**Multiple Quarantine Treatment Using Bale Compression and a Three-Day Fumigation to Control Hessian Fly (Diptera: Cecidomyiidae) in Exported Hay**

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**ABSTRACT**  A multiple quarantine treatment was developed to control Hessian fly puparia, *Mayetiola destructor* (Say), the stage of regulatory concern in exported hay. In a commercial test using 51,389 puparia, no insects survived to the adult stage after exposure to bale compression at 137 kg/cm² and fumigation with 61 g/28.3 m³ hydrogen phosphide for 3 d. The puparia were fumigated in infested wheat seedlings in cloth bags inside compressed timothy bales placed in different locations in three replicate freight containers in a heated building. Fumigant concentrations were 345–522 ppm on day 1; 580–824 ppm on day 2; and 680–861 ppm on day 3. Monitored temperatures were <20°C in all locations allowing the fumigation temperature to be established at ≥20°C. Copper detection plate corrosion values were severe inside the freight container doors, and moderate in the middle of bales in all locations, providing visual confirmation of exposure to hydrogen phosphide. Hydrogen phosphide residues in exposed hay bales were found in trace amounts, below the U.S. Environmental Protection Agency tolerance of 0.1 ppm for animal feeds. Timothy hay used in the commercial test is the representative species for all previously exported hay and straw species. The new multiple quarantine treatment is proposed for use with all previously tested bale sizes and wrapper styles for which 3-d fumigation data has been reported, and for bales and wrappers derived from those tested.

**KEY WORDS**  *Mayetiola destructor* (Say), hydrogen phosphide, commodity treatment, system approach, quarantine security

Hessian fly, *Mayetiola destructor* (Say), is a domestic pest of regulatory importance in hay exported to Asia Pacific and Middle East markets, and some countries may accept a treatment as an option to other procedures such as inspection upon entry to ensure that accidental introductions of the pest do not occur through imported hay. In the life-cycle of Hessian fly (Packard 1928, Pike and Antonelli 1981), larvae feed and develop into puparia, the stage that overwinters and oversummers in wheat stalks. The puparia may occur in harvested hay, and is therefore the life stage of regulatory concern in exported stalks. The puparia may occur in harvested hay, and is therefore the life stage of regulatory concern in exported stalks. However, Hessian fly is unlikely to be found in export quality hay grown and harvested in the western United States. The pest is excluded by elimination of potential weed hosts during crop cultivation. Furthermore, most exported hay species do not serve as plant hosts. In addition, field sanitation and harvesting practices cause a high level of insect mortality (Yokoyama and Cambron 2013), further reducing the risk of insect contamination.

Export size bales of harvested hay are produced in modern compressors that use high levels of hydraulic pressure. Bale compression combined with hydrogen phosphide fumigation has been shown to cause complete mortality of high numbers of experimental Hessian fly puparia, the life stage of regulatory concern (Yokoyama et al., 1993a,b, 1994a,b, 1996, 1999, Yokoyama and Miller 2003; Yokoyama 2011). A multiple quarantine treatment for compressed bales, film-wrapped compressed bales (Yokoyama et al. 1999), and large-size, polypropylene fabric-wrapped bales (Yokoyama 2011) was approved by the U.S. and foreign regulatory agencies for control of Hessian fly. The duration of the fumigation phase used in this treatment is currently 7 d, but a shorter fumigation period would expedite handling procedures and reduce costs to process the commodity for export markets. A 3-d fumigation in a preliminary commercial test was shown to cause complete control of 2,160 Hessian fly puparia in compressed standard bales (Yokoyama and Miller 2003). Development of a new quarantine treatment with a shorter fumigation period requires testing a large number of insects to confirm treatment efficacy. To fulfill these requirements, a commercial test of the multiple quarantine treatment using bale compression and a 3-d hydrogen phosphide fumigation to
control Hessian fly was conducted during spring 2012 at Ward Rugh, Ellensburg, WA.

Materials and Methods

Test and Control Insects. Hessian fly puparia were reared on 'Eden' wheat seedlings in flats (11 rows per flat; 36 cm in width by 51 cm in length by 6.5 cm in height) with 14 flats per each of two benches in a glass greenhouse at the U.S. Department of Agriculture–Agricultural Research Service (USDA-ARS), San Joaquin Valley Agricultural Sciences Center (SJVASC), Parlier, CA, according to methods described by Yokoyama et al. (1996). The number of wheat seedlings per row was calculated from the mean ± SEM of six replicates of 11 rows selected at random, with one to two rows per flat, and three of the six replicates taken from each of two benches.

After infestation, wheat seedlings infested with Hessian fly puparia were harvested by cutting the plants below the roots. Excess roots, soil, and leaves above the stems were removed. In total, 256 rows were harvested for the commercial test, and 21 rows were used for controls in 308 rows planted. The remaining 31 rows were not harvestable because of the severe insect damage.

Controls were handled according to previously developed procedures (Yokoyama et al. 1994a,b) for determining efficacy in fumigation tests and consisted of 100 wheat seedlings infested with Hessian fly puparia selected at random and harvested from 21 rows in 28 flats. Each sample of 100 infested wheat seedlings was divided into 50 plants, and placed on a plastic pot (≈10.0 cm in diameter at the rim by 7.1 cm in diameter at the base by 10.2 cm in height; model 1255, Anderson Die and Manufacturing, Portland, OR) filled with vermiculite to a depth of 7.6 cm and saturated with water. A cage cover was made with a clear plastic cup (≈8.5 cm in diameter at the rim by 5.8 cm in diameter at the base by 10.7 cm in height; model KC12S, Fabri-Kal, Kalamazoo, MI) that had a 3-cm-diameter hole cut in the bottom and a 1.2-cm hole cut in the side. The bottom hole was used for ventilation and was covered with a nylon net held in place with hot glue. The side hole was used for access to aspirate emerging adults and was plugged with a size 00 rubber stopper. The cage was inverted and placed over the infested wheat seedlings in the pot. Each caged pot was considered a replicate. Pink flagging tape (122 cm in length) was attached to the top of the bag to facilitate placement in the bales and recovery after the test. In total, 90 bags were constructed. Approximately 1.4 rows of infested wheat seedlings from a flat were placed into each pouch. In total, 180 pouches were filled with 256 rows of infested wheat seedlings. The openings to the pouches were stitched closed and the bags were randomized.

Copper detection plates, 5 cm in width by 3 cm in height, in plastic holders were used to determine the severity of exposure to hydrogen phosphate by corrosive darkening of the exposed surface.

Bale Compression. Cloth exposure bags containing wheat seedlings infested with Hessian fly puparia, and a copper detection plate were placed in timothy, Phleum pratense L., hay before compression. The visual rating of hay quality was premium dairy grade. Two adjacent bags were placed near each end and in the middle of each test bale (six bags per bale) and the copper plate was placed in the middle of the bale. Fifteen bales were prepared with test materials (a total of 90 bags with two pouches per bag, and 15 copper plates). The bales were compressed in a Huntwood Technologies FC 9000, 4-tie bale compressor. Pressure on each bale was determined from values recorded from the compressor monitor and each bale was weighed after compression. The results reported as the mean ± SEM of 15 bales.

Freight Containers. Three replicate freight containers (≈2.4 m in width by 12.2 m in length by 2.9 m in height, volume 76.4 m$^3$) were loaded with test and nontest bales. Twenty-seven rows of compressed 4-strap bales with 16 bales per row (four bales in width by four bales in height) were placed into each freight container. Each bale containing six bags of Hessian fly-infested wheat seedlings and a copper plate was placed at random in each of the following five positions in each replicate freight container: row 1, front top and bottom; row 14, middle; and row 27, back top
and bottom. A copper plate was attached to the inside of the right, back door of each freight container.

**Temperature Monitors.** Thermistor probes (11.4 cm in length; accuracy ± 0.1°C; model ON-403-PP, Omega, Stamford, CT) were placed into the side of each test bale and into the middle air space of the freight container. The thermistor probes had vinyl cables that extended to the back of the freight container. The cables terminated in phone-plug connectors that extended under the door and outside of the freight container. Temperatures were monitored with a digital thermistor thermometer (accuracy ± 0.25°C; model 450-ATH, Omega, Stamford, CT) and recorded once each day at the same time after the test was begun, and also 7 h before the daily reading.

Data loggers were used to monitor temperatures among the test bales and in the middle air space of the freight container. The sensor of the data logger was placed in a 9-mm-diameter channel drilled into the bales, except in two freight containers where the sensors were between the bales in the front top and front bottom locations. The data loggers were wrapped in plastic bags and fastened to the bales with cloth tape.

**Gas Lines.** Colored, polyethylene gas lines (4.3-mm inner diameter by 6.4-mm outer diameter) to monitor fumigant concentrations were connected by tubing to type 304 stainless steel tubes (34 cm in length by 4.9-mm inner diameter by 6.4-mm outer diameter) driven into bales with test materials. The gas lines from the test bales in each of the five positions in the freight container (red front top, blue front bottom, green middle bale, yellow back top, and black back bottom) and from the middle-air space (white) were extended to the back door, under the bottom door seal to the exterior, and closed with a dust cap made of tubing and tape.

**Fumigation.** Each freight container was fumigated with 61 g/28.3 m³ hydrogen phosphide using five packages of 33 aluminum phosphide, 3 g tablets (one tablet per 1 g hydrogen phosphide; Phostoxin, Degesch America, Weyers Cave, VA). The tablet packages were attached approximately 183 cm apart with binder rings on a 4-mm-diameter nylon rope. The end of the rope with the first tablet package was attached to a polyvinyl chloride pipe, 2.5 cm in diameter by 12.2 m in length, and pushed into the air space above the rows of bales in each freight container. The freight containers were placed in a building (18.3 m in width by 48.8 m in length) heated with natural gas radiant tube heaters thermostatically controlled at 19.4°C for 3 d.

Gas concentrations were determined with a Porta-Sens II detector (No. 00-1034, 200–2,000 ppm PH₃ sensor; Analytical Technology, Collegeville, PA), calibrated for ±5% accuracy, each day at the same time after the beginning of fumigation for 3 d. Additional concentrations were determined approximately 7 h before the daily reading. One 4-strap compressed bale was placed near the three freight containers and used in residue analysis to determine natural levels of volatile phosphorus compounds in the hay. Temperatures and fumigant concentrations were reported as the mean ± SEM in the different locations of the three replicate freight containers at 1–3 d. Temperatures inside the heated building were monitored with a temperature and relative humidity recorder (model CTXL-TRH-W, ±1°C accuracy, Omega Engineering, Stamford, CT) and three data loggers and reported as the mean ± SEM.

At the end of the 3-d fumigation, the freight containers were aerated for 24 h and unloaded. The test materials were removed from the test bales and transported to the SJVASC, Parlier, CA, for evaluation.

Corrosion of copper detection plates used to visually confirm exposure to fumigant in each test bale and from the freight container door were scored as 1, light; 2, moderate; and 3, severe; and reported as the mean ± SEM of the three replicates for each location.

**Evaluation of Hessian Fly Survival.** Infested wheat seedlings exposed to bale compression and fumigation in the commercial test were removed from the fabric bags. The infested wheat seedlings from one pouch of each bag was placed on a pot of vermiculite saturated with water, covered with a plastic cage, and handled in the same manner as the unexposed controls. The presence of an adult was used as the criteria of treatment survival during a minimum 95-d evaluation period followed by an additional 35 consecutive days of no adult emergence in controls. Thereafter, the bottom of the caged pots containing infested wheat seedlings that had been exposed to compression and fumigation were examined for dead Hessian fly adults.

The total number of Hessian fly puparia exposed to compression and hydrogen phosphide fumigation in the three replicate freight containers in the commercial test was calculated by multiplying the number of wheat seedlings used in the commercial test by the number of Hessian fly adults reared per plant in the controls.

**Residue Analysis.** Three samples of hay (≈100 g per sample) were collected at random from bales containing test materials in the front, middle, and back locations in each of the three replicate freight containers after aeration and during recovery of test materials. Three samples of hay were also collected from the nonfumigated bale that was held with the freight containers in the heated building. The samples were placed in closable plastic bags, transported to the USDA-ARS, Parlier, CA, and frozen until used for residue analysis.

### Table 1. Mean (± SEM) number of infested wheat seedlings per row, adults reared in controls, and the total number of Hessian fly puparia in the commercial test of the multiple quarantine treatment using bale compression and a 3-d hydrogen phosphide fumigation

<table>
<thead>
<tr>
<th>No. plants per rowa</th>
<th>No. adults per plantb</th>
<th>Total no. pupariac</th>
</tr>
</thead>
<tbody>
<tr>
<td>114.5 ± 4.7</td>
<td>1.76 ± 0.12</td>
<td>51, 589</td>
</tr>
</tbody>
</table>

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a Six replicates of 11 rows.
b Number of adults in controls reared per plant in 42 replicates of infested plants (50 plants per replicate; n = 2,100) harvested from 21 rows selected at random from 28 flats.
c Number of wheat seedlings per row multiplied by 256 rows in three replicate freight containers, multiplied by the number of adults reared per plant in the controls.
A 25-g sample of hay from each plastic bag was placed in a 500-ml blender jar containing 50 ml of water, covered with a lid containing a septum, homogenized for 1 min and allowed to equilibrate for 3 min. Headspace gas samples were collected through the septum with a gas-tight syringe, and injected into the gas chromatograph using a gas-sampling valve with a 0.25-ml loop. Retention time for hydrogen phosphide was 3.0 min. Headspace gas samples were collected by placing in a 500-ml blender jar containing 50 ml of timothy hay fumigated (61 g/28.3 m³ hydrogen phosphide at 1.2 kg/cm², and the make-up gas flow rate was 20°C and a 24 h aeration in a commercial test.

**Results**

The calculated total number of Hessian fly puparia exposed to the multiple quarantine treatment of bale compression and a 3-d hydrogen phosphide fumigation was 51,589 (Table 1) based on adult emergence in controls. About 17,196 puparia were tested in different bale locations in each of the three replicate freight containers. Wheat seedlings infested with Hessian fly puparia from exposed test bales and nonexposed controls were maintained in caged pots at 21.7 ± 0.3°C (mean ± SEM) in the laboratory. No Hessian fly adults developed from puparia exposed to the multiple quarantine treatment (Table 2).

Bale compression was 137.4 ± 1.3 kg/cm² in the first phase of the multiple quarantine treatment, and resultant bale weight was 58.4 ± 1.9 kg. Test bale and middle air space temperatures recorded with data loggers (Table 2) and thermistor probes were <20°C during fumigation. Temperatures ranged from 13.7 to 19.8°C and from 17.2 to 19.9°C during the 3-d fumigation as determined by data loggers (Table 2) and thermistor probes, respectively. Daily temperatures determined with data loggers during the fumigation phase are shown in Table 2. Data logger temperatures inside the heated building were 18.0 ± 0.2°C.

Fumigant concentrations (Table 2) in all locations with test bales in the three replicate freight containers ranged as follows: day 1, 345–522 ppm; day 2, 580–824 ppm; day 3, 680–861 ppm, and peak concentrations were observed before the end of the day 3 (Fig. 1), indicating maximum fumigant was liberated from aluminum phosphide tablets within 3 d.

Mean copper plate corrosion values on freight container doors and in test bales had severe and moderate corrosion scores (Table 2), respectively, and provided...

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**Table 2. Mean (± SEM) Hessian fly adults emerging from exposed puparia, temperatures and fumigant concentrations, and copper detection plate values in different locations in three replicate freight containers containing 4-strap bales of compressed (137 kg/cm²) timothy hay fumigated (61 g/28.3 m³ hydrogen phosphide at < 20°C) for 3 d to control Hessian fly in a commercial test**

<table>
<thead>
<tr>
<th>Location</th>
<th>No. adults</th>
<th>Temp° (C)</th>
<th>PH₃ concn (ppm)</th>
<th>Temp° (C)</th>
<th>PH₃ concn (ppm)</th>
<th>Temp° (C)</th>
<th>PH₃ concn (ppm)</th>
<th>Copperplate value &lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front top</td>
<td>0</td>
<td>18.6 ± 0.5</td>
<td>372.3 ± 10.2</td>
<td>18.8 ± 0.3</td>
<td>632.0 ± 15.6</td>
<td>18.9 ± 0.2</td>
<td>735.3 ± 3.3</td>
<td>2 ± 0</td>
</tr>
<tr>
<td>Front bottom</td>
<td>0</td>
<td>17.6 ± 0.3</td>
<td>369.3 ± 12.7</td>
<td>18.0 ± 0.2</td>
<td>615.3 ± 18.0</td>
<td>18.0 ± 0.3</td>
<td>728.7 ± 24.4</td>
<td>2 ± 0</td>
</tr>
<tr>
<td>Middle bale</td>
<td>0</td>
<td>17.2 ± 0.2</td>
<td>434.7 ± 15.9</td>
<td>17.5 ± 0.2</td>
<td>683.7 ± 29.2</td>
<td>17.6 ± 0.1</td>
<td>750.0 ± 15.7</td>
<td>2 ± 0</td>
</tr>
<tr>
<td>Middle air</td>
<td>0</td>
<td>17.5 ± 0.3</td>
<td>490.3 ± 16.3</td>
<td>17.7 ± 0.2</td>
<td>746.3 ± 40.4</td>
<td>17.8 ± 0.1</td>
<td>828.3 ± 11.7</td>
<td>2 ± 0</td>
</tr>
<tr>
<td>Back top</td>
<td>0</td>
<td>18.0 ± 0.3</td>
<td>447.0 ± 11.0</td>
<td>18.5 ± 0.2</td>
<td>704.3 ± 25.8</td>
<td>18.5 ± 0.2</td>
<td>842.7 ± 10.4</td>
<td>2 ± 0</td>
</tr>
<tr>
<td>Back bottom</td>
<td>0</td>
<td>17.1 ± 0.5</td>
<td>454.3 ± 5.9</td>
<td>17.6 ± 0.4</td>
<td>715.3 ± 19.2</td>
<td>17.4 ± 0.5</td>
<td>827.7 ± 6.5</td>
<td>2 ± 0</td>
</tr>
<tr>
<td>Door</td>
<td>0</td>
<td>17.1 ± 0.5</td>
<td>454.3 ± 5.9</td>
<td>17.6 ± 0.4</td>
<td>715.3 ± 19.2</td>
<td>17.4 ± 0.5</td>
<td>827.7 ± 6.5</td>
<td>2 ± 0</td>
</tr>
</tbody>
</table>

<sup>a</sup> Three replicates of 96 determinations per day with temperature loggers with external sensors inside test bale, except with sensors between bales in the front top and front bottom of two replicates.

<sup>b</sup> Three replicates of one determination per day.

<sup>c</sup> Three replicates of degrees of corrosion: 1, light; 2, moderate; and 3, severe.

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**Fig. 1.** Mean (±SEM) total hydrogen phosphide concentrations in all locations of three freight containers during a 3-d fumigation with 61 g/28.3 m³ hydrogen phosphide at <20°C.
visual verification of fumigation. Trace fumigant residues (Table 3) were detected in hay samples from three locations in each of the three replicate freight containers and did not exceed 0.01 ppb.

**Discussion**

Implementation of this new treatment to control Hessian fly in exported hay will provide quarantine security and expedited processing of bales produced and shipped from the western states. The commercial test fulfills the U.S. and other regulatory agency requirements including those of Japan, for zero survivors in 30,000 insects tested. Therefore, certification of containers as free of any Hessian fly after treatment will allow the unimpeded movement of containers of hay to customers in foreign markets without further restriction at ports of entry.

The two-phase, multiple quarantine treatment of bale compression to produce 4-strap bales of the dimensions and weight shown in Table 4, followed by a 3-d fumigation with 61 g/28.3 m³ hydrogen phosphide at ≃20°C has been submitted to the U.S. and foreign regulatory agencies for approval. The procedure was confirmed to control Hessian fly with resultant fumigant residues below the 0.1 ppm tolerance for animal feed (Degesch America 2010), verifying that treated hay is safe for livestock consumption. The use of bale compression as a single treatment has been proposed for hay is safe for livestock consumption. The use of bale compression as a single treatment has been proposed as the standard is consistent with previously accepted multiple quarantine treatments developed for the Japanese market. Other hay species exported to Asia Pacific countries include perennial ryegrass, *Lolium* L.; annual ryegrass, *Lolium* L.; brome grass, *Bromus inermis* Leyss.; bluegrass, *Poa* L.; fescue, *Festuca* L.; teff, *Eragrostis tef* (Zuccagni) Trotter; orchardgrass, *Dactylis glomerata* L.; kleingrass, *Agrostis L.*; and bentgrass, *Alopecurus pratensis* L.; and the use of timothy grass, *Phleum pratense* L., and Bermuda grass, *Cynodon dactylon* (L.).

Implementation of the new multiple quarantine treatment provides a modern update of previous techniques to control Hessian fly, and provides a high quality product especially when a continuous supply of hay may be needed (Yokoyama 2012). The treatment helps fulfill a changing market for different processed forage products, enhances the economy of the U.S. hay export industry, and provides foreign livestock producers with a premium domestic product.

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References Cited

Degesch America. 2010. Applicator’s manual for Degesch phostoxin tablet prepac and prepac rope. Degesch America, Weyers Cave, VA.


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