Normal YY	-323.1	384.1
Normal ZZ	-115.3	141.4
Shear XY	-121.8	157.2
Shear YZ	-66.26	66.09
Shear ZX	-104.7	104.2
Displacement total (mm)	0	3.121
X	-0.007205	2.216
Y	-2.198	0.5473
Z	-0.004175	0.003852
Reaction Force total (N)	0	5642
X	-4258	1688
Y	-4027	4939
Z	-217.9	196.6
Strain Equivalent (mm/mm)	9.958E-09	0.002568
1st Principal	-2.863E-07	0.002872
3rd Principal	-0.002122	5.263E-06
Normal XX	-6.224E-04	0.00105
Normal YY	-0.001094	0.001607
Normal ZZ	-6.352E-04	2.532E-04
Shear XY	-0.001565	0.002021
Shear YZ	-8.514E-04	8.493E-04
Shear ZX	-0.001346	0.001339
Contact Pressure total (MPa)	0	207
X	-80.16	134.1
Y	-145.9	86.01
Z	-59.98	59.65

was determined that for this shape of the DPFA to achieve the minimum SF from 2 to 2.5, the main material properties of carbon steel should possess a high yield strength of 800 MPa and ultimate strength of not less than 900 MPa, using Young's Modulus of 207×10^{-3} MPa with Poisson's Ratio of 0.33. Moreover, it is always necessary to consider all physical and mechanical properties in order to control a wear-resistance property depending on working conditions [25, 26].

Referring to Table 1 of the material properties of the original chisel plow the yield strength and ultimate strength are much less than it was obtained in the simulation. This result occurred because it used a greater applied

force than in the previous study. However, the total mass was reduced by 0.26 kg due to the fact that the overall design of the original chisel plow was changed.

The static simulation for 6000 N shows that the DPFA model had maximum stress of 379.9 MPa (Figure 10, (c)), the equivalent maximum strain of 25.6×10^{-4} mm/mm (Figure 10, (d)), the maximum displacement of 3.1 mm (Figure 10, (b)), the total reaction force of 5642 N (Figure 10 (e)), and the total contact pressure of 207 MPa (Figure 10, (f)). In Table 4 is a detailed results summary of the simulation for 0.25 m depth with 6000 N loaded force.

The static simulation for 4500 and 5000 N had the maximum stress of 285.4 and 316.8 MPa, the maximum equivalent strain of 19.3×10^{-4} and 21.4×10^{-4} mm/mm, the maximum displacement of 1.5 and 2.1 mm, the total reaction force of 3243 and 3930 N, and the total contact pressure of 153.3 and 172.5 MPa, respectively. A brief results summary is specified in Tables 5 and 6.

Table 5: Result summary of 0.15 m by 4500 N loaded force

Category	Minimum	Maximum
Safety Factor (Per Body)	3.16	15
Stress Von Mises (MPa)	6.309E-07	285.4
Displacement total (mm)	0	1.571
Reaction Force total (N)	0	3243
Strain Equivalent (mm/mm)	3.96E-12	0.00193
Contact Pressure total (MPa)	0	153.3

Table 6: Result summary of 0.20 m by 5000 N loaded force

Category	Minimum	Maximum
Safety Factor (Per Body)	2.84	15
Stress Von Mises (MPa)	9.922E-05	316.8
Displacement total (mm)	0	2.152
Reaction Force total (N)	0	3930
Strain Equivalent (mm/mm)	4.819E-10	0.00214
Contact Pressure total (MPa)	0	172.5

Furthermore, the stress and strain analysis of the static simulation showed the most stressed areas where there are stress concentrations on the DPFA and areas of expected breaks. These two criteria are important to improve

the future design of machinery parts and practical experiments [27, 28]. For instance, the stress analysis shows the areas where strain gages can be attached for practical experiments to obtain soil resistance force and strain induced on the DPFA.

3.3 Further research steps

As the second step of the study, based on the simulation results and the selected material properties, a DPFA prototype was manufactured and assembled with the seeder prototype for further field experiments. Figure 11 illustrates the manufactured DPFA and developed seeder prototype at Primorskaya State Academy of Agriculture, Russia.

Figure 11: DPFA and Seeder prototype, 2019
a) – Manufactured DPFA; b) – Developed seeder prototype

Further field experiments with additional equipment (e.g. Universal data logger recorder with strain gages) are necessary to verify the applied simulation force and selected material property. Moreover, it is necessary to improve practically the final shape of the DPFA before its produced in significant quantities. Furthermore, the field experiments can also verify the developed fertilizer pipe in the point of fertilizer transportation, and soil sticking to the outlet of the fertilizer pipe. In addition, soil resistance properties such as soil compactness and assumptions related to soil moisture should be considered in field experiments.

4 Conclusions

This study was focused on the new design of the DPFA, optimum material selection and obtaining the required

safety factor of the DPFA for soybean cultivation. A new fertilizer pipe was developed to transport fertilizer into the soil, which is not increasing the tractive resistance. However, practical field experiments are needed to verify the practical application of the DPFA.

The FEM was used as the main technique for the static simulation of the DPFA to select the optimum material properties and improve the safety factor. Three different applied forces in the static simulation (4500, 5000 and 6000 N) were considered as for three different application depths of fertilizers (0.15, 0.20, and 0.25 m). According to the study, the simulation results can be summarized as follows:

1. The best selected material property for the DPFA was the AISI 4135 QT carbon steel plating with high yield strength of 780 MPa and ultimate tensile strength of 950 MPa, Young's Modulus of 207 GPa and with Poisson's Ratio of 0.33.
2. The maximum applied force of 6000 N shows that the DPFA model had the maximum stress of 379.9 MPa and strain of 25.6×10^{-4} mm/mm, the total reaction force of 5642 N, contact pressure of 207 MPa, and the maximum displacement of 3.1 mm.
3. The applied force of 4500 and 5000 N had the maximum stress of 285.4 and 316.8 MPa, maximum strain of 19.3×10^{-4} and 21.4×10^{-4} mm/mm, the maximum displacement of 1.5 and 2.1 mm, total reaction force of 3243 and 3930 N, and total contact pressure of 153.3 and 172.5 MPa, respectively.
4. The total mass of the DPFA was 11.78 kg.
5. Based on the simulation result, a DPFA prototype was manufactured and assembled with the seeder prototype for further field experiments.

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