Development of a canopy opener to increase spray deposition and coverage inside soybean canopies

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Abstract. At the growth stage from R3 to R5, the foliage at the top of a soybean canopy takes the most part of the canopy and these top leaves cover the most area of the field. Because of the high foliage density at the top of canopy, conventional boom sprayers can hardly deliver sufficient chemical droplets to inner part of canopies. An experimental canopy opener was developed and attached on a conventional boom sprayer to increase spray deposition and coverage inside soybean canopies. The canopy opener consisted of a conduit pipe mounted on the spray boom upwind the nozzles. The conduit pipe opened the top part of canopies as the sprayer traveled to achieve better penetration of spray into lower parts of the soybean plant, where the rust infection first starts. Conventional flat fan nozzles were used for the test with the canopy opener for the application rate of 145 L/ha. Spray deposition and coverage at two heights inside canopies were determined. Treatments included three depths of the opener inside canopies, three horizontal distances of the opener from nozzles, and two nozzle sizes. A mathematical model was also developed to determine the plant deflection and traveling time so that droplets could be delivered inside canopies before the top part of canopy returning to vertical positions. Spray deposition and coverage inside canopies with the opener were also compared with a conventional boom sprayer without the opener. With the help of the canopy opener to push the top part of canopies, spray droplets had more space to reach middle and bottom of canopies, resulting in higher spray deposition and coverage on targets inside canopies.

Keywords. Soybean rust, New sprayer, Mechanical bender, Pesticide, Boom sprayer.
Introduction

Soybean yield will be greatly reduced from the soybean rust disease if not treated effectively. The soybean rust infection usually starts at lower plant surfaces and moves upwards during R3 and R5 stages. To effectively control the disease, it is essential to deliver fungicides sufficiently covering tissues from the bottom to the middle of canopies. However, between R3 and R5 stages, soybean canopies are tall and dense, and the most foliage on a plant is on the top part of the canopy. Conventional boom sprayers with hydraulic nozzles, due to their simplicity, are widely used in the field applications for controls of weeds, insects and fungi, but the deposition uniformity inside dense canopies is very poor (Zhu et al., 2002, 2004). Air-assist sprayers can effectively deliver pest control agents inside dense canopies (Reichard et al., 1979; Fox et al., 1982); however, relatively high labor and machinery costs should be added to achieve their mission.

The conventional boom sprayers may lack of penetration capability to transport adequate spray deposition and coverage to the bottom and middle of dense soybean canopies. Opening and disturbing the top leaves can certainly help droplets from conventional boom sprayers straightforwardly reach lower leaves and stems inside canopies.

The objective of this research was to develop a mechanical canopy opener, simply attached on the conventional boom sprayers, to improve spray deposition and coverage inside dense soybean canopies.

Materials and Methods

Development of canopy opener

The hypothesis is that spray penetration into dense canopies from conventional boom sprayers can be improved by simply attaching a simple straight bar in front of the spray nozzles. When the sprayer travels, the attached bar can push the canopy ahead of the spray pattern, and open the canopy for spray droplets to reach the middle and bottom of the canopy.

The original idea of making the opener was that the bar should perform as a roller when it pushed plants to open enough space for spray droplets reaching inside canopies. When the bar impacts the plant, it would rotate freely to damp the impact force on the plants. PVC pipes were originally selected for the bar to open canopies, but they did not work well because they were not straight (a bow shape toward the ground) after their two ends were attached on two vertical holders. The final selection of the bar was a 2.5 cm diameter steel pipe. The two ends of the pipe were attached on vertical holders with lock nuts (Fig. 1).

The canopy opener was fabricated with a straight metal pipe, two vertical metal stands to hold the metal pipe, and two brackets to mount the plates on the spray boom. The metal

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pipe was 3.6 m long and 2.5 cm diameter. The height of the pipe could be adjusted by changing positions of the screws on the plates. The horizontal distance between the pipe and nozzles could be adjusted by moving the plate holders horizontally on the bracket (Fig. 1).

Figure 1. 3-D schematic drawing of the canopy opener.

A three-point hitch plot sprayer with a 3 m off-set spray boom was used as a trial sprayer to attach the mechanical opener. The sprayer was consisted of a gasoline engine-driven diaphragm pump, a 200 L water tank, and a 3 m long spray boom, and was supported with a three-point hitch behind the tractor. The spray boom was equipped with 7 nozzles (50 cm apart), and was mounted on the right side of the tractor. The first nozzle was 50 cm away from the tractor back tire, and nozzles were spaced 0.45 m apart. The boom height could be adjusted from 110 to 170 cm above the ground.

Models to determine plant deflection and time

A critical design element of the opener was to determine the opener depth inside canopies and the horizontal width between the pipe and nozzles. Plant deflection was affected by the opener depth. Sufficient opener width allows adequate time for droplets to reach targets inside canopies before the canopies return to the normal position. After the opener leaves the canopy, the canopy will return its original position due to the spring effect. The time for droplets traveling from the nozzle to the targets inside canopy should be shorter than the time for the plant returning to its vertical position.
From beam theory, the motion of a plant can be modeled as an oscillating beam,

\[
\rho \frac{\partial^2 y}{\partial^2 t} = -E k^2 \frac{\partial^4 y}{\partial x^4}
\]  

(1)

with boundary and initial conditions,

\[y(0,t)=0, \ y(h,0)=y_0, \ \frac{\partial y}{\partial t}(h,0) = 0, \ \frac{\partial^2 y}{\partial x}(0,t) = 0\]

and

\[\frac{\partial^2 y}{\partial^2 x}(h,t) = 0, \ \frac{\partial^3 y}{\partial^3 x}(h,t) = 0\]

In modeling, bending of a soybean plant, a fundamental question was: can ordinary beam theory be used? An immediate problem was that in most applications of beam theory, deflections are so small that distance measured along the beam changes very little in comparison with no-load conditions. In the case of a comparatively tall and slender soybean plant, deflections of interest can be so large that nominal end-of-beam distances measured under no-load conditions can be significantly greater than the end of beam distance for a deflected “beam”. This factor suggested a model effectively using a series of short cantilever beams end to end load in succession from the uppermost loading point and progressing downward to a fixed base. Therefore, a solution of equation (1) is,

\[y = \frac{16 hp x}{3AE \delta(x \delta + d_0)} e^{-\alpha \omega t} \left[ \frac{\alpha \sin(\sqrt{1-\alpha^2 \omega^2})}{\sqrt{1-\alpha^2}} + \cos(\sqrt{1-\alpha^2 \omega^2}) \right] \]

(2)

where \(p\) is the load, \(h\) is the height of stem to the point of application of bending force, \(E\) is the elastic modulus, \(A\) is the plant cross-section area, \(d_0\) is the plant bottom diameter, \(\omega\) is the frequency, \(\delta\) and \(\alpha\) are the constants.

The maximum deflection of plants occurs at \(x = h\), that is,

\[y_{\text{max}} = \frac{16 h^2 p}{3AE \delta[h \delta + d_0]} \]

(3)

After the opener leaves the plants, the plants will return their normal positions. The movement of plants follows a linear differential equation for a damped harmonic
oscillator, and the time for the plant to return to the vertical position after the opener leaves the plant will be,

\[ T = \frac{1}{\omega \sqrt{1 - \alpha^2}} \arctan\left(\frac{\sqrt{1 - \alpha^2}}{\alpha^2}\right) \]  

(4)

**Field experiments**

Spray deposition and coverage experiments were conducted in a field with drilled bean canopies planted at 18 cm row spacing. At the time of the tests, the soybean plants had average height of 107 cm and weight of 194 grams. The bottom stem diameter was 11.6 cm and the top stem was 6.0 cm. They had reached the R5 development stage. The test plot in the field was 46 m long and 4.6 m wide for each treatment. Each treatment was replicated 4 times. Treatments were organized in a randomized block design with four replications.

Experiments were conducted with 18 different treatments which included three different depths of the opener inside soybean canopies, three different distances between nozzles and the opener, and two different flat fan pattern nozzles. The opener depth inside canopies was 7.5, 15 and 22.5 cm, respectively. The horizontal distance between nozzles and opener were 15, 25 and 35 cm, respectively. Nozzles used in tests were XR8002EVS and XR8004EVS flat fan nozzles (Spraying Systems, Wheaton, IL) operated at 276 kPa. The spray boom was set 22.5 cm above the canopies. The application rate for all treatments was adjusted to 145 L/ha by the travel speed. For the XR8002EVS nozzle the travel speed was 6.4 km/h, and for the XR8004EVS nozzle the travel speed was 11.2 km/h. For comparison, additional two treatments were also conducted with the two nozzles without the opener. A spray mixture containing water and Brilliant Sulfaflavine at a concentration of 2 g/L was used for all treatments.

The artificial targets to collect spray deposits inside canopies representing leaves were 2.5 x 7.5 cm sheet metal plates. The artificial targets to determine spray coverage inside canopies were 5.0 x 7.5 cm water sensitive papers. Three stakes for supporting artificial targets were placed 17, 23, and 29 m from the beginning edge of each plot. The artificial targets were positioned 30 cm and 60 cm above the ground, representing the bottom and middle parts of canopies, respectively. At each height, two plates were used and separated at a 180° angle and two water sensitive papers were used and also separated at a 180° angle. The artificial targets were mounted horizontally with their longer dimension normal to the stake and with 90° radial separation from each other at each height. The midpoint of each plate was 11 cm from the stake. The artificial targets were oriented to avoid overlapping between two heights.

The artificial targets were collected 5 minutes after spraying. The plates were stored in 125-ml wide-mouth glass bottles in non-transparent boxes. The water sensitive papers were stored in plastic sandwich bags.

Spray deposits on metal plates were washed and dissolved in 20 ml of purified water (prepared with the Barnstead Mega-pure System, Model MP-12A). Then, a 4 ml sample
solution was placed in a cuvette for determination of peak fluorescent intensity with a Model LS 50B Luminescence Spectrometer at an excitation wavelength of 460 nm. If a sample concentration fell outside the calibration range, it was further diluted and measured again. Spray deposits on plates were then converted to the volume of spray liquid per square centimeter (µL/cm²).

The spray coverage on each water sensitive paper was analyzed with a computer imaging system which includes a desktop computer, an HP Scanjet 5530 photo-smart scanner and a image software Imaging Tool Windows Version 3.00 (The University of Texas Health Science Center, San Antonio, TX). The resolution for the image analysis was 600 dpi.

Leaf area index (LAI) of the soybean canopy was determined using an LAI-2000 plant canopy analyser (LI-COR®, Inc., Lincoln, Nebraska) with two sensor modes. Three small sections in each plot were randomly selected for the LAI measurement. For each small section, four measurements of LAI at four orientations in a square shape were conducted. The sky was fully covered by clouds at the moment of measurement. The LAI sensor was also calibrated under fully-cloudy conditions.

The time was also measured for the plants returning to the vertical position after the opener left from the plants for the 9 combinations of three opener depths and three distances between nozzles and the opener. After the field experiments, 20 soybean plants were cut above the soil surface, and their weight, height, bottom stem diameter and top stem diameter were measured. These parameters were used for the mathematical deflection model development.

Droplet sizes from nozzles used in the tests were measured with the Oxford Lasers VisiSizer particle/droplet image analysis system. Droplet size distributions were determined 0.3 m below the nozzle orifice across the centerline of the spray pattern width. A minimum 10,000 droplets were counted at each sampling position for the droplet size distribution analysis.

Data were analyzed by one way ANOVA and differences among means were determined with Duncan’s New Multiple-Range Test using the ProStat version 3.8 (Poly Software International, Inc., Pearl River, NY). All significant differences were determined at the 0.05 level of significance.

<table>
<thead>
<tr>
<th>Opener depth (cm)</th>
<th>XR8002 Spray deposit (µL/cm²)</th>
<th>XR8004 Spray deposit (µL/cm²)</th>
<th>XR8002 Spray coverage (%)</th>
<th>XR8004 Spray coverage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Middle</td>
<td>Bottom</td>
<td>Middle</td>
<td>Bottom</td>
</tr>
<tr>
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<td>0.0489</td>
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<td>0.1653</td>
<td>0.0575</td>
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<td>0.0544</td>
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<td>22.5</td>
<td>0.1522</td>
<td>0.0592</td>
<td>0.1891</td>
<td>0.0515</td>
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</table>
Results and Discussion

Field tests

For both 8002 and 8004 nozzles, the sprayer with the opener had higher spray deposition and coverage at the middle and bottom of soybean canopies than the sprayer without the opener (figs. 3, 4, 5, 6).

Because the application rate for both 8002 and 8004 nozzles was 145 L/ha, the XR 8002 and XR8004 nozzles did not have significantly different spray deposition and coverage inside canopies when the opener was used (Tables 1 and 2). Although the 8002 nozzle produced smaller droplet size than the 8004 nozzle, the number of droplets from the 8002 nozzle was greater than the 8004 nozzle.

With either 8002 or 8004 nozzle, there was no significant difference for spray deposits at the middle of canopies among the three opener depths inside canopies (figs. 3 and 4). This result was also true for the deposit at the bottom of canopies. For example, when the opener was 25 cm away from the spray boom, the spray deposit at the bottom of canopies from the XR8004 nozzle was 0.044, 0.070, and 0.054 µL/cm² when the opener depth was 7.5, 15, and 22.5 cm, respectively. At the middle of canopies with the XR8004 nozzle, the average spray deposit from three opener widths was 0.161, 0.170 and 0.190 µL/cm² when the opener depth was 7.5, 15 and 22.5 cm, respectively (Table 1).

Table 2. Average spray deposit and coverage among three opener depths for XR8002 and XR8004 nozzles with opener at three different widths

<table>
<thead>
<tr>
<th>Opener width (cm)</th>
<th>Spray deposit (µL/cm²)</th>
<th>Spray coverage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>XR8002</td>
<td>XR8004</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>Bottom</td>
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<td>0.0418</td>
</tr>
<tr>
<td>25</td>
<td>0.1755</td>
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</tr>
<tr>
<td>35</td>
<td>0.1745</td>
<td>0.0665</td>
</tr>
</tbody>
</table>

Figure 3. Spray deposits at the middle and bottom of soybean canopies from 8002 nozzles with and without the canopy opener at three different opener depths and three different opener widths.
Similar to the deposition results with XR8002 and XR8004 nozzles, there was no significant difference for the spray coverage on targets at either bottom or middle of canopies among the three opener depths (figs. 5 and 6). With the XR8004 nozzle at the 25 cm opener width, spray coverage at the bottom of canopies varied from 3.3 to 3.9% when the opener depth changed from 7.5 to 22.5 cm. At the middle of canopies with the XR8004 nozzle, the average spray coverage for three opener widths was 6.2, 6.3 and 6.8 % when the opener depth was 7.5, 15 and 22.5 cm, respectively (Table 1).

The fact that the amount of spray deposition and percentage of spray coverage inside canopies were not influenced by the opener depth might be because the opener depths tested in this study were beyond the densest part of canopy so that the opener could create enough space inside canopies for droplets to travel.

For XR8002 and XR8004 nozzles, the opener with 25 and 35 cm width had higher spray deposits at middle and bottom of canopies than the opener with 15 cm width for all three opener depths (figs. 3 and 4). For example, at 15 cm opener depth with XR8004 nozzle, the amount of spray deposits at the bottom of canopy was 0.035, 0.070, and 0.058 µL/cm² when the opener width was 15, 25, and 35 cm, respectively. At the middle of canopies with the XR8004 nozzle, the average spray deposit for three opener depths was 0.121, 0.197 and 0.202 µL/cm² when the opener width was 15, 25 and 35 cm, respectively (Table 2). With a narrower opener width, the canopies might return their vertical positions before droplets have enough time to reach bottom part of canopies.

The percentage of spray coverage at the middle of canopies also varied with the opener width for both XR8002 and XR8004 nozzles. (Figs. 5 and 6). In most cases with three
different opener depths, the 15 cm opener width had lower percentage of spray coverage at the middle of canopies for both XR8002 and XR8004 nozzles. However, for both XR8002 and XR8004 nozzles, there was no significant difference for the spray coverage at the bottom of canopies among the 15, 25 and 35 cm opener widths. At the bottom of canopies with the XR8004 nozzle, the average spray coverage from three opener depths was 5.2, 7.2 and 6.8 % for the opener width of 15, 25 and 35 cm, respectively (Table 2). The bottom coverage result was mainly because deposits at bottom of canopies were relatively low and were mostly from large droplets.

Mathematical models

Figure 7 shows the calculated plant deflection along the plant height after the opener left the plant, and figure 8 shows the calculated deflection at the top of plant at different times after the opener left the plant. Curves in the figures represent the situation of plant deflection when the opener depth was 15 cm with assumed values for the parameters shown in equation (2). The values of these parameters will be further verified from future field experiments. According to the calculation, the maximum deflection at the top of the plant was about 30 cm when the opener depth inside canopies was 15 cm (Fig. 7). It took about 0.8 s for the plant to return to near the vertical

Figure 6. Spray coverage at the middle and bottom of soybean canopies from 8004 nozzles with and without the canopy opener at three different opener depths and three different opener widths.

Figure 7. Calculated deflection of a soybean plant before opener leaves plant by equation (2).

Figure 8. Calculated deflection at the top of a soybean plant at different times after opener leaves the plant by equation (2).
position and 2 s for the plant to completely return to the vertical position (Fig. 8). The accuracy of equation (2) will be further verified in the future study.

**Summary**

The amount of spray deposition and percentage of spray coverage at the bottom and middle area inside canopies were not influenced by the opener depth inside canopies when the opener depth was between 7.5 and 22.5 cm. However, quantity of spray deposition and coverage was influenced by the width between the opener and nozzles. Narrower width resulted in less spray deposition and coverage at the bottom of canopies.

However, there could be some potential disadvantages with the current opener design for long spray booms. The opener weight and plant resistance might cause long booms failure. Also, the depth of the opener inside canopies might have great fluctuation across the long boom because the boom might frequently bounce up and down during its travel. Another concern about using the opener was it might transfer other diseases from one place to other place because the opener always touched crops.

Spray deposition and coverage inside canopies were greatly improved by attaching a mechanical canopy opener to a conventional short-boom sprayer. The opener design proved that greater deposition and coverage inside soybean canopies could be achieved by opening and disturbing the top of canopies.

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**References**


