AN APPARATUS TO INJECT SOIL FUMIGANTS UNDER RAISED, PLASTIC-MULCHED BEDS

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ABSTRACT. An under bed fumigator was designed, fabricated, and tested for injecting soil fumigants underneath raised planting beds covered by plastic mulch without disturbing the integrity of the beds. Two opposing armature systems mounted on a tractor tool bar at a 15° angle were used to deliver fumigants to the center of plastic mulched beds. Using a virtually impermeable plastic mulch, uniform concentrations of a fumigant mixture of 1,3-dichloropropene and chloropicrin were obtained across the beds. The under bed fumigator mitigates worker exposure to fumigants by separating land preparation activities from fumigant application process. It provides growers without access to drip irrigation the opportunity to disinfect soil prior to the planting of a second (double) crop in existing mulched beds. Effective control of soilborne pests was obtained when the under bed fumigator was used in conjunction with a virtually impermeable film on 0.5 ha of a commercial tomato production field.

Keywords. Soil fumigation, Low-density polyethylene plastic mulch, Virtually impermeable plastic mulch, 1,3-dichloropropene, chloropicrin.

Pre-plant soil fumigation is a critical component of high value crop production systems, including fresh market tomato and pepper (Noling, 1997; Wilhelm and Paulus, 1980). Florida is the leading producer of fresh market tomato and pepper in the United States, where these crops have a combined annual farm gate value of $751 million (NASS, 2002). Crops are cultivated on 15− to 30-cm high by 70− to 100-cm wide beds that have been fumigated and covered with polyethylene mulch. Fumigants are shank injected using chisels spaced 30 cm apart as the soil is being pulled up to form the beds (Gilreath et al., 1999; Jones et al., 1995; Locascio et al., 1997). Beds are then covered immediately with polyethylene plastic, which functions as a mulch. The soil fumigant methyl bromide has been used almost exclusively by these industries since the 1970s but its use has been subjected to a mandatory phase-out due to environmental concerns (US−EPA, 2002).

Florida fresh market tomato and pepper production accounts for 24% of the methyl bromide consumed in the United States for soil fumigation (US−EPA, 1997). Without a suitable replacement, economic losses have been projected to exceed $1 billion (Spreen et al., 1995). Several studies have identified mixtures of 1,3-dichloropropene and chloropicrin (1,3-D + Pic) as the best alternative fumigant to methyl bromide (Gilreath et al., 1999; Jones et al., 1995; Locascio et al., 1997). In the past, concerns over exposure of workers present in the field during plastic laying operations restricted its application potential. In order to minimize human exposure, application technology is needed to separate plastic laying operations from the application of fumigants. Fumigants may be applied to plastic-mulched beds via drip irrigation (Ajwa et al., 2002). However, many growers in Florida still cultivate their crops with seepage irrigation systems and cannot easily convert to drip irrigation technology.

Reducing fumigant application rates without comprising their efficacy can be achieved by extending the exposure time of pest propagules to the fumigant (Munnecke and Van Gundy, 1979). One way this can be accomplished is by trapping the fumigant in the soil. While polyethylene plastic films offer little resistance to fumigant diffusion, new virtually impermeable films (VIF) are available (Gan et al, 1998; Papiernik et al., 2001; Wang et al., 1998; Yates et al., 1997; 2000). For growers who do not use drip irrigation systems, an apparatus to inject fumigants under established VIF mulched beds would expand the use of this technology.

The objective of this research was to design, fabricate, and test an apparatus for injecting soil fumigants under existing raised, plastic-mulched beds. Success of this research would improve the potential of 1,3-D + Pic as a replacement for methyl bromide and maximize the benefits of VIF technology.

MATERIALS AND METHODS

DESCRIPTION OF THE APPARATUS

The fumigation system, referred to as the under bed fumigator, consisted of a tractor, a fumigant tank, a nitrogen gas cylinder, a toolbar with weights, and two opposing armature systems for injecting fumigants underneath the plastic-mulched beds. Fumigant and nitrogen tanks were mounted on the front of the tractor. The armature systems and
weights were mounted to the tool bar. Nitrogen was used to push the fumigant from the fumigant reservoir to the armature systems. Each armature system included a main arm assembly, a hub and spindle assembly, a close-wheel assembly, and a fumigant dispersal assembly (fig. 1). Armatures were mounted to the toolbar at an angle to permit the fumigant dispersal assembly to reach under the planting bed without disturbing the integrity of the bed shoulders. In preliminary trials, an angle of 10° to 20° facilitated optimum fumigant injection and minimized stress on the injection blade. An angle greater than 20° caused disturbance to the plastic mulch and placed additional stress on the hub and spindle assembly. An angle less than 10° caused the fumigant to disperse into the unmulched areas located between the raised beds. Mounting the armatures at 0° did not allow the fumigant or injection blade to reach up into the bed and placed the injection blade at a horizontal position, subjecting it to extreme stress from the resistance of the soil as it was dragged through the field and increasing the potential for bending or breaking the blade.

Any arm assembly from a commercial coulter system could be used for the main arm assembly. The under bed fumigator used a main arm assembly system obtained from a Yetter 30 Avenger (Yetter Farm Equipment, Colchester, Ill.). The under bed fumigator used a main arm assembly system obtained from a Yetter 30 Avenger (Yetter Farm Equipment, Colchester, Ill.). The arm assembly was modified to permit attachment of the assembly to the tool bar at angles between 10° and 20° by welding a plate and mounting bracket to the tool bar. The mounting bracket also included a shim placed between the attachment plate of the arm assembly and the tool bar to create a 5° variation in the horizontal direction of each armature. This angle changed the width of the knife groove (opening in the soil created by the coulter blade) and reduced drag of the assembly.

For the hub and spindle assembly, any assembly from a commercial coulter system could be used. The hub and spindle assembly used for this apparatus was also obtained from a Yetter 30 Avenger. A 76-cm coulter was attached to the spindle assembly to create a track for the fumigant delivery assembly to enter the soil while minimizing disturbance to the soil profile.

The fumigant dispersal assembly consisted of a knife, blade, and conduit tube attached to a support bracket (fig. 2). The knife was 40 cm long, 12 cm wide, and had a contoured surface roughly conforming to the arc of the circular perimeter of the coulter blade. The knife tip was blunt, permitting field debris to clear under the knife. A blade was permanently attached to the inner side of the knife at a 90° angle, 2.5 cm from the bottom of the knife. The outer-facing edge of the blade was flush with the rear-facing edge of the knife. The inner edge of the blade was 9 cm wide and the outer end was 5 cm wide. The blade was beveled with a 2–cm double kerf. A conduit delivered fumigant from the fumigant tank to the main arm assembly of the armature. A 3-mm stainless steel fumigant feed tube was welded to the back edge of the knife and the outer edge of the blade and delivered the fumigant from the main arm assembly to an orifice located 2 cm from the blade tip.

**FIELD EVALUATIONS**

Two experiments were conducted at the USDA Header Canal Research Farm (St. Lucie County, Fla.). The soil type was a Riviera fine sand (loamy, siliceous, hyperthermic, Arenic Glossaqualfs). Soil organic matter was 1.7%; soil pH 7.4; and the soil texture was 96% sand, 2% silt, and 2% clay. Soil moisture at the initiation of experiments ranged from 6.7% to 9.0% by weight.

The first experiment was designed to determine the distribution of a fumigant under different plastic mulches following their application with the under bed fumigator. A 61%:35% mixture of 1,3-dichloropropene plus chloropicrin

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**Figure 1. Exploded view of a complete armature system.**
(Telone C–35, Dow AgroSciences, Indianapolis, Ind.) was applied at 327 L/ha under beds covered by polyethylene (white over black, co–extruded, embossed, and 30 μm thick, Pliant Corporation, Schaumburg, Ill.) or virtually impermeable (white over black, triple–extruded, smooth, and 35 μm thick, Hytibarrier Flex, Klers Plastic, Hoogstraten, Belgium) plastic mulch. The fumigant was applied using the under bed fumigator. Four beds 30 m in length were prepared for each plastic type. Beds were arranged on 2–m row centers. Bed dimensions were 102 cm at the base and 91 cm at the top. Beds were 25 cm high and were pressed prior to applying the plastic with a single row plastic layer. Raised beds were prepared and covered with plastic and then fumigated on 19 August 2002.

The concentration of 1,3–dichloropropene plus chloropicrin in the soil atmosphere was measured after removing a 2.5– × 12.5–cm soil core and sampling the airspace. Total concentrations were estimated using a GasTec Model GV–100 Gas Sampling Pump (Sensidyne Inc, Clearwater, Fla.) with Gastec 132HA trichloroethylene detector tubes (GasTec Corp., Ayase–City, Japan). Concentrations were adjusted using a 2X correction factor as recommended by the manufacturer. Samples were collected 1, 2, 3, 4, 7, 10, and 18 days after fumigant application at six locations: on both edges of the bed, 20 cm from both edges of the bed, the center of the bed, and in the furrow (unmulched area between each raised bed). Four samples were collected for each location on each sample date.

The second experiment was designed to measure the efficiency of the under bed fumigator in delivering fumigants at lower application rates. A 61%:35% mixture of 1,3–dichloropropene plus chloropicrin was applied at 94, 187 and 280 L/ha under beds covered by virtually impermeable plastic mulch (white over black, triple–extruded, smooth and 35 μm thick, Hytibarrier Flex). The fumigant was applied using the under bed fumigator. Four beds 30 m in length were prepared for each plastic type. Beds were arranged on 2–m row centers. Bed dimensions were 102 cm at the base and 91 cm at the top. Beds were 25 cm high and were pressed prior to applying the plastic with a single row plastic layer. Raised beds were prepared and covered with plastic and then fumigated on 26 August 2002. Fumigant concentrations were measured as described previously after removing a 2.5– × 12.5–cm soil core from the center of the bed and sampling the air space. Four samples for each application rate were collected 4 and 10 days after application.

**FIELD VALIATION**

To test its feasibility and durability, the under bed fumigator was used to treat 0.5 ha of a commercial tomato production farm located in St. Lucie County Florida. To access its effectiveness, the incidence of soilborne pests and marketable yields were compared to adjacent areas of the farm fumigated with a 67:33 mixture of methyl bromide:chloropicrin at 448 kg/ha. Beds in the test area were prepared and covered with a virtually impermeable plastic mulch (white on black, smooth, 35 μm thick, ‘Bromostop,’ Industria Plastica Monregalese, Mondovi, Italy) on 6 August 2003. Beds in the methyl–bromide–treated areas were prepared, fumigated, and covered with a high–density polyethylene plastic mulch (white on black, embossed, 20 μm thick, Sonoco Plastic Co., Orlando, Fla.) on 6 August. Bed dimensions were 76 cm wide by 25 cm wide. On 12 August, a 61%:35% mixture of 1,3–dichloropropene plus chloropicrin was applied at 327 L/ha under beds covered by the virtually impermeable plastic using the under bed fumigator. Tomato seedlings (cv. Florida–47) were transplanted into the beds on 6 September. Plots were harvested on 17 and 28 November and the marketable yield was determined. Plots were rated with the incidence of soilborne disease and weed populations on 9 December.

**RESULTS AND DISCUSSION**

The final configuration of the under bed fumigator was determined after multiple tests conducted over an 18–month period. The performance of the under bed fumigator was assessed at tractor speeds up to 8 km/h. No disruption to the integrity of the beds was observed and the apparatus was not damaged by repeated applications. The number of weights mounted above the tool bar was varied to compensate for differences in soil types and moisture.

The fumigant mixture of 1,3–dichloropropene plus chloropicrin was detected between the beds (in the furrow) in the row middles up to 4 days after application (figs. 3 and 4). Concentrations in the furrow were highly variable (0 to 500 ppm) and peaked 1 day after application. No fumigant was detected in the row middles after 4 days. Movement into the row middles may have been caused by a horizontal gap in the soil profile created by the blade or by abrupt changes in the depth of the fumigant placement due to uneven field terrain.

In beds covered by the polyethylene mulch, concentrations of 1,3–D plus chloropicrin peaked 2 days after application (fig. 3). Concentrations were highly variable through the soil profile. The highest fumigant concentration was measured at the edge of the bed, where it reached an average level of 840 ppm. Fumigant concentrations declined to 480 ppm, 20 cm from the edge of the bed and only reached 220 ppm in the center of the bed. No fumigant could be detected in the soil 7 days after application.

In beds covered by the virtually impermeable mulch, concentrations of 1,3–dichloropropene plus chloropicrin peaked four days after application at 900 ppm (fig. 4). Because chloropicrin has a half–life in soil of less than 24 h,
it was assumed that the concentration of fumigant in the soil after 4 days was primarily 1,3-D. At 10 days after application, fumigant concentrations were still greater than 250 ppm. Fumigant concentrations in the bed were uniform after 4 days and remained uniformly distributed at 10 days after application. By 18 days after application, no fumigant could be detected in the beds.

Using an application rate of 94 L/ha, 250 ppm of 1,3-dichloropropene plus chloropicrin was detected in the center of beds covered by a virtually impermeable plastic mulch (fig. 5). Thus, the under bed fumigator was able to deliver fumigants to the center of the planting beds when the application rate was reduced by 72%.

Differences in fumigant concentration and distribution under the two types of plastic were related to the permeability of the plastic. Polyethylene films are highly permeable to fumigants including methyl bromide and 1,3-dichloropropene (Gan et al, 1998; Yates et al., 1997). By contrast, VIF films are up to 1000 times less permeable to methyl bromide and 1,3-dichloropropene than high-density polyethylene films (Papiernik et al., 2001; Wang et al., 1998). The VIF films used in this study have been reported to be 1 million times less permeable to 1,3-dichloropropene than high-density polyethylene (Papiernik et al., 2001). Thus, under the polyethylene mulch, most of the fumigant migrated vertically through the soil profile and passed directly through the plastic into the atmosphere.

In the field validation test, the under bed fumigator performed under commercial conditions without compromising the application procedure or the integrity of the planting beds. No phytotoxicity to the transplanted tomato seedlings was observed. The marketable yield of plants grown in beds fumigated with methyl bromide:chloropicrin and covered with a polyethylene plastic mulch was 29,680 kg/ha (table 1). The marketable yield of plants grown in beds where the under bed fumigator was used to apply 1,3-dichloropropene:chloropicrin under beds covered by a virtually impermeable plastic mulch was 32,256 kg/ha. Thus, under commercial conditions, an 8% increase in marketable yield was achieved using the under bed fumigator to apply a fumigant alternative to methyl bromide under a virtually impermeable plastic mulch. Weed populations in the test area and methyl bromide treated area remained less than 1 per 10 m of row. The incidence of Fusarium wilt (a soilborne fungal disease caused by Fusarium oxysporum f. sp. lycopersici Race 3) was 9.0% in the methyl bromide fumigated beds and 4.7% when the under bed fumigator was used to apply 1,3-dichloropropene:chloropicrin under beds covered by a virtually impermeable plastic mulch (table 1).

One additional use of the under bed fumigator that has not been thoroughly explored is its ability to disinfest beds prior to planting a second crop. Although successive cropping of existing mulched beds is recommended to make effective use of the polyethylene mulch and fumigant (Simonne and Hochmuth, 2001), rapid increases in pathogen, nematode, and weed populations during cultivation of the first crop prevent re-use of the beds for a second (double) crop. Shank injection of fumigants into existing plastic-mulched beds is not possible using the standard application equipment. The under bed fumigator may have additional application potential in this area.

**CONCLUSION**

The under bed fumigator was developed to apply fumigants under established raised beds covered by plastic mulch.
Irrigation systems. A patent application was submitted to the United States Patent & Trademark Office on 3 October 2002 for the use of personal protective equipment by separating the gates and regulatory hurdles associated with worker exposure and mulch production systems. The under bed fumigator mitigates exposure by creating opportunities to disinfest soil in fields that do not have access to fumigant injection through drip irrigation systems. It allows growers to make more efficient use of their production capacity and eliminates the need for personal protective equipment.

Its application potential was validated in a 0.5–ha trial conducted in a commercial tomato production field. It is recommended for small- to medium-scale producers of horticultural and ornamental crops with raised-bed, plastic-mulch production systems. A patent application was submitted to the United States Patent & Trademark Office on 3 October 2002 (Serial No.: 10/263, 107 and Docket No.: 0113.02).

### REFERENCES


### Table 1. Marketable yield and incidence of Fusarium wilt in a commercial tomato field using conventional fumigation practices or the under bed fumigator in combination with methyl bromide alternatives.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Marketable Yield (kg/ha)</th>
<th>Disease Incidence (%)</th>
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<tbody>
<tr>
<td>Conventional[a]</td>
<td>29.680</td>
<td>9.0</td>
</tr>
<tr>
<td>Under bed fumigator[b]</td>
<td>32.256</td>
<td>4.7</td>
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</tbody>
</table>

[a] A 67:33 mixture of methyl bromide chloropicrin applied at 448 kg/ha during formation of planting beds. Beds covered immediately with a high-density polyethylene plastic mulch.

[b] A 65:35 mixture of 1,3-dichloropropene plus chloropicrin applied using the under bed fumigator 7 days after beds were formed and covered with a virtually impermeable plastic film. Treated area was 0.5 ha.