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Evaluating Row Cover Establishment Systems for Cantaloupe and Summer Squash[1]

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Abstract

Use of row covers offer an alternative to pesticide application for management of insect feeding and disease transmission and can be beneficial for extending the growing season. Unfortunately, labor required to establish cover is significant (particularly for single rows) and larger pieces of multi-row cover are subject to fatigue from wind and sun. Development of a mechanized single-row cover system or a durable multi-row cover system advances potential for use of covers. Field tests of a commercial semi-mechanized cover implement were conducted. Successful wire insertion ranged from 74 to 100% and depended on careful adjustment of the implement. Success was unaffected by soil type, but partially improved with wetter soil ($R^2 = 0.37$).

Costs of a single-row mechanized system using spunbond polypropylene or polyethylene mesh as row covers were compared to those of a conventional chemical application strategy without cover. Total costs of the spunbond polypropylene system were \$1620 ha^{-1} to \$5290 ha^{-1} (\$650 acre^{-1} to \$2140 acre^{-1}) greater than the conventional system depending on operational size. Smaller production areas were more costly due to machinery costs. The polyethylene mesh system was \$1500 ha^{-1} (\$600 acre^{-1}) more costly than using spunbond polypropylene due to material costs. In addition, a multi-row cover system using either of the two types of cover material was investigated including evaluation of support structure during mid-summer field conditions (wind and sun). Sagging cover material over time suggested limiting distance between single supports to 2 m (7 ft) or less. Tennis balls atop single supports avoided cover damage better than rebar caps. Spunbond polypropylene had more tears and damage than polyethylene mesh. Wire hoops spaced 2.3 m along the row avoided cover damage while keeping material off the crop.

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Introduction

About 41,000 growers in the eastern half of the U.S. produce $1.02 billion in value from cucurbit crops such as cantaloupe and summer squash on 140,000 ha (374,000 acres; USDA-NASS, 2008). A major challenge for growers is feeding on the plants by cucumber beetle (*Acalymma vittatum* and *Diabrotica undecimpunctata howardi*) and squash bug (*Anasa tristis*). In addition to direct feeding, these insects also transmit bacterial wilt (*Erwinia tracheiphila*; Rand and Enlows, 1916). Bacterial wilt can reduce cantaloupe and cucumber production by 80% and also impact pumpkin, winter squash, and zucchini (Latin, 1993; McGrath, 2001). The cost of this disease to eastern U.S. growers is $18.9 million annually (Adams and Riley, 1997). Polk et al. (2015) provides a comprehensive review of cucurbit crop production, major factors which impact cucurbit growth and production, and impacts of pests on production. Pesticide strategies require frequent applications (as many as eight in a single season; Brusi and Foster, 1999), can be costly, and require different options for organic growers.

Row covers are fabrics permeable to rain and air and are used to protect plants from early season cold temperatures (Soltani et al., 1995) as well as hasten crop development for early yield (Ibarra et al., 2001; Jenni, 1996; Wells and Loy, 1985; Wolfe et al., 1989). Covers also may extend growing season by mitigating late season frosts (Gaye et al., 1991). In addition to temperature moderation, row covers provide a barrier to exclude insect feeding and related disease transmission (Bextine et al., 2001; Natwick and Laemmlen, 1993; Orozco-Santos and Lopez-Arriaga, 1995; Vaissiere and Froissart, 1996). Row covers used for production of horticultural row crops such as melons and squash (cucurbits) have reduced insect feeding and disease in direct relation to their ability to exclude insects, thereby increasing fruit production potential (Mueller et al. 2006; Rojas et al., 2011).

A cover system potentially increases feasibility for organic production as it shifts input costs from pesticide application to cover. A cover installed from seeding to pollination excludes early season insect feeding and bacterial wilt. Besides cost of cover material, timely installation of row cover immediately after planting and subsequent removal for pollinator access during flowering requires multiple laborers. Cantaloupe and squash growers prefer covers to not rest directly (i.e., ‘float’) on plants but instead use a support structure to keep cover away from leaf surfaces, and thus require installation of a support system along with cover.

Support hoops and spunbond covers are typically installed manually, requiring several additional workers at an already labor intensive time during transplanting. Normal within-row spacing of hoops is about 1.4 m (4.7 ft), requiring a large number of hoops to be placed even in small land areas (1630 ha^{-1}; 660 $acre^{-1}$).

For single rows, a potential semi-mechanized solution to installing cover material is to use an existing implement marketed to install clear polyethylene plastic cover over individual rows to extend an earlier growing season in colder climates. A tractor-mounted implement (model 95 Tunnel Layer; Mechanical Transplanter, Holland, MI; figures 1 and 2), is marketed for this application. Spunbond polypropylene is more fragile than polyethylene plastic. Also, successful insertion of support wires with the implement has been observed as a problem by horticultural researchers. Identifying requirements for successful wire insertion to establish cover by the field implement may allow the process to be adopted.

Figure 1. Tractor mounted tunnel layer implement inserting wire hoops and establishing row cover over hoops. The process is semi-mechanized requiring an operator to singulate and place the wire for hoops into the insertion mechanism.

Figure 2. Wire inserted by cam-activated fingers on two rotating arms.

A mechanized system for individual row installation would reduce labor requirements, but capitalization cost would likely need to be amortized over larger production areas. Spreading a single cover over multiple rows may also reduce labor; however, ambient wind and sun environmental conditions may prematurely fatigue larger covers due to wind action.

Objectives

In order to evaluate the feasibility and potential costs of row cover establishment systems, the three primary objectives of this study were to:

1. measure the performance of a single-row cover mechanized implement in establishing row covers,
2. compare the cost of a cover (mechanical exclusion) pest strategy with a conventional multiple-spraying chemical strategy, and
3. evaluate the performance of a multi-row cover system during mid-summer wind and sun conditions in Iowa.

Methods and materials

Mechanized single-row cover establishment

Wire and soil resisting forces

Initial tests of wire and soil resisting forces were done in the laboratory to evaluate a minimum depth wire should be inserted to resist springing out of the ground in three soil moisture conditions. A preliminary series of four tests were completed. Tests were carried out in smaller soil containers (20 L, 5 gal) with a silty clay loam typical of central Iowa glacial till soils at 2.5, 10.0, and 12.9% (low, medium, and high) moisture contents. Measurements were replicated four times in medium and high moisture content soils and three times in low moisture content soils. A 2.6-mm (0.10-in.) diameter wire 2.13 m (7 ft) long similar to that used for the tunnel layer was used. Tensile force to move the wire was measured by a tensile scale used to weigh luggage. In each test wire was inserted to depths of 5, 7.5, 10, 12.5, 15, 17.5, and 20 cm (2, 3, 4, 5, 6, 7, and 8 in.).

Test #1 measured the horizontal force applied at the soil surface to move the wire after one end was inserted vertically into the soil (figure 3). Test #2 was similar except the wire was bent into a hoop shape typical of field insertion with the other end inserted into a soil container with the same moisture content. The force required to initiate horizontal displacement of wire on one side of the hoop was measured. Test #3 was similar to test #2 except the maximum force during a 5-cm (2-in.) horizontal displacement of the wire was recorded. Test #4 measured the amount of tensile pulling force applied at the buried end of the wire, at a 45° angle upward from horizontal, to initiate wire displacement.

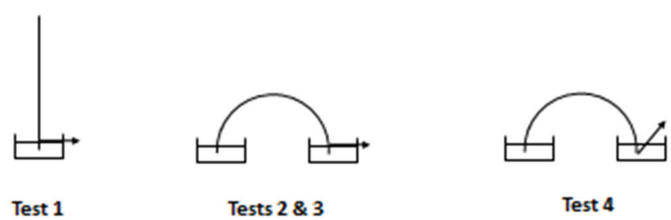

Figure 3. Four tests were performed to determine the force required to move wire in soil containers.

In each of the tests (#1 - #4) and at all three soil moistures, a statistical correlation between force required to move wire and insertion depth was done to estimate how much soil resisting force is present to prevent inserted wire from springing out of the soil due to latent spring force of the bent wire.

To measure latent spring force present in the wire, one end of the wire was fixed while the amount of force was measured to bend the wire into a hoop shape similar to field use (slightly narrower with 1.1 m (3.6 ft) across wire ends at the base). Measurements of spring force were replicated six times with different wires.

Field tests

An initial field test with the Model 95 Tunnel Layer immediately following lab tests (May 2013) compared two different implement depth-wheel settings for wire insertion (10 and 15 cm; 4 and 6 in.) to determine minimum required depth for successful insertion during field operation. Travel speed was limited to about 1.4 km h^{-1} (0.9 mi h^{-1}) during this initial (and also subsequent field tests) so that an operator on the implement could keep pace with singulating and placing individual wires into a receiving cradle for wire insertion (figure 1).

After establishing a suitable field insertion depth from the May 2013 test, subsequent field tests during summers of 2013 and 2015 measured parameters affecting successful wire insertion in medium- and coarse-textured soil over a range of moisture conditions when the implement was judged to be optimally adjusted. The tunnel layer was operated four times during 2013 and five times during 2015 from late June to early August at Iowa State University's Agricultural Engineering Agronomy Farm and Applied Science Farm near Ames, IA over a range of soil moisture contents in medium- (silty clay loam) and coarse- (fine sandy loam) soil conditions.

In each combination of soil type and moisture, approximately 30 to 45 minutes was allotted for operator adjustment and practice operation of the tunnel layer in raised-bed plot areas before field measurements were recorded. Prior to each mid-summer test in a soil texture/moisture combination, sixteen different implement adjustments were evaluated. Measurements included depth wheel height, height and angle of trenching and covering discs for spunbond polypropylene (Agribon® 30, 3 g/m^2 (0.01 oz./ft^2)) insertion, grasping finger mechanism cam plate operating angle and distance away from grasping finger (all both left- and right-sides of implement), angular position of grasping finger arms at the point of opening, and front toolbar height. Recorded information helped to develop a better understanding of the implement and enhance success of wire insertion and reduce adjustments required in subsequent field conditions.

After the adjustment period, about 70 to 80 hoops each were inserted along the raised-bed plot row in three runs. Following this, the tunnel layer laid two runs of 15 m (50 ft) each of Agribon® while inserting support hoops. Cover material establishment was evaluated by inspecting for tears or rips in Agribon® material and presence of any gaps more than 0.5 m (1.5 ft) long in the soil covering the edges of the material by covering discs to anchor material and exclude insects.

Several measurements were taken to assess wire insertion in uncovered runs. Measurement on each hoop included: 1) successful (or not) insertion of both wire ends into the soil, 2) insertion depth of both left- and right-sides of the hoop (as viewed in the direction of travel), 3) vertical angle of the hoop in the direction of travel, and 4) maximum height of the hoop's peak above the raised-bed soil surface. Hoop angles that differed substantially from a 90° vertical angle to the soil surface indicated how hoops were being inserted into the ground or dislodged by machine operation. Hoop width at the base on the soil surface and distance between hoops were generally fixed by implement configuration, but were measured three times during each of the four field tests in 2013. Measuring uncovered hoops facilitated height measurement and evaluated parameters for wire insertion success, but did not evaluate reduction in hoop angle when cover was placed over the hoops. Wire insertion measurements were tested to determine if there was correlation with soil moisture content or if soil texture caused a difference.

A statistical paired t-test was done each year for wire insertion measurements of hoop height, left- and right-side insertion depth and hoop angle. Each t-test compared over 100 individual measurements in the medium soil with those in the coarse soil.

Cost comparison between cover and chemical spray strategies

A mechanized system to install single-row covers avoids multiple insecticide sprayings, but creates added cost for mechanization, cover material, and structural supports. Determining additional cost for mechanization and cover material choices allows growers to evaluate adoption potential of mechanized technology. Two covered systems (spunbond polypropylene, Agribon® and polyethylene mesh, (Proteknet®, 60 g/m^2 (0.197 $oz./ft^2$)) were compared with a conventional multiple-spray system.

General economic analysis

To conduct the cost assessment, it was assumed that the equipment would be used on production land sizes of 0.2, 0.4, 0.8, 2.0, and 4.0 ha (0.5, 1.0, 2.0, 5.0, and 10.0 acres). Annual costs on a per hectare (acre) basis were calculated assuming operation over a 10-year period. For all operations and land sizes, a standard field row was assumed to be 61.0 m long by 2.1 m wide (200 ft by 7 ft). A diesel cost of \$1.06 L^{-1} (\$4.00 gal^{-1}) was assumed for all operations.

Machinery costs were divided into fixed (depreciation, interest, taxes, insurance and housing) and variable (repairs and maintenance, fuel and labor) costs. Salvage value of the tractor and implement was determined by a remaining value factor (0.235 tractor, 0.3 tunnel layer, 0.35 planter, 0.4 sprayer) multiplied by the new cost of the implement (ASABE Standards 496.3 and 497.7). Implement (machinery) costs for each system and acreage were determined using calculations of fixed and variable costs for each individual implement. Hourly tractor costs were also included with each implement based on number of hours each implement was used on the various production area sizes. A capitalization rate of 8 percent (interest plus inflation) was assumed with guidance from Edwards (2015). The chemical spray system did not require the use of the tunnel layer implement. All three systems (Agribon®, Proteknet®, and sprayed) utilized the bed shaper and mulch layer as well as the sprayers. An hourly wage of $10 was assumed. Labor costs were determined to be $11 per hour and were calculated by multiplying the hourly wage by a multiplier of 1.1 (Edwards, 2015) and considered the average field efficiency of a worker. Labor costs were included in hourly operational costs for the tractor and each implement and total operational costs for each implement included both tractor and implement labor needed. Labor cost for cover removal was not included in the analysis.

Tractor

Hourly cost was calculated for tractor operation, and was associated with implement operations of the tunnel layer or bed shaper and mulch layer, depending on their hours of use. It was assumed that a 45 kW (60 hp) tractor would be purchased 'used' after 5 years, kept with the farming operation for 10 years, and used 350 hours annually for all farm work. The cost of the tractor was determined through research of tractors for sale on tractorhouse.com (January 2015). The average purchase cost for a 5 year old, 45 kW (60 hp) tractor was determined to be $22,000. The purchase price of a new 45 kW (60 hp) tractor was found to be $33,327.00 (Bobcat of Ames, IA).

Implements

Implements included the tunnel layer, bed shaper and mulch layer, and the option of using two types of sprayers, a boom sprayer on a pick-up truck (truck-mounted sprayer) or backpack sprayer for chemical application. Including both truck and backpack sprayers allowed analysis of which sprayer was more cost-effective when used on different size land areas. All implements were assumed to be purchased new. The purchase price for the tunnel layer and bed shaper and mulch layer were received from the company (Mechanical Transplanter, Holland, MI). Costs for the two sprayers were determined based on average market data from online sellers. Table 1 indicates the purchasing cost, assumed total repair costs, and economic life of each implement.

Table 1: Economic Life, Purchasing Costs, and Repair Costs for implements

Implement	Economic Life (Years)	Purchase Price	Repair Costs[a]
Tunnel Layer	10	$6467	$500
Bed Shaper & Mulch Layer	10	$3154	$540
Sprayer			
Truck	10	$330	$60
Backpack	10	$80	$60

[a]Assumed total repair costs over 10-year period

Staff at the Iowa State University Horticulture Farm have found that crops usually must be sprayed one time for the mechanical exclusion method (before covering or after cover removal), and 4 times for the conventional chemical method. For this analysis, one spray application was assumed for the exclusion method and four spray applications for the conventional method. The number of annual hours required to use each implement on the various production areas was determined through calculations accounting for travel speed and field efficiency of each implement. Table 2 indicates the annual hours each implement was used as well as assumed travel speed and field efficiency. Time required was not strictly proportional to area due to standard fixed length and width of rows.

Table 2: Annual hours used for implements, travel speed, and field efficiency.

System &		Tunnel layer	Bed shaper & mulch layer	Sprayer	
Hectares	Acres			Truck	Backpack
Covered[a]					
0.2	0.5	1.17	0.49	0.37	0.65
0.4	1.0	2.29	0.96	0.72	1.27
0.8	2.0	4.70	1.96	1.47	2.61
2.0	5.0	11.67	4.86	3.65	6.48
4.0	10.0	23.50	9.79	7.34	13.06
Sprayed					
0.2	0.5		0.49	1.48	2.65
0.4	1.0		0.96	2.88	5.08
0.8	2.0		1.96	5.88	10.44
2.0	5.0		4.86	14.60	25.92
4.0	10.0		9.79	29.36	52.24
Travel speed, km h^{-1}		1.6	4.8	6.4	3.2
mi h^{-1}		1.0	3.0	4.0	2.0
Field efficiency		50%	60%	60%	55%

[a] Agribon® & Proteknet®

Truck

The portable sprayer was mounted to a truck for spraying operations. The cost of the truck was determined by rental rates of Iowa State University Transportation Services. It was assumed that a half-ton truck would be rented. The full day, eight hour, cost of a half-ton truck was \$40.6 d^{-1}, while the half day, four hour cost was \$20.3 d^{-1}. Most calculations involving the rental truck assumed a full half day rental cost during each spraying, although longer rental times were used (if required) based on the number of hours the truck-mounted sprayer was used for the varying field areas.

Material

Two cover materials for the exclusion method were analyzed: spunbond polypropylene (Agribon® 30, 3 g/m^2 (0.01 oz./ft^2)) in current use for cover systems, and polyethylene mesh (Proteknet®, 60 g/m^2 (0.197 oz./ft^2)), a heavier, more expensive product used for bird netting in horticultural applications. Based on use at university research farms in Iowa and Kentucky, Proteknet® and wire hoops were assumed to last the entire 10 year life of the analysis without replacement whereas Agribon® was assumed to be replaced two additional times (3.3 year life).

The costs of the materials were based on the purchase price of each material used in Iowa State University field tests. Proteknet® costs $2,133.34 per roll, 100 m (328 feet) by 8 m (26.2 feet). Cost included splicing of two 4-meter rolls sewn together. A cost of $2.67 m^{-2} ($.25 ft^{-2}) of Proteknet® calculated from this price was used to determine costs. Agribon® costs $115.00 per roll, 152 m long by 2.1 m wide (500 ft long by 7 ft wide). Cost of the wire hoops to support the row cover material was $.48 per hoop (Mechanical Transplanter, Holland, MI). Hoops are spaced at 1.5 m (5 ft). Black plastic mulch costs $109.95 per roll (Mechanical Transplanter, Holland, MI) 610 m by 0.9 m (2000 ft by 3 ft), and was used in both covered and conventional multiple-spraying systems.

Insecticides

Imidacloprid (Admire), the most commonly used insecticide for cucurbit production at Iowa State University, was used for economic analysis. Imidacloprid costs were $20.28 ha^{-1} ($8.21 $acre^{-1}$) for the exclusion method (one spray), and $81.11 ha^{-1} ($32.85 $acre^{-1}$) for the conventional spray method (four sprays).

Multi-row cover evaluation

Field experiments were done in three tests. Crop row spacing was 2.1 m (7 ft), similar to tests with the mechanized tunnel layer. Treatments were replicated three times in the field to evaluate system durability in wind and sun without a growing crop underneath (figure 4). Row cover materials were supported over individual plots 6.1 m (20 ft) long by two rows wide (4.3 m, 14 ft). In selection of structural support materials, consideration was given to cost, manual labor requirements, potential for future mechanization, and effectiveness of reliably supporting the cover. Pole supports were investigated initially due to concerns of mechanizing hoop installation.

Figure 4. Cover treatments being established. Uncovered rebar supports with end caps in foreground.

Pole supports with plastic caps

Row cover supports used in field tests included: (1) concrete reinforcement bar (rebar, 13 mm (0.5 in.) diameter) and (2) plastic-covered hollow metal rod tomato stakes (13 mm (0.5 in.) diameter). Each support was cut to a length of 53 cm (21 in.) and inserted 13 cm (5 in.) into the soil leaving 41 cm (16 in.) of exposed height. Horizontal rebar (hemispherical) plastic end caps (test P) were placed atop supports to provide a smoother and larger surface area for contact with cover material. Each type of support (rebar, tomato stakes) was tested in both 1.5 m (5 ft) and 3 m (10 ft) spacing along the row direction.

Cover material used was spunbond polypropylene (Agribon®) in sheets 8 m (26 ft) wide by approximately 12 m (40 ft) long, mounted over a support structure spanning 9.1 m (30 ft) along the row and two rows (4.3 m, 14 ft) wide. Three supports across two rows were on 2.1-m (7-ft) spacing. In addition to these four treatments, Agribon®, on either rebar or tomato stakes on 1.5 or 3 m (5 or 10 ft) spacing along the row, a fifth treatment used a polyethylene mesh (Proteknet®; Dubois Ag Innovation, St. Remi, Quebec, Canada). This cover material was only tested on rebar spaced 3 m (10 ft) along the row. Treatment names are shown in Table 3.

Table 3. Treatment names for the multi-row cover field tests.

Treatment	Cover material	Supports	Support spacing	
			m	ft
A/T/10[a][b]	Agribon®	Tomato stakes	3	10
A/T/5{c}	Agribon®	Tomato stakes	1.5	5
A/R/10	Agribon®	Rebar	3	10
A/R/5	Agribon®	Rebar	1.5	5
P/R/10	Proteknet®	Rebar	3	10

[a]End cap changed from plastic for test P to tennis ball for tests TH and N
[b]Support spacing changed to 1.2 m (4 ft) during test N
[c]Support changed from tomato stakes to wire hoops on 2.3 m (7.5 ft) spacing during tests TH and N

After the row covers were in place, treatments were evaluated using three criteria: 1) number of caps causing fatigue due to abrasion or visible wear on the row cover material, 2) number of caps completely wearing and poking through the material, and 3) number of caps wearing through the material and then falling off or somehow being removed from the stake. Measurements were planned over weeks of time but supports on some of the Agribon® covered treatments protruded through holes worn into the Agribon® within one day, so that data were taken one day after, two days after, and five days after application of the row covers over the support structures in the field. A cap causing fatigue on day 1, but still not poking through by day 2 or 5, was still recorded each day as an occurrence of fatigue. After a cap or support top poked through material, it was recorded as "poked through" rather than simply a "fatigued" spot.

Tennis balls and wire hoops

During the first test P (pole supports with plastic caps), a small burr approximately 1 mm tall on the end caps (possibly from the plastic molding process) was too abrasive, and caps were abrading through the Agribon® (figure 5).

Figure 5. Plastic end cap atop support abrading through spunbond polypropylene cover material.

During test TH (tennis balls and wire hoops) the two treatments using tomato stakes were changed. Caps on treatment plots using tomato stakes on 3-m (10-ft) spacing were replaced with tennis balls and new Agribon® covers. A small slit was cut in the tennis ball and the tomato stake was inserted into the slit. Treatment plots that had used 1.5-m (5-ft) spacing of tomato stakes were changed to using wire hoops for support, on 2.3 m (7.5 ft) spacing along the row and covered with a new sheet of Agribon®. This method had been used before on 1.4 m (4.5 ft) spacing along single row coverings but not multiple rows. Observations continued with the three treatments using rebar supports to assess longer-term effects of plastic caps and Proteknet® showed no damage.

Narrower spacing

Three-m (10-ft) support distances used with tennis balls (test TH) to minimize material cost allowed the row cover material to sag midway between supports within 13 cm (5 in.) of the soil surface which could cause a problem of physical interaction between the row cover material and the plant architecture. During test N (narrower spacing), support distance in the tennis ball treatment was changed to 1.2 m (4 ft) along the row. This doubled the number of supports (three to six) along the 6 m (20 ft) nominal length of each plot.

Results and discussion

Mechanized single-row cover establishment

Wire and soil resisting forces

Soil resisting force to wire movement was well correlated with depth of insertion, allowing a soil resisting force per unit of insertion depth to be calculated (table 4). Correlation coefficients between insertion depth and force across tests 1, 2, 3, and 4 and all three soil moisture contents ranged from 0.80 to 0.97, averaging 0.88.

Table 4. Soil resisting force to wire movement per wire insertion depth into soil, N cm^{-1} (lb in^{-1})

Soil moisture[a]	Test 1	Test 2	Test 3	Test 4
Low	2.56 (1.46)	1.38 (0.79)	2.45 (1.40)	N/A[b]
Medium	1.33 (0.76)	1.16 (0.66)	3.50 (2.00)	1.93 (1.10)
High	2.36 (1.35)	2.35 (1.34)	2.89 (1.65)	2.19 (1.25)

[a]Low = 2.5% m.c.; Medium = 10.0% m.c.; High = 12.9% m.c.
[b]Test information not available.

Average latent spring force measured between the ends of the wire when bent into a hoop shape similar to field use was 2.24 N (0.50 lb). The minimum soil resisting force in table 4 (1.16 N cm^{-1}, 0.66 lb in.$^{-1}$) suggested that on average a wire hoop inserted in any of these soil moisture conditions to a depth of at least 2 cm (0.8 in.) would resist spring wire force dislodging one end of the wire from the ground (assuming both wire ends are initially successfully inserted below the soil surface).

Field tests

Manually placed hoops often result in wire insertion of about 8 to 10 cm (3 to 4 in.). Depth-gauge wheels on the implement were set for a nominal 10 cm (4 in.) wire insertion depth during the first replicated trial for ‘shallow’ insertion in the initial field test (May 2013), but resulted in a major problem when over 70% of wire hoops failed to successfully insert. Depth setting for the additional two shallow replications was set to 12.5 cm (5 in.). Average wire insertion measurement parameters are shown in table 5 for each depth test in this initial test comparing ‘shallow’ and ‘deep’ settings for depth-gauge wheels. Soil moisture content was 19.3%.

Table 5. Wire measurements for shallow and deep insertion treatments in initial field test

Depth[a]	Measurement				
	Hoop height, cm	Left depth, cm	Right depth, cm	Angle toward tractor, °	Insertion success, %
Deep #1	36.3	19.4	10.0	92.8	80
Shallow #1	39.9	12.6	10.4	88.9	24
Deep #2	34.3	16.3	13.4	89.4	96
Shallow #2	35.1	15.3	12.4	90.0	78
Deep #3	34.6	18.2	11.5	90.6	70
Shallow #3	36.5	14.6	11.3	92.0	78
$LSD_{\alpha=0.05}$[b]	NS	NS	NS	NS	NS

[a]Deep is 15 cm (6 in.) for all three replications. Shallow is 10 cm (4 in.) for replication #1 and 12.5 cm (5 in.) for replications #2 and #3.
[b]Least significant difference between shallow and deep treatments; no statistical differences detected.

Perhaps due in part to just three replicated measurement trials at shallow and deep depths, no statistical differences were detected between setting the implement depth wheels for shallow or deep insertion for hoop height, left- and right-insertion depths, insertion angle, or success rate. Although success rate was greatly reduced in the first shallow trial, success rate for later shallow trials (after depth-gauge wheels were raised for nominal 12.5 cm (5 in.) insertion) was similar to success rate for deep trials. Although experimental design limited the number of field replications that could be done in a single day's time to detect statistical differences, hoop height seemed to be slightly greater with shallower insertion and hoop angle was unaffected. Left-side insertion was statistically deeper than right-side insertion when means from each of the six test runs were compared perhaps due to implement operation.

Because of the difference between sides, in later tests (during the summers of 2013 and 2015 across two soil textures and a range of moisture contents), extra care was taken with other factors on the implement such as placement of wire in the receiving cradle by the operator on the implement, and timing and placement geometry of operating fingers grasping the wire for insertion on the implement. Since wire insertion success seemed independent of depth wheel adjustment but perhaps related to other implement adjustments, depth wheel setting for further summer field tests was a nominal 13 cm (5 in.). More attention was given to adjustments involving release of the wire at the insertion point, and settings for trenching and covering discs. It was observed that discs on the implement used to create a trench and then cover edges of the cover material could affect wire insertion by supporting the implement further above the soil surface or affecting surface topography near the wire insertion point.

Average (and range) of wire insertion measurement parameters for each of the nine summer (2013 and 2015) field tests during insertion of wire only without Agribon® cover were: hoop height 42.5 cm (16.7 in.) (40.2 – 46 cm; 15.8 – 18.1 in.), right insertion depth 14.2 cm (5.6 in.) (9.5 – 18.0 cm; 3.7 – 7.1 in.), left insertion depth 13.4 cm (5.3 in.) (9.0 – 15.9 cm;

3.5 – 6.3 in.), hoop vertical angle 89° (85 – 98 °), and success 89 % (74 – 100 %). Measured wire insertion parameters were not related to soil moisture content (R^2 less than 0.1) with the possible exception of success ($R^2 = 0.37$). Neither were any significant differences detected among wire insertion parameters between soil types (five silty clay loam and four fine sandy loam replications over two summers).

Probability of numerically larger t-values are shown in table 6. Hoops leaned more in coarse textured soil and were observed to lean more when covered with Agribon® both years. Sandy soil may have provided less resistance if a cross-piece on the implement brushed against the top of a hoop that had been inserted or as cover material was laid and stretched over the hoops in either soil. Depth of wire insertion was greater in the coarse-textured soil in 2013 in relatively dry soil conditions perhaps because of low cohesive strength, but reversed and was shallower in 2015 when coarse moisture contents were greater than 15%. This effect contributed also to greater hoop height on coarse soil in 2015.

Table 6. Probability of numerically larger t value for paired tests of soil insertion measurements between soil textures

	Soil insertion measurements			
Year	Hoop height	Left depth	Right depth	Hoop angle
2013	0.24	<0.01	<0.01	<0.01
2015	<0.01	<0.01	<0.01	<0.01

Successfully inserted hoops were 1.20 m (3.8 ft) wide at the soil surface and spaced 1.37 m (4.5 ft) along the row length due to spacing of wire insertion arms and ground drive, respectively, of the implement.

Inspection of the two 15-m (50-ft) long Agribon® segments installed in each soil texture/moisture combination showed no tearing of the cover material. There were no gaps in soil coverage along material edges greater than 0.5 m, except for an occasional time (three total during all tests) when a cross-wind gust lifted material away from the reach of a covering press wheel between trenching and covering discs that pushed material down into a trench created by the first disc on each side of the implement. A gap was also created during a single run when discs on one side lost soil contact due to a misshapen raised bed.

Cost comparison between cover and chemical spray strategies

The bed shaper and mulch layer costs were identical for the covered and sprayed systems. In all three systems (Agribon®, Proteknet®, and sprayed), as expected, the truck sprayer was more cost effective for fields with larger production areas, and the backpack sprayer was more cost effective for fields of smaller areas (table 7). For the chemical spray system, the truck-mounted sprayer was \$395 ha^{-1} (\$160 $acre^{-1}$) more than the backpack sprayer at 0.2 ha (0.5 acre), and \$129 ha^{-1} (\$52.25 $acre^{-1}$) more than the backpack sprayer at 0.4 ha (1 acre). As production areas increased to 0.8, 2, and 4 ha (2, 5, and 10 acre), the cost increased by a range of \$7 to \$94 per hectare (\$3 to \$38 per acre) more for the backpack sprayer.

Table 7: Annual machinery costs per hectare or acre for system and production area

System		Tunnel layer		Bed shaper & mulch layer		Sprayer			
						Truck sprayer		Backpack sprayer	
Hectare	Acre	Hectare	Acre	Hectare	Acre	Hectare	Acre	Hectare	Acre
Covered[a]									
0.2	0.5	$4173	$1689	$1960	$793	$307	$124	$108	$44
0.4	1.0	$2187	$885	$1008	$408	$152	$62	$70	$28
0.8	2.0	$1201	$486	$536	$217	$77	$31	$54	$22
2.0	5.0	$605	$245	$251	$101	$31	$13	$42	$17
4.0	10.0	$453	$183	$162	$65	$20	$8	$39	$16
Sprayed									
0.2	0.5			$1960	$793	$608	$246	$214	$86
0.4	1.0			$1008	$408	$303	$123	$174	$70
0.8	2.0			$536	$217	$152	$62	$160	$65
2.0	5.0			$251	$101	$61	$25	$148	$60
4.0	10.0			$162	$65	$51	$20	$146	$59

[a] Agribon® & Proteknet®

Calculation of support and cover material costs for each size system are included along with machinery, and insecticide costs to determine total cost for each system and production area. Table 8 indicates the materials cost, machinery cost using either the truck-mounted or backpack sprayer, insecticide cost, and total costs for Agribon®, Proteknet®, or conventional systems on varying production areas.

Table 8: Total annual machinery and material costs per hectare or acre for conventional chemical and mechanical exclusion methods (10 year operation assumed).

System		Materials[a]		Machinery[b]				Insecticide		Total Cost			
				Truck sprayer		Backpack sprayer				Truck sprayer		Backpack sprayer	
Hectare	Acre	Hectare	Acre	Hectare	Acre	Hectare	Acre	Hectare	Acre	Hectare	Acre	Hectare	Acre
Agribon® covered													
0.2	0.5	$2366	$957	$6440	$2606	$6240	$2525	$20	$8	$8826	$3572	$8626	$3491
0.4	1.0	$2465	$998	$3347	$1355	$3265	$1321	$20	$8	$5833	$2361	$5751	$2327

0.8	2.0	$2282	$924	$1814	$734	$1791	$725	$20	$8	$4116	$1666	$4093	$1656
2.0	5.0	$2191	$887	$887	$359	$898	$364	$20	$8	$3098	$1254	$3110	$1259
4.0	10.0	$2201	$891	$635	$257	$654	$265	$20	$8	$2857	$1156	$2875	$1164
Proteknet® covered													
0.2	0.5	$3885	$1572	$6440	$2606	$6240	$2525	$20	$8	$10,345	$4187	$10,146	$4106
0.4	1.0	$3901	$1579	$3346	$1354	$3265	$1321	$20	$8	$7267	$2941	$7186	$2908
0.8	2.0	$3765	$1524	$1814	$734	$1791	$725	$20	$8	$5599	$2266	$5576	$2257
2.0	5.0	$3683	$1491	$887	$359	$899	$364	$20	$8	$4590	$1858	$4602	$1862
4.0	10.0	$3684	$1491	$635	$257	$654	$265	$20	$8	$4339	$1756	$4358	$1764
Sprayed													
0.2	0.5	$1087	$440	$2568	$1039	$2173	$880	$81	$33	$3736	$1512	$3341	$1352
0.4	1.0	$1087	$440	$1311	$531	$1182	$478	$81	$33	$2479	$1003	$2350	$951
0.8	2.0	$951	$385	$688	$278	$696	$282	$81	$33	$1720	$696	$1728	$699
2.0	5.0	$869	$352	$312	$126	$399	$161	$81	$33	$1262	$511	$1350	$546
4.0	10.0	$869	$352	$212	$86	$307	$124	$81	$33	$1163	$471	$1258	$509

[a]Materials include plastic mulch for all systems and cover material and supports for cover systems.
[b]Total annual machinery costs include all machinery (tractor associated with implement, bed layer, and tunnel layer/sprayer (also truck if needed) appropriate for the system) and operator (labor).

The total material costs for the Agribon® and Proteknet® systems ranged from $1280 to $2810 more per hectare ($520 to $1,140 more per acre) than the conventional system. Adding machine (and insecticide) for total costs, the Agribon® system cost $1620 ha^{-1} ($650 acre^{-1}) more over 4 ha (10 acres) or $5290 ha^{-1} ($2140 acre^{-1}) more over a smaller 0.2 ha (0.5 acre) system. Price difference decreased as the acreage size increased. The Proteknet® system added an additional $1500 ha^{-1} ($600 acre^{-1}) annual cost to these values (due to materials costs). Total costs of the Proteknet® system, using the truck sprayer and the backpack sprayer, ranged from $3100 to $6800 per hectare ($1,250 to $2750 per acre) more than the conventional system.

Using the mounted truck sprayer on 0.2, 0.4, and 0.8 ha (0.5, 1, and 2 acre) Agribon® and Proteknet® systems, machinery costs ranged from $25 to $200 per hectare ($10 to $80 per acre) more than when using the backpack sprayer. As the production area size increased to 2 and 4 ha (5 and 10 acres), the truck sprayer cost $12 to $19 per hectare ($5 to $8 per acre) less than the backpack sprayer. Overall, it appears that using either Proteknet® or Agribon® will at least double production costs vs. the conventional system.

Multi-row cover evaluation

Pole supports with plastic caps

Average percentage of supports fatiguing and poking through cover material for each treatment is shown in figure 6 for observations one, two, and five days after establishing the plots. Percentage of supports causing damage is used because treatments with 1.5-m (5-ft) support spacing along the rows used 15 supports per plot compared with just 9 total supports used for treatments with 3-m (10-ft) support spacing along the rows.

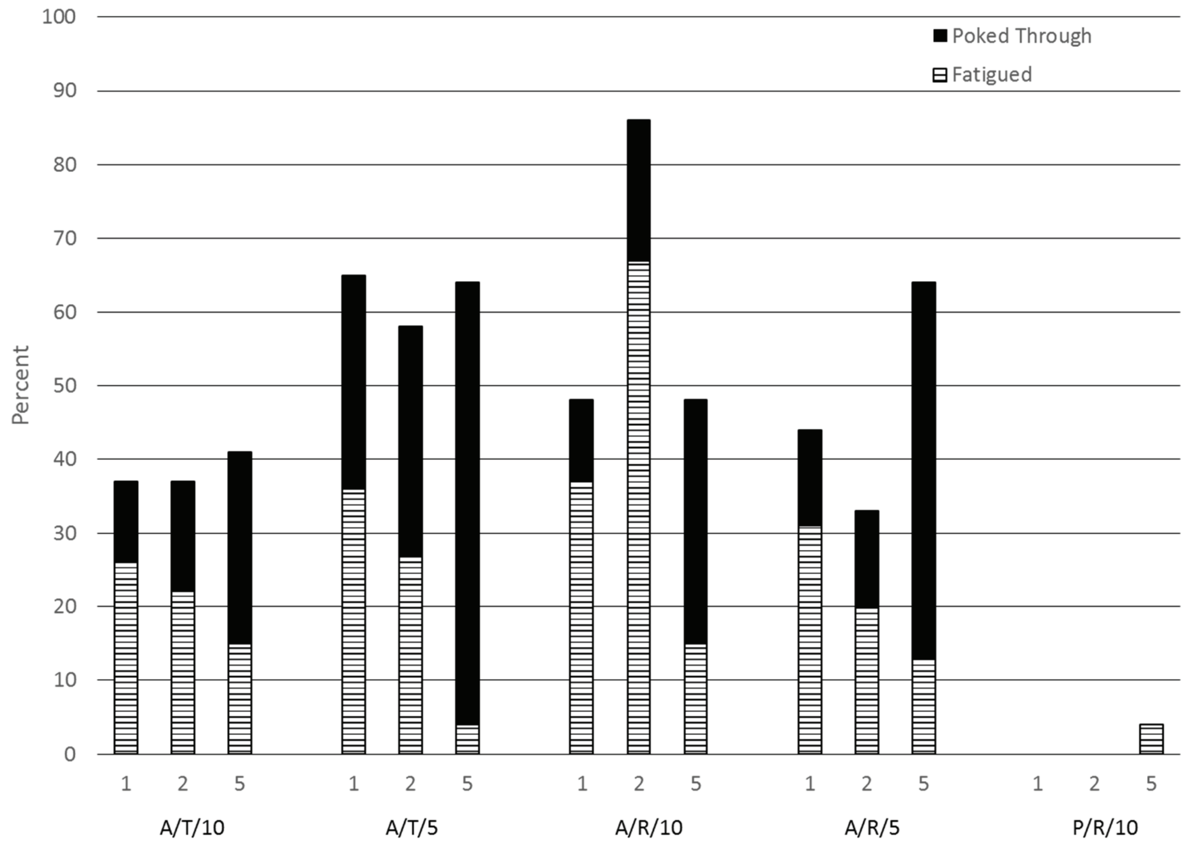

Figure 6. Percentage of supports either showing fatigue on cover material or poking through cover after one, two, or five days by treatment (Agribon® (A) or Proteknet® (P) / tomato (T) stake or rebar (R) / support spacing (5 or 10 ft)).

The combined percentage of fatigued and poked through locations generally increased as time progressed. Some locations initially classified as fatigued later changed to poked through. Dynamic movement of cover material with ambient wind currents seemed to be the primary cause of material wear against plastic rebar caps covering the supports. In some locations supports poked through material overnight without prior evidence of fatigue.

An apparent anomaly occurred in some cases, notably for treatment A/R/10, when the number of locations with supports fatigued were less than values observed in an earlier period (although poked through locations continued to increase). Two phenomena may have caused this. First, cover material that was tensioned across supports initially by small plastic stakes anchoring borders of the cover, became loose over time from dynamic movement of the cover by wind. If cover material loosely bunched up at the top of a support without direct contact, further abrasion was stopped and it was difficult to observe earlier small spots that may have been fatigued. Secondly, small fatigued spots near each other that were first individually recorded could combine into a larger single area that often ultimately allowed a single poked through location.

For Proteknet®, in treatment P/R/10, fatigue was only observed one time, and it was only on one cap. The Proteknet® was not as susceptible to fatigue. No instances of material failure were observed in the Proteknet® material.

Figure 7 shows the average percentage of caps that had fallen off of the support stake for each separate treatment. Cap removal from the top of the support was likely due to wind elevating cover material up and down over the cap after it had poked through material, but could have been caused by wildlife or an unknown factor.

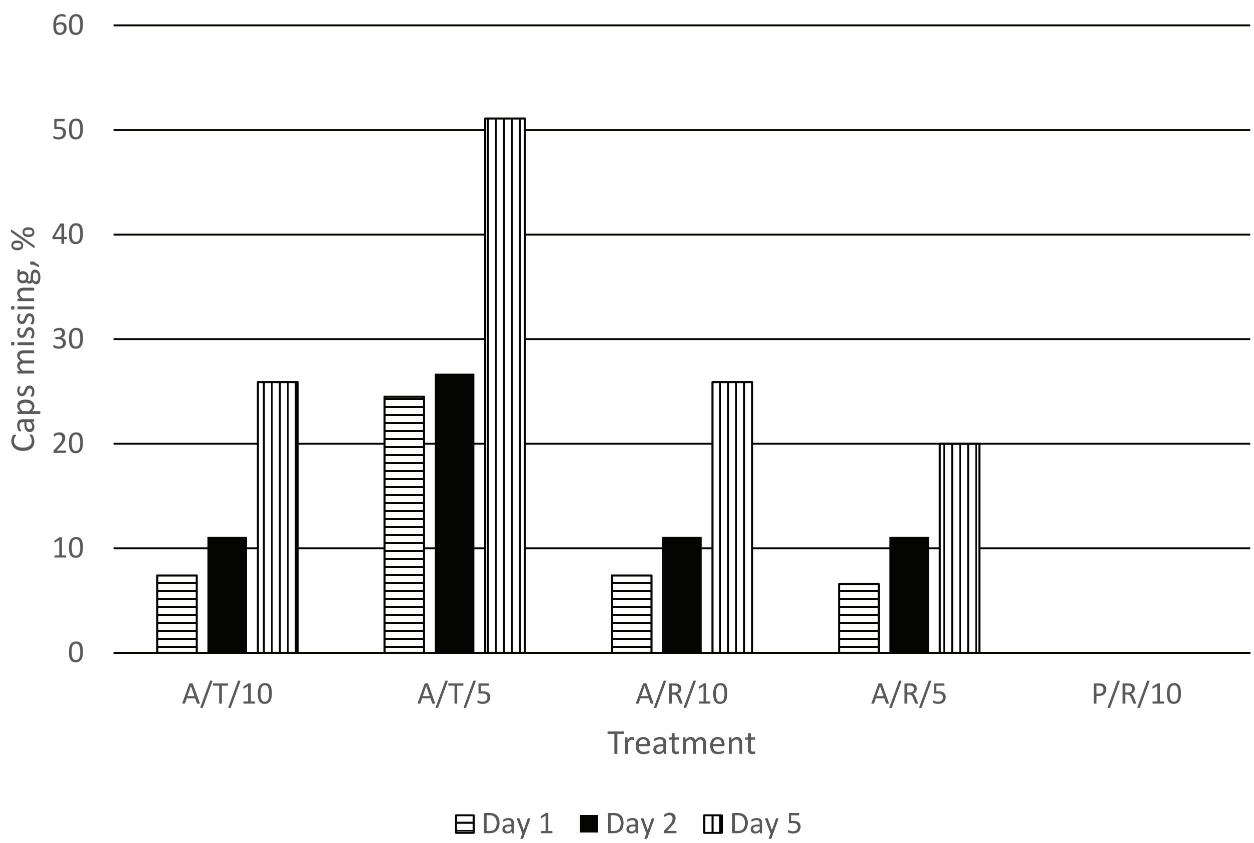

Figure 7. Average number of missing caps atop supports after one, two, or five days by treatment (Agribon® (A) or Proteknet® (P) / tomato (T) stake or rebar (R) / support spacing (5 or 10 ft)).

Tennis balls and wire hoops

Replacing plastic caps with tennis balls on top of supports or replacing single support stakes with wire hoops showed much more positive results. After two weeks, there was still no visual fatigue on the row cover material where it made contact with either the tennis ball or the wire hoop. Weeds growing underneath the row cover had grown considerably taller than they were in test P. Taller weeds lifted the row cover in some places, relieving the pressure of the weight of the row cover on both the tennis balls and wire hoops in some locations. This may have lessened damage potential.

Narrower spacing

As expected, reduced spacing between supports (3 m or 10 ft to 1.2 m or 4 ft) helped keep cover elevated over the row. The combination of the tennis ball caps and closer spacing seemed to result in lesser degradation as well. The tennis ball had a less abrasive surface and the closer supports helped to spread the weight and pressure.

Conclusions

Mechanized single-row cover establishment

Within the range of conditions tested for the tunnel layer implement and wire:

- Wire inserted at various depths into soil in soil bins suggested that a minimal insertion depth of 2 cm (1 in.) would supply adequate force to resist wire hoops from springing out of the ground after placement.
- During initial field tests, wire insertion success was less than 50% until depth-gauging wheels were set at least for a nominal 12.5 cm (5 in.) insertion depth. Other implement adjustments including timing and placement of the finger mechanism used during wire insertion, and disc placement for cover insertion and establishment were noted and recorded after field adjustment in subsequent tests.
- Successful wire insertion continued to be challenging (74 to 100%). Success increased somewhat with wetter soil ($R^2 = 0.37$). Sixteen implement adjustments were recorded before each run and evaluated with field tests.
- Hoops tended to deviate more from a vertical plane in coarser soil. Ends of wire hoops tended to insert more shallowly into coarser soil when wet (with correspondingly greater hoop height). If coarse soil was dry hoops inserted more deeply than in medium-textured soil.

Overall success rate with the implement suggests further work with adjustment or modification, if greater than 95% successful wire insertion rate is desired for this type of application.

Cost comparison between cover and chemical spray strategies

The cover exclusion technique added an annual cost of about $1620 to $5290 per hectare ($650 to $2140 per acre) when Agribon® was used, and $3100 to $6800 per hectare ($1250 to $2750 per acre) when the Proteknet® was used as compared to a chemical spray application strategy. The greatest increase in price for the exclusion method was due to the addition of the tunnel layer implement for smaller acreages up to about 0.4 ha (one acre). Systems larger than 0.4 ha (one acre) were more effectively able to amortize initial cost of the tunnel layer but materials costs per area remained similar.

Although Proteknet® was assumed to last three times as long (10 years) as Agribon® before replacement, an extra \$1500 ha^{-1} (\$600 $acre^{-1}$) annual cost was incurred using assumed current prices. The annual price of the Agribon® and Proteknet® systems decreased as the production area size increased.

Determining the most cost effective sprayer option depends on production area size. For production areas 0.4 ha (1 acre) or less, the backpack sprayer was the most cost effective while for larger areas the truck-mounted sprayer was the most cost effective.

Additional annual costs for the mechanical exclusion methods of \$1620 to \$5290 per hectare (\$650 to \$2140 per acre) may be able to be recouped by the grower if fruit can be marketed with a premium due to lower pesticide use and/or greater amounts of fruit are produced.

Multi-row cover evaluation

Tests during summer field conditions in Iowa support the following conclusions:

- Spunbond polypropylene cover material (Agribon®) was rapidly torn and degraded at points of contact with plastic rebar caps.
- Polyethylene mesh cover material (Proteknet®) showed negligible degradation, but adds expense at three times the cost of spunbond polypropylene.
- Substituting tennis balls to protect polypropylene cover material resulted in negligible degradation, however distance between single support stakes needed to be reduced from 3 m to 1.2 m (10 ft to 4 ft) for cover material to maintain acceptable height for the crop.
- Using wire hoops for cover support across the row area, with 2.3 m (7.5 ft) spacing along the row direction had negligible degradation to polypropylene cover material and maintained acceptable height for the crop over the center of the row.

The concept of using row covers to improve the sustainability of vegetable farms has merit, but operational and economic challenges must be overcome in order to see this approach realized commercially.

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